Monitoring of unconventional oil and gas extraction and its policy implications: A case study from South Africa

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ABSTRACT

Biophysical and socio-economic monitoring during unconventional oil and gas (UOG) extraction is important to assess change and to have reference conditions against which to identify UOG extraction activity impacts. The large-scale cumulative impacts of UOG extraction standardised monitoring across geographic and socio-political regions important. This article emphasises the importance of a robust monitoring framework that must serve as a guideline for planning monitoring activities during UOG extraction. A case study from South Africa is presented to illustrate important aspects to address during the development of a UOG extraction monitoring framework. The South African case is critically assessed and resultant policy implications are discussed. Important policy considerations include performing baseline monitoring during UOG extraction, performing UOG extraction monitoring in an integrated, systematic, and standardised manner, ensuring that proper resources are available to perform the monitoring and implementing an adaptive management plan that is linked to UOG extraction monitoring.

Keywords: Unconventional oil and gas, biophysical, socio-economic, monitoring, framework, policy development, South Africa

1. Introduction

In recent years, unconventional oil and gas (UOG) has become an increasingly important additional resource for many countries to augment their energy resources (EIA, 2017; Castro-Alvarez et al, 2017; Agerton et al, 2017). UOG is defined as oil and gas trapped in geological formations with low permeability, requiring stimulation to free the gas (Broomfield, 2012). Typically, stimulation entails hydraulic fracturing. This method requires the pumping of hydraulic fracturing fluid into the target formations via a deep well, resulting in microfractures in the rock through which oil and or gas is released. The microfractures are kept open by solid particles (typically sand) which is included in the hydraulic fracturing fluid. This enables trapped oil or gas to flow out to the surface. Until quite recently these resources were not accessible for extraction, but as a result of technological advances such as hydraulic fracturing, they are increasingly within reach.

UOG extraction is associated with a range of interlinking impacts of concern at a regional scale. Possible negative environmental impacts include impacts on the quality and quantity of both surface water and groundwater resources (Jackson et al., 2014; Broderick, 2011; Herridge et al., 2012; Rahm et al., 2013; Rahm and Riha, 2012) and possible increased seismicity associated with deep well wastewater injection as well as fracking operations (Kijko et al., 2016; Rubenstein and Mahani, 2015; Keranen, 2013; NRC, 2012a). Air quality impacts can also ensure from fugitive releases and flaring (Farina, 2011; Elvidge, 2011), while UOG extraction can also cause landscape fragmentation and biodiversity impacts (Slonecker et al, 2012). The negative social-economic impacts resulting from UOG extraction can include: (1) the disruption of social cohesion, (2) competition over water between oil and gas companies and existing lawful water users, (3) the potential health risks associated with lack of access to water and adequate sanitation, and (4) higher population density in ecologically sensitive and water scarce areas (Redelinghuys 2016; Schafft et al., 2013, Warren, 2013; Broderick et al., 2011; Dolesh, 2011;).

The impacts that may emanate from UOG extraction makes environmental and socio-economic monitoring of various aspects before, during and after unconventional oil and gas (UOG) exploration and extraction vital. Through effective monitoring of areas of concern decision-makers are able to assess changes in these aspects and act to either prevent or mitigate potential impacts. The complex nature of UOG extraction and its related impacts calls for a robust monitoring plan to limit potentially harmful environmental and socio-economic impacts and to gather relevant data that can be used by governments to manage UOG extraction. A monitoring framework that includes information on the biophysical and socio-economic aspects to be monitored; the frequency of monitoring and; parties responsible for the monitoring would be a useful tool for governments in this regard. A UOG extraction monitoring framework can also be used as a guideline for planning monitoring activities during the various phases of UOG extraction. The usefulness of monitoring frameworks to gather environmental data of complex development activities have been illustrated by various researchers (Li et al., 2016; Harris et al., 2016; Kinchy et al., 2015; Phinn, 2010; Vos et al., 2000).

This article describes the development of the South African UOG extraction monitoring framework and its policy implications. Two monitoring aspects of this framework, namely surface water and socio-economics, are presented in the form of a case study to illustrate the importance of monitoring both biophysical and socio-economic aspects during UOG extraction.

2. Monitoring UOG extraction impacts on water resources and socio-economics: The global and South African context

The Global context

Policy-relevant aquatic resources monitoring for UOG extraction is lacking in most countries (Brantley et al., 2014; Small et al., 2014; Vidic et al., 2013). Water resources monitoring is mostly focused on groundwater protection and to ensure well integrity (Kang et al., 2014; Ingraffea et al., 2014; Jackson et al., 2013). In most cases, the availability of monitoring data to assess surface water contamination events are limited (Brantley et al., 2014; Kurek et al., 2013; Entrekin et al., 2011). For the purpose of developing sound environmental policy, Entrekin et al. (2011) and Kurek et al. (2013) stress the need for a well-executed monitoring programme to assess changes in aquatic ecosystem structure and function caused by UOG extraction.

In the US, baseline information for surface and groundwater quality is usually sparse or non-existent (Bowen et al., 2015). Here, water resources monitoring is typically coordinated at the state level and requirements vary by state, while data collected by private oil and gas companies are proprietary and not available to the public (Bowen et al., 2015). This limits the availability of consistent monitoring data across regions. Bowen et al. (2015) conclude that, because water quality for UOG extraction is monitored at state level and not for set analytes at an appropriate spatial distribution at regional level, this data cannot assess water quality at national level. This was also a concern in Norway (Gray et al., 1999) and Canada (Seitz et al, 2011). Jefferies (2012) and Tan et al. (2014) reiterates the importance of regional monitoring of water resources to assess the cumulative risk of UOG extraction.

Important recommendations for existing water resources monitoring programmes include, amongst others:

- High quality baseline surveys of water resources should be performed before UOG extraction (Krupnick et al., 2014; Sheelanere et al., 2013; Cook et al., 2013).
- Best monitoring practice should be followed (Cook et al., 2013).
- Aquatic monitoring programmes should establish an ongoing system of independent scientific input to the program (Ayles et al., 2004).
- Monitoring programmes should use adaptive feedback loops and change the monitoring programme based on findings (Ayles et al., 2004).
- Monitoring should include an information management system (Sheelanere et al., 2013; Ayles et al., 2004).
- Monitoring data should be made available to all stakeholders (Sheelanere et al., 2013).
- The correct variables for water resources need to be monitored during UOG extraction (Dube et al., 2006).
- Consistency between monitoring efforts in different regions and on different administrative levels needs to be improved (Sheelanere et al., 2013; Dube et al., 2006).

With regard to socio-economic variables, in spite of the potential value of socio-economic monitoring of the impacts of UOG extraction, it is rarely done at local, state or federal level in the US (Haggerty and McBride, 2016). Some states mandate pre-development impact assessments, but no socio-economic monitoring occurs during and after UOG extraction (Haggerty and McBride, 2016). Any monitoring for socio-economic impacts of UOG development typically occur on an ad hoc basis and at a localised level. Perry (2013), for example used ethnography to monitor chronic stress in individuals and communities associated with UOG development, while Esswein et al. (2014) offers an example of the monitoring of the health of UOG industry workers. Werner et al (2015) also note that most of the studies on the environmental health impacts of UOG extraction lacks methodological rigour.

Socio-economic impacts from UOG extraction may include diminished long-term economic performance due to boom-bust cycles, poverty, unemployment, property devaluation and social disruption when rapid industrialization and population growth intersect with limited local capacity (Haggerty and McBride, 2016; Jacquet, 2014). Mining companies will typically attempt to secure a "social license to operate" (SLO) through various community initiatives, including charity, infrastructure improvement, health programs, support to local businesses through procurement policies and sustainable livelihood projects (Kotilainen et al., 2015; Curran, 2017). These company interactions with local community groups may create dependency relations (Kotilainen et al., 2015), or relationships of patronage and clientelism in the local community (Rajak, 2012), which may reduce the willingness of local leaders to monitor UOG company activities.

Rapid UOG development can also increase the nature and level of risks faced by local authorities (Jacquet, 2009) as development often proceeds at a pace that exceeds the ability of governments to keep up with necessary service delivery and infrastructure needs. Local authorities often have to bear the brunt of new service delivery demands immediately following mining developments, but the expected revenue does not arrive until much later, either from local taxation or government grants (Jacquet, 2009; Chapman et al., 2014). To alleviate the strain on government, the European Commission's *Oil and Gas Sector Guide on Implementing the UN Guiding Principles on Business and Human Rights* advises that UOG companies should monitor the impact of their activities on the human rights of employees and communities (EC, n.d.).

The South African context

In 2011, various UOG extraction companies applied for exploration licenses with the Petroleum Agency of South Africa (ASSAF, 2016). At that time, the researchers realised that this new extractive technique could impact negatively on the biophysical and socio-economic environments in South Africa. After studying the possible biophysical and socio-economic impacts of UOG extraction (Esterhuyse et al., 2014) the researchers realised the importance of preparing for the possibility of UOG extraction by performing baseline monitoring before exploration starts. In view of this, the research team developed a monitoring framework for UOG extraction in South Africa from funding provided by the South African Water Research Commission.

After the development of this framework, the South African government, through Cabinet and various other decision-making institutions, has made high-level public commitments to shale gas exploration (Scholes et al., 2016). This monitoring framework (Esterhuyse et al., 2014) was subsequently taken up in the Strategic Environmental Assessment (SEA) for shale gas development, which was commissioned by the Department of Environmental Affairs in South Africa (Scholes et al., 2016). The aim of the SEA was to provide an integrated assessment and decision-making framework to enable South Africa to establish effective policy, legislation and sustainability conditions under which shale gas development could occur (Scholes et al., 2016). The monitoring framework thus serves as a guide for national government in effective policymaking for the protection of natural resources and to improve the current state of socio-economic development.

This framework had to include both biophysical and socio-economic aspects, as these two issues are interlinked. The following discussion elucidates the environmental and socio-economic context underlying the development of this monitoring framework.

South Africa is a water scarce country (Muller, 2013) and large water requirements for fracking (Guo et al., 2017) and the potential influx of people to oil and gas development areas will put additional pressure on already strained local water resources (Hobbs et al., 2016, Esterhuyse et al., 2016) and water-related infrastructure (i.e. sanitation systems) (Oelofse et al., 2016). Communities in targeted UOG extraction areas are subjected to a range of environmental and socio-economic challenges that render them vulnerable to the potential impacts of UOG development. The communities in question are, firstly, dependent on limited water resources, with most of the towns in the targeted area being solely dependent on groundwater as a source of drinking water (Redelinghuys 2016; Woodford et al., n.d.). In most rural towns in South Africa, poverty, unemployment, welfare dependence and destitution converge to create localities of extreme socio-economic vulnerability (Nel et al. 2011). Poverty rates in these rural towns range from between 40 - 60% (Atkinson et al., 2016) and local government structures are challenged severely in coping with service delivery demand in the face of high levels of socio-economic vulnerability (Van der Byl, 2014).

Since any negative UOG extraction impacts (such as in-migration, rising health issues, decreased economic diversity and associated increased unemployment and crime) would be much more severe in communities that already suffer from low levels of health and well-being, monitoring the socio-economic impact of UOG extraction on such communities is paramount. Baseline monitoring would ensure that the relevant government structures (i.e. the National Department of Social Development, responsible for social welfare) have known reference conditions against which to identify any possible impacts emanating from UOG extraction activities.

Ideally, UOG extraction should not proceed before a comprehensive set of baseline data for the proposed extraction area has been established for both biophysical and socio-economic aspects (Krupnick et al., 2014; Sheelanere et al., 2013; Cook et al., 2013). Compliance monitoring during baseline monitoring, as well as during UOG exploration and extraction, is also important to ensure compliance with regulatory monitoring requirements. As UOG impacts could occur during any of the phases of UOG extraction (from exploration through production and after well decommissioning) the monitoring framework that we developed, focused on all of these phases. This would ensure that any baseline monitoring would tie in seamlessly with monitoring performed during UOG production and post production.

3. Development of the Unconventional Oil and Gas extraction monitoring framework for South Africa

A number of issues guided the development of the UOG extraction monitoring framework. Firstly, the monitoring framework had to cater for each phase of UOG development. UOG extraction follows the phases from *Exploration* during which a resource is located and the economic viability of extracting the oil and/or gas is assessed, after which the *Extraction phase* follows, if an economically viable resource is found. Once a well stops producing gas, it is decommissioned during the *Post extraction phase*. Impacts that have been identified per UOG extraction phase, can vary greatly across phases (Figure 1), necessitating a phased monitoring approach.

Figure 2 addresses three additional issues of importance related to the development of a monitoring framework for UOG extraction: 1) The guiding questions underlying the development of a monitoring framework, 2) Possible models to identifiy the relevant parties that should assume responsibility for performing the monitoring of UOG development activities and 3) core considerations during the development of a UOG monitoring framework. Section 1 (Guiding questions for the development of a monitoring framework) is based on the monitoring framework by Wilderman and Monismith (2012) and has been adapted to also include the question “Who must do the monitoring?”

UOG Exploration phase

Activities: Locate gas reservoirs using geophysical surveys, drilling, test core samples with lab techniques.

Thereafter test economic viability with e.g. hydraulic fracturing (HF) & test flaring.

Impacts:

During reconnaisance:

Environmental impacts on biodiversity, soil & water

During economic vaibility testing:

Environmental impacts on biodiversity, soil, water & air quality

Impacts on visual astronomy & radio astronomy

UOG Extraction phase

Activities: Mine gas with HF, place wells to produce gas optimally, have infrastructure in place to capture & transport gas, wastewater management facilities

Impacts:

Environmental impacts

Water use

Employment impacts

Health impacts & social ills

Agriculture & food security impacts

Post UOG extraction phase

Activities: Decommissioning of unproductive gas wells

Impacts:

Legacies of contaminated land, land devaluation.

Long term waste management

Borehole deformation , disintegration and leakage over long term (50+ years).

Economic and employment impacts in former UOG extraction areas

Figure 1: Activities and impacts per UOG development phase

Section 1: Guiding questions for the development of a monitoring framework

1. Why do we want to monitor?
2. What do we need to monitor?
3. How will we monitor?
4. Where do we need to monitor?
5. When do we need to monitor?
6. Who must do the monitoring?

Section 2: Who must do the monitoring? Possible models

Model 1: Government monitors all aspects (from oil and gas company operations through to regional aspects, i.e. water resources);
Model 2: The industry is allowed total self-regulation, monitors all aspects and reports to government;
Model 3: An independent entity monitors all aspects; or
Model 4: A hybrid model is followed (government, industry and independent organisations all monitor different aspects)

Section 3: Core considerations in the development of a UOG monitoring framework

1. A phased monitoring approach is required (UOG extraction may range over many years and is extracted and developed in a phased approach).
2. Certain monitoring activities (especially for water resources and seismicity) need to start before exploration commences.
3. The regional scale of impacts makes integrated, systematic, standardised monitoring across regions crucial, in addition to integration between government agencies, and alignment between different pieces of legislation.
4. If alignment of government entities and legislation and the clear identification of mandates, roles, and responsibilities is not achieved, a central entity may need to perform the monitoring functions. Existing government structures may be re-aligned or academia can assist in the execution of these functions.
5. The monitoring entity must be independent and be perceived as being independent from oil and gas companies, and must perform the monitoring task in such a manner that it will have legal standing.
6. All monitoring performed by oil and gas companies as part of their operations, must adhere to strict reporting requirements to government and/or the independent monitoring institution and should be verified by independent monitoring.
7. Ensure that the person or entity responsible for the monitoring, is capable to execute such monitoring effectively and timeously.

Section 4: Finalisation and adaption of framework based on monitoring outcomes

Figure 2: Questions to be answered during the development of the UOG monitoring framework

The first five questions of the monitoring framework (Figure 2, Section 1) are usually easy to answer, but the question of who will do the monitoring (as described in Figure 1, Section 2) required more in-depth analysis for the South African case. There are some clear shortcomings to the first two models presented, where government monitors all aspects and where the industry is allowed total self-regulation. Governments may not have institutional capacity and human resources to perform all the monitoring, but if oil and gas companies perform total self-regulation, data may not be trustworthy due to a lack of independent verification (Huot and Grant, 2011). Handing over all monitoring to an independent entity (model 3) without verification and oversight could also be a cause for concern. The most suitable model may thus be a hybrid (model 4) where different parties have different monitoring responsibilities and there are various levels of cross-verification. This model would require a totally transparent regulatory framework (Sheelanere et al., 2013) and consistent application of rules and regulations (Sheelanere et al., 2013; Dube et al., 2006). The complexity of UOG operations typically involves mixtures of government regulation, industry self-regulation, and regulation by new institutions evolving from ad hoc multi-stakeholder collaborations (Boutilier and Black, 2013).

Other core considerations (Figure 2, Section 3) in the development of the UOG monitoring framework include, amongst others, the monitoring time-frame and scale, the independence of the entity that does the monitoring, and integration of monitoring across different institutional structures (Sheelanere et al., 2013; Dube et al., 2006). The cumulative nature and regional scale of possible impacts make integrated, systematic and standardised monitoring across regions very important, and necessitates integration between local and provincial government, alignment and cooperative governance between different government departments, and alignment between different pieces of legislation, among others, to make monitoring efforts in South Africa successful.

If government functions cannot be aligned, it may be necessary to develop a central entity to perform monitoring functions in an integrated and coordinated fashion. At this stage in South Africa, each government department is responsible for the data management related to its respective mandate. For example, the Department of Water and Sanitation is the custodian of water resources and protection and the related storage of water resource information (such as geological information, borehole logs, water quality data, etc.), while the Council for Geoscience is responsible for data management and storage (and archiving) of geology-related information, including mapping information and seismic data. These different entities with their respective mandates may make effective data curation problematic.

Data from government departments are, for the most part, open to the public and academia at no cost. However, some UOG company information may be classified as sensitive, making access to information problematic. It is therefore important to enhance public disclosure of fracking data to ensure that policymakers, researchers, industry and other stakeholders have access to comprehensive and reliable information on the localities of active and abandoned wells (Konschink and Dayalu, 2016), as well as related data that is required for the protection of natural resources and human health (Dundon et al., 2015; Brantley et al., 2014; Sheelanere et al., 2013; Huot and Grant, 2011). Effective curation of new information is therefore paramount (Sheelanere et al., 2013), as is the requirement that industry report any monitoring data to the government.

Lastly, it is important to assess monitoring results and adapt the monitoring framework (Ayles et al., 2004), if required (Figure 2, Section 4). UOG monitoring approaches may need to be adapted due to advances in technology, or because monitoring results indicate a required change in monitoring efforts (e.g. less monitoring would be required if no significant environmental change is observed over an extended period of time after closure, or if a pollution incident occurred it could require more intensive monitoring). Examples of advances in technology include increasingly sensitive remote sensing techniques, as well as data processing techniques related to computing capacity increases. Monitoring without assessment and adaptive management would constitute a waste of financial and human resources. All these aspects were addressed in the monitoring framework that was developed.

4. Highlighting selected aspects of the South African UOG monitoring framework

This section highlights selected aspects of the South African monitoring framework, namely surface water (to illustrate a biophysical monitoring aspect), and socio-economics (to illustrate the monitoring of socio-economic aspects). The frameworks presented here are based on the South Africa case, but offer relevant considerations for other countries. The surface water monitoring framework was also taken up in the strategic environmental assessment (Scholes et al., 2016), as mentioned earlier.

4.1 Surface water

The possible impacts of UOG extraction on water resources, including large consumption of water for fracking and water resources contamination (Broderick, 2011; Herridge et al., 2012; Rahm et al., 2013; Rahm and Riha, 2012; Guo et al., 2017) makes monitoring of surface water resources before, during and after UOG extraction extremely important for any country planning to embark on UOG extraction. In South Africa specifically, large areas where UOG development is being proposed have very little baseline data on surface water systems (rivers, pans, and wetlands). This lack of baseline data is attributed to the temporary nature of surface water in this area, and because very little development of water resources requiring water-use licenses has occurred here (Esterhuyse et al., 2014).

Based on the risk that UOG development poses to water resources and the limited available data, the precautionary principle should be applied (Avenant et al., 2016). This is especially the case if the threat of irreversible impacts on the biodiversity of the surface water systems is present.

In addition, most catchment areas identified for UOG extraction in South Africa are already stressed due to water demand currently outstripping supply, as well as the current state of pollution of water resources (Muller, 2013). With respect to South Africa's non-perennial rivers, stream permanency, stream flow intermittency, river conditions, and the condition of wetlands and pans are all important aspects that would influence the severity of the impact on surface water resources in the area of concern (Avenant et al., 2016). Climate change will likely put additional strain on the functioning of these, already vulnerable, systems (Hobbs et al., 2016). Impacts from UOG extraction on non-perennial river systems in water-stressed regions, coupled with the additional stressor of climate change, is also a serious concern for countries such as Australia where UOG extraction is currently performed (Cook et al., 2013; Kuch et al., 2013). This monitoring framework would therefore be useful for countries with similar climatic conditions.

To ensure that surface water resources remain sustainable, it is essential that monitoring is done on a regular basis. Importantly, a baseline that considers water quantity, quality, and habitat integrity, should be established prior to the commencement of any UOG exploration or extraction. The baseline data should cover all four seasons and, if possible, a wet and dry year in arid to semi-arid regions. The high natural variability of most environmental parameters in arid regions necessitates long-term monitoring before UOG exploration and extraction commences in order to compare data collected before, during and post extraction. Similar baselines would also be required in other countries considering UOG extraction, especially those with high climatic variability.

The monitoring framework for surface water resources is outlined in Table 1. Impacts of concern that need to be monitored during each phase include water quality, quantity, habitat integrity, present ecological state, and regulatory aspects (Bowen et al., 2015; Krupnick et al., 2014; Sheelanere et al., 2013). The table explains why, how and where this monitoring is to be done, and also describes who is responsible for the monitoring. Possible impacts of concern that need to be monitored during each phase, include:

Before exploration: Baseline quality and quantity of water resources for rivers, pans and wetlands (Bowen et al, 2015; Sheelanere et al, 2013; Krupnick et al, 2014) on screening level for current and expected UOG contaminants, and baseline habitat and present ecological state (PES). The baseline water quality and quantity parameters include river flow, depth measurements and daily rainfall. Habitat integrity can be assessed via the rapid habitat assessment method (DWAF, 2009a; DWAF 2009b) or the instream habitat integrity assessment tool (Kleynhans, 1996; Kleynhans et al., 2008) to determine habitat baseline. Observational and visual monitoring should also be performed as a control for the baseline. A representative site must be monitored in each resource unit, wetland or pan type, identified in proximity to possible extraction sites.

During exploration: Quality, quantity impacts on the water resource itself (Guo et al., 2017; Grant and Chrisholm, 2014) for physical parameters and specific trace elements and habitat impacts related to changes in river sediment delivery, loss of critical habitat (Zorn et al., 2008) and biota diversity (Davis et al., 2006). Monitor habitat change and PES. The rate and amount of water withdrawal should also

Table 1: Monitoring framework for surface water

Phases	Before exploration	During exploration	During extraction	After extraction
Possible impacts of concern that needs to be monitored **(WHY?)**	• No significant impacts during this phase Must however gather appropriate baseline information	• Quality, quantity impacts on the water resource itself • Habitat impacts and loss of critical habitat and biota diversity		• Long-term water quality impacts and bioaccumulation of toxic substances in fish • Habitat quality changes due to exposure to toxic substances
Aspects that need to be monitored **(WHAT)**	• Baseline quality and quantity of water resources • Baseline habitat and present ecological state (PES)	• Water resource quality and quantity changes (water withdrawal rates and volumes) • Habitat change and PES • Regulatory compliance monitoring		• Long term quality and quantity of water resources • Habitat change after closure • Regulatory compliance to mine closure specifications
How should these aspects be monitored?	• Determine baseline water quality • Assess habitat integrity to determine habitat baseline • Determine PES of water resources. • Perform observational and visual monitoring as a control for the baseline	• Monitor changes in water quality and quantity • Assess changes from habitat baseline • Determine PES of water resources • Perform observational and visual monitoring to determine the change from baseline • Adapt monitoring programme based on monitoring results assessment		• Monitor for long term changes in regional surface water quality • Monitor surface water quality if groundwater pollution is suspected. • Perform observational and visual monitoring to determine change from previous phases • Monitor compliance with mine closure specifications
Where must these aspects be monitored?	• A representative site in each resource unit, wetland or pan type, identified in proximity to possible extraction sites	• A representative site in each resource unit, wetland or pan type, identified in proximity to possible extraction sites • Monitor flowback and produced water at the source, at the point of discharge, and downstream of discharge		• A representative site in each resource unit, wetland or pan type, identified in proximity to possible extraction sites • Sites in at least a 1km radius from closed production sites should be monitored if contamination is suspected
Who must do the monitoring?	• State department mandated to monitor water resources (as oversight and umbrella organisation), UOG company (to provide site-specific information) and an independent organisation (if state department cannot provide umbrella / oversight function)			• State department mandated to monitor water resources (long term regional monitoring), UOG company (monitor for a period after closure) and an independent organisation (if state department cannot provide regional monitoring)

be monitored and reported to state agencies, while regulatory compliance monitoring to license conditions is also required (Sheelanere et al, 2013). A representative site in each resource unit, wetland or pan type, identified in proximity to possible extraction sites would have to be monitored. In addition, flowback and produced water at the source, at the point of discharge, and downstream of discharge, must also be monitored.

During extraction: Quality, quantity impacts on the water resource itself from pollution incidents and water requirements for fracking (Guo et al., 2017; Zorn et al., 2008). Habitat impacts related to water quality or due to changes in river sediment delivery due to infrastructure development (Herridge et al., 2012; Rahm and Riha, 2012; Lyons, 2012; Scott et al., 2011; Jackson et al., 2011), loss of critical habitat, loss of biota diversity (Davis et al., 2006). Aspects that need to be monitored include quality and quantity of water resources (Guo et al., 2017; 2: Grant and Chrisholm, 2014) for physical parameters and specific trace elements, baseline habitat and PES. The rate and amount of water withdrawal should also be monitored and reported to state agencies, while regulatory compliance monitoring to license conditions is also required (Sheelanere et al, 2013). Assess changes from habitat baseline (use country-specific tools or rapid habitat assessment method (Kleynhans, 1996; Kleynhans et al., 2008). Determine PES of water resources using the standard methods prescribed by the state entity. Perform observational and visual monitoring to determine the change from baseline. Adapt monitoring programme based on monitoring results assessment (Ayles et al., 2004). The same sites that have been monitored during exploration, would also have to be monitored during extraction.

After extraction: Long-term water quality impacts and bioaccumulation of toxic substances in fish (Bishop, 2011; Davis, 2008; Lloyd-Smith and Senjen, 2011) and reduced habitat quality due to exposure to toxic substances must be monitored. In addition, surface water resources quality and quantity (rivers, pans and wetlands) must also be monitored over the long term (Guo et al., 2017; Grant and Chrisholm, 2014) for physical parameters and specific trace elements. This is because contamination from groundwater resources that may interact with surface water resources, may only be identified long after fracking has ceased in an area. Habitat change monitoring after closure and regulatory compliance monitoring to mine closure specifications is also required (Sheelanere et al, 2013). If groundwater pollution is suspected in a certain area, surface water quality monitoring efforts should be accordingly adapted to detect if surface water systems have been influenced (Guo et al., 2017; Grant and Chrisholm) due to surface water-groundwater interaction that makes migration of pollutants possible

(Hobbs et al., 2016). The same representative sites in each resource unit, wetland or pan type that have been monitored during exploration and extraction, would have to be monitored after extraction, to identify contamination that may only present itself later via surface water-groundwater interaction. Sites in at least a 1km radius from closed production sites should also be monitored if contamination is suspected in a specific area.

In terms of the responsible party, a hybrid model is recommended for monitoring surface water resources, where the mandated or responsible state department for water resources must perform the compliance monitoring before exploration, during exploration and during extraction (Sheelanere et al., 2013) and the UOG company must perform the on-site monitoring (Dundon et al., 2015). After closure, long term regional monitoring must be performed by the state entity mandated to protect water resources. At the same time, UOG companies that operated in the area, must monitor fracking sites for a period after closure. In the case where the identified entities responsible for the monitoring, is not able to perform such monitoring reliably or is not trustworthy, an independent organisation can also perform such monitoring in addition to the above-mentioned entities, or in the place of the above-mentioned entities (ASSAF, 2016; Hobbs et al., 2016; Esterhuyse et al., 2014.

As can be seen from the table, although limited impacts are expected during the exploration phase, surface water monitoring in the proposed UOG extraction site before exploration would be required to establish a baseline for water quality and habitat integrity. The failure of not performing baseline monitoring to compare Post UOG extraction monitoring results to, is clearly illustrated by examples from the USA, where possible UOG-related impacts could not be linked to UOG activities as no baseline data existed to test this assertion (Bowen et al., 2015; GAO, 2012a; GAO, 2012b; Nelson, 2012). Details on important parameters that should be monitored, can be obtained from Esterhuyse et al. (2014) and Hobbs et al. (2016).

As water resources are required for fracking and since water pollution can impact on human health, for example (Genthe et al., 2016), it inextricably links with socio-economic impacts (Kuch et al., 2013). Section 3.2 describes socio-economic aspects that need to be monitored before, during and after UOG extraction.

4.2 Socio-economics

The monitoring of socio-economic impacts is an important component of accountability to stakeholders and affected parties, more so where UOG extraction is potentially harmful to vulnerable sectors of communities affected by these developments (Pelser et al., 2005).

From a legislative standpoint, in South Africa, the *Constitution of the Republic of South Africa, 1996 (*RSA, 1996), the National Environmental Management Act (*NEMA)* (RSA, 1998) and the Mineral Resources and Petroleum Development Act (*MPRDA)* (RSA, 2002) underpin the assessment and monitoring of social issues that may arise from proposed UOG exploration and extraction. The assessment and monitoring of socio-economic impacts is necessary to ensure that any development complies with the rights to human dignity, equality, well-being and freedom of South African citizens. Internationally, similar requirements are set (Kemp et al., 2010; Fulmer et al., 2008).

The proposed socio-economic monitoring framework describes the monitoring of impacts of UOG exploration and extraction based on the population-environment-development or PED-nexus[1]. The population dimension is monitored by specifically looking at changes to the population structure and distribution of a population. The environment dimension is monitored by looking at changes in the health status of the population, while the development component is monitored by looking at economic and social well-being.

When monitoring the *population* dimension (P), the mobility of the population, more specifically temporary and permanent migration flows, and changes in the age and sex structures are important aspects to monitor as these changes may impact on, among others, the social cohesion, economic well-being and municipal service delivery in these communities (Schaft et al., 2013; Weigle, 2011; Wynveen, 2011).

With regards to the e*nvironment dimension* (E), the health status of the population offers valuable insight into the impacts that environmental change has on community health and well-being. Health status is monitored successfully through measuring age- and sex-specific mortality. A sharp increase

[1] The PED nexus is a theoretical and analytical framework used to analyse the linkages between population, environment and development, with all three these elements impacting on each other in a multitude of complex interactions (Groenewald, 2011).

in the infant mortality rate, or the under-five mortality rate, for example, are powerful indicators with which to measure the impacts of UOG extraction on the health status of the population as these age groups are very sensitive to environmental problems such as water pollution and air pollution (Esterhuyse et al., 2014). Also, changes in the mortality of either men or women may point out increased vulnerability of either gender to the social consequences of mining-related activities, i.e. increased HIV-related morbidity and mortality for women is a well-documented impact of mining (Pelser, 2012).

With regards to the d*evelopment dimension* (D), the focus is on measuring and monitoring well-being. To adequately monitor socio-economic well-being, it is necessary to monitor changes in the economic status, changes in social well-being, as well as changes to the institutional environments affected by UOG development. Indicators that would indicate negative economic impacts of UOG extraction on the community include the unemployment rate, sectoral employment, and the number and proportion of female-headed households. Social well-being is further monitored by looking at how secure and integrated the community members perceive themselves to be in a specific community.

Table 2 shows a generic framework to inform future socio-economic monitoring of the impacts of UOG on affected communities for the three above-mentioned dimensions. The table explains why, how and where this monitoring is to be done, and also describes who is responsible for the monitoring. Possible impacts of concern that need to be monitored during each phase, include:

Before exploration: Although impacts of concern may be limited before exploration, countries planning to frack would already need to monitor baseline sex ratio's, age structure, as well as population size, structure and distribution in affected communities (sending and receiving communities) under the population dimension (Esteves, 2008, Lockie et al., 2009; Pelser et al., 2005; Pelser, 2012; Heunis et al., 2012; Chapman et al, 2015; Jacquet and Kay, 2014). This would inform governments about population mobility and structure. Under the environment dimension countries must monitor the baseline disease prevalence for HIV, STDs, TB, respiratory diseases, water-borne diseases, and the incidence of disease and disability resulting from trauma and injury. In addition the cause of death, age (infant mortality and under-five mortality rates) and sex-specific mortality need to be determined (Esteves, 2008, Larson et al., 2011; Broderick et al., 2011; Dolesh, 2011; Marsa, 2011; Beemster and Beemster, 2011; NIEHS, 2014; Newton, 2015). Under the development dimension, baseline economic and social well-being status must be determined by assessing gender-based poverty rates,

Table 2: Monitoring framework for socio-economics

<table>
<tr><th>Phases</th><th>Before exploration</th><th>During exploration</th><th>During extraction (at predetermined intervals)</th><th>After extraction</th></tr>
<tr><td>Possible impacts of concern that need to be monitored
(WHY?)</td><td colspan="4">Population: Unbalanced sex ratios, unbalanced age structures, influxes of people, out-migration that result from extraction and exploration
Environment: Adverse environmental changes, socio-economic changes and population changes impacting on human health.
Development: Potentially harmful impacts of UOG extraction on the socio-economic well-being of the population.</td></tr>
<tr><td rowspan="2">Aspects that need to be monitored
(WHAT?)</td><td>Population: Determine baseline population mobility and structure
Environment: Determine baseline morbidity & mortality with specific reference to disease prevalence and cause of death</td><td colspan="3">Population: Monitor changes to population mobility and structure
Environment: Monitor changes in morbidity & mortality with specific reference to disease prevalence and cause of death</td></tr>
<tr><td colspan="4">Development: Monitor changes in economic and social well-being
• Economic: Poverty rates (also gender-based), unemployment rates, economic diversity
• Political: Infrastructure, public participation, corporate social responsibility
• Human well-being: Crime rates, pride in community, living culture, education</td></tr>
<tr><td>How should these aspects be monitored?</td><td>Population and Environment: Use databases from Statistics department, Health Department, local government development plans, public meetings, key informant interviews
Development: Gather baseline data from existing data sources, key informant interviews, qualitative assessment of community dynamics through in-depth interviews with community members</td><td colspan="3">Population and Environment: Comparative analysis of existing country-specific databases, public meetings, key informant interviews
Development: Comparative analysis of baseline data from statistics department, triangulated with inputs for key informant interviews and in-depth qualitative site-specific studies on community well-being.</td></tr>
<tr><td>Where must these aspects be monitored?</td><td colspan="4">On the drill site and regionally to provide for comparative analysis</td></tr>
<tr><td>Who must do the monitoring?</td><td colspan="4">Population: Social development department in collaboration with independent research institutions (research consulting firms, academic institutions)
Environment: During exploration: Baseline data, usually available from country-specific Statistics department, Health Department; During and after extraction: Health department in collaboration with independent research institutions (consulting firms and academia)
Development: Mineral Resources Department in collaboration with independent research institutions (consulting firms and academia).</td></tr>
</table>

unemployment rates, economic diversity (collectively termed economic indicators), infrastructure, public participation, corporate social responsibility (collectively termed political indicators) and crime rates, pride in community, living culture and education (collectively termed human well-being indicators) need to be monitored (Coburn et al., 2011; Chung and Hoffnagle, 2011; Considine et al., 2011, Mason et al., 2014; Mersich, 2013). Existing country-specific databases such as Statistics departments, Health Departments, local government development plans, public meetings, key informant interviews can be used to monitor population and environment indicators. For development indicators baseline data from existing data sources, key informant interviews and qualitative assessment of community dynamics through in-depth interviews with community members can be used.

During exploration: The same indicators that were measured during the baseline, need to be monitored during exploration to determine changes in the sex ratio and age structure from the baseline, as well as migration flows to and from sending/ receiving communities under the population dimension. Under Environment (health status) the same indicators that were measured during the baseline, need to be monitored to determine changes from the baseline. The same goes for the development indicators. Comparative analysis of baseline data (prior to extraction) obtained from country-specific statistics department must be triangulated with information from public meetings, inputs from key informant interviews and in-depth qualitative site-specific studies on community well-being.

During extraction: At predetermined intervals, the same indicators that were monitored before and during exploration, need to be monitored during extraction to determine any changes in the sex ratio and age structure, as well as migration flows to and from sending/ receiving communities under the population dimension. Under the environment dimension (health status), the same indicators that were monitored before and during exploration, need to be monitored now to identify any negative changes. The same development indicators must be monitored. In this phase a comparative analysis of baseline data (prior to extraction) and data obtained during exploration from a country's statistics department, must be triangulated with information from public meetings, inputs from key informant interviews and in-depth qualitative site-specific studies on community well-being.

After extraction: The same indicators that were previously monitored for all dimensions, need to be continued during this phase. A comparative analysis must again be performed for the data gathered during this and previous phases of extraction.

The PED indicators must be monitored on the drill site and regionally during all the phases of UOG extraction in order to provide for the comparative analyses. The parties responsible for monitoring the population dimension indicators, are the country-specific social development department, in collaboration with independent research institutions (research consulting firms, academic institutions) as part of social impact assessment process. The responsible parties for the environment dimension indicators before and during exploration, are the Statistics department and Health Department of the country planning to embark on UOG extraction. During and after extraction the health department in collaboration with independent research institutions (consulting firms and academia would need to monitor the environment indicators. The Mineral Resources Department of the country planning to embark on UOG extraction, in collaboration with independent research institutions (consulting firms and academia) would be responsible for monitoring the indicators of the development dimension.

5. Critical assessment and wider implications of the South African case study

The South African monitoring framework for UOG extraction is innovative with regards to the following aspects:

- It requires that high quality baseline surveys of water resources should be performed before UOG extraction.
- It includes the monitoring of socio-economic aspects in addition to the usual monitoring of environmental aspects.
- It calls for policy-relevant monitoring of aquatic resources that must include *both* groundwater resources and surface water resources.
- It calls for the use adaptive feedback loops in order to change the monitoring programme based on findings.
- The regional monitoring approach of the South African monitoring framework will ensure consistency between monitoring efforts in different regions and on different administrative levels.

High quality baseline surveys of water resources is a definite requirement before UOG extraction starts (Sheelanere et al., 2013 Krupnick et al., 2014; Cook et al., 2013). In many cases this has not been done and biophysical monitoring was only added after the fact in countries where UOG is currently extracted (Jackson et al., 2011, Jackson et al., 2013). In the U.S., one of the major producers of UOG, socio-economic monitoring of the impacts of UOG extraction is rarely done, despite its value (Haggerty and McBride, 2016). Internationally, environmental monitoring for UOG extraction is in most cases not policy-relevant (Brantley et al., 2014; Small et al., 2014; Vidic et al., 2013), as the incorrect parameters are monitored, or the data is not in an accessible format. Internationally, water resources monitoring is also mostly focused on groundwater protection by ensuring well integrity (Jackson et al., 2013; Kang et al., 2014; Ingraffea et al., 2014), while monitoring to assess surface water contamination events are limited (Entrekin et al., 2011; Brantley et al., 2014; Kurek et al., 2013). Both Entrekin et al. (2011) and Kurek et al. (2013) stress the need for a well-executed monitoring programme to assess changes in aquatic ecosystem structure and function caused by UOG extraction and develop sound environmental policy. Dube et al., (2006) and Sheelanere et al. (2013) stress the need to improve monitoring efforts in different regions and on different administrative levels, which is an issue of concern in many countries where UOG is currently extracted (Torres et al., 2016; Werner et al. 2015).

Although the South African case recommends novel monitoring approaches, the following aspects might be problematic to implement in the South African case. Performing high quality baseline surveys of water resources before UOG extraction is currently proving problematic since the national government is struggling to determine who should be responsible for this monitoring (and by implication, who should bear the costs related to such monitoring). Although the government can require high quality surveys of local environmental conditions from oil and gas companies, government should ideally perform regional monitoring in order to attain independence. Governments in developing countries usually do not have adequate financial or human resources for this endeavour. One way to address this challenge would be for the South African government to require royalties / taxes from oil and gas operators, which should be channelled to paying for monitoring efforts (Thurber et al., 2011). Developing an information management system (Ayles et al., 2004 and Sheelanere et al., 2013) and using adaptive feedback loops to amend the monitoring programme as required (Ayles et al., 2004), may be hampered for the same reasons stated above. Making monitoring data available to all stakeholders (Sheelanere et al., 2013) can also prove problematic, especially in the case of disclosure of proprietary information such as fracking fluid compositions (Cook et al., 2016; Maule et al., 2013, Warner and Shapiro 2013). It is however very important that such information be made publically available, as it is required for proper policy development (Cook et al., 2016, Maule et al., 2013). Lastly, achieving consistency between monitoring efforts in different regions and on different administrative levels (Dube et al., 2006; Sheelanere et al., 2013), would be challenging in the South African case. Although cooperative governance is a requirement in South Africa (Glazewski and Esterhuyse, 2016), it is rarely achieved in practice. Here, local government can fill regulatory gaps where cooperative governance is not adequate. Local government also enjoys a rather significant degree of constitutionally entrenched authority in relation to land-use planning, which can ensure proper environmental protection during UOG extraction.

6. Policy recommendations

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 UOG extraction process. Active monitoring of certain entities can address some of the concerns linked to UOG extraction and will assist in identifying possible problems (such as pollution or a specific socio-economic impact) timeously. A few important policy recommendations follow.

The importance of monitoring socio-economic aspects in addition to biophysical aspects

While most countries realise the importance of monitoring impacts of UOG extraction on biophysical resources, especially water resources, many do not spend money on socio-economic monitoring. Socio-economic monitoring must assess various impacts of UOG extraction on population mobility and structure, on the health of populations, as well as on economic and social well-being. Such monitoring is crucial for poorer communities with less resilience, as is the case in South Africa (Atkinson et al., 2016). South African communities face a myriad of existing challenges, including a high prevalence of HIV/AIDS, as well as poor sanitation and associated water-borne diseases that render them vulnerable to the negative impacts of UOG development. Communities in UOG extraction areas would be more vulnerable to the spread of HIV and increased social ills that are brought about by the influx of money and workers into these areas. As such, the South African socio-economic monitoring programme recommends the monitoring of disease prevalence of HIV, TB and water-borne diseases. Socio-economic monitoring would also be advisable for developed countries to timeously address issues that disproportionally affect the vulnerable populations in these countries and to assist in policy development that aims at mitigating or preventing possible harmful impacts on communities affected by UOG development.

The importance of baseline monitoring

Any country that plans to embark on UOG extraction should perform baseline monitoring of important biophysical and socio-economic aspects before exploration starts. This will ensure that the country has known reference conditions against which to measure the impacts of UOG extraction activities. UOG extraction should not proceed before a comprehensive set of baseline data for proposed extraction area has been established. Compliance monitoring during baseline monitoring, as well as during UOG exploration and extraction, is also important to ensure compliance with regulatory monitoring requirements.

The importance of Post UOG extraction monitoring

While it goes without saying that monitoring must occur during UOG exploration and extraction (to address impacts as they occur in order to minimise and/or mitigate the effects of these impacts), governments may not be as keen to spend money on the monitoring of natural resources and socio-economic aspects post-UOG extraction, due to additional resource requirements on governments. Post-UOG extraction monitoring is however very necessary since some of the impacts may only be observed long after oil and gas wells in a certain UOG extraction area have been decommissioned and after the oil and gas companies have moved on to another part of the oil and gas reservoir. The complex and interlinked nature of ecological and social impacts also makes post-UOG extraction monitoring of surface water and socio-economic aspects, among others, essential.

An important consideration is the fact that post-UOG extraction water resources legacy impacts will occur, linked to the abandonment of producing wells or the poor sealing of wells after well decommissioning (ANU, 2012, NRC, 2012b). According to ANU (2012) there are more than 100,000 orphan gas wells and gas production sites in the United States, while Bishop (2011) puts the estimate of orphan or abandoned wells in the USA at 1.2 million, of which approximately 200,000 are leaking. Almost all oil and gas wells would eventually leak (over a 50-year period, for example) due to mechanical failure of well casings (Bishop, 2011). Monitoring before, during and after UOG extraction can make these impacts traceable and would assist in mitigating or managing such impacts.

In order to address post-UOG extraction impacts and its monitoring requirements, a government may require post-UOG extraction monitoring to be performed by the UOG extraction company for a certain period of time, after which this function may be transferred to the government when latent and residual environmental impacts are deemed less likely. Based on the cradle-to-grave-principle, governments may also require the identification and quantification of such impacts, and securing related financial provision to manage these impacts post-UOG extraction, such as is done in South Africa (CER, 2014).

The importance of integrated, systematic and standardised monitoring

Since UOG extraction impacts may be cumulative and may occur on a regional scale, systematic and standardised monitoring across regions are very important (Sheelanere et al., 2013; Gray et al., 1999) to make monitoring efforts successful. Standarised monitoring necessitates integration between different levels of government and alignment between different pieces of legislation.

In order to ensure proper management of monitoring activities before, during, and after UOG extraction, it is imperative that data be available from all spheres of government, for, among others, proper assessment of the cumulative impact of UOG extraction on a regional scale, as well as for research purposes. Industry would also have to report specified data to government, for example on water usage and on chemical usage during fracking. If cooperation between government departments and the effective dissemination of data is deemed to be problematic, then serious consideration should be given to an independent entity to perform the task of accepting and storing data, as well as to ensure dissemination of data. In South Africa for example, the identification or establishment of a central body for data curation and assessment of the data gathered through monitoring activities is thus highly recommended due to the fragmentation observed between different government structures (Hobbs et al., 2016; Scholes et al., 2016).

Resources required for effective monitoring

Limited human and financial resources at the government departments responsible for monitoring, may seriously affect the quality of monitoring that is performed (Huot and Grant, 2011; Sheelanere et al., 2013). For example, for water resources, compliance monitoring could include monitoring regulatory compliance with fluid storage specifications, volumes of waste produced per well, reporting frequencies to authorities and monitoring compliance with license conditions. Executing this compliance monitoring would require additional manpower as well as financial resources under the department responsible for water resource protection. Even if a government does not perform all the monitoring of the impact of UOG extraction on natural resources and the related socio-economic impacts themselves, just regulatory compliance monitoring of UOG companies during full scale UOG extraction will put more pressure on the available resources of public agencies (Pershee, 2011).

Many government departments in developing countries are not necessarily in a position to perform ongoing monitoring that would be legally defensible, as they may be hampered by the lack of institutional capacity to perform adequate monitoring, or by a lack of funding. It is imperative that such issues be addressed to ensure effective monitoring. Atkinson et al. (2016) recommends that UOG companies take special efforts to engage local government and offer to assist them in crucial functions, particularly to prevent growing backlogs in aspects such as license processing and infrastructure maintenance. In addition, the integration of monitoring functions, as well as information across government departments, should be encouraged as it would mean easier access and interpretation of monitoring data, affording the country that embarks on UOG extraction the opportunity to apply adaptive management. Such integration across departments would require a functioning system of cooperative governance. In the absence of this, it is highly recommended that an independent agency is established to perform this task, as well as to store, interpret and disseminate data, as is the case with some traditional communities in British Columbia that insist on third-party or independent resource monitoring and enforcement (Garvie and Shaw, 2015). Such data also then need to be stored in a publically accessible database.

Linking monitoring to an adaptive management plan

Monitoring data should ideally be used for calibration and verification of prediction and assessment models, for evaluating and auditing the success of management plans, and for assessing the extent of compliance with prescribed standards and regulations. UOG extraction resource monitoring must be linked to a management plan to ensure that water and other natural resources are protected and that action is taken when certain set thresholds are exceeded.

Ideally, the monitoring plan should address the following:

- the design of the initial monitoring programme;
- methods of sampling, collecting and capturing the data;
- methods for analysing the data;
- the format for reporting the findings to the relevant authorities;
- mechanisms for auditing, and for recommending and implementing changes to the monitoring programme.

All licences granted to the developers would need to take the principles of adaptive management into account, and modifications of UOG activities based on results of the monitoring programme should be enforced.

7. Conclusion

A UOG extraction monitoring framework can be used as a guideline for planning monitoring activities and as a tool to implement adaptive management based on the outcomes of monitoring results. A UOG extraction monitoring framework must ideally identify the important entities to be monitored during the various phases and prescribe where monitoring must be performed (site-specific or regional), when it must be performed (related to the different phases of UOG extraction), how it must be performed (by discussing aspects such as parameters to be monitored as well as data management) and who the relevant parties are that should do this monitoring (oil and gas companies vs. regulators). These aspects would be important considerations for any country considering to develop a monitoring framework for UOG extraction. This article discusses the importance of UOG extraction monitoring for environmental protection by using the South African case where such a monitoring framework was developed. This framework is critically assessed within the wider context of international monitoring efforts during UOG extraction, while the policy implications of a monitoring framework for UOG extraction are also discussed. Important policy considerations include performing baseline monitoring during UOG extraction, performing UOG extraction monitoring in an integrated, systematic, and standardised manner, ensuring that proper resources are available to perform the monitoring and implementing an adaptive management plan that is linked to UOG extraction monitoring.

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