POTENTIAL IMPACTS OF FRACKING ON GROUNDWATER IN THE KAROO BASIN OF SOUTH AFRICA

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Abstract

Determining impacts associated with the production of shale gas in the semi-arid Karoo on groundwater is vital to people living in the Karoo. On the one hand shale gas can be a game-changer for energy supply but on the other it may have a devastating effect on the environment. Knowing the potential impacts of shale gas mining beforehand, the government can set appropriate regulatory protocols and tools in place to mitigate potential risks. This paper describes research done on the potential impact that hydraulic fracturing could have on groundwater in the Karoo. A wild card that only exists in the Karoo Basin of South Africa is the numerous dolerite intrusions. These dolerite structures are associated with relative high yielding boreholes because of the fractured contact aureole that exist between solid dolerite and the adjacent Karoo sediments. Compromised cement annuli of gas wells are the major preferential flow paths along which methane and fracking fluid can escape into shallow, fresh water aquifers. This study focused solely on the impact of compromised cement annuli of gas wells. The Karoo Basin is under artesian conditions which imply that any pollutant will always try to migrate upwards in the Karoo. The warm water springs in the Karoo indicate that upward velocities of water are relative high (the spring water take only days to travel from deep down to the surface). The cubic law was used to estimate potential upward leakage rates from gas wells (during production but after cessation thereof as well, when pressures will rebuild because of artesian behaviour of the Karoo Formations). Potential leakage rates along faulty annuli of a well can vary between a value close to zero to 2 liters per second in the case of an aperture of 0,5 mm. These leakage rates were used as input to a 2D numerical groundwater flow and mass transport model. The 2D model was run for 30 years and the movement of pollution from the gas wells on the pad simulated. The model indicates that an area of 300 ha could be contaminated over a period of 30 years in a downstream groundwater flow direction. If an abstraction borehole drilled along a fault zone or a dyke, intersecting the fracked 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. The total impact that fracking will have on the groundwater in the Karoo, is a function of the total area that will be fracked.

The outcomes of this research clearly show that fracking in South Africa cannot be done in the same way than it is currently done worldwide. A rule that will force gas companies to disclose fracking fluid contents is non-negotiable. Companies should also be required to measure pressures in the fracked gas reservoir **after** closure. An additional requirement to enforce sealing of the entire fracked reservoir with a very dense material like bentonite or a mud with a very high density to capture the fracking fluids deep down in the gas reservoir should not be negotiable.

1. INTRODUCTION

In this paper the word "fracking" implies all activities associated with the process of shale gas mining - drilling, one-day of actual fissuring the shale, capturing and disposal of the back flow and produced water, production phase and then the very important abandonment phase after production.

The promise of natural gas to be a "game-changer" in energy-related questions has stimulated interest in the Karoo Ecca shale and the political leadership is engaging in shale gas development. Shale gas is explicitly mentioned as a source of the future energy mix (National Planning Commission, NDP, 2011). The moratorium issued by Energy Minister Shabangu on application requests by energy firms to explore economically viable gas reserves has been lifted in September 2012 and the public debate is gaining momentum concerning the effects of fracking.

One of the key issues being debated is the protection of groundwater resources in rural areas, since most of South Africa's rural and some inland cities are dependent on groundwater for potable water supply. Much interest in the country is now directed towards the Karoo because of its potential to deliver shale gas as future fuel source (DMR, 2012; Steyl and van Tonder, 2013). Production of shale gas by means of hydraulic fracturing has the potential of contaminating shallow groundwater resources (de Wit, 2011; Steyl et al, 2012). A large range of chemical elements that could pollute the fresh water is possible e.g. (a) the current groundwater and methane that is captured in the organic Ecca shale, (b) fracking fluids that will be used during the process and (c) existing elements in the shale that will be released due to input of fracking fluids (e.g. NORMs). The water currently captured in the organic shale is not suitable for drinking by humans. Due to the unique geological structure of the Karoo, the presence of dolerite structures, a number of risk mitigation methods might be required to successfully develop hydraulically fractured wells. Holistically, the chemical and hydrogeological impacts related to well field development cannot be ignored in the Karoo aquifer system, as it has the potential to directly influence human and environmental health.

The main causes of groundwater pollution recorded to date are:

- During drilling of a well, intersecting shallow gas pockets can cause migration of volatiles;
- Drilling of a number of wells on one well pad can cause cement annuli to crack;
- Flow back and produced water spills;
- Volatiles and contaminated water can leak into the shallow fresh water aquifer via faulty casings during the production phase; and
- After production, well pressures will return to initial equilibrium conditions and migration can occur along compromised casings as well as faults and dolerite structures in the Karoo.

There is real cause for concern that groundwater will be polluted during the processes of drilling, hydraulic fracturing, actual gas production and subsequent abandonment of a gas well. Some questions highlight current gaps in information that is not available or maybe available but not shared by industry:

- What will the companies do with the hazardous back flow water from gas wells after fracking?
- Why is no monitoring of pressure gradients in abandoned wells currently being done?
- What are the long term effects of fracking? - The actual fracking process of one day rarely poses a significant risk to groundwater pollution. The Karoo basin is under artesian and sub-artesian pressures which mean that when punctured by a gas well, water and volatile gases from deep below surface will rise and will reach the ground surface or shallow fresh water. In the case of preferential pathways, arrival times will be short – measured in days or months.

Laboratory tests as well as field observations during investigations have proven that the cement annulus between the steel casing and the adjacent rock will be compromised over time and that it will form a preferential pathway for methane gas and water containing hazardous substances to migrate upwards towards shallow aquifers that is the livelihood of farmers and local communities in the Karoo. The local people who will be affected by shale gas development are afraid that the fresh water in the Karoo will be polluted by the process. They want to be assured that after abandonment and closure of a gas well, the company will still be responsible if pollution of water takes place. Soekor has drilled 24 deep boreholes in the Karoo during the 1960's looking for oil. Some of these deep boreholes were artesian and we know that this water was undrinkable (Roswell and de Swardt, 1976). Will the flow back water contains radioactive material?

Myers (2012) discussed the possible pathways from hydraulic fractured Marcellus shale to the fresh water aquifer in Pennsylvania and find that two potential pathways could exists. The two pathways are advective transport through bulk media and preferential flow through fractures. With interpretative modeling Myers shows that advective transport could require up to tens of thousands of years to move contaminants to the surface, but also that fracking the shale could reduce that transport time to tens or hundreds of years. Conductive faults or fracture zones, as found throughout the Marcellus shale region, could reduce the travel time further to less than 10 years. Myers used Modflow, which is a 3D porous flow model. His results for traveling times in the matrix should be in the correct order but traveling times along faulty borehole annuli and fault zones will be overestimated and could actually be less than 1 year. Possible contamination of drinking groundwater associated with shale gas extraction has been reported from the Marcellus shale, in Pennsylvania (Osborn et al., 2011, Warner, et al, 2013, Jackson et al, 2013). These authors found that methane concentrations are substantially higher closer to shale gas wells than the regional natural concentration. These contaminations are more likely to be due to leakages related to the construction of the wells than to seepage through the shale. Researchers at the University of Texas at Arlington (Fontenot et al, 2013) have found elevated levels of arsenic and other heavy metals in private drinking water wells near natural gas wells in North Texas' Barnett Shale. They analyzed samples from 100 wells, both inside and outside of the Barnett Shale. Although arsenic was found in 99 of the 100 wells, levels were "significantly higher in active [gas] extraction areas.

In South Africa the dolerite intrusions in the Karoo can definitely be regarded as another preferential pathway for the movement of the fracking chemical and volatiles. These dolerite sill and dyke intrusions make SA more prone to the movement of pollutants

2 CRANEMERE EXPLORATION AREA

Exploring for oil, SOEKOR drilled 24 deep boreholes during the 1960's. For descriptive purposes study SOEKOR well, CR 1/68 will be used as example. Information regarding CR 1/68 (Roswell and de Swardt, 1976) is as follows (Refer to Figure 1 and Figure 2):

Depth of borehole = 4,658 m;
Depth to top of Ecca shale = 2,137 m;
Depth of bottom of Ecca shale = 3,671 m;
Dwyka Formation intersected from 3,671 – 4,290 m; and
Table Mountain Group (TMG) top elevation = 4,512 m.

Gas was intersected in the Ecca Formation at different depths with main strikes between 2,485 – 2,533 m in the Fort Brown shale. At a depth of 2,612 m, on the contact with a dolerite sill with a thickness of 27m, a major "blowout" of gas and water occurred. Bottom hole pressure of the well was 320 bar (well was artesian).

Let's assume that Challenger/Bundu Energy, who owns the exploration rights of in the area of 4 200 km^2, wants to produce gas from their exploration area around the old Cranemere Soekor well (GPS: 32.4854, 25.0087) - close to Pearston in the Eastern Cape.

With the current information available, two models were constructed (one for flow in the vertical direction and the other one for horizontal flow and mass transport to investigate the probable spread of the pollution in the fresh aquifer.

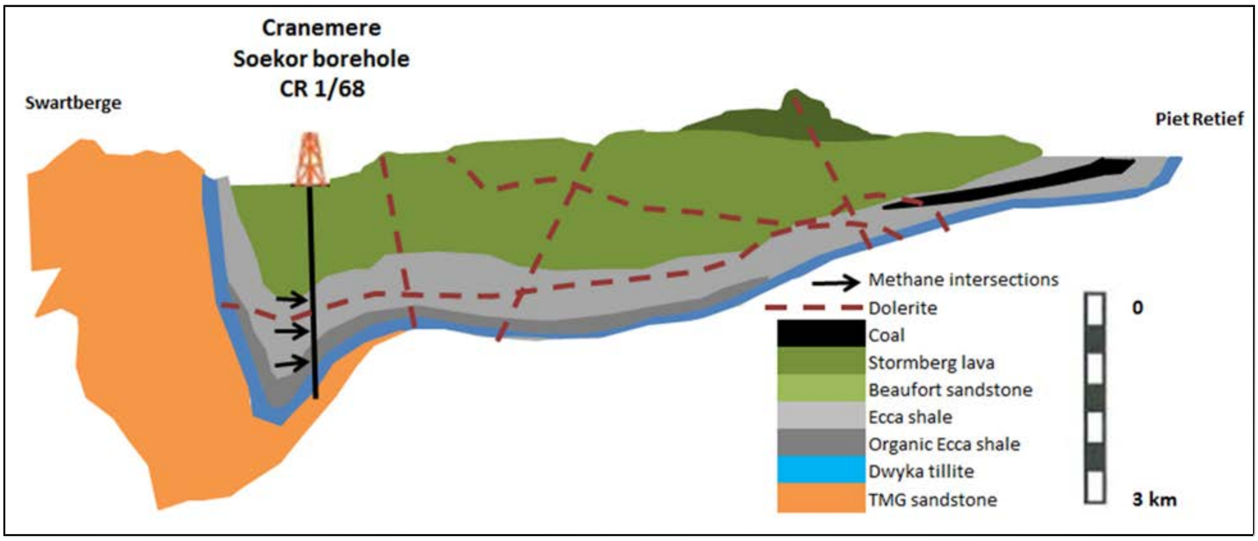

Figure 1. Position of Soekor borehole CR 1/68 in relation with generalized Karoo geology.

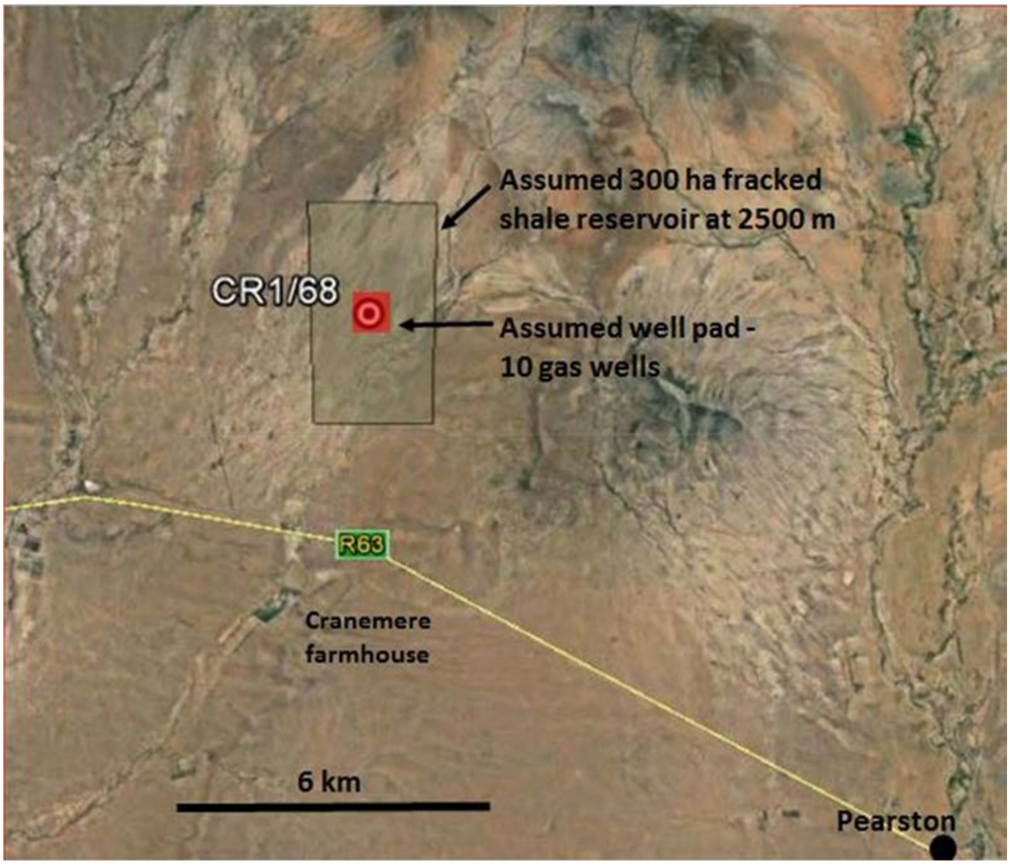

Figure 2: General layout around the Cranemere Soekor CR 1/68 borehole

4 VERTICAL FLOW MODEL

4.1 Assumptions for the vertical flow model:

A vertical upwards flow gradient exists in the Karoo Basin. This assumption is supported by:

- Existence of more than 14 warm water springs in the Karoo;
- All SOEKOR wells which have a surface elevation of less than 1,000 mamsl were artesian (e.g. SA 1/66, CR 1/68, KL 1/66 and VR 1/67) with flows between 0,5 and 7 L/s and total dissolved solids between 1 100 to 10 200 mg/l.

Fig. 3 Tap on artesian borehole SA 1/66 (left) and warm water containing methane flowing from it after tap was opened. Total dissolved solids = 8 100 mg/l

- Thermogenic gas is known to be formed at temperatures in excess of 70 °C (Kaplan et al, 1997). Samples from the Soekor boreholes, with higher δ13C of methane would, in this model be derived from depths > 2500m (Talma and Esterhuizen, 2013)
- All the deep gold boreholes drilled through the Karoo formations were artesian;
- Many of the warm water springs contain thermogenic methane, which proves an origin from a deep source with temperatures greater than 70 °C (Talma and Esterhuizen, 2013, Durban GW conference);
- The association of helium and methane in part of the Karoo basin suggests that these gases could be indicators of preferential pathways from depth Helium/methane content of water intersected during the tunnelling of the Orange-Fish tunnel, confirmed the existence of preferential flow paths from depth (Vogel et al, 1980 and Heaton and Vogel, 1979); and

It is assumed that the upward flow of water along the faulty cement annuli can be approximated by the well-known Cubic Law (parallel plate model for fractures): We can represent a fracture as a planar void with two flat parallel surfaces.

- The hydraulic conductivity of this fracture is defined as:

  $$= 2 \quad \_^{\rho g}$$

  where 2 is the fracture aperture, ρ is the density of water, g is acceleration due to gravity and is the viscosity of water.
- The mean groundwater velocity through the fracture, V can be calculated as the product of the fracture hydraulic conductivity and the hydraulic gradient:

  $$= \quad —$$

  where / is the hydraulic gradient.
- The transmissivity of an individual fracture is then:

  $$= 2 \quad \_^{\rho g}$$

- And the flux along the fracture

  Q = Tf* δi / δz (Eq. 1)

  Where Q is flow in m^3/d per m width
- The validity of the cubic law for laminar flow of fluids through open fractures consisting of parallel planar plates has been established over a wide range of conditions with apertures ranging down to a minimum of 0.2 µm. Witherspoon et al (1980) artificially induced tension fractures and the laboratory setup used radial as well as straight flow geometries. Apertures ranged from 250 down to 4 µm, which was the minimum size that could be attained under a normal stress of 20 MPa. The cubic law was found to be valid whether the fracture surfaces were held open or were being closed under stress, and the results are not dependent on rock type. Permeability was uniquely defined by fracture aperture and was independent of the stress history used in these investigations.

The fracked reservoir is not bounded by impervious boundaries; and

An upwards flow gradient = 0.02 was used in the present study (based on pressures measured at CR 1/68. Interesting is that the upwards flow gradient in the Marcellus is also in the order of 0.02 (Meyer, 2012).

5 HORISONTAL FLOW AND MASS TRANSPORT MODEL

A porous numerical flow and mass transport (2D Aquawin) was used for the study

Assumptions for the horizontal flow and mass transport model include:

The concentration of the up-flowing vertical water = 100% (thus C=100) was used as mass input into the 2D finite element model;

It was assumed that 10 horisontal-fracked gas wells exist on the well pad – the10 wells was drilled around the SOEKOR CR 1/68 well;

Beneath the 10 gas wells an area of 300 ha with a thickness of 100 m was fracked at a depth of 2,500 m below surface;

Only 30 % of the methane and the water were mined during the production phase and after the production phase the pressures steadily increased to initial values after closure;

Both methane and water will refill in the fracked reservoir and when the pressure has increased to higher than hydrostatic pressure (for water), the abandoned gas wells will start leaking gas and water into the fresh water aquifer;

The upward migrating water contains methane which will leak into the fresh water aquifer (also at a concentration of C = 100). The up flowing water has also a C=100;

The fresh water aquifer is unconfined with parameters of T=10 m^2/d, S_y=0.05; kinematic porosity of 0.03; and

The water level in the fresh aquifer follows the surface elevation (a valid assumption for shallow fresh water aquifers in SA). Bayesian interpolation was used to obtain the initial groundwater level contours as shown in Figure 4.

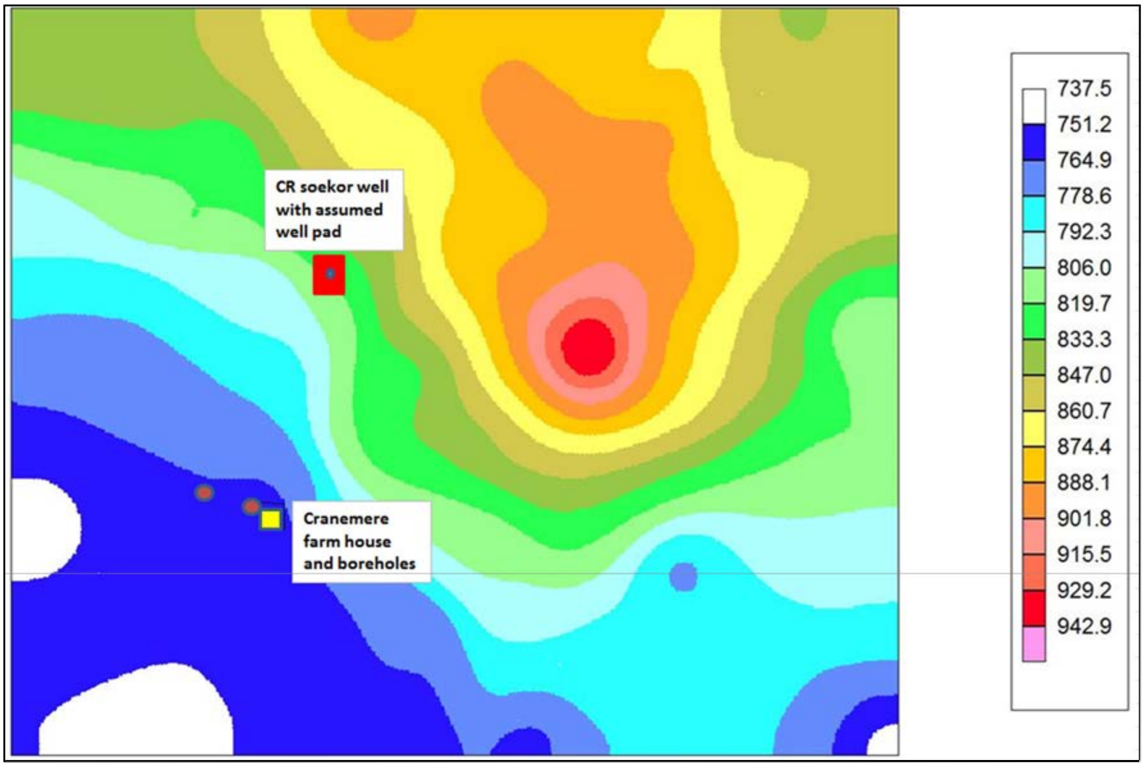

Figure 4: Interpolated Bayesian groundwater level contours on the Cranemere Farm

6 MODELLING RESULTS

6.1 Cubic Law

Figure 5 depicts the estimated upward fluxes generated by the parallel plate model. If cracks in faulty cement annuli are assumed to have apertures between 0,0025 and 0,5 mm, the expected upward flows can vary between 0,00024 – 1,87 L/s per borehole.

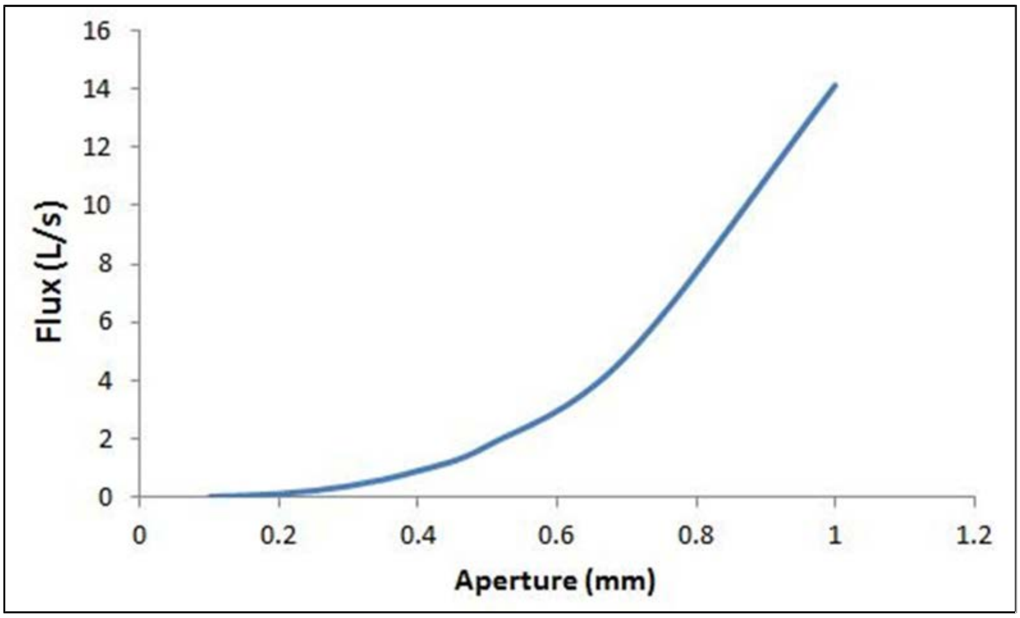

Figure 5: Probable estimated vertical fluxes along a faulty borehole cement casing as a function of the aperture of the fracture (parallel plate model used). The width of flow = circumference of well = 0.16m

6.2 2D Finite Element Model

Figure 6 shows the estimated movement of the pollutant plume from the well-pad for a time period of 30 years. It was assumed that the pollutant will travel under natural conditions (no abstraction boreholes in action).

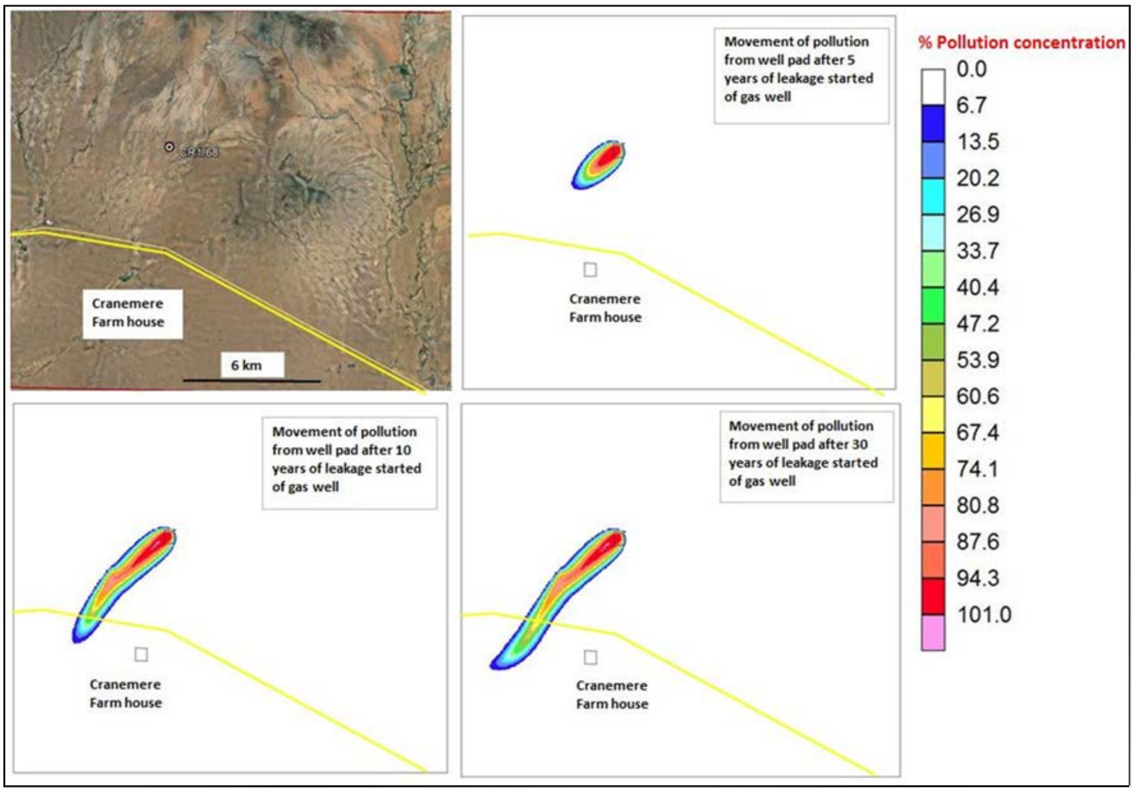

Figure 6: Model simulated movement of pollutants from the gas well-pad at Cranemere under natural conditions (no pumping). Input concentration of pollutant = 100%. It is clear that after 30 years the pollutant already has moved a distance of more than 7 km. An area of more than 300 ha is contaminated

As a second scenario, abstraction borehole 1 was introduced into the model and the model was re-run. Figure 7 shows the simulated movement of the pollution plume

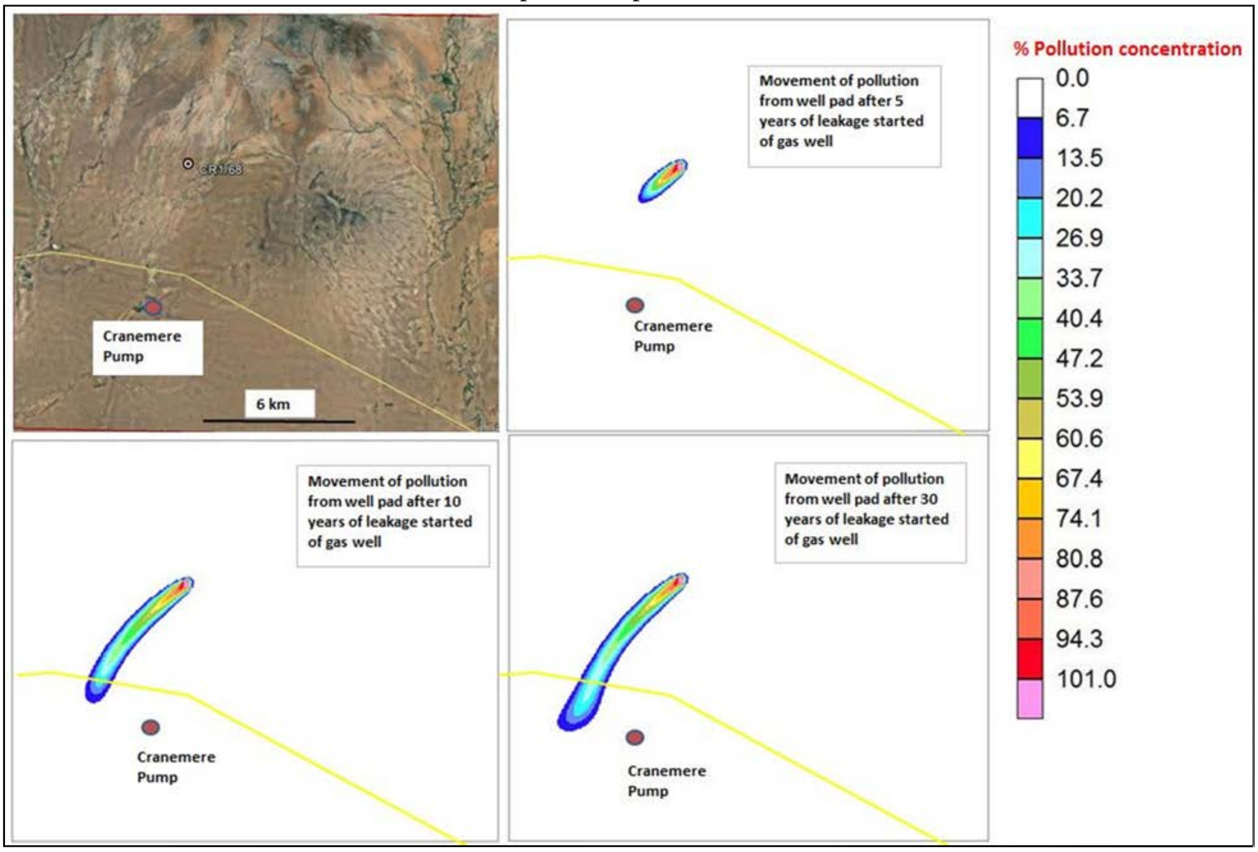

Figure 7: Estimated movement of the pollutant at Cranemere in the case where the abstraction borehole at the farm house at Cranemere was introduced into the model. The abstraction rate used was 0.5 L/s

As a final scenario it was assumed that a fault transects the area and borehole 2 at Cranemere was activated to abstract water. For this case the pollutant has reached the farmer's borehole after 10 years. Figure 8 and Figure 9 show the results.

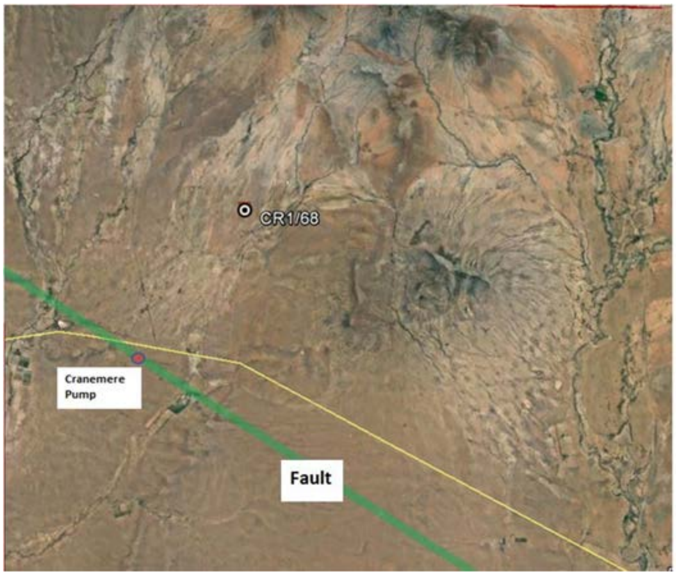

Figure 8: Position of the assumed fault at Cranemere

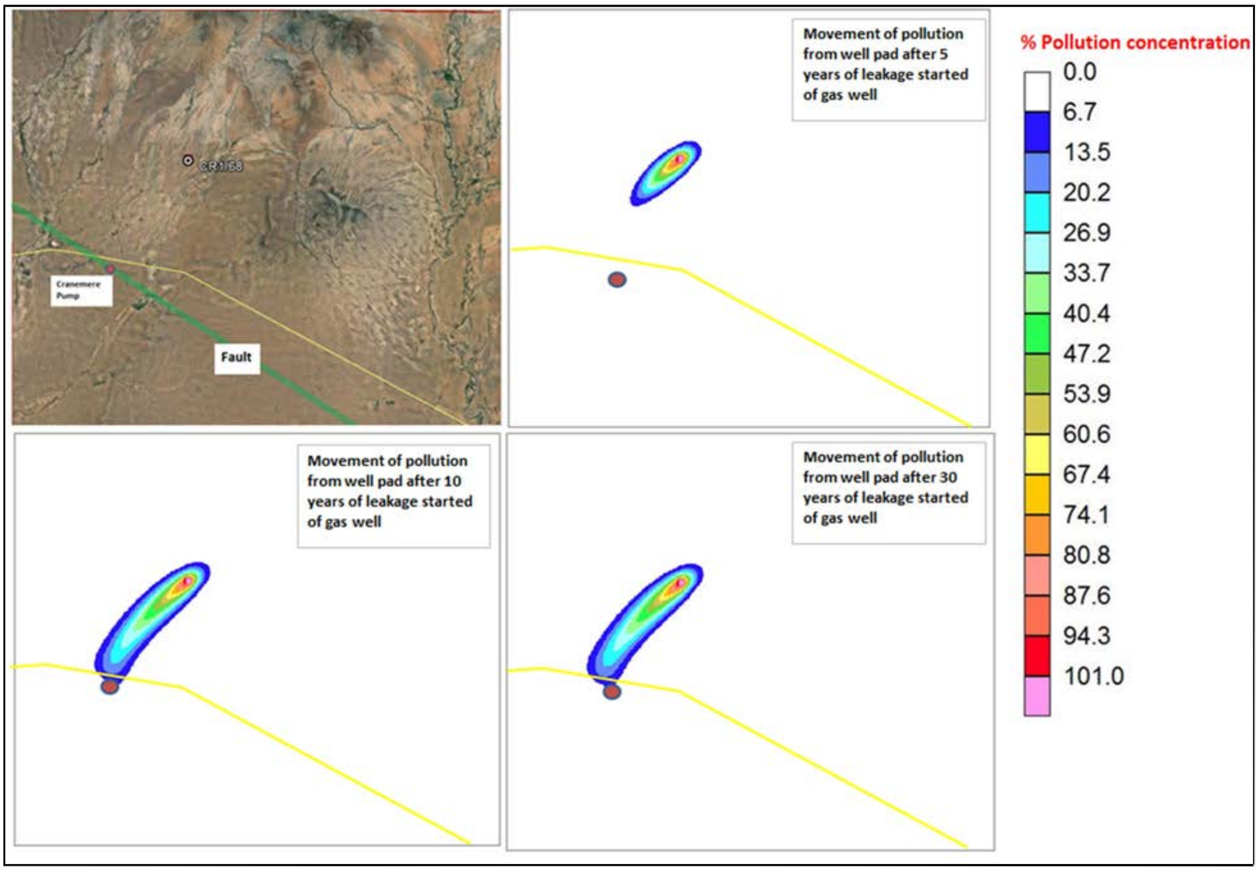

Figure 9: Estimated movement of the pollutant plume in the case where a fault crossed the area. The pollutant with a concentration of 10% has reached the abstraction borehole of the farmer after 10 years.

If an abstraction borehole is intersected the same fracture than gas wells on the well pad, traveling times between the well pad and the abstraction borehole can be very rapid. Tracer tests conducted in a Karoo aquifer at Bloemfontein (de Lange, 1999) showed that flow velocities along a fracture can be as high as 120 m per day. A pollutant can thus travel along a fracture more than 3 000 m per month. In the Cranemere example above, a pollutant will take less than two months to travel from the well pad to the abstraction borehole.

7 CONCLUSIONS

The following conclusions are made from the present study:

- In the case where just the cement annuli from gas boreholes will leak harmful water from the fracked reservoir, a typical leakage can vary between 0.0001 L/s to 1.8 L/s;
- The area that will be contaminated will vary according to the aquifer parameters and the upward leakage rate. A typical contaminated area from one well pad with 10 gas boreholes situated on it could easily be 300 ha after 30 years. This area will increase with time until a stream or no-flow boundary is reached;
- The area which will be polluted from one well pad, could be much more than estimated in this study because existing preferential flow paths along faults and dolerite structures, which are numerous in the Karoo, were not taken into account;
- The total areal impact of groundwater pollution due the fracking will be a function of the total number of well-pads and could run into thousands and thousands of hectares at the end of fracking in the Karoo;
- The impact of groundwater pollution due to fracking could be enormous in years to come in the world and much more than given by gas companies and also scientists in the USA;
- The results of the present study should raise alarm bells for the government of SA, and
- Gas companies must set mitigation processes in place before fracking started in SA. For example are they willing to plug the entire gas reservoir after the production phase is finished? Water pressures in the reservoir should be regulated such that no artesian conditions exists

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