Submission in response to *Background and Issues Paper* for Inquiry into Hydraulic Fracturing in the Northern Territory

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Author background and relevant expertise

I am currently employed full-time as a Senior Lecturer in the School of Engineering at RMIT University, in Melbourne. I received my PhD from Monash University in 2011, on the use of environmental isotopes and geochemistry to assess sustainability of groundwater usage and controls on groundwater quality in a water-stressed region of northern China. For the last 6 years, while employed at RMIT, I have taught hydrogeology, geochemistry and groundwater modelling to environmental and civil engineering students, and supervised Masters and PhD projects in applied hydrogeology research. I have been awarded more than half a million dollars in research funding as a lead chief investigator on more than 10 research grants, which have supported projects examining groundwater sustainability and contamination issues in Australia and China. I have published more than 25 peer-reviewed international journal articles, which have been cited more than 400 times, and I am on the editorial board of the *Hydrogeology Journal* (the journal of the International Association of Hydrogeologists).

I acted as an independent scientific expert witness regarding hydrogeology and groundwater quality issues during the Victorian Parliamentary Inquiry into unconventional gas in 2015. My submission to the inquiry was extensively cited in the committee's final report (Parliament of Victoria, 2015). I was also commissioned by the then Department of Environment and Primary Industries (DEPI) to carry out baseline monitoring of methane and isotopes in groundwater in areas of potential future unconventional gas activity – particularly the Gippsland Basin. This work was recently published in a peer-reviewed international journal article (Currell et al, 2016).

Summary: Risks to groundwater and the environment from unconventional gas

There are a number of potential risks to the environment (particularly groundwater and surface water) and human health from unconventional gas, and these have been the subject of intense worldwide debate over the last five years or so (Osborne et al, 2011; Vidic et al, 2013; Vengosh et al, 2014; Jackson et al, 2014; US EPA, 2016). Since 2010, a growing body of research has been carried out worldwide (particularly in the United States) to understand the risks and impacts to the environment and human health associated with hydraulic fracturing and other aspects of the unconventional gas life cycle.

The list of risks presented in the *Background and Issues paper* prepared by the scientific inquiry panel identifies many of these risks and is comprehensive as a 'high level' first-pass assessment of the major issues. This submission seeks to provide further detail and advice with respect to more detailed assessment and management of particular risks that are within my field of expertise and which were identified in the paper, in particular:

a) Groundwater and surface water contamination associated with spills of 'flow-back' or 'produced' water generated during hydraulic fracturing and/or gas well development;
b) Release of stray or 'fugitive' gas into shallow aquifers and/or the near surface atmosphere;
c) Creation of new pathways for fluids (including potential contaminants) to travel between different geological layers and contaminate groundwater or surface water bodies.

Figure 1 provides a schematic representation of where these risks apply in association with unconventional gas:

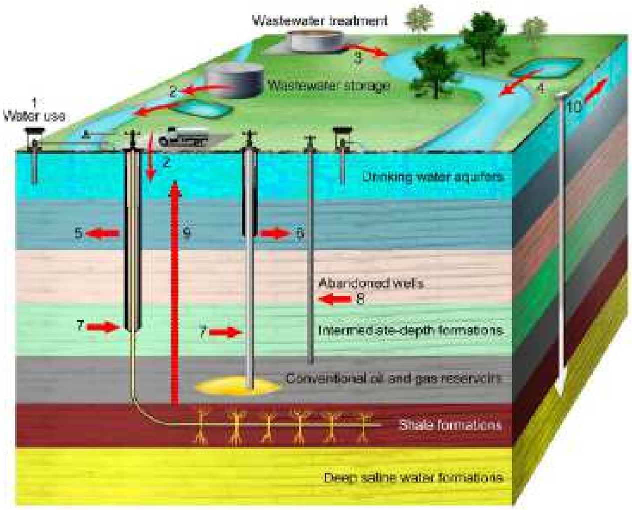

Figure 1 – Simplified representation of unconventional gas extraction and potential pathways for impacts to water resources and the environment. From: Vengosh et al. (2014).

1. Groundwater and surface water contamination

Contamination of groundwater and surface water are major environmental risks that require careful management in any unconventional gas operation (Hamawand et al, 2013; Vengosh et al, 2014; Vidic et al, 2013; Jackson et al, 2014). The major pathways by which contamination of surface and/or groundwater can take place (whether hydraulic fracturing is involved in the gas project or not) are:

a) Contamination by wastewater, including hydraulic fracturing fluids, produced water or ‘flowback water’ that may be spilled, leaked and/or inappropriately managed as it is brought to the surface and stored, treated and transported around a site;
b) Contamination due to well integrity failures, legacy/abandoned boreholes, or geological pathways such as faults and fractures that may allow gas and/or fluids to escape from unconventional gas reservoirs and cross-contaminate other aquifers.

According to Professor Robert Jackson (from the Stanford University School of Earth Sciences) and colleagues, who have published extensive peer-reviewed studies on the environmental impacts of unconventional gas in the United States:

> “Maintaining well integrity and reducing surface spills and improper wastewater disposal are central to minimizing contamination from the hundreds of chemicals found in fracturing fluids and from naturally occurring contaminants such as salts, metals, and radioactivity found in oil and gas wastewaters.” (Jackson et al, 2014; p.241).

To this end, any assessment of the environmental risks associated with a potential future unconventional gas development should contain detailed datasets and analysis that includes the following:

1. Detailed baseline groundwater chemistry data for any formation water occurring in the strata targeted for gas development, and overlying aquifers which may be affected by contamination (e.g. Currell et al, 2016);

2. Detailed chemical characterisation of the fluids to be used (or proposed to be used) for hydraulic fracturing, as well as chemical characterisation of produced water/flowback water generated during any preliminary gas exploration activity;

3. Analysis of the potential pathways and mechanisms by which contamination of shallow aquifers by fluids or gases may take place - such as:
    a) legacy/abandoned boreholes,
    b) well faults (e.g. engineering failures, ruptured casing, blow-outs)
    c) geological features, such as major faults and fracture zones
    d) Surface spills and leaks of hydraulic fracturing fluids or flowback water from well-heads, storage dams or pipelines

4. Programs to locate, identify and mitigate such risk pathways – such as surveys of legacy boreholes (and if required, cementing/decommissioning of abandoned or faulty wells), detailed geological surveys to identify locations of faulting/fracture zones, and carefully engineered surface infrastructure to handle produced water and minimise the risk of spills and leaks

5. Risk assessment strategies, whereby the hazard, likelihood and consequence of contamination associated with hydraulic fracturing and produced water are assessed, with detailed supporting assumptions and relevant data;

6. Ongoing monitoring plans to rapidly detect any incidences of groundwater contamination with fluids of gases associated with these risk pathways;

7. Detailed strategies to rapidly minimise and mitigate any such impacts as they are detected

1.1 Risks due to flow-back water and other produced fluids during unconventional gas development

'Flowback' water is the fluid which returns to the surface (via the gas well) following hydraulic fracturing. This water contains a mixture of the original hydraulic fracturing fluid (approximately 10 to 40%), plus formation water which mixes with the fracking fluid while underground – for shale gas this usually comprises saline formation brines (Jackson et al, 2014). Flowback water is generally poor quality, and it contains a number of potential pollutants including high salinity, elevated heavy metal contents, radio-nuclides and organic chemicals used in the fracturing fluid mixture (e.g. Warner et al, 2013). As such it must be carefully managed and appropriately treated. Recent research has shown that the large scale and rapid development of the shale gas industry in the United States has created problems with the management of flowback water (as well as hydraulic fracturing fluids prior to their injection into gas wells), and leaks and spills which contaminate the environment are relatively common (U.S. EPA, 2016; Patterson et al, 2017).

A recent study by Duke University and the United States Geological Survey (Patterson et al, 2017), showed that some form of spill or leakage of wastewater has occurred at between 2 and 16% of unconventional gas wells drilled and operated in the United States, for which data have been collected. These rates appear to be relatively consistent, regardless of whether the gas wells are subject to hydraulic fracturing or not (Figure 2). The Patterson et al, survey includes a large, representative dataset - tens of thousands of individual gas wells across different states and different types of unconventional gas projects. According to their data, the risk of such spillage/leakage incidents is greatest within the first 3 years of drilling and development of a given gas well. The US EPA's 5-year nation-wide review of impacts of shale gas on drinking water (US EPA, 2016), estimated a similar percentage of spillage incidents (on the basis of smaller sample size), associated with hydraulic fracturing fluids specifically, and noted that spills occur both prior to hydraulic fracturing (e.g. during mixing and preparation of the fracking fluid at the well-head) and following hydraulic fracturing (flowback water).

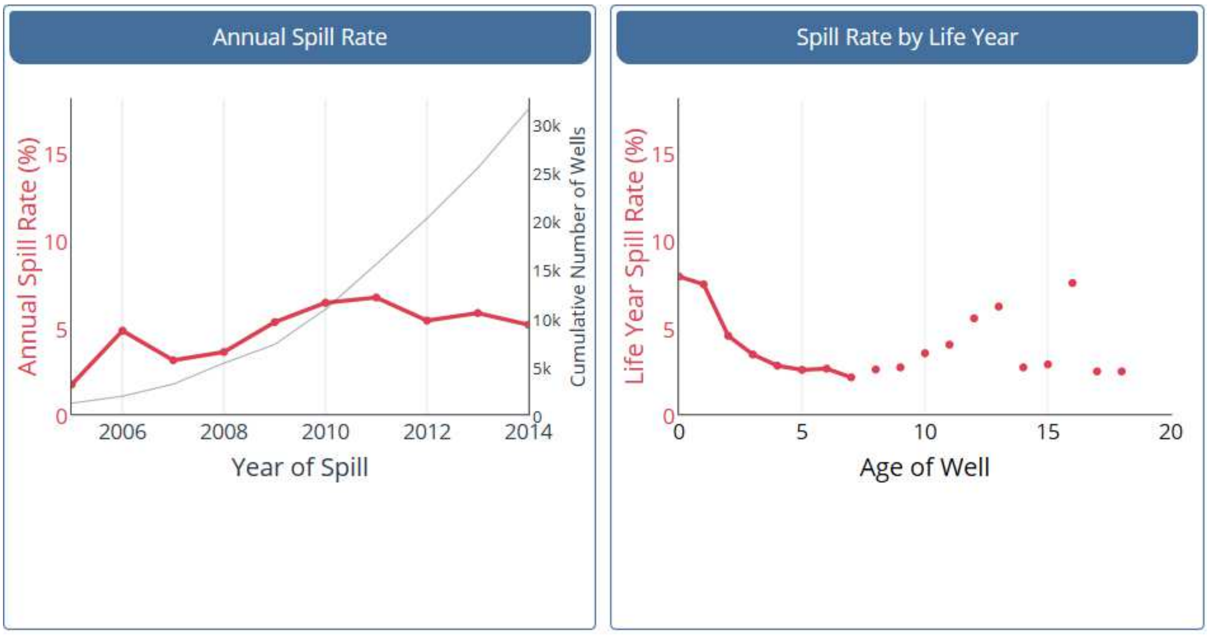

Figure 2 - Wastewater spill rates in the United States per number of wells in shale, coal and tight gas & oil operations. Data sourced from the National Center for Ecological Analysis and Synthesis spills data visualization tool: http://snappartnership.net/groups/hydraulic-fracturing/webapp/spills.html

Spills and leaks of wastewater at unconventional gas wells occur due to a variety of reasons, including accidents during storage and transport of wastewater via flow lines, equipment failure and human error (Figures 3 & 4).

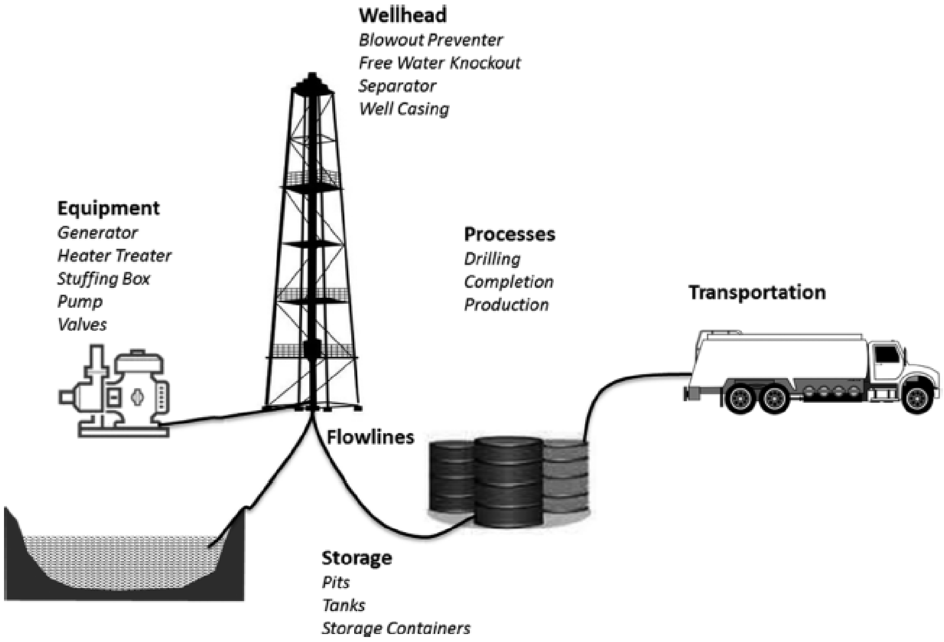

Figure 3 – Conceptual diagram of unconventional gas set-up, showing points at which spillage/leakage of waste water commonly occur. From: Patterson et al. (2017).

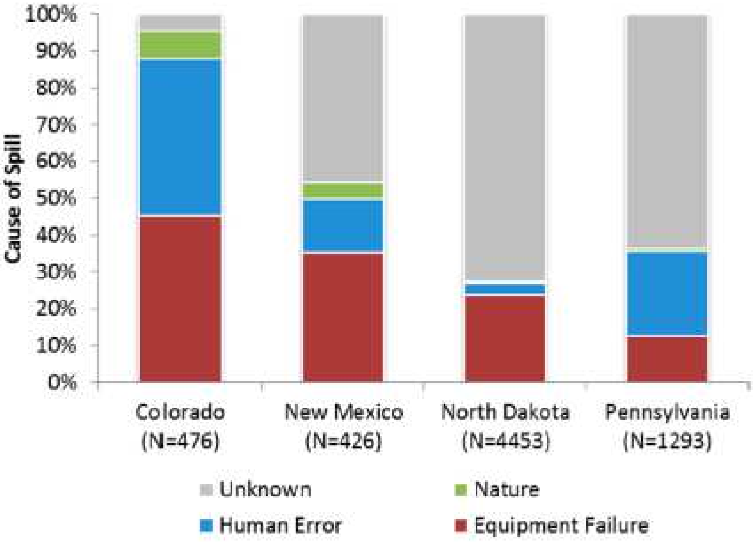

Figure 4 – breakdown of the number and cause of waste water spills from unconventional gas operations in four states in the U.S. From: Patterson et al. (2017).

On the basis of these data, it is reasonable to conclude that regardless of the level of care, and the desire of project operators to minimise spills and leaks of unconventional gas wastewater, there will inevitably be some spillage/leakage incidents associated with any unconventional gas project of significant size, whereby flowback water or other wastewater is unintentionally released to the environment. A cautious and conservative approach to this issue, which recognises that spills and leaks will inevitably happen, is therefore warranted. The key questions in the minds of project operators and regulators should thus be not *whether* wastewater spills and leaks will occur, but rather:

a) *how to minimise* the incidence of these events to the greatest extent possible, so that the number of spill/leak incidents approaches the low end of the typical range (e.g. 2% of wells rather than 15%);
b) *how to detect* as rapidly as possible when these events do take place, through leak/spill detection systems and an extensive network of shallow groundwater monitoring wells; and
c) *how to contain and mitigate* the consequences of these events so that they have minimal impact on the environment.

Baseline groundwater geochemical data (collected before any development takes place) is a critical requirement in this approach. An example of a baseline data collection program in Australia conducted prior to unconventional gas development (in areas known to be prospective for tight gas) is the Victorian Water Science Studies (Jacobs, 2015; Currell et al, 2016). Further detail and data from these studies is shown below in section 2.

2. Contamination of aquifers and the atmosphere with fugitive (stray) gas

2.1 Groundwater contamination with fugitive methane

It is now well documented that contamination of shallow aquifers with 'stray gas' or 'fugitive methane' has occurred in a number of areas of the United States due to unconventional gas development (Bair, 2010, Osborn et al 2011, Ground Water Protection Council, 2012, Jackson et al, 2013, Darrah et al, 2014, Jackson et al, 2014).

As is noted in the review by Professor Robert Jackson and colleagues, most instances of fugitive gas contamination impacting shallow groundwater due to unconventional gas have to date occurred as a result of problems with the casing and cementing of gas and/or water wells in the project areas. Abandoned (legacy) wells are another possible conduit for cross-contamination of aquifers with fugitive methane:

> "In well leakage, fluids (liquids or gases) can migrate through holes or defects in the steel casing, through joints between casing, and through defective mechanical seals or cement inside or outside the well. A build-up of pressure inside the well annulus is called sustained casing pressure (SCP) and can force fluids out of the wellbore and into the environment. In external leaks, fluids escape between the

> tubing and the rock wall where cement is absent or incompletely applied. The leaking fluids [including stray gas] can then reach shallow groundwater or the atmosphere." (Jackson et al, 2014, p. 337).

In some extreme cases, gas contamination of shallow aquifers can result due to major well-failure incidents such as 'blow-outs', which take place when there is a significant build-up of sustained casing pressure in the well. Bair (2010) describe the findings of an expert panel appointed to document the mechanism of one such incident in Bainbridge County, Ohio, which resulted in methane contamination of shallow water bores, and an explosion in a home basement from fugitive methane build-up (Figure 5):

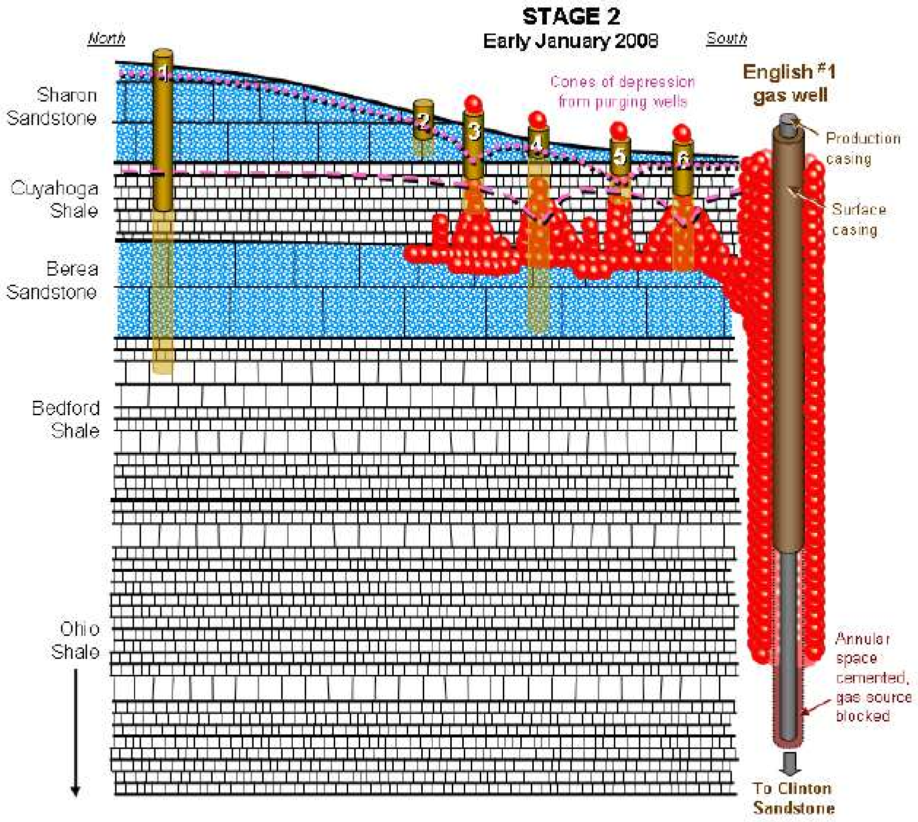

Figure 5 - Schematic diagram showing mechanism of gas contamination of shallow aquifers, based on a case study in Bainbridge County, Ohio. From: Bair, (2010).

As with surface leaks of unconventional gas wastewater, it is acknowledged in the technical and research literature that faults in a small percentage of gas wells are inevitable, and as such it is not possible to eliminate the risk of stray gas (or fluid) contamination associated with well faults entirely - particularly in a gas project with a large number of wells. Jackson et al, (2014) cited data showing that between 3 and 6% of wells in the Marcellus Shale in Pennsylvania (a highly developed shale gas resource in the United States) experienced failures within the first 3 years of operation. Similar rates of failure are reported for wells drilled for conventional or unconventional oil and gas projects in the United States (Jackson et al, 2013b).

As with CSG wastewater contamination of groundwater from the surface, a rigorous assessment and management plan for possible fugitive gas contamination via well faults requires that extensive and detailed baseline groundwater chemistry datasets be collected prior to development of the project. As discussed in section 1, such baseline groundwater chemistry data is a pre-requisite for effectively monitoring and detecting any possible leakage of gas (or fluids) into shallow groundwater as a result of gas development activity (such as hydraulic fracturing). An example of a baseline monitoring program which included repeated measurements of methane in shallow (and deep) groundwater above gas-bearing geological formations is the Victorian Water Science Studies, carried out in 2015 in association with the Gippsland Bioregional Assessment project (e.g., Jacobs, 2015). This program used specialised groundwater and gas sampling techniques to determine baseline concentrations of methane in groundwater in the Gippsland and Otway basins – which at the time were considered potential future areas of unconventional gas development. The baseline data served to document pre-existing levels of gas in groundwater.

In partnership with this sampling, an isotope sampling program was conducted by Currell et al (2016). This allowed existing sources of methane and associated geochemical processes in aquifers overlying gas deposits to be better understood. Isotopic characterisation allows for ‘fingerprinting’ of gases from particular sources- such as naturally occurring bacterial methane produced in relatively shallow sedimentary formations, and thermogenic gases produced at great depth, which are the typical targets for gas development. As an example, an increase in the concentrations of thermogenic type gas in water wells containing little pre-existing methane and/or methane with a different isotopic signature (such as biogenic gas), would be a clear indication of contamination by fugitive gas, which may be more difficult to establish without the isotope data in addition to baseline concentrations. Examples of data collected in these monitoring programs are shown below in figures 6 to 8. Datasets of this kind provide a mechanism to understand pre-existing levels of dissolved gases and other potential contaminants that could be associated with unconventional gas development, characterise the current-day processes controlling groundwater quality in aquifers near potential gas targets, and identify any changes that might occur to groundwater chemistry (such as dissolved gas concentrations or other associated changes), following hydraulic fracturing or other unconventional gas activity.

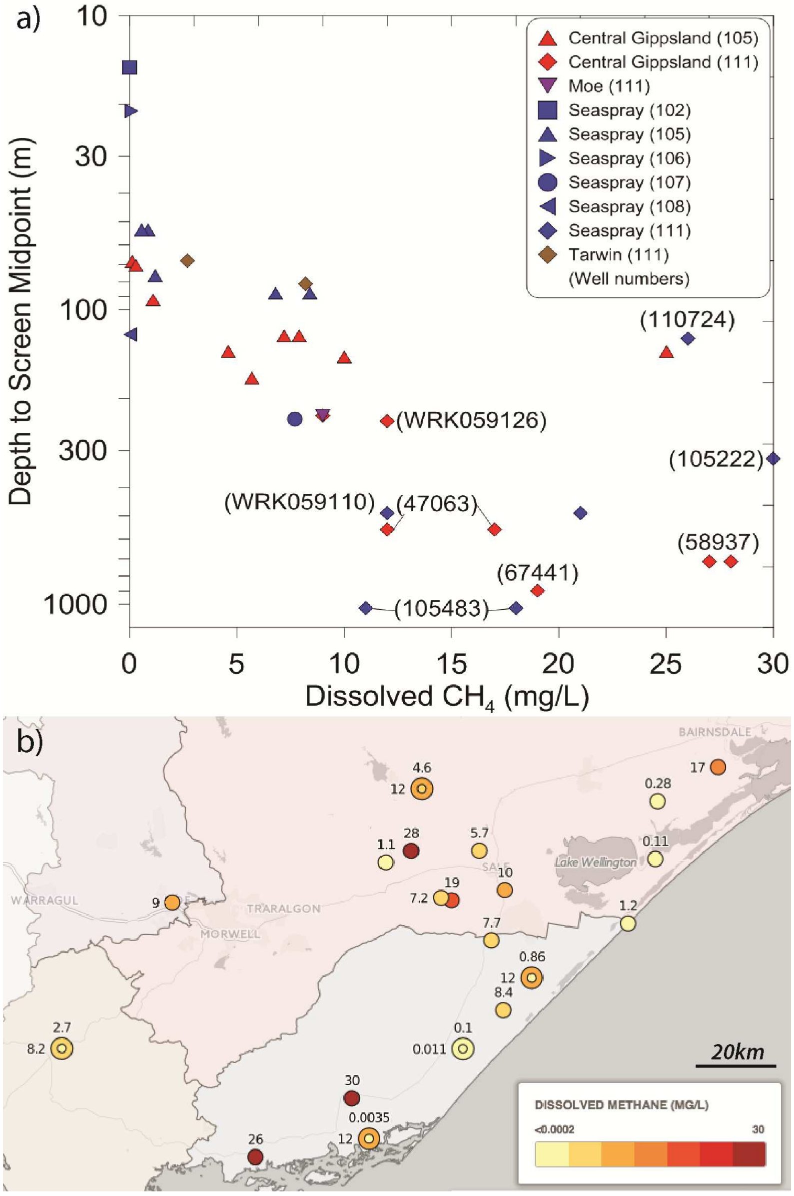

Figure 6 – Example of baseline data collected in Gippsland basin, showing concentrations of dissolved methane in groundwater at different depths and aquifers overlying a potential unconventional gas target (Currell et al, 2016)

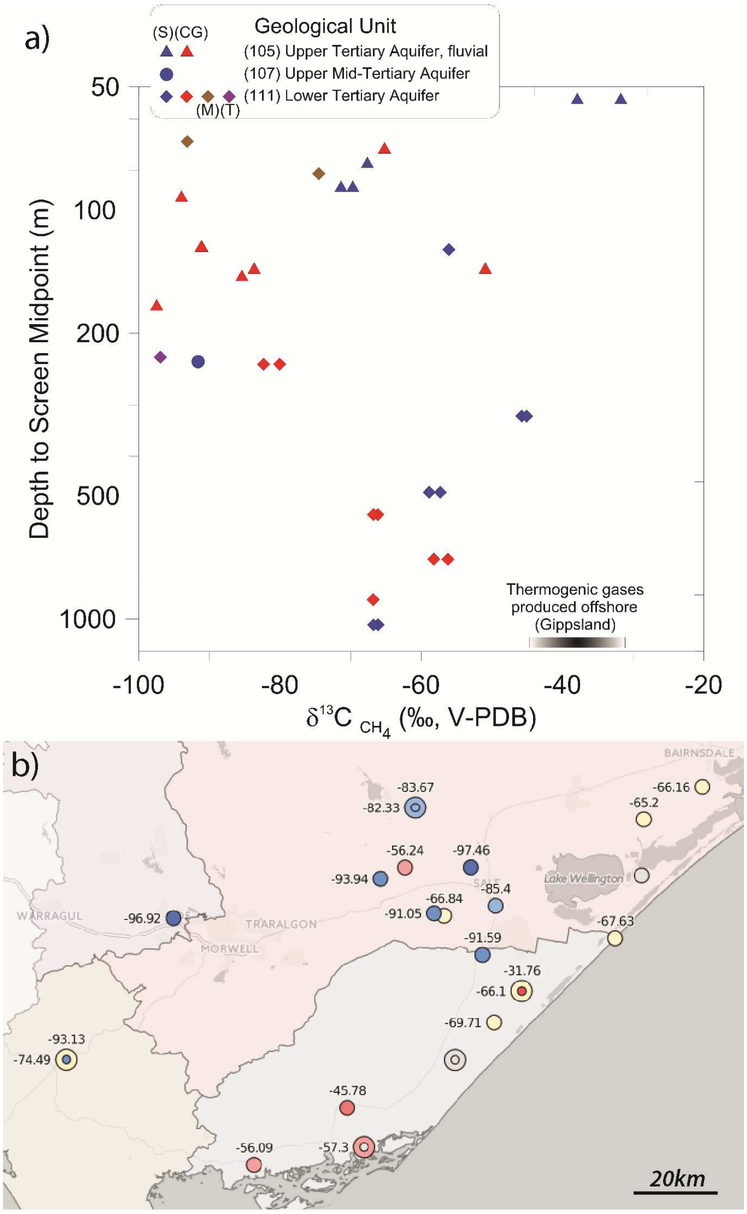

Figure 7 – Baseline isotopic characterisation of methane in groundwater in the Gippsland Basin (Currell et al, 2016).

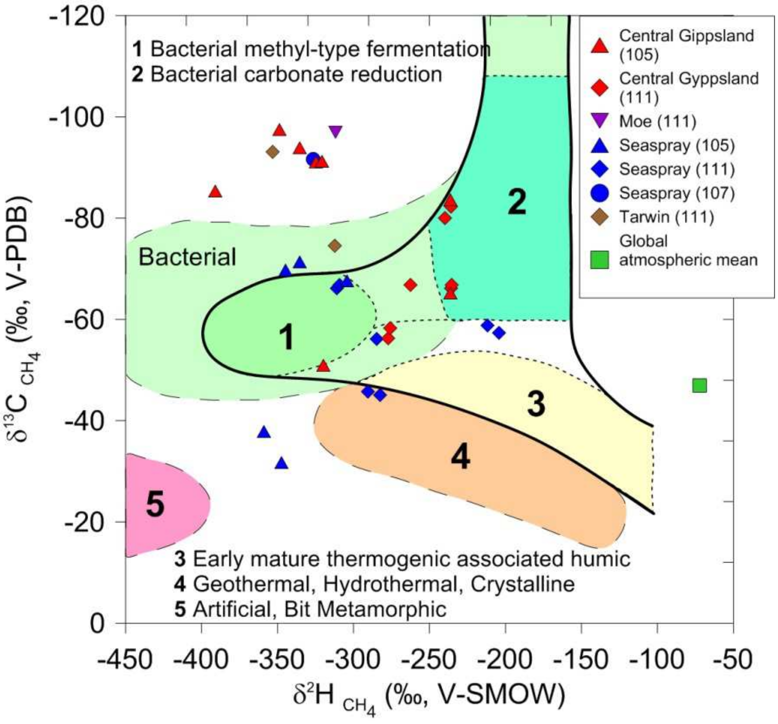

Figure 8 - Baseline isotopic characterisation of dissolved methane in groundwater from the Gippsland basin, showing likely sources of dissolved gases under current conditions. Isotopic compositions can fingerprint gases from different sources (Currell et al, 2016).

Similar baseline programs have been carried out in the Richmond River catchment in northern NSW (Atkins et al, 2015) and Alberta Canada (e.g., Humez et al, 2016). Such monitoring programs (reporting methane concentrations and isotopic compositions in groundwater in areas of possible unconventional gas development) should be standard practice for any unconventional gas project of significant size, to ensure a rigorous baseline exists for assessing fugitive methane or other contamination impacts on overlying groundwater resources.

2.2 Fugitive methane release to the surface atmosphere

In addition to the risk of contaminating water supply aquifers with fugitive gas, emissions of methane to the atmosphere during unconventional gas development are a significant potential source of greenhouse gas emissions. Methane is a potent greenhouse gas, with approximately 30 times the global warming potential of carbon dioxide on a 100-year timeframe. The potential sources of increased methane emissions to the atmosphere from unconventional gas include leaks from gas well-heads (e.g. leaking valves or joins, see Day et al, 2014); venting from wells and other gas collection, transport and processing infrastructure; leakage that occurs during gas well drilling – this was recently determined to be a significant source associated with shale gas drilling in the United States (Caulton et al, 2014); and de-gassing of methane from produced water that is stored in above-ground dams (Kort et al., 2014; Iverach et al, 2015).

In 2011, William Howarth (a professor at Cornell University) and colleagues proposed that fugitive methane to the atmosphere from unconventional gas development due to well, pipeline and other leaks in the United States was being systematically under-estimated by national greenhouse gas inventories (Howarth et al, 2011). Subsequently, a number of studies looked to quantify fugitive methane to the atmosphere in areas inside and outside unconventional gas fields, including U.S. shale gas and coal-bed methane fields, and Australian coal seam gas fields (e.g. Kort et al, 2014; Maher et al, 2014; Day et al, 2014; Caulton et al, 2014; Melbourne Energy Institute, 2016). These studies have largely confirmed the hypothesis that direct leakage of methane to the atmosphere during the 'upstream' part of the unconventional gas process (extraction, transport and processing of the gas) can be a significant GHG source, and potentially negate the relatively lower CO_2 equivalent emissions associated with the 'downstream' burning of natural gas for energy (as compared to coal or oil).

In Australia, Maher et al (2014) monitored near-surface methane concentrations in northern New South Wales and southeast Queensland, comparing areas within coal seam gas development (the Tara and Casino gas fields) with areas outside gas fields. They showed that near-surface atmospheric methane concentrations were elevated in the coal seam gas fields (up to 6.5 parts per million, and consistently above 2ppm) relative to areas of no coal seam gas development and similar geology. Possible explanations proposed were leaks around gas well production and collection infrastructure, increased soil gas emissions and/or de-gassing from produced water stored in above ground ponds containing dissolved methane.

Work conducted through the CSIRO by Day et al., (2014) examined gas leaks in some of Queensland's coal seam gas fields using similar technology. They targeted gas production wells and pipelines, looking to identify point source leakage to the atmosphere. They found that the majority of operating CSG wells showed little or no evidence of gas leakage, and that in general gas contents were at background atmospheric levels. However, one well was identified where increased levels of methane emission were occurring to the atmosphere, due to a valve which periodically vented gas to the atmosphere.

A recent study by Dana Caulton and colleagues published in the *Proceedings of the National Academy of Sciences, USA* used both 'top down' estimates (using aircraft-based measurements of greenhouse gases) and 'bottom up' estimates (using ground based monitoring instruments) to determine fluxes of fugitive methane to the atmosphere in areas of shale gas production (Marcellus Shale) in Pennsylvania. This work showed significantly higher fluxes associated with gas drilling, transport and processing than were previously documented and used in industry and government inventories of fugitive methane emissions, and highlighted the significance of emissions during drilling and well-pad development:

> "An instrumented aircraft platform was used to identify large sources of methane and quantify emission rates in southwestern PA in June 2012. A large regional flux, 2.0–14 g CH_4 s^{-1} km^{-2}, was quantified for a ~2,800-km^2 area, which did not differ statistically from a bottom-up inventory, 2.3–4.6 g CH_4 s^{-1} km^{-2}. Large emissions averaging 34 g CH_4/s per well were observed from seven well

> pads determined to be in the drilling phase, 2 to 3 orders of magnitude greater than US Environmental Protection Agency estimates for this operational phase. The emissions from these well pads, representing ∼1% of the total number of wells, account for 4–30% of the observed regional flux. More work is needed to determine all of the sources of methane emissions from natural gas production, to ascertain why these emissions occur and to evaluate their climate and atmospheric chemistry impacts" (Caulton et al, 2014).

Other methods of detecting and quantifying such emissions, including satellite-based estimation of atmospheric methane fluxes, have highlighted significant emissions from coal seam gas (called 'coal-bed methane' in the US) in New Mexico (Kort et al, 2014). The significant methane emission anomaly identified in this area was attributed to either leakage from CSG wells and/or de-gassing from CSG wastewater produced and stored in open ponds at the surface. The estimates of methane flux from the satellite derived methods also showed higher levels of emission than those previously accounted for by the US EPA's inventories. These studies highlight that increased methane emissions to the atmosphere are a common problem associated with unconventional gas development, which may cause significant under-estimation of the greenhouse gas emissions from these projects. The work of Howarth and colleagues (e.g. Howarth et al, 2011; Howarth, 2014) proposes that these 'upstream' sources of greenhouse gas may neutralise the 'donwstream' benefits of natural gas as a fuel in comparison to coal and other fossil fuel energy sources.

As with groundwater, the collection of baseline data on methane concentrations (and preferably also isotopic compositions) in the near surface atmosphere in areas of potential unconventional gas development is therefore another critical step in ensuring fugitive methane resulting from gas projects can be accurately assessed and quantified. Surveys of the pre-gas development levels of atmospheric methane, using both 'bottom up' (e.g. ground surveys) and 'top-down' (e.g. aircraft and/or satellite-based monitoring) should be conducted to provide an accurate baseline to compare emissions before, during and after gas development. Analysis of the isotopic composition of the atmospheric methane, using mobile continuous-flow isotope mass spectrometry, can also help to 'fingerprint' the sources of atmospheric methane in a given area, such as agriculture, landfills, wastewater treatment plants and gas wells.

An example of such a program conducted in Australia is the monitoring conducted in 2014 for AGL's Camden gas project. In this program, methane levels in the atmosphere were collected using ground-based portable infrared mass spectrometers deployed at a range of locations up-wind and down-wind of the CSG operations, and data on both the atmospheric concentrations, and isotopic compositions of methane were collected (Pacific Environment, 2014). This study allowed pre-existing sources unrelated to CSG (such as landfills and livestock) to be measured and accounted for as well as CSG related emissions – in this case one event of significant methane emission was detected due to gas processing activities at the AGL plant.

Any unconventional gas project proposal should outline detailed strategies for both collection of such baseline data, and ongoing monitoring to detect changes in fugitive methane emissions due to gas activity. Rapid and effective response plans should also be developed to address any detected contamination with fugitive methane, and quickly cut the contamination pathway(s).

2.3 Radon and other hazardous gas emissions

In some cases, shale formations are associated with relatively high concentrations of naturally occurring radioactive material (NORM) (e.g. Warner et al, 2013). There is currently debate in the United States over whether hydraulic fracturing is causing increased levels of emission and exposure of such radio-nuclides – particularly through emission of radon gas and/or radium in wastewater discharged to the environment.

A recent study conducted by Casey et al, (2015) examined nearly 1 million measurements of radon gas (Rn^{222}) from the basements of houses situated above the Marcellus Shale, where hydraulic fracturing has been extensive in recent years. They found that there was a statistically significant increase in levels of radon in basements above areas of hydraulic fracturing compared to areas without shale gas development, posing a potential lung cancer risk. While the precise mechanism and link with unconventional gas is not clearly delineated in this work, the data support the hypothesis of increased overall fluxes of soil gas from underlying geological formations stimulated by hydraulic fracturing in areas where such activity is intensively conducted.

These findings are consistent with work carried out in Australia by Tait et al, (2013) who also showed that areas of intensive coal seam gas development (e.g. Tara gas field, Surat Basin) in Australia were characterized by higher fluxes of radon and CO_2 from soil gas than other nearby regions. In this case it is notable that hydraulic fracturing is not extensively conducted associated with gas extraction. Hence, the flux of soil gas may relate to other pathways such as de-pressurisation (driven by extraction of water from the gas formations) or drilling activity, providing enhanced pathways. Again, conclusive resolution of the mechanism and pathways of these soil gas emissions (and the relationship to gas development) has not been documented, and there is ongoing debate about this issue.

Warner et al, 2013 showed that areas where shale gas wastewater was being treated and released to the environment in Pennsylvania exhibited increased levels of salinity and radium in stream sediments downstream of water treatment plant discharge points. Hence treatment of flowback water and other wastewater from unconventional gas before re-use or release to the environment requires careful geochemical assessment, as the treated water may contain levels of particular elements above background for a particular region.

As with the other risks outlined in this submission, baseline data is the critical pre-requisite for a robust assessment of whether the above issues are a significant issue for a given project, and for risk management of such projects.

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