Research paper

Prospective policy safeguards to mitigate hydrogeological risk pathways in advance of shale gas development in the Karoo basin, South Africa

Kevin Pietersen a,*, Luc Chevallier b, Audrey Levine a, c, Thandokazi Maceba a, Zaheed Gaffoor a, Thokozani Kanyerere a

a University of the Western Cape, Private Bag X17, Bellville, 7535, South Africa
b Council for Geoscience, P.O. Box 572, Bellville, 7535, South Africa
c County of Santa Cruz-Health Services Agency-Environmental Health Division, 701 Ocean Street, Room 312, Santa Cruz, CA, 95060, USA

ARTICLE INFO

Keywords:
Shale gas
Hydrogeologic risk pathways
Karoo basin
Adaptive management policies

ABSTRACT

Policies surrounding energy development are frequently implemented in response to known or perceived problems. South Africa is in a unique position to develop prospective policies that build on knowledge gained from elsewhere. This paper provides a prospective analysis of hydrogeological risk pathways and vulnerability attributes in advance of anticipated shale gas operations in the Karoo Basin of South Africa. The ‘hazard-pathways-receptors’ approach is applied to define the hydrogeologic system in the context of potential sources of water resource contamination. This case study focuses on two critical hydrogeological risk pathways: regional groundwater flow and discrete structural features. Depending on the targeted area (hydro-litho-structural domain, depth of target, presence of aquitard, intrusion ratio), the capacity of deep natural pathways to enable hydraulic fracturing fluids, chemicals, or produced water to reach shallow groundwater, will be reduced or difficult. Deep artesian water could however be intercepted at different depths and, based on past groundwater exploration in the Karoo, water could flow into horizontal fractures or openings characterising the shallow aquifers: sills-ring complexes, lithological contacts, and transgressive fractures across dolerite dykes. However, above-ground water and wastewater management safeguards are needed to protect shallow groundwater from potential water quality degradation due to a) flowback or produced water b) stray gas and/or c) spills or illicit discharges that could introduce contaminants into groundwater resources. This paper describes a systematic approach to evaluate hydrogeologic risk pathways and informs adaptive management policies to protect South African groundwater resources.

1. Introduction

Since the 1960s, unconventional gas resources in the southern and central parts of South Africa’s Karoo Basin have been documented (Krol and Weinert, 1966; Rowell and De Swardt, 1976; van Vuuren et al., 1998). Oil exploration and stratigraphic boreholes, drilled throughout the Karoo basin in the late sixties, are receiving renewed attention (Cole et al., 2011; Cole, 2014; Chere et al., 2017) as the technology for extracting unconventional gas has become more available and affordable (Pietersen et al., 2016). In addition, large hydrogeological programmes and groundwater drilling have been carried out in the Karoo by the Department of Water Affairs and the Water Research commission (Botha et al., 1998; Woodford and Chevallier, 2001, 2002; Murray et al., 2015). They were aiming at aquifer characterisation and water quality for supply. However, risks related to unconventional gas exploration were not the concerns of the researches at the time.

However, protection of the region’s vulnerable water resources is paramount, since most of South Africa’s rural areas and some inland small towns are dependent on groundwater for potable water supply. While risks to surface water systems are mostly transient with exceptions (e.g. Cozzarelli et al., 2017), groundwater systems are vulnerable to longer-term risks that are associated to deep drilling exploration that are more difficult to identify, track, or mitigate.

Opportunity is now given to study the role of hydrogeological pathways in the Karoo by reconsidering the different structural features with. The irregular distribution of high and low permeability zones also complicates the effective estimation of regional groundwater flow parameters. Groundwater systems can serve as conduits for gases,
2. Methods

This paper includes two approaches: 1) identification of hydrogeological pathways and potential groundwater contamination and 2) evaluation of adaptive management strategies to formulate recommendations. The hydrogeological pathway study is based on a structural analysis and interpretation of the existing geological (regional mapping, lithostratigraphic exploration holes, hydrogeological drilling) of the Western Karoo basin with particular emphasis on qualitative evaluation of ground water contamination risk in shale gas exploration. Once the hydro-structural analysis has been done the source-pathway-receptor model (Loveless et al., 2018) was applied as an organizing principle to evaluate the feasibility of adaptive management strategies that could be conducted in tandem with shale gas development activities. The model by Loveless et al. (2018) is generic and allows for investigation of various empirical and hypothetical scenarios.

2.1. The source-pathway-receptor model

The source-pathway-receptor model is used to structure existing knowledge, identify knowledge gaps and make policy recommendations for adaptive management. The focus of this study is to evaluate linkages between pollution sources and migration pathways with potential receptors. The focus of this study is to evaluate linkages between pollution sources and migration pathways with potential receptors. The shallow aquifers, depending on the size of the aperture (Cai and Otterdinger, 2014) and whether local geological conditions foster transport (Gassiat et al., 2013; Atangana and van Tonder, 2014; Smythe, 2016) or are insignificant (Saiers and Barth, 2012; Cohen et al., 2013; Flewelling and Sharma, 2013, 2015; Flewelling et al., 2013; Dusseault and Jackson, 2014; Birdsell, 2016; Engelder, 2016; Pfunt et al., 2016; Verdon, 2016; Westaway, 2016; Taherdangkoo et al., 2017).

There is therefore a gap in our identification, understanding and mitigating hydrogeological risk pathways in the context of shale gas exploration in the Karoo basin. Different types of groundwater contamination from unconventional gas development could be using these pathways: a) shallow groundwater contamination with deep saline water where drilling triggers a connection; b) stray gas contamination due to migration of gases and flowback from wells; and c) produced water spills from above ground or subsurface spill (Vengosh et al., 2014; Digiglio and Jackson, 2016; USEPA, 2016; Soeder, 2018).

Hydrogeological risk pathways are derived from groundwater exploration research, models, and data that have been reported in the Western Karoo Basin. The uncertainties that are associated with shale gas development can be translated into adaptive management practices for groundwater protection.

2.3. Hydro-litho-structural domains of the southwestern Karoo Basin

Regional geological cross sections through the Western Karoo were recently made for a deep drilling and geo-environmental baseline programme by the Council for Geosciences for the Department of Mineral Resources (CGS/DMR). The sections are based on stratigraphic borehole logs, CGS geological maps and regional seismic profiles. One of these regional sections, going through Beaufort West, where the sweet spot has been defined, is shown in Fig. 2 (Chevallier et al., 2016, 2017; Nxokwana et al., 2019). The section illustrates the three major hydro-litho-structural domains of the Western Karoo:

- The sweet spot domain
- The Cape fold belt trough domain, south of the sweet spot
- The high Karoo domain, north of the sweet spot

2.3.1. The sweet spot domain

The sweet spot domain for the high potential exploration area is characterised by the distance to the top of the carbonaceous shale of the 60 m thick Whitehill Formation (Lower Ecca) at a depth ranging between 2000 and 3000 m. The stack of dolerite sills appears to be intruded much above the Whitehill Formation reducing the risk of baking of the carbonaceous shale. Overlying the Whitehill Formation, the Tierberg Formation (see Table 1) is up to 1000 m thick and consists of a tight argillaceous dark grey shale that is considered to be an aquitard. Research boreholes drilled in this Formation (Chevallier et al., 2001; Nxokwana et al., 2019) show that the Tierberg shale (Upper Ecca) is devoid of water strikes. The overlying Adelaide Subgroup is dominated by silstone and sandstone and intruded by dolerite sills. It usually forms good aquifers especially at prominent lithological contacts like sandstone bars or dolerite sills. Below the Whitehill Formation, the Prince Albert Formation (200 m of mudstone and dark shale) possesses a lower gas potential (Mosavel et al., 2019). Below the Dywka Group is up to 600 m thick and fractured as seen in borehole SA1/66 that intercepted chemicals, and formation fluids that accumulate in the subsurface, migrate, or are released during exploration and production activities. Numerous dolerite dykes and sills, which intruded the Karoo Supergroup during the early Jurassic period as well as faults may also provide pathways for upward migration of gas and other contaminants to shallow aquifers, depending on the size of the aperture (Cai and Otterdinger, 2014) and whether local geological conditions foster transport (Gassiat et al., 2013; Atangana and van Tonder, 2014; Smythe, 2016) or are insignificant (Saiers and Barth, 2012; Cohen et al., 2013; Flewelling and Sharma, 2013, 2015; Flewelling et al., 2013; Dusseault and Jackson, 2014; Birdsell, 2016; Engelder, 2016; Pfunt et al., 2016; Verdon, 2016; Westaway, 2016; Taherdangkoo et al., 2017).

The Jurassic dolerite dykes and sills intruded into the sediments of the Karoo Supergroup during a period of extensive magmatic activity that occurred in one of the phases of the Gondwanaland break-up. The dykes and sills represent the roots and the feeders of the extrusive Drakensberg basalts and comprise up to 30% of the Basin’s thickness (Chevallier and Woodford, 1999). The dolerite intrusions consist of an interconnected network of dykes (sometime up to 500-km (km) long and 20 m (m) thick), sills (up to 100 m in thickness) and ring-like (saucer-shape) intrusions. In many cases, intrusions near vertical dykes’ branch onto the sill and rings or cut through them without evidence of a specific intrusive or tectonic event.
artesian water and gas at a depth of 3150 m (Woodford and Chevallier et al., 2001a; Rosewarne et al., 2013a, b). The hydrostratigraphy of this domain can be summarised as a succession of deep aquifers in the Dwyka tillite below the targeted carbonaceous shales, a 1000 m thick aquitard above the target and a series of sandstone and mudstone intruded by dolerite sills where shallow fractured aquifers are found.

This domain targeted for exploration represents therefore a good example of potential contamination of shallow aquifers by deep waters or exploration fluids.

2.3.2. The Cape fold belt trough

The domain south of the sweet spot, corresponds to a trough in the foreland Karoo basin. It is characterised by a depth to the top of the Lower Ecca between 3000 m and 4000 m as confirmed by geophysical analysis (Scheiber-Enslin et al., 2015). The Whitehill shale is devoid of dolerite sills but is affected by folds and thrust faults along with hot springs. Fold axes related to the Cape Fold Belt tectonic events, and more specifically anticlinal axes, are often targeted for shallow aquifers due to deformation and fracturing (Murray et al., 2012). On the other hand, seismic profiling has shown that listric thrust faults could be deeply rooted at the contact with the Dwyka Group or the Cape Supergroup (Lindeque et al., 2007). Borehole SA1/66 intercepted artesian water and gas in the Dwyka at a depth of 3150 m with Total Dissolved Solids (TDS) of up to 10,000 mg per litre (mg/L) and temperatures up to 76 °C (Rosewarne et al., 2013a, b). Borehole KL 1/65 intercepted 3 strikes of artesian water at depths of 3000 m into the Bokkeveld Group. These deeper groundwater flow systems (Goes and Rosewarne, 2012; Rosewarne et al., 2013b) only occur between the Great Escarpment in the North and the Cape Fold Belt in the South and are due to regional head and stratigraphic/structural characteristics.

2.3.3. The higher karoo domain

The domain north of the sweet spot is characterised by shallow carbonaceous shale. Multiple dykes and flat lying dolerite sills have caused baking of the shale. These dolerite sills display evidence of contact metamorphism with devolatisation of the sediments above the contact, veining and melting, and nodules with radiating cracks (Adjeyi et al., 2018). Complete loss of organic carbon in the sediment aureole next to the dolerite sills is common. This massive sill and dyke emplacement led to widespread phreatic and phreatomagmatic activity and the release of thousands of gigatons of carbon gas from the contact.

![Fig. 1. The South-western Karoo Basin showing the extent of the outcropping Whitehill Formation and its eastern limit. Also shown are the SOEKOR boreholes and the two KARIN boreholes (de Kock et al., 2016a, b). The sweet spot is a high potential area for shale gas exploration (Cole, 2014; Chevallier et al., 2017). The black line delineates the potential area defined by Mowzer and Adams (2015).](image-url)
metamorphosed organic-rich sediments (Svensen et al., 2007; Aarnes et al., 2011). In the Adelaide Subgroup (mudstone, sandstone and siltstone) the dolerite intrusions consist of an interconnected network of dykes, sills, inclined sheets and ring-like (saucer–shape) intrusions (Chevallier and Woodford, 1999) and it is nearly impossible identify specific intrusive or tectonic events. Fractured aquifers, compartmented by dolerite sills and dykes, appear to be recharged by modern water (Goes and Rosewarne, 2012; Harkness et al., 2018) and have been found down to the 300 m depth associated with exploratory drilling in the Karoo (Chevallier et al., 2001). However, the De Vrede 1/66 borehole east of Graaff Reinet intercepted water below a sill at 600 m. Drilling at Qoqodola, near Queenstown found water at 300 m which is associated with a sill-ring, and geophysical profiling has detected possible water at around 600 m (Chevallier et al., 2001). Borehole KZF-01 (Tankwa Karoo), drilled by the KARIN project intercepted three water strikes: fresh water at 400 m, sulphurous water at 615 m at Prince Albert and artesian warm water in the Dwyka at 660 m (Cole et al., 2012; de Kock et al., 2016a). The Northern domain is also characterised by kimberlite dykes with limited evidence of groundwater availability (Woodford and Chevallier, 2002).

2.4. Natural hydrogeological potential pathways

The hydro-litho-structural domain analysis has shown the complexity and the variation in the hydrogeological systems of the Western Karoo Basin and therefore the possibilities for various natural hydrogeological pathways. Natural groundwater pathways include regional water flow and discrete structural features. There is overlap and interdependency between these pathways. The discrete structural features are the complementary source of water to the regional flow after deep circulation.

2.4.1. Regional water flow

The slow water migration through the low transmissivity sedimentary basin or intervening volume of rock under unconfined or artesian conditions is classified as regional water flow. van Tonder and de Lange (2012) and van Tonder et al. (2013) suggested that the Karoo Basin is under pressure and can mimic an artesian aquifer. Deep artesian water has been found in the Karoo (KL 1/65, SA 1/66, CR 1/68 and VR 1/67) in the brecciated Cape Supergroup and in the Dwyka tillite and was released by exploration drilling. The existence of isolated confined pressurized compartments could result from the lithostatic pressurisation in the deeper sections as proposed by van Wyk (2013) or from the unique tectonic setting associated with low grade metamorphism that favour the presence of deep confined aquifers. The only way that the different aquifer systems can mix is through secondary features and induced pathways due to the lack of direct connectivity.

Fig. 2. A) Simplified geological map of the Western Karoo Basin and deep stratigraphic exploration boreholes showing the distribution of the carbonaceous shale of the White Hill and the Prince Edward Formations. B) Regional cross-section showing the 3 litho-structural domains: The sweet spot domain, the Cape fold belt trough domain in the South and the High Karoo domain in the North. The location of the planned Beaufort West deep borehole (BW) by CGS/DMR in the high potential area (sweet spot) is also shown (Mosavel et al., 2016; Chevallier et al., 2017; Nxokwana et al., 2019).
2.4.2. Discrete structural features

Discrete structural features extending over a large area may enable preferential vertical or horizontal flow paths. The Jurassic dolerite dykes and sills and cretaceous kimberlites intrusions have generated extensive fracturing of the surrounding sedimentary rocks in the southwestern Karoo basin (Senger et al., 2015).

Exploration boreholes in different types of dykes and sills have been drilled to investigate groundwater potential (Woodford and Chevallier, 2001; Chevallier et al., 2001, 2004). Two types of dykes are often found. Regular dykes like the one of Fig. 3 (drilled in the Victoria West area) are characterised by straight contact with the sediment and many water strikes in the first 100 m where it is enhanced by weathering, jointing and uplifting (Woodford and Chevallier, 2002). At depths of over 100 m, the role of dyke contact as a vertical transmissive zone seems to be reduced.

Other types of dykes possess more complex habits and structural features such as sub-horizontal transgressive fractures cutting through that can influence lateral groundwater circulation as shown in Fig. 4 (Chevallier and Woodford, 1999; Chevallier et al., 2001, 2004; Woodford and Chevallier., 2002; Botha et al., 1998; Botha and Cloot, 2004).

In addition, horizontal open fractures often develop at the bottom of dolerite sills and can be conducive to lateral groundwater circulation.
However, limited information is available on the structure of deep dolerite sills (>600 m) and associated deep groundwater and water strikes in the Karoo lithostratigraphic formations. These deeper groundwater flow systems can be associated with hot springs (Murray et al., 2015; Swana et al., 2015; Eilers et al., 2015).

The effects of horizontal drilling through deeper (>500 m) vertical dykes remain an unknown hydrogeological risk. It appears that transmissivity and groundwater movement along horizontal fractures...
(transgressive fractures across dykes or sill contacts) at shallower depth are enhanced along dolerite dykes contact in the first 100 m.

3. Results: potential risk pathways due to shale gas development activities

Applying knowledge about geological features in the context of hazard-pathways-receptors is a starting point for defining and mitigating credible groundwater contamination risk pathways (Ferguson, 1999 as referred by Younger, 2016). There are three primary categories of risks: a) contamination from flowback or produced water b) stray gas contamination and/or c) spills or illicit discharges. Understanding risk pathways can guide further investigations of geological structures in the context of potential shale gas development.

3.1. Contamination from flowback or produced water

Karoo shallow aquifers are at least 600 m below ground surface. A key focal point is the artesian status of the Basin (van Tonder and de Lange, 2012; Hohne et al., 2019). It is likely that, during exploration, artesian water could be intercepted at different depths and in different Karoo rock formations (Fig. 5). It is evident that water could flow into horizontal fractures or openings characterising the shallow aquifers: sills-ring complexes, lithological contacts, and transgressive fractures across dolerite dykes. Artesian water flow rates vary over an order of magnitude from about 0.5 to 7 L per second (L/s) (Rosewarne et al., 2013a, b). The rate at which site-specific contamination could migrate depends on the artesian water flow rates. The reported concentrations of total dissolved solids also vary over about one order of magnitude from about 1100 to 10,200 mg/L (Rosewarne et al., 2013a, 2013b) and, as such, would require some level of demineralization to be useable as a source for potable or irrigation water. The variability of flow and dissolved solids is significant for differentiating background conditions from potential impacts of shale gas development activities on groundwater quantity and quality.

Vertical movement of deeper groundwater under artesian conditions depends on aquifer/aquitard thickness, vertical hydraulic conductivity and storativity (Hart et al., 2006; Flewelling and Sharma, 2013). Larger aquitard thicknesses, such as the Tierberg Formation, can protect aquifers from the impacts of shale gas extraction and reduce overall vulnerability. Similarly, vertical hydraulic conductivity is directly correlated to aquifer vulnerability. Fluid movement through and from shales tends to be extremely slow – typically between $3.9 \times 10^{-6}$ and $9.63 \times 10^{-4}$ m per day (Davies et al., 2014). While flow direction and flow rates vary from site-to-site, these qualitative results encompass the spectrum of whether contamination could be attributed to gas development activities and help to define response actions.

The potential for deep shales to contaminate the near-surface...
environment is low (Shanafield et al., 2019) in the absence of faults or intrusions (Mallants et al., 2018). However, over longer geological timescales, it is plausible that hydrocarbon migration could occur from shale reservoirs that have not been hydraulically fractured (Davies et al., 2014). Thus, the risk of contamination to aquifers from shale gas operations increases with reduced vertical separation distances between the exploited shale and aquifer (Loveless et al., 2018; Shanafield et al., 2019). To mitigate this issue, a minimum vertical distance between the freshwater aquifers and shallowest edge of induced fractures must be maintained for safe separation. Defining an appropriate minimum distance requires an adaptive data-driven approach. This prospective study provides a framework for more in-depth scenario analysis and associated cost-benefit assessments. Follow-up modelling and field studies are important for adaptive management safeguards relevant to shale gas development.

3.2. Stray gas contamination and flowback from wells after drilling

Possible contamination of gas in groundwater has been reported for the Marcellus shale in Pennsylvania, USA (Osborn et al., 2011a,b), particularly within a kilometre of gas-wells. In other cases, gas migration has been refuted (Saba and Orzechowski, 2011; Schon, 2011). Siegel et al. (2015) found no statistically significant relationship between dissolved methane concentrations in groundwater from domestic water wells and proximity to pre-existing oil or gas wells using a much larger dataset. After production, the re-establishment of equilibrium well pressures can foster hydraulic fluid migration along pathways. This source of contamination has been attributed to faulty casing or cracked cement annuli (Li et al., 2016; Rice et al., 2018). The Karoo Basin can benefit from the experience of Li et al. (2016) and Rice et al. (2018) in designing pro-active monitoring systems. It is envisioned that routine targeted monitoring site evaluation could serve as a warning system to detect and address any occurrences.

The natural migration of hydraulic fracturing fluid through the sediment pile is poorly documented. The stack of sedimentary strata above the targeted formation in the Karoo consists of a succession of shale, mud rock, sandstone and dolerite. Many of these rock-types are generally characterised by low matrix transmissivities/permeability (between 0.5 and 50 m²/day; Dondo et al., 2010) at relatively shallow depths (less than 200 m deep). Groundwater flow modelling of the Cranemere exploration area in the Karoo (borehole CR 1/68, van Tonder et al., 2013) suggests that potential leakage rates along faulty well annuli can range from negligible to 2 L/s, depending on the size of the aperture. The model simulated contaminant migration from wells on the pad to estimate the potential for contamination over a 30-year time horizon. Based on the model, an area of 300 ha could be contaminated in a downstream groundwater flow direction (van Tonder et al., 2013). If a pumping borehole drilled along a fault zone intersecting the fractured reservoir is introduced into the model, results predict that the pollutant will reach the borehole in less than two months if the borehole is situated 6 km from the well pad (van Tonder et al., 2013). Such predictions inform the basis for implementing adaptive management practices to fast-track the movement of the predicted pollutants alongside observation data from nearby wells. Such significant out-of-zone vertical migration of fracturing fluid will occur only in the case of the target formation being penetrated by a nearby abandoned or producing well with poor cement completion, a corroded casing, or some other pathway (open perforations) that could allow the fluid injected above fracture pressure to escape from the target formation (Dusseault and Jackson, 2014). While model validation is important, the qualitative results from this study serve as precautionary insights to define appropriate and meaningful adaptive management protocols.

3.3. Produced water spills from above ground or subsurface spills

Water and wastewater management practices associated with shale gas development may impair groundwater quality of shallow aquifers in the aftermath of spills (Drollette et al., 2015; Llewellyn et al., 2015; Shanafield et al., 2019). In general, problems can be averted through implementing prudent engineering safeguards for drilling, integrity testing, impoundment construction, and liner installation, along with meaningful institutional controls and rigorous inspection protocols (Ziemkiewicz et al., 2014). Where feasible, shale gas development activities should avoid proximity to shallow aquifer systems. In the absence of field data, applying the precautionary principle to set a minimum distance from shallow wells to shallow aquifers is important for protecting fragile groundwater resources.

4. Discussion: recommendations for adaptive management practices

Implementing adaptive management tools prior to initiation of shale-gas extraction is critical for water resource protection as a precautionary principle. The precautionary principle (On, 2018; Prpich and Coulon, 2018) suggests that hydraulic fracturing should not be carried out near potentially conductive faults. The frequency, scope, and duration of monitoring programs needs to be consistent with the scale of hydraulic fracturing activities, and therefore will differ from traditional water resources management programs (Gassiat et al., 2013). Recommendations for mitigation of hydrogeologic risk pathways include detailed mapping, designating groundwater control areas, defining separation distances, and requiring proper sealing of abandoned wells. An overview of four high priority adaptive management strategies and policy options is provided in Table 2.

4.1. Map co-location of aquifers, discrete structural features and shales

Careful three-dimensional mapping of aquifers, discrete structural features and shales is a key step towards assessing the risk of groundwater pollution from shale gas development activities. When drinking water resources are in close proximity to oil and gas resources, it is important to maintain a vertical separation between the hydraulically fractured rock formation and the bottom of the underground drinking water resource (Digiulio and Jackson, 2016). Although the results of the deeper surveys (1000 m+) have a high commercial value, details about locations of major faults, formation tops and bottoms and borehole geophysical logs should be required as part of any licensing agreements (van der Gun et al., 2012). Further, operators should be required to develop and validate a detailed hydrogeologic models of the area of influence.

4.2. Designate groundwater control areas

Pre-emptive banning of shale gas development activities should be considered for strategic water source areas (Le Maitre et al., 2018). Strategic areas include places that are nationally important because they either supply a large quantity of mean annual surface water runoff in relation to their size and/or have high groundwater recharge and where
the groundwater forms a nationally important resource. These qualitative findings should be verified with field investigations in advance of shale gas development.

4.3. Determine minimum separation distances

Horizontal and vertical separation distances need to be protective of water resources. Site-specific factors are important in defining minimum distances.

4.3.1. Horizontal separation distances

To reduce the risks of fault reactivation and discrete structural features acting as fluid conduits to groundwater resources, fluid injection needs to be carried out at sufficient distances away from structural features (Westwood et al., 2017; Wilson et al., 2018). Wilson et al. (2018) suggest a horizontal distance of greater than 800 m between horizontal boreholes orientated perpendicular to the maximum horizontal stress direction and faults optimally orientated for failure under the regional stress state. In-depth site characterisation is a necessary component of defining relevant safeguards.

4.3.2. Vertical separation distances

A method to define a safe minimum separation distance is important between the zone of hydraulic fracturing and the overlying aquifers. The methodology should include fault height and pervasiveness in conjunction with shale-aquifer vertical separation, and the hydraulic properties of the intervening units (AMECFW, 2015; Loveless et al., 2018). The minimum separation distance should be set at 1000 m based on literature reviews (AMECFW, 2015). The upward migration of hydraulic fluid can be in the order of 100 m through relatively low-permeability overburden, even if no permeable pathways exist and the likelihood of a continuous permeable pathway to the receptor will increase as the separation distance decreases (Birdsell, 2016). Regulations should specify minimum vertical separation distances between hydraulic fracturing operations and aquifers tailored to site-specific conditions based on field investigations and modelling. The environmental impact assessment process provides a mechanism for independent review and verification of relevant minimum distances where shale gas development is proposed.

4.4. Sealing of abandoned production wells

Technical failure of casing installation in combination with unfavorable geological conditions could have serious consequences releasing fugitive gas into adjacent geologic formations and overlying soils (Dusseault and Jackson, 2014; Cahill et al., 2019). Adaptive management strategies should include risk-reducing techniques such as double or triple well sealing (Schwartz, 2015). This requires ownership and liability of wells to be transferred to a competent authority on surrender of the site licence (AMECFW, 2015). Regular inspection of wells is necessary along with specific closure and post-closure requirements. The geologic conditions of the study area are similar to those reported in the literature (Schwartz, 2015; Dusseault and Jackson, 2014 and Cahill et al., 2019) and many of the basic concepts can be directly applied, however site-specific field data is integral to all aspects of shale gas development.

5. Conclusion

Policies surrounding energy development are typically developed in response to known or perceived problems. In this study we have built on the global experience and scientific literature related to shale gas development. For example, South Africa is in a unique position to develop prospective policies that build upon knowledge gained from elsewhere. This paper provides an initial assessment of the potential hydrogeologic risk pathways due to the proposed shale gas development activities using the Karoo Basin as a case study. The systematic approach can be tailored to other locations including the study area for this paper. Even in the absence of site-specific data, it is possible to define policy safeguards that include a) mapping co-location of aquifers, discrete structural features and shales; b) designating groundwater control areas; c) determining minimum vertical separation distances; and d) sealing of abandoned production wells. Whilst the geological risks from shale gas development activities are considered minor compared with technical risks such as casing failure, mitigating risks of hydraulic fracturing to groundwater resources in more complex hydro-litho-structural domains requires pro-active practices that should lead to policy safeguards. Applying the precautionary principle for protecting groundwater resources remains fundamental. Data-driven adaptive management strategies provide a path forward that can inform field investigations and policy decisions. It is critical to note that not implementing safeguards because no data exist can lead more a legacy of environmental and resource problems which would be undesirable.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors acknowledge the South African Water Research Commission for funding this work. The reviewers are thanked for their invaluable comments assisting in the revision of the paper.

References


