Review of Environmental Impact Statement – Santos Narrabri Gas Project

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Introduction

I was briefed by EDO NSW on behalf of the North West Alliance to provide expert advice on the Narrabri Gas Project. The following report outlines my opinions regarding the environmental impact statement (EIS) that has been prepared for Santos' Narrabri Gas Project, particularly regarding issues related to groundwater and surface water quality. I have prepared this report in accordance with the Expert Witness Code of Conduct.

Background and relevant expertise

I am a Senior Lecturer in the School of Engineering at RMIT University, in Melbourne, Australia. I received my PhD from Monash University in 2011, on the use of environmental isotopes and geochemistry to assess the 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 isotopic indicators in groundwater in areas of potential future unconventional gas activity (Currell et al, 2016).

Summary of my opinion

It is my opinion that there are significant potential environmental impacts that could arise from Santos' proposed Narrabri Gas Project, and that the risk of these impacts occurring has not been given full and adequate consideration in the relevant sections of the EIS. Specifically, two major environmental risks associated with the project are:

1. Groundwater and surface water contamination, particularly with coal seam gas (CSG) produced water and/or other wastewater produced as a result of the project; and

2. Fugitive gas migration into aquifers overlying the target coal seams (a groundwater contamination and safety hazard) and/or to the atmosphere (a greenhouse gas and/or air pollution risk).

In my view, these are important risks that could lead to detrimental impacts to the environment and/or water users, if not appropriately managed. Decision-makers reviewing the EIS should be aware that these potential risks exist, and should be presented with detailed discussion, analysis and datasets to inform rigorous assessment of their potential magnitude and consequences, including:

- Careful analysis and discussion of both of these specific risks (1 and 2), drawing on:
  a) lessons learned from international and local experience with similar unconventional gas projects (e.g., based on appropriate literature);
  b) scientific information regarding the particular environmental features and factors in the project area that may cause these risks to be of greater or lesser significance; such as detailed information on groundwater recharge rates and mechanisms and the geochemical processes controlling groundwater quality.

- Appropriate baseline data related to these issues specifically, in order to characterise the pre-development levels of potential contaminants of concern (including fugitive gas and those present in produced water), and understand natural variability and drivers of changes in these;

- Detailed risk assessments and predictive modelling to inform a rigorous analysis of likelihood and consequence of various risk pathways that could result in groundwater contamination and/or fugitive methane impacts;

- Detailed management and mitigation strategies to rapidly detect, diagnose and respond to instances of environmental contamination from these mechanisms through the life of the project.

These two major risk areas are discussed further in detail below, referring to relevant literature and experience from other unconventional gas projects around the world, and examining the level to which the issues have been investigated, discussed and accounted for in the baseline data, monitoring programs, mitigation and management strategies presented in the EIS.

1. Groundwater and surface water contamination

Contamination of groundwater and surface water are major environmental risks that require careful management in any unconventional[1] 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, regardless of whether hydraulic fracturing is involved or not, are:

a) Contamination by wastewater (e.g. produced water or drilling fluids) that is spilled, leaked and/or inappropriately managed as it is brought to the surface and subsequently stored, treated and transported around the site;
b) Contamination due to well integrity failures, or legacy/abandoned boreholes, which 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 his colleagues, who have published extensively on the topic of 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…naturally occurring contaminants such as salts, metals, and radioactivity found in oil and gas wastewaters. Several recent reviews have discussed the potential water risks of unconventional energy development" (Jackson et al, 2014, p.241).

For coal CSG projects such as the Narrabri Gas Project, the major potential contamination source is 'produced water' that would be pumped from the coal seams in order to de-pressurise these and allow gas to de-sorb and flow freely (via the gas wells) to the surface. CSG produced water typically exhibits poor

[1] Note: In this report (as is standard in the research literature), the term 'unconventional gas' covers any project that extracts gas from onshore areas using directional (e.g., horizontal) drilling, in geological formations that do not have significant natural permeability, including coal, shale or other 'tight' sedimentary rocks. The term 'unconventional' includes gas developments in these settings, with or without hydraulic fracturing – which is not proposed to be adopted in the Narrabri Gas Project.

quality, due to its extended periods of residence within coals (Hamawand et al, 2013; Khan and Kordek, 2014). Contaminants that are characteristic of CSG produced water include high levels of sodium, heavy metals and other trace elements (such as barium and boron); high levels of salinity (e.g., total dissolved ion contents of >5g/L, in some cases up to 30g/L); fluoride, ammonia, organic carbon and other potential contaminants (APLNG, 2012; Biggs et al, 2012; Hamawand et al, 2013; Khan and Kordek, 2014).

The risks associated with potential groundwater and/or surface water contamination with produced CSG water are of particular significance in the Narrabri Gas Project (in comparison with other gas projects), due to:

a) The apparently unusually poor water quality associated with the particular coal seams targeted in the project (Gunnedah Basin coals), and
b) The unusually high quality of the shallow groundwater and surface water in the project area, which covers areas of potential recharge for the Pilliga Sandstone[2] – one of the main aquifers in the southern Great Artesian Basin (as is further discussed below in section 1.3), as well as the importance of water in the Namoi Alluvium (which also occurs within or close to the project area) to local water users.

To this end, the EIS should contain:

1. Detailed chemical characterisation of produced waters sampled during gas exploration activity in the project area to date, and detailed baseline groundwater chemistry data in overlying aquifers which may be affected by contamination with such water, such as the Pilliga Sandstone and Namoi Alluvium;
2. Discussion and analysis of the potential pathways and mechanisms by which contamination of shallow aquifers by produced water could occur, such as surface spills at CSG wells, pipeline leaks or leakage/overflow from storage dams;
3. Discussion and analysis of previous incidents where spillage or leakage of produced water has taken place in the project area (e.g. in association with previous CSG exploration);
4. Risk assessment strategies, whereby the hazard, likelihood and consequence of contamination associated with the produced water stream (prior, during and following water treatment) are assessed, with detailed supporting assumptions and relevant data;
5. Extensive baseline datasets, extensive physical monitoring infrastructure and detailed ongoing monitoring plans to rapidly detect any incidences of groundwater contamination associated with produced water as they occur;
6. Detailed strategies to minimise and mitigate the impacts associated with produced water contamination of shallow groundwater, soil and surface water in the project area.

While some limited baseline data, and basic information covering these topics is included within various parts of the EIS (e.g. Chapter 7, Chapter 11, Chapter 14, Chapter 28, Appendix F, Appendix G3 and Appendix G4), the information provided relating to assessment and management of groundwater and surface water contamination lacks detail and/or critical supporting data commensurate with the significance of the risks and the potentially impacted receptors.

1.1 Relevant project activities

Gas will be extracted from up to 850 wells drilled throughout the life of the project[3]. It is estimated that approximately 37.5 billion litres (GL) of water (up to 80GL) will be produced from the target coal seams via these wells during the life of the Narrabri Gas Project (see EIS Chapter 11), or approximately 1.5 GL per year. It is documented in the EIS (Chapter 7) that this water is saline – with TDS values said to be

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[2] The executive summary to the EIS claims that the project is "not located in a major recharge area for the GAB"; however this statement is made in the absence of detailed field-based investigations of groundwater recharge rates, and it is questionable based on a number of lines of evidence, as discussed in section 1.3 of this report.

[3] According to Chapter 2, wells already drilled for exploration/pilot CSG operations within the project area may also be operated on top of the 850 new wells proposed.

'around 14,000 µS/cm' (approximately 9 g/L), although raw data showing the range of salinities and detailed chemical composition of produced waters is not included in this chapter, or the Water baseline report (Appendix G4). The quoted salinity value in the EIS is also lower than previously published estimates of the produced waters from coal seams in the project area, based on testing of produced waters from the Bibblewindi Gas Exploration Pilot project (see Khan and Kordek, 2014 who cite an average total dissolved solids content of 18 g/L and a range from 14.5 to 31 g/L).

These salinity levels are significantly higher than typical CSG production water – for example the water extracted from coal seams in the Surat and Bowen basins of Queensland, which are the largest existing CSG projects in Australia (these typically produce water with TDS contents below 5 g/L, see Biggs et al, 2012). As documented in a 2014 report to the Office of the Chief Scientist and Engineer (Khan and Kordek, 2014), in addition to having high salinity, the water produced from the coal seams in the Narrabri region also contains significant levels of heavy metals, boron and fluoride, which could make the water an environmental and human health hazard, and a major potential source of groundwater and surface water contamination in the area.

Produced water will be generated at all CSG wells drilled for the project - potentially 850 new wells, plus existing wells drilled during exploration - throughout their operating life (see figure 7-2 of Chapter 7 of the EIS). The produced water pumped from the target coal seams is planned to be managed through a 'network of water gathering lines and in-field balance tanks' (Chapter 7 of the EIS). Prior to treatment, the water will be stored in (lined) above ground ponds. Water production from the CSG wells is expected to peak at approximately 10 ML/day, within the first 5 years of the project, and then decline – this is typical of CSG projects (e.g. QGC, 2012). The produced water from each CSG well will be collected and piped through a network of gathering lines and pipes, and transported to water treatment facilities (Leewood and Bibblewindi), where it will be treated by reverse osmosis and a range of other standard water treatment techniques. Treated water will then be amended with gypsum salt, to reduce the sodium absorption ratio, in an effort to make the resulting water suitable for irrigation in the region (Chapter 7 of the EIS).

This water treatment system, whereby wastewater from each CSG well is transported to the Leewood facility and Bibblewindi site, means that there will be hundreds of potential sites of contamination. Point-source contamination with produced water could occur by spills and/or leaks at each CSG well-head and all of the gathering lines, pipelines and joins in the network. Above ground dams which store the produced water may also leak and/or overflow, for example in the event of major storms. Any spills or leaks of produced water that occur en-route to or during storage at the water treatment facilities, could potentially detrimentally affect the surrounding land and shallow groundwater in the uppermost unconfined water table aquifer(s).

The treatment of produced water will result in two major products being produced continuously through the life of the project:

1. Treated water (in an amount similar or equal in volume to the amount of raw produced water from the CSG wells), which will be made available for irrigation in the area. It is estimated that the treated water will have an electrical conductivity of approximately 370 µS/cm, following amendment with gypsum salt. Excess treated water is also proposed to be disposed of via direct discharge into Bohena Creek (during high-flow events). It is unclear from the produced water management plan (Chapter 7) exactly how much of this water will be stored at the Leewood facility at a given point in time, and also not clear what the proponent plans to do if there is insufficient irrigation demand or capacity to discharge to the environment (e.g. enough high-flow events to allow this), in order to absorb the volumes being produced by the gas wells and treatment plant at a given time. There are potential environmental impacts from the widespread introduction of treated wastewater into the environment, either as irrigation return flow - which would seep through the soil profile and partly re-infiltrate the water table aquifer, or as surface water discharged to Bohena Creek. While the salinity of the treated water is proposed to be relatively fresh, and similar to much of the native shallow groundwater and surface water in the area, there may be issues that arise due to the different chemistry of this water compared to the natural surface

runoff and shallow groundwater (e.g. differences in the redox, pH, alkalinity and sodicity parameters).

2. Waste brine (salt) produced from the reverse osmosis process. In the EIS it is estimated that ~41,000 tonnes of salt per year (115t per day) will be produced in the early stages of the project (see Chapter 7). However, this estimate should be viewed as somewhat uncertain, as it depends on both the volume of produced water that ultimately comes from the gas wells, and the salinity of this water. Based on the TDS estimates of produced water associated with CSG exploration in the project area provided in Khan and Kordek, 2014 (e.g., approximately 18 g/L rather than 9 g/L, as is quoted in the EIS), the overall volume of salt may be under-estimated by a factor of two. The brine produced from the Leewood facility will be a hazardous material, enriched in the chemical elements that occur in the produced water. No detailed chemical assay of this waste brine was provided in the project EIS to aid a detailed risk assessment of the production, handling and disposal of the material.

While Chapter 7 of the EIS details plans to transport the waste brine to a licensed facility, at a rate of approximately '2 to 3 B-double truck-loads' per day, outstanding questions that are not addressed in the produced water management plan include:

- Has a suitable facility been identified and have they agreed to accept the material in the estimated volumes proposed?
- How much brine can be accepted per day by the facility, and what is the total capacity of the facility (e.g. is it adequate to accept all of the waste through the project life – on the order of 1Mt of brine)?
- How much brine will be allowed to be stored at any one time at the Leewood facility awaiting transport?
- Have detailed chemical analyses and hazard assessment of the brine material been conducted, based on the wastes produced during the Bibblewindi Pilot project ?

An additional risk associated with the project (in terms of groundwater and surface water quality) is the disposal of drilling fluids. The EIS estimates (in Chapter 28) that approximately 178,000 m^3 of drilling fluid will be produced throughout the life of the project. Such fluids are generally saline, turbid and contain high levels of elements used to control density, such as potassium and barium. The proponent plans to recycle as much of the drilling fluid as possible, which is a sound principle. Like produced water however, such drilling fluid is a potential land and/or shallow groundwater contamination risk if not managed appropriately and thus detailed storage, transport and management protocols should be outlined in the EIS.

1.2 Potential mechanisms of groundwater and surface water contamination

Based on international experience with unconventional gas, the size of the Narrabri Gas Project (e.g. number of wells and required infrastructure to collect, transport and store the produced water) and the past track record of CSG operations in the Pilliga region (e.g. Khan and Kordek, 2014), there is a strong likelihood that leaks and/or spills of produced water will occur throughout the life of the Narrabri Gas Project, risking contamination of shallow aquifers and surface water bodies in the area. This conclusion is based on an assessment of international literature reporting experience with numerous gas projects of similar size, for which large empirical datasets on the rates of wastewater spills and leaks have now been collected, predominantly in the United States (U.S. EPA, 2016; Patterson et al, 2017). The U.S. is a valuable example to study in this context, as it now has well over a decade of experience with unconventional gas development, and has hundreds of thousands of operating gas wells across many states and project types (shale gas, coal seam gas, tight gas). While arguably, the risks associated with wastewater spills and leaks are of a different nature in the Narrabri Gas Project (and CSG projects generally) in comparison to shale gas, which is the more common form of unconventional gas in the U.S., the risks are in some regards greater in the case of CSG, as volumes of wastewater produced per well for CSG are typically larger (Hamawand et al, 2013).

A recent study by Duke University and the United States Geological Survey (Patterson et al, 2017), showed that some form of spillage or leakage of wastewater has occurred at between 2 and 16% of unconventional gas wells drilled and operated in the United States (regardless of whether the wells are subject to hydraulic fracturing or not). Their survey included a large, representative dataset, including tens of thousands of individual wells across different states and types of unconventional gas projects. According to the 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 hydraulic fracturing 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 (it is noted that hydraulic fracturing will not be conducted in the Narrabri Gas Project). The Patterson et al, (2017) study included both wells that were subject to hydraulic fracturing and those that weren't, had a larger sample size, and looked at the full unconventional gas lifecycle from drilling through to decommissioning of wells, and is therefore more relevant to the Narrabri Gas Project.

Spills and leakage of wastewater at unconventional gas wells occur due to a variety of reasons, including storage and movement of wastewater via flow lines, as well as equipment failure and human error:

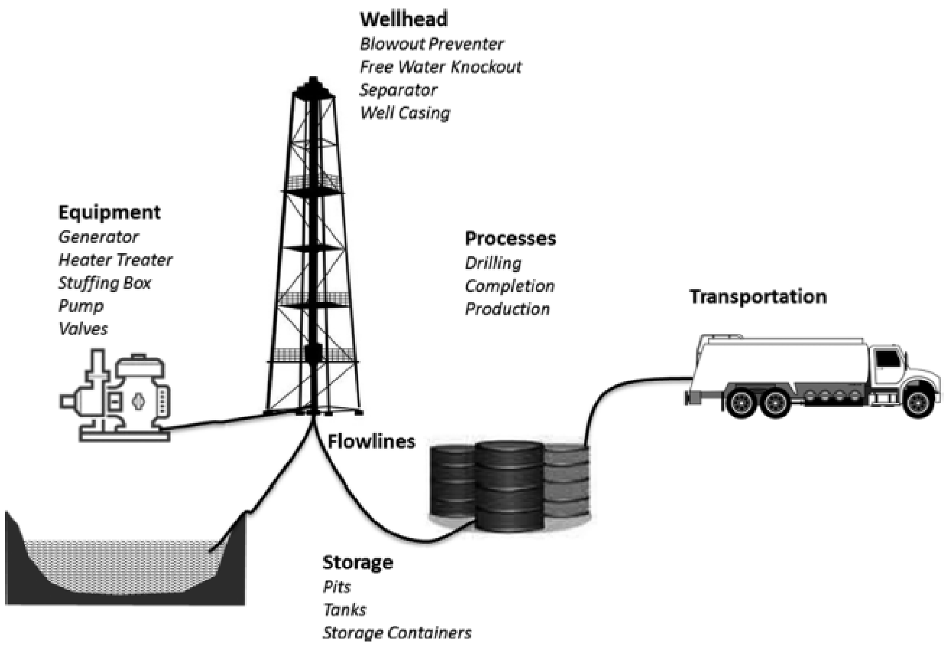

Figure 1 – conceptual diagram of unconventional gas set-up, showing points at which spillage/leakage of waste water commonly occur. From: Patterson et al, 2017.

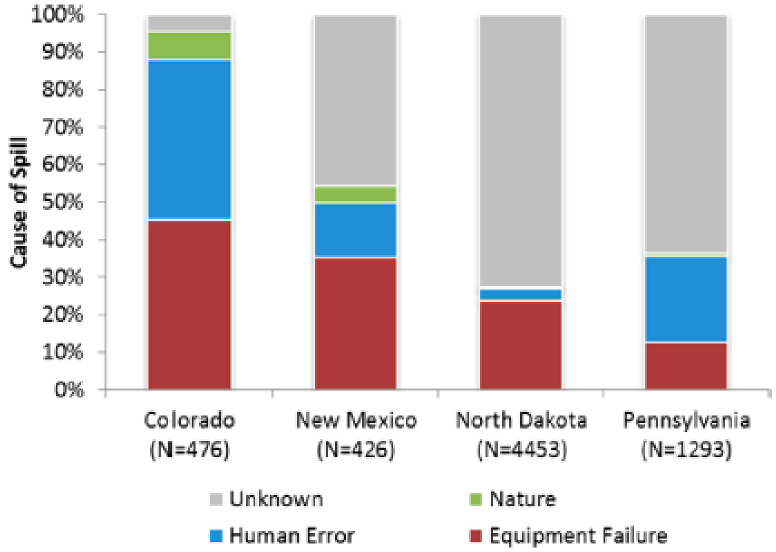

Figure 2 – breakdown of the number and cause of waste water spills from unconventional gas operations in four states in the U.S. From: Patterson et al, 2017.

Using these spill rates, which are based on tens of thousands of wells across the U.S., something on the order of 15 to 130 spills of wastewater could be expected to occur in association with the Narrabri Gas Project, if the planned 850 wells are drilled. For example, taking a conservative spill rate of 3.5% of all wells, this would equate to approximately 30 spill incidents arising from the project. As is shown in figure 3 below, the overall annual spill rate from unconventional gas and oil wells in the U.S., based on the best available data, is approximately 5%, which would equate to more than 40 spills for the Narrabri Gas Project if all 850 wells are drilled.

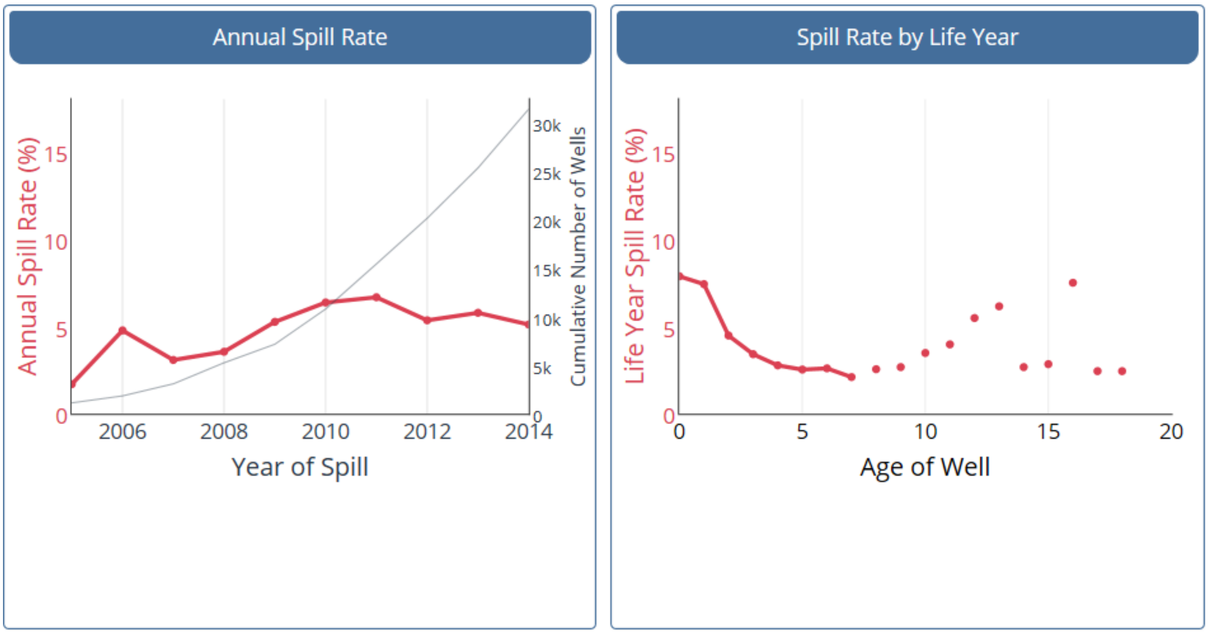

Figure 3 - Wastewater spill rates in the United States per number of wells in shale, coal and tight gas & oil operations. Data sourced from the National Center for Ecological Analysis and Synthesis spills data visualization tool: http://snappartnership.net/groups/hydraulic-fracturing/webapp/spills.html

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, there will inevitably be some wastewater spillage/leakage incidents, whereby produced water can potentially contaminate the environment. A cautious and conservative approach to this issue, which recognises that spills and leaks will inevitably happen is therefore warranted. This shifts the question from not *whether* wastewater spills and leaks will occur throughout the life of the Narrabri Gas Project, but rather:

a) *how to minimise* the incidence of these events to the greatest extent possible (so that the number approaches the low end of the range, say 2% of wells rather 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.

Based on Chapter 7 (Produced Water Management), Chapter 14 (Soils and Land Contamination) and Appendix G4 (Water Monitoring Plan) it appears the proponent may be under-estimating the risk of wastewater spills and leaks, which could leave the project vulnerable and poorly equipped to respond to the incidents that do arise. For example, there is no reference to the literature or data cited above, characterising typical spill rates and mechanisms associated with unconventional gas in the United States (or elsewhere in the world) and only descriptive information (rather than detailed analysis) regarding previous spill incidents involving produced water in the project area (see Chapter 14). All tanks, gathering lines, ponds and well-heads which are storing and transmitting CSG produced water have some potential to act as sites of spills and/or leaks (e.g. Figure 1), and as such a detailed life-cycle risk assessment, and monitoring plans to detect and isolate contamination should be included in the EIS (e.g. in Chapter 7 and/or Chapter 11).

Of some concern it the fact that there is already a track-record of spills and leaks of produced water having occurred in the Narrabri Gas Project area, associated with CSG activity carried out prior to 2012. At least one major spill incident and a number of other smaller incidents have taken place associated with production, handling and treatment of produced water from pilot CSG exploration activities (e.g., the Bibblewindi Pilot project). These incidents are recorded in the EIS (Chapter 14, pages 11 and 12).

Additional information regarding these incidents is provided in the report by Khan and Kordek (2014) to the NSW Office of the Chief Scientist and Engineer:

> "In June 2011, approximately 10,000 litres of untreated saline water leaked from a pipe near the reverse osmosis plant at Bibblewindi. Operations at the Bibblewindi Water Management Facility were subsequently suspended. Santos is currently undertaking a $20 million rehabilitation of the Bibblewindi Water Management Facility site. The plant was decommissioned and removed from the site in December 2012. The three storage ponds located at the Bibblewindi facility were also found to be unsuitable for long term use and Santos has commenced their removal and subsequent rehabilitation of the site. A number of other storage ponds in the Pilliga, including at Bohena have already been removed and site rehabilitation initiated."

Also noted in this report are similar instances, where:
- 'Multiple leaks and spills at the Bibblewindi Water Management Faicility' occurred during 2009 to early 2011,
- 'An unknown volume of produced water overtopped a tank at the Bibblewindi Water Management Facility and spilled into the Pilliga and an ephemeral watercourse that was flowing at the time' in 2010[4]

The contamination issues that have already been experienced to date at the site, when only a fraction of the number of wells proposed in the Narrabri Gas Project had been drilled and tested, underlines the significant possibility that future incidents of a similar nature (or other mechanisms highlighted in Figures 1 & 2) will occur over the 25-year life of the project. While Chapter 14 describes these prior incidents with produced water, as well as additional issues encountered at the Tintsfield Water Treatment Facility, there is little analysis of the mechanisms of failure, and steps that should be taken to ensure the risk of similar incidents

[4] Khan and Kordek, 2014, p.17.

occurring in future is minimised. The EIS includes some basic information about steps that will be taken but little detail:

> "The risk of a recurrence of these types of incidents going forward has been significantly reduced through the design, construction and operation of new infrastructure, changes to operational procedures and ongoing monitoring."

And:

> "The recently constructed Leewood Water Management Facility now contains the majority of the produced water and brine associated with the Narrabri operations. The Leewood facility includes two double lined ponds with leak detection equipment installed. The facility meets the requirements of the NSW *Produced Water Management, Storage and Transfer* (NSW Department of Industry, Skills and Regional Development 2015c). Small volumes of produced water are also stored at the Tintsfield Water Management Facility which now operates under a Liner Integrity Management Program, as outlined above. These changes, together with the extensive infrastructure and groundwater monitoring undertaken across the activities and the implementation of Santos systems for infrastructure operation and environmental management, minimises the risk of potential pollution incidents."

Further:

> "The likelihood of leaks or spills of produced water are considered low given the design and operational engineering controls and extensive monitoring and management systems that would form part of the project.
>
> - the produced water and brine storages at the Leewood Water Management Facility include double lined ponds that have leak detection equipment installed. The ponds meet the requirements of the *Exploration Code of Practice: Produced Water Management, Storage and Transfer* (NSW Department of Industry, Skills and Regional Development 2015c)
> - continuous pressure monitoring of produced water pipelines for indications of a leak. Water pressures at well heads and within water gathering lines is low
> - programmed inspections and maintenance of plant and equipment
> - all facilities would be designed and operated under the applicable Australian safety standard and protocols
> - operations in accordance with the requirements of the Environment Protection Licence and a Produced Water Management Plan
> - the ability to remotely operate and shut in wells if required.
>
> In the unlikely event that a spill or leak did occur the risk of human health and the environment is negligible. Design and engineering controls along with monitoring systems would enable leaks to be detected and rectified quickly. Additionally, there is a low risk that bores would be affected as these generally take from sources that are over 50 metres below perched or shallow water bodies that could be impacted by a spill. In addition, the presence of relatively impermeable geological units in addition to perched water bodies having very low transmissivity further minimises the risk." – page 14-20 of Chapter 14.

The risk assessment outlined in Table 14-2 also indicates that the proponent believes both the pre and post-mitigated significance of the risk from produced water leaks or spills to be 'moderate' sensitivity, and 'low' magnitude and significance, which warrants some careful consideration. While these engineering techniques and management protocols described are warranted, they would be aided by in-depth discussion of the mechanism(s) of past wastewater spills and leaks in the project area, and in other similar incidents overseas or elsewhere in Australia. This is particularly given that the scale of the Narrabri Gas Project is an order of magnitude larger than the previous CSG activities at the site, during which the prior incidents of spills and leaks arose. Details regarding the 'perched water bodies', 'relatively impermeable geological units' or the site specific groundwater monitoring related to these previous contamination incidents, are not readily available to examine in the EIS, and should be included (e.g. in technical appendices).

As discussed further below, the current monitoring network for shallow groundwater outlined in Appendix G3 includes six monitoring sites (with bores screened at one or more depths) in the Pilliga Sandstone in the project area boundary (see Fig 3-5 of Appendix G3) and four monitoring sites in the Alluvium in the project area (Figure 3-4), as well as additional bores in these aquifers outside the project area. This network is highly unlikely to be adequate in order to rapidly detect shallow groundwater contamination incidents resulting from produced water spills and leaks in the project area. Given that there will potentially be 850 operating CSG wells across more than 400 well-pads, there will be a ratio of more than 50 gas wells for every shallow monitoring site in the project area, meaning only a fraction of the area potentially affected by produced water leaks and spills will have any baseline groundwater quality data or be actively monitored throughout the project (discussed further below in section 1.4).

The past incidents of spillage and leakage of wastewater are discussed in the 'Soils and Land Contamination' chapter (Chapter 14) of the EIS. The risk of shallow groundwater contamination by this mechanism is given minimal consideration in the 'Groundwater and geology' (Chapter 11) and Appendix G3 'Water Monitoring Plan'. The Water Monitoring Plan (Appendix G3) does not acknowledge the risk of groundwater contamination from produced water leakage and spills as one of its listed 'NGP water-affecting activities and potential effects that may be caused to groundwater sources addressed by this WMP' (Table 2-5). Hence, there is no indication that groundwater monitoring will be undertaken specifically to address this risk. Such contamination is one of the primary risk pathways which could impact the environment and water users, and should thus be carefully monitored and managed throughout the life of the project.

Another potential mechanism of groundwater contamination is well-faults, which may arise during construction, operation and following de-commissioning of the project. Improper sealing of gas wells and/or the presence of legacy or abandoned oil, gas or water exploration or production wells in an area of unconventional gas can potentially create pathways for cross-contamination between aquifers, for both fluids and fugitive gases (Vidic et al, 2013; Darrah et al, 2014; Jackson et al, 2014).

Regarding this issue, the EIS states:

> "Losses of drilling fluid into the soil profile is very unlikely due to the drilling methodology and engineering and operational controls that would be implemented. Drilling would comply with the Code of Practice for Coal Seam Gas: Well Integrity (DTIRIS 2012) which sets out the design, construction and maintenance requirements for gas wells to ensure the safe and environmentally sound production of gas. Under the conventional overbalanced drilling fluid system that would be used for the project, the pressure of the column of drilling fluid is equal to, or greater than, the pressure of the various downhole formations through which they are drilled. This prevents influx of water or gas into the well bore whilst drilling. Surface drilling occurs to allow a steel pipe, called a conductor, to be cemented into the ground generally to 10 to 20 metres below the surface. This isolates loose or unconsolidated rock near the surface and prevents any impacts to the surface soils during the rest of the drilling process and the ongoing operation of the well. Well integrity will be monitored throughout the life of the well in accordance with the requirements of the Code of Practice."

The Executive Summary also states that drilling will be conducted in accordance with the Code of Practice. Well integrity is an issue throughout all phases of unconventional gas development, and must be carefully monitored and managed throughout the full life-cycle, including drilling, operation and decommissioning of gas wells (Jackson et al, 2014). Detailed protocols and mechanisms to minimise well integrity risks are not discussed in the EIS, for example, descriptions of what steps will be taken to monitor build-up of sustained casing pressure in the gas wells during the drilling and operational phases (see further discussion in section 2, below).

1.3 Particular risks to receptors, and relevant environmental values in the Narrabri Gas Project area

The combination of significant volumes (e.g. >1GL/yr) of poor quality water being produced and managed across hundreds of sites in the project area over a period of 25 years, and the otherwise high quality of the groundwater hosted in the Pilliga Sandstone Aquifer (the predominant shallow aquifer in the region), and Alluvium, raises significant concerns from an environmental and water management perspective.

From the data contained in the EIS it is clear that groundwater is of an unusually high quality in the Pilliga Sandstone aquifer (e.g., Table 4-10 of the baseline water data shows the aquifer has average EC values around 400 µS/cm, or approximately 250mg/L), which makes it a viable potable water source for landholders in the region (most shallow aquifers on the Australian continent do not contain water so fresh and suitable for potable use – e.g., see Harrington and Cook, 2014).

The project area includes land on which the Pilliga Sandstone aquifer outcrops (is directly exposed) or sub-crops at the surface, and therefore can be expected to receive direct groundwater recharge via rainfall runoff in some areas, where hydraulic gradients permit this (Figure 11-3 of Chapter 11 and Table 2-2 of Appendix G3 notes that the Pilliga Sandstone: "Represents a GAB recharge bed"). In spite of this being shown on the geological map of the project in Chapter 11 and acknowledged in Table 2-2, in the executive summary of the EIS, it is stated that the project area is: "not located in a major recharge area for the GAB". This statement is made without detailed supporting evidence (such as a field-based investigation of groundwater recharge rates, hydraulic gradients or detailed lithological logs), and is questionable in the absence of such data. Evidence that is consistent with parts of the project area being a significant recharge area for this Great Artesian Basin (GAB) aquifer includes:

- the fact that the geological map shows that the project area is one of the few major areas where the Pilliga Sandstone (a GAB aquifer) is exposed at the surface, and that previous studies of the Great Artesian Basin (E.g. Habermahl et al, 1997; Brownbill, 2000; Herczeg et al, 2008; Ransley and Smerdon, 2012), map the area as a region of recharge and subsequent north-westerly groundwater flow to the wider Great Artesian Basin (see figure 4 below):

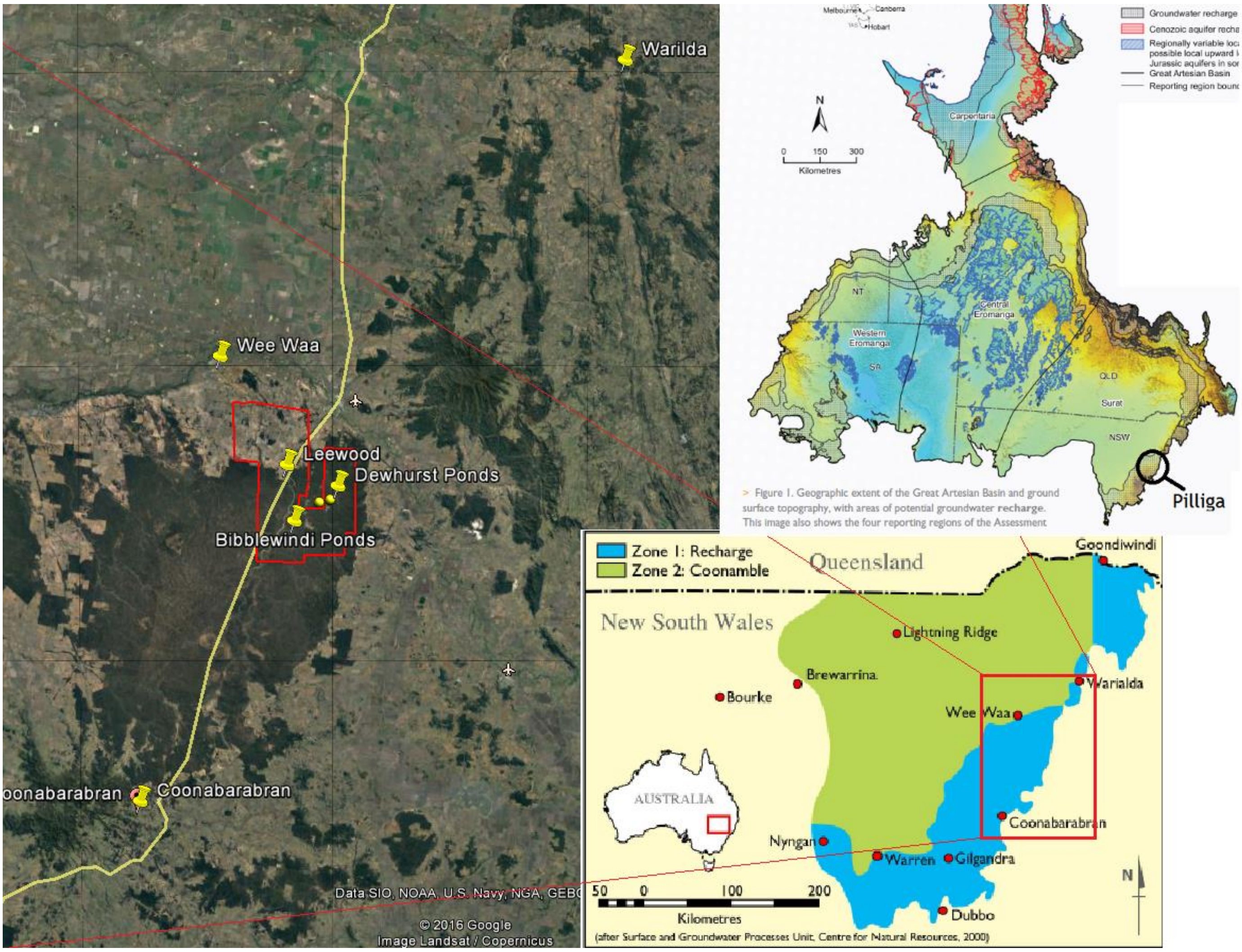

Figure 4 – Google Earth image showing project area (red outline) and mapped recharge areas for the southern Great Artesian Basin according to Herczeg, 2008 and Ransley and Smerdon, 2012. In both instances the project area is mapped within one of the restricted geographic areas of groundwater recharge to the southern GAB aquifers.

- The fact that ‘rejected recharge springs’ occur in the nearby area (as described in Chapter 11 of the EIS). Such springs are characteristic of GAB recharge areas (see Fensham et al., 2010)

- The unusual freshness of the groundwater. One of the standard techniques of recharge estimation used in Australia and worldwide is the Chloride Mass Balance method (e.g. Scanlon et al, 2002; Crosbie et al, 2010, Healy, 2010). According to this method, the chloride content of groundwater is inversely proportional to the recharge rate; hence a low chloride concentration (as is reported in the baseline water quality monitoring for the Pilliga Sandstone in Appendix G4) corresponds to high recharge rates.

1.3.1 Recharge estimation in the project area

Estimation of groundwater recharge is of vital importance to any hydrogeological study, from both groundwater quality and quantity perspectives (Healy, 2010). Within the EIS conceptual and numerical hydrogeological models, there is some limited attempt to estimate recharge to the various aquifers in the project area, including the Pilliga Sandstone, however the methods adopted provide a low level of confidence regarding actual rates. Additional data contained in the EIS could have been used to provide further estimates of recharge, as follows:

Using the Chloride mass balance method, under the assumption of steady state recharge (e.g. Crosbie et al, 2010), the amount of recharge to a groundwater aquifer that is unconfined (e.g. exposed to the surface and in which the water table occurs) can be estimated as the ratio of chloride delivered in rainfall per unit time, to the amount of chloride in groundwater:

$$P \times Cl_P = R \times Cl_R$$

P = Precipitation, R = Recharge, Clp = Chloride delivered by precipitation, Clr chloride in recharging groundwater

Rainfall chloride concentrations in the study area are likely to be approximately 1.5mg/L, as Biggs (2006) determined rainfall chloride concentrations to be 1.41 mg/L to the north of the project area, at an equivalent distance from the coastline (at Goondiwindi). Distance from the coast is the primary determinant on chloride deposition in rainfall – see Crosbie et al, (2012). Given an average rainfall of 639mm/year at (Chapter 13 of the EIS), and that groundwater in the Pilliga Sandstone contains chloride concentrations averaging 31.5 mg/L (from Table 4-4 of Appendix G4 of the EIS), an average recharge of approximately 28.5 mm/year can be expected. This is a significant recharge volume, and higher than most of the Australian continent (see Herczeg, 2011 p.52) and most of the Great Artesian Basin (e.g., Ransley and Smerdon, 2012).

This estimated recharge value is also higher than what is provided in the conceptual hydrogeological model included in the Groundwater Impact Assessment of the EIS (Appendix F), which instead uses the 'method of last resort' to estimate recharge as being in the broad range 1 to 20 mm/year. It should be noted that the estimates of recharge presented in the EIS using this method are:

a) acknowledged by the authors of the method (Crosbie et al, 2010) to be a highly uncertain method with low reliability, and only to be used as a starting point in the absence of better data (such as chloride values in groundwater and rainfall).

b) not sufficiently spatially resolved to be applied to the project area (see Figure 5-14 of Appendix F, in which the project area is hardly discernible, and the contour increments too large to give meaningful data on local recharge rates).

As the authors of the 'method of last resort' recharge estimation technique noted when they described their method (quoting from Crosbie et al, 2010):

> "The intention of this work was to provide a simple means of estimating recharge in data-poor areas where detailed work was not warranted." – Crosbie et al, 2010 p.2035

Clearly, the study area does represent one in which detailed work is warranted, given the size and significance of the Narrabri Gas Project. Also quoting from Crosbie et al, 2010:

> "This comparison of methods has shown that different methods can give recharge estimates that appear to be very different, but with an understanding of what was actually being measured they can provide complimentary information. This again highlights the need for using multiple methods of estimating recharge as not all methods are suitable for all purposes." – Crosbie et al, (2010) p.2029

The approach taken in the Groundwater Impact Assessment (Appendix F) has made little attempt to cross-compare different methods, or verify estimates based on additional data collection and field work. The chloride mass balance based estimate above is based on easily available data that is included in the EIS; it is not clear why this was not used to complement the lower reliability method that was selected in the EIS.

Further, within the groundwater model (Appendix F), recharge to the Pilliga Sandstone (and other aquifers outside the Namoi Alluvium) is estimated as a flat percentage of rainfall – in the case of the Pilliga Sandstone, 1% or rainfall or 8 mm/year has been used, according to Figure 6-14. A flat percentage of rainfall is another method that should be considered as having low reliability. Little justification is given in the modelling documentation (e.g. section 6.4.5 of Appendix F) as to why a value of 1% of rainfall was considered appropriate for estimating recharge to this aquifer.

The lack of any further study of recharge processes and rates using field-based techniques is a major oversight, given the significance of the Pilliga Sandstone as a southern GAB aquifer, and the potential for water quality (and possibly, quantity) impacts associated with CSG development. Techniques that can and should be used in areas where detailed study is warranted to better determine the rates, mechanisms and specific locations of recharge (as reviewed in Healy, 2010) include:

- Chloride mass balance analysis (using saturated and/or unsaturated zone data)
- Water table fluctuation monitoring;
- Double-ring infiltrometer or lysimeter testing
- Sampling for 'young' environmental tracers, such as tritium or SF_6

The fact that the area is likely to (or at least plausibly may) contain areas of significant recharge, and that no attempt has been made to understand recharge in the area using the above techniques, is concerning. It indicates that the groundwater impact assessment is missing rigorous estimates of a fundamental water balance parameter, and suggests that the risk of groundwater contamination (due to the mechanisms described in section 1.2) occurring in an area containing high quality groundwater resources, is not being given sufficient attention in the scientific program or design of the monitoring and management programs.

In a recharge area, any impact to groundwater quality (e.g. due to CSG wastewater spills or leaks) will in the long term affect groundwater further down-gradient in the aquifer– in the case of the Narrabri Gas Project area, this means the GAB aquifers to the northwest of the project. The restricted geographic areas where aquifer units are exposed at the surface and where direct groundwater recharge occurs are the hydrogeological equivalent to the 'headwaters' of a river catchment. Impacts to water quality occurring in such areas affect groundwater in the aquifer downstream of these regions eventually as well. The fact that to date the Pilliga is a relatively pristine area, with few existing land-use impacts threatening groundwater quality, means that the project area is one where particularly high quality water can be ensured to enter the GAB. As such, a greater than normal level of protection (e.g. restriction of potentially polluting land-use activities) may be warranted - as is standard practice for many drinking water catchments. This argument is further outlined in relation to the Pilliga region in Currell, (2015).

If spillage/leakage of wastewater occurs at rates that are standard for unconventional gas around the world (e.g. Patterson et al, 2017, see section 1.2) this could have a significant material impact on the quality of groundwater in the area, and threaten the viability of the aquifer as a potable water source, as wells as the long-term quality of the groundwater recharge entering the Pilliga sandstone.

1.4 Adequacy of baseline groundwater quality data

Groundwater quality baseline data is a critical requirement for assessing current water quality and chemistry, determining the factors and processes controlling groundwater quality, and assessing future impacts due to CSG.

Some baseline data are included within Appendix F (Groundwater Impact Assessment) and Appendix G4 (Water Baseline Report) of the EIS. These data contain significant gaps and deficiencies, and do not constitute a rigorous baseline with which to assess existing groundwater geochemical conditions, document natural variability in groundwater quality (and the processes governing changes in quality) and/or adequately determine in future whether the gas project is causing impacts to groundwater quality through mechanisms such as those described above and below (section 2). Deficiencies include:

1. The relatively low number of bores in each aquifer, and the geographical spread of monitoring sites throughout the project area. In total, there are 58 groundwater monitoring bores installed, with a further 8 bores planned for monitoring water level and water quality. This total number is divided among the various aquifers, for example according to Table 4-1 of Appendix G4, there are 17

monitoring bores in total in the Pilliga Sandstone, and only some of these bores (confined to six localities) are within the project area (additional monitoring bores are located outside the project boundary). There are a similar number of bores in the Namoi alluvium, and fewer within the Gunnedah-Oxley Basin. This compares with up to 850 CSG wells that will be drilled; a very high ratio of gas bores to monitoring bores (e.g. tens of gas wells for every monitoring well). It is highly questionable whether this coverage is adequate, and concerning that there are large areas (such as the central and eastern parts of the project area) in which there appears to be no monitoring bore coverage at all (see figures 3-3 through 3-6 in Appendix G3). Particular areas, such as those surrounding the Leewood treatment plant (where a significant amount of wastewater will be transported and managed) should be extensively installed with shallow monitoring wells to reflect the fact that large volumes of wastewater will be transported to and stored at this site. Likewise all major areas in which the proposed CSG well pads are constructed need to be covered by a network of shallow and deep monitoring bores, including sites both up-gradient and down-gradient of the pads, to make a proper assessments of whether any groundwater quality impacts are occurring.

2. An inadequate number of parameters and constituents analysed in the baseline groundwater quality samples taken to date, and in particular, contaminants that may be present in CSG produced water or fugitive gas are absent in the groundwater baseline datasets in Appendix G4. Tables 4.3-4.7 provide summary statistics of water quality characteristics in four main aquifers in the project area. Missing from these are any analysis of the dissolved oxygen or redox potential (e.g. Eh/ORP), which are critical ‘master parameters’, vital to any assessment of the geochemistry of the groundwater, such as the level of saturation with respect to minerals and gases, the speciation of particular ions, the amount of organic matter and potential for redox reactions – all of which are important controls on groundwater quality (e.g. Appelo and Postma, 2005). It is not clear whether the metals analysis reported in these tables represents dissolved or total metals. This is an important consideration when assessing the form and likely behaviour of metals in the groundwater.

   Other important analytes that are missing from these tables, and which may be future contaminants impacting the groundwater due to CSG activity (e.g. via wastewater spills or fugitive gas migration), include:

   - Iron (as both total and dissolved; Fe^{2+}/Fe^{3+})
   - Arsenic
   - Aluminium
   - Ammonia
   - Dissolved and Total organic carbon
   - Dissolved methane
   - Hydrogen sulfide
   - Uranium & other radionuclides (e.g. ^{222}Rn, radium)

   Without any baseline data on these particular species that could be present in significant quantities in produced water and/or which may be sensitive to changes in the geochemistry brought about by CSG-related activity, any future assessment of whether groundwater quality has been impacted by CSG (and the causal mechanism of such impacts) will be extremely difficult.

3. A lack of time-series data showing any trends in groundwater chemistry/quality through time at individual sites, or any maps showing spatial trends in groundwater quality through the region (e.g. salinity contour maps or element maps in each unit). Such trend analysis is vital to understanding the current influences controlling groundwater quality and assessing future change.

4. A lack of any reported baseline information on the chemical composition of produced water from the target coal seams, which was generated during exploration for CSG in the region. A detailed analysis of the geochemistry of water produced from the coal seams is a vital pre-requisite for assessing future possible impacts from spills or leaks associated with the storage, transport and

treatment of produced water (see section 1.2), and for determining whether such incidents are impacting groundwater quality during operation of the gas project. Some basic information about water quality from two monitoring sites in the Gunnedah-Oxley basin sequences is included in Tables 4-8 and 4-9 of Appendix G4. However, these data are again missing key analytes (e.g., those listed above) and give little indication of the variability and range of geochemistry and water quality of fluids that will be extracted from the coal seams in these sequences specifically. It is unclear whether the water quality data for these sequences represents water extracted from just the coal seams in the overall sequence (which would be representative of future produced waters coming from CSG wells) or whether it includes water intersected from horizons of other geological material hosting different quality groundwater, that might be intersected by long-screen monitoring wells in addition to water in the coal seams themselves.

5. A lack of microbiological characterisation of the groundwater and produced water. Particular microbial communities may occur in the produced water (as is documented for oil and gas wastewaters – see Van Stempvoort et al, 2005), and these and other bacterial communities may impact groundwater quality if they are introduced to aquifers in which they were previously absent (e.g. through leaks or spills of produced water).

6. Lack of an indication of where exactly the CSG wells will be drilled, and where pipelines for gas and produced water will be constructed. The groundwater monitoring network and baseline data should complement the layout of the well pads and pipelines to ensure all areas of active CSG extraction are adequately covered.

2. Fugitive gas contamination of shallow groundwater and the surface atmosphere

Methane is a potent greenhouse gas (when emitted to the atmosphere) and a potential groundwater contaminant that can lead to pump failures and potential explosion hazards in landholder bores (Walker and Mallants, 2014). When a gas reservoir is disturbed by drilling, hydraulic fracturing, de-watering or any combination of these, gas may potentially migrate from the reservoir to other parts of the sub-surface, such as aquifers above the gas deposit (which may be used for water supply), and/or the surface atmosphere. Some researchers argue that fugitive methane emissions associated with gas drilling, production and processing potentially render unconventional gas an equal or worse source of greenhouse gas pollution in comparison to coal (Howarth et al., 2011; McJeon et al, 2014, Howarth, 2014; Melbourne Energy Institute, 2016).

Leakage of methane into shallow aquifers and/or the atmosphere is now a well-documented phenomenon associated with unconventional gas development (Osborne et al, 2011; Howarth et al, 2011; Jackson et al, 2013b; Darrah et al, 2014; Vengosh et al, 2014; Jackson et al, 2014). Detailed analysis of the potential pathways for fugitive methane to enter shallow aquifers and/or the atmosphere as a result of CSG, and detailed strategies to minimise fugitive methane pathways, monitor fugitive methane, and address any impacts that are detected are thus needed to ensure this risk is properly managed. At present, there is very limited discussion or acknowledgement of this risk in the EIS, and limited (or no) baseline data regarding methane and other dissolved gas contents in groundwater, to allow future assessment of changes to shallow groundwater or surface atmospheric methane concentrations that might arise as a result of the project.

2.1 Relevant project activities

Fugitive methane release to either the atmosphere or shallow aquifers is a risk associated with all parts of the unconventional gas lifecycle, including drilling of the gas wells (Caulton et al, 2014), operation of the gas wells (Day et al, 2014), management and transport of wastewater (e.g. methane may de-gas from wastewater stored in dams at the surface) (Kort et al, 2014; Iverach et al, 2015) and gas distribution and processing (e.g. leakage of gas from pipelines into shallow groundwater; venting of gas that includes methane). In the case of the Narrabri Gas Project, the fugitive methane to shallow groundwater and/or the atmosphere could occur during all of these activities.

2.2 Mechanisms of stray/fugitive gas contamination

2.2.1 Groundwater contamination with fugitive methane

It is now well documented that contamination of shallow aquifers with 'stray gas' (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 taken place due to 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 can then reach shallow groundwater or the atmosphere.[5]"

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):

[5] Jackson, R. et al, 2014 p. 337

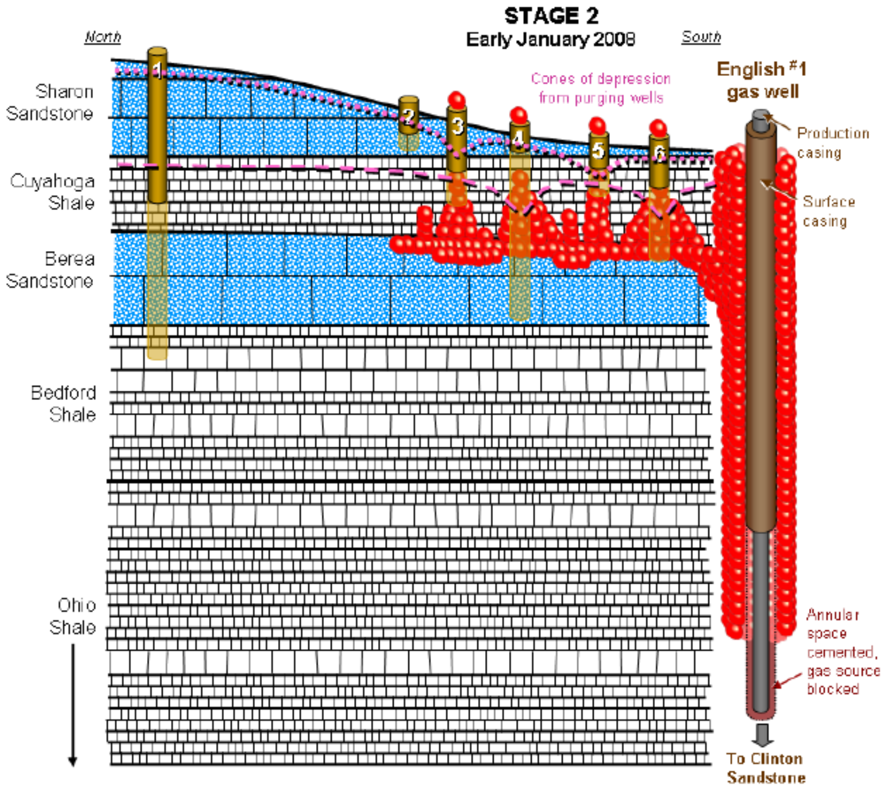

Figure 5 - Schematic diagram showing mechanism of gas contamination of shallow aquifers, based on a case study in Bainbridge County, Ohio (Bair, 2010).

As with surface leaks of unconventional gas wastewater (such as CSG produced water), 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 (such as the Narrabri Gas Project). Jackson et al, (2014) cite 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).

In the case of the Narrabri Gas Project, it is therefore important to recognise that well failures and faults will be likely to occur at some stage. Clear protocols and plans to monitor, rapidly detect and mitigate such problems as quickly as possible thus need to be in place before the first gas well is drilled. These protocols and plans must be carefully observed and independently monitored throughout the full lifecycle of the project, through to decommissioning of the gas wells and ongoing monitoring of the site after gas has been extracted.

So far, the EIS contains limited information regarding methods by which well integrity will be monitored and ensured throughout the life of the project, other than reference to the fact that the NSW *Code of Practice for Coal Seam Gas Well Integrity* (DTIRIS, 2012) will be followed during construction of the gas wells (e.g. see the EIS executive summary and Chapter 14). Whether all wells (water, gas, oil, active, inactive, abandoned) in the project area can be effectively identified, monitored, maintained and prevented from acting as pathways for fugitive methane contamination, is a question of critical importance to understanding fugitive gas contamination risks.

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 1.4, 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 CSG activity. 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 levels of methane in the Gippsland and Otway basins – which at the time of the survey were considered potential future areas of unconventional gas development. The baseline data served to document pre-existing levels of gas in groundwater, and coupled with isotopic sampling conducted by Currell et al (2016), allowed the existing sources of methane and associated geochemical processes in the gas-bearing aquifers and overlying units to be understood. A similar program has been carried out in the Richmond River catchment in northern NSW (Atkins et al, 2015) and overseas (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 CSG project of significant size, to ensure a rigorous baseline exists for assessing any future fugitive methane contamination of groundwater. This would also allow 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 the type of data that can be produced from this type of sampling in an area of potential future unconventional gas development are shown below in Figures 6 to 8 (based on data collected by Currell et al, 2016 in the Gippsland Basin in Victoria):

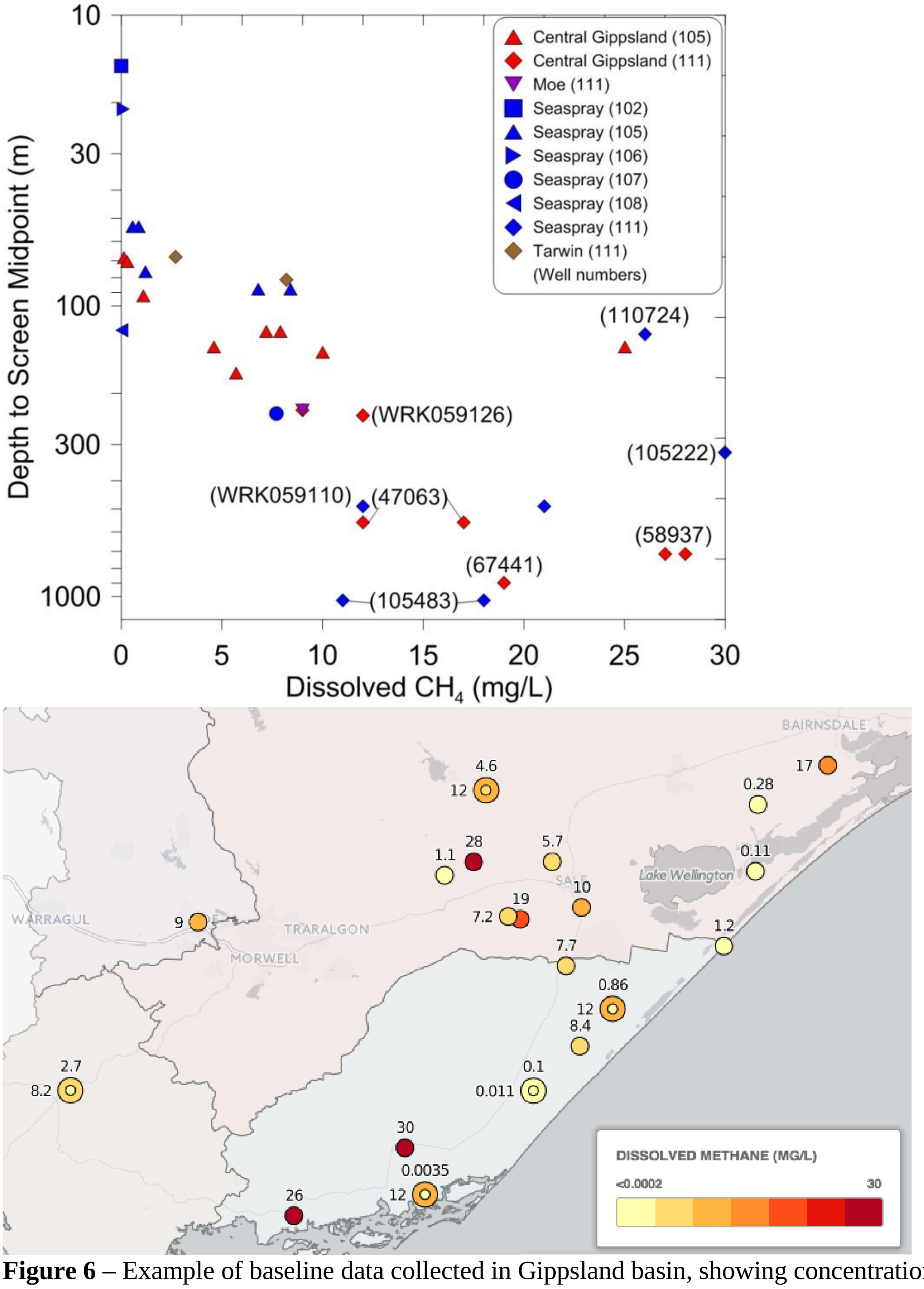

Figure 6 – Example of baseline data collected in Gippsland basin, showing concentrations of dissolved methane in groundwater at different depths and aquifers overlying potential unconventional gas target (Currell et al, 2016)

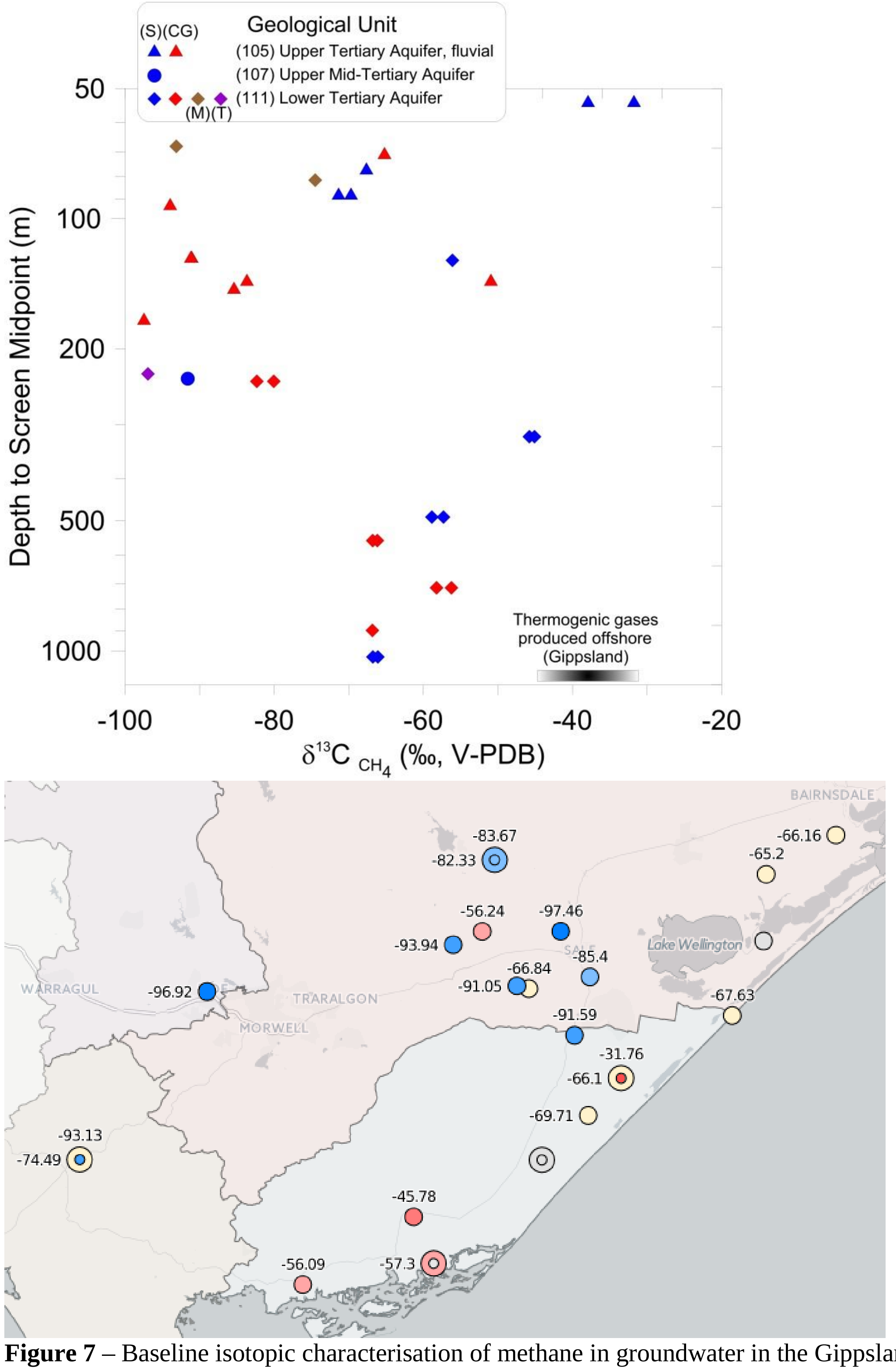

Figure 7 – Baseline isotopic characterisation of methane in groundwater in the Gippsland Basin (Currell et al, 2016).

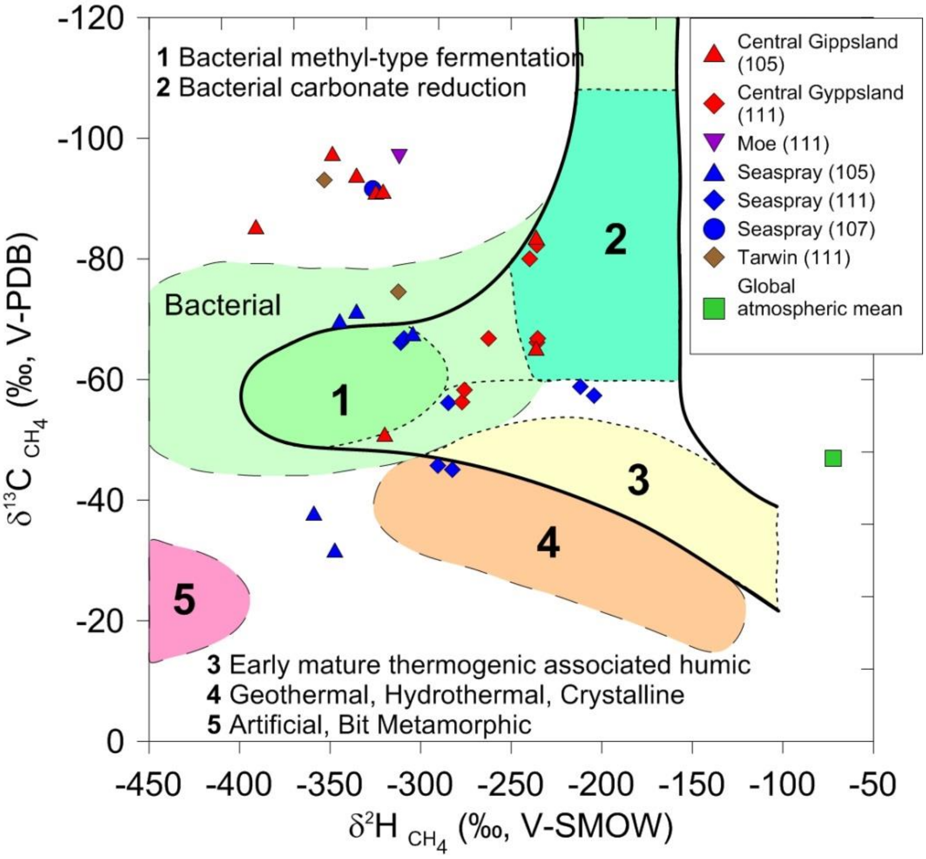

Figure 8 - Baseline isotopic characterisation of dissolved methane in groundwater from the Gippsland basin, showing likely sources of dissolved gases under current conditions. Isotopic compositions can fingerprint gases from different sources (Currell et al, 2016).

At present, the baseline data reported in the EIS are not adequate for the purpose of managing the risk of fugitive gas contamination in groundwater. In particular, the water baseline report (Appendix G3) contains no data reporting methane concentrations or other hydrocarbons in groundwater from any monitoring wells, and hence there is no baseline with which to detect and assess any changes in methane levels in groundwater, e.g., due to fugitive gas or fluid migration. As is discussed in the report on the inquiry into onshore unconventional gas in Victoria (Parliament of Victoria, 2015), and other literature (e.g. Walker and Mallants, 2014; Humez et al, 2016), determination of dissolved and/or 'free' methane concentrations in groundwater needs to be done in order to detect any fugitive gas contamination of aquifers in regions of unconventional gas. Additional sampling to determine the isotope composition of methane in the coal seams, and other aquifers where it may naturally occur is also a valuable tool to determine different sources of methane, and accurately delineate the source of any increases in methane concentrations observed during groundwater monitoring (Iverach et al, 2015; Currell et al, 2016; Humez et al, 2016). The fact that methane has not been included in the water baseline report (Appendix G3) and does not appear to be included in the list of analytes to be regularly sampled in the project area to date is thus a major oversight in the EIS.

2.2.2 Fugitive methane release to the surface atmosphere

In addition to the risk of contaminating water supply aquifers with gas, emissions of methane to the atmosphere during unconventional gas development are a significant potential source of greenhouse gas emissions. Within the EIS Chapter on greenhouse gas emissions (Chapter 24), the proponent does not discuss some of the common potential sources of fugitive methane emissions to the atmosphere from unconventional gas development within its Scope 1 emissions sources (direct emissions). These sources include leaks from gas well-heads (e.g. leaking valves or joins) – e.g. see Day et al, (2014); leakage that occurs during gas well drilling – which has recently been determined to be a significant source of fugitive methane associated with shale gas drilling in the United State (see Caulton et al, 2014); and de-gassing of methane from produced water stored in above-ground dams (e.g., see Iverach et al, 2015).

The assessment of greenhouse gas emissions for the Narrabri Gas Project appears to down-play the importance of these sources of methane emissions to the atmosphere, ignoring the recent international research which shows that these emission sources can be significant (Caulton et al, 2014; Kort et al, 2014; Howarth, 2014; Melbourne Energy Institute, 2016). Quoting from the EIS page 24-5:

> "upstream emissions for fossil fuel supplies are those emitted in the extraction, processing and transportation of the fuel product (i.e. coal or gas)
>
> downstream emissions are those emitted from the combustion of the fuel by the end-user.
>
> Upstream emissions form only a small proportion of the total lifecycle emissions for energy generation. Consequently, it is the downstream emissions that have by far the greatest bearing on the emissions intensity of the energy."

Contrary to this opinion, in 2011 William Howarth (a professor at Cornell University) 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, and constitutes a significant greenhouse gas emission source. Subsequently, a number of studies looked to quantify fugitive methane to the atmosphere in areas inside and outside unconventional gas fields, including Australian CSG fields (e.g. Kort et al, 2014, Leifer et al, 2013; 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 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 CSG development (the Tara gas field) with areas outside gas fields. They showed that near-surface atmospheric methane concentrations were elevated in CSG fields (up to 6.5 parts per million, and consistently above 2ppm) relative to areas of no CSG development and equivalent geology. Possible explanations are 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 by Day et al., (2014), examined gas leaks in some of Queensland's CSG fields, using similar technology. They targeted gas production wells and pipelines, looking to identify leakage to the atmosphere. They found that the majority of operating CSG wells showed little or no evidence of any methane leakage, and that in general gas contents were at background atmospheric levels. However, one well was identified with increased levels of methane emission to the atmosphere, associated with a valve on the well which periodically vented gas containing methane 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 unconventional gas in the Marcellus Shale of Pennsylvania. This work showed significantly higher fluxes associated with gas drilling, transport and processing than 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:

> "The identification and quantification of methane emissions from natural gas production has become increasingly important owing to the increase in the natural gas component of the energy sector. 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"[6] (Caulton et al, 2014).

Other methods including satellite-based estimation of atmospheric methane fluxes have highlighted significant emissions from CSG (called 'coalbed methane' in the US) in New Mexico (Kort et al, 2014). The significant methane emission anomaly identified in this area was attributed to either leaks from CSG wells and/or de-gassing from produced water 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.

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.

In the EIS chapter on greenhouse gas (Chapter 24) there is no detailed discussion of these issues, and only a brief indication that fugitive methane to the atmosphere in the 'upstream' part of the project will be monitored and managed; section 24.2:

> "A leak detection and repair program approved by the NSW Environment Protection Authority will be implemented to identify and minimise fugitive emissions."

However, no baseline data for atmospheric levels of methane in and around the proposed project area are presented. The collection of baseline data on methane concentrations (and preferably isotopic compositions) in the near surface atmosphere (as for groundwater) in areas of potential unconventional gas development is a critical step in ensuring fugitive methane resulting from CSG projects can be accurately assessed and quantified. An example of such a program conducted in Australia is AGL's Camden gas project. In this program, methane levels in the atmosphere were collected using 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 non-CSG related sources (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 emissions from the gas operation was detected, due to gas processing activities at the AGL plant.

A similar monitoring program with baseline data and ongoing monitoring should be carried out as part of the management strategy for detecting and minimising fugitive methane to the atmosphere due to the Narrabri Gas Project. While this may be planned (e.g. in conjunction with the 'leak detection and repair program'), as yet there appears to have been no such program designed or conducted. While a baseline air quality monitoring program was carried out in the project area in 2014 (see Appendix L of the EIS), methane monitoring was not included in this program.

Appendix R (Greenhouse Gas Assessment) of the EIS mentions the issue of fugitive methane emissions, and makes estimates of total emissions through the life of the project (see Table 2-3). This is based on National Greenhouse and Energy Reporting (Measurement) Determination 2008 and the American Petroleum Institute compendium of 2009. This assessment includes a number of assumptions. For example, in Table 2-3 of Appendix R, it is stated:

> "No material methane venting is expected to occur during the (well) completion phase"

This contradicts the findings of Caulton et al, (2014) and other studies described above. It is also not clear whether or not de-gassing of methane from CSG produced water storage dams has or will be monitored or

[6] Caulton et al, 2014, p.6237.

accounted for; given evidence that this may constitute a significant source (Kort et al, 2014; Iverach et al, 2015) it should be part of the baseline data and monitoring program.

Importantly, while it is proposed that methane emissions will be monitored and reported in the Greenhouse Gas Assessment (Appendix R), there is no detail of whether or how emissions of methane from the fugitive sources listed above will be monitored and reported. The EIS should thus outline detailed strategies for:

a) Monitoring groundwater and near surface atmospheric methane concentrations and isotopic compositions regularly, in order to detect any changes and establish the cause (whether related to a contamination problem or natural influences); and
b) Rapid and effective response plans to address any detected contamination of groundwater or the atmosphere with fugitive methane and other pollutants, to quickly cut the contamination pathway(s).

References

APLNG 2012. Appendix D-Surface Water Monitoring and Management. Milton, Australia: Australian Pacific LNG.

Atkins, M.L., Santos, I.R., Maher, D.T. Groundwater methane in a potential coal seam gas extraction region. *Journal of Hydrology: Regional Studies*, 4: 452-471.

Bair ES, Freeman, DC, Senko JM. 2010. Subsurface gas invasion, Bainbridge township, Geauga County, Ohio. Expert Panel Technical Report for Ohio Department of Natural Resources: https://oilandgas.ohiodnr.gov/portals/oilgas/pdf/bainbridge/DMRM%200%20Title%20Page,%20Preface,%20Acknowledgements.pdf

Biggs, A.J.W. 2006. Rainfall salt accessions in the Queensland Murray-Darling Basin. *Australian Journal of Soil Research* 44: 637-645.

Biggs, AJW, Witheyman, SL, Williams, KM, Cupples N, de Voil CA, Power, RE, Stone, BJ, 2012. Assessing the salinity impacts of coal seam gas water on landscapes and surface streams. August 2012. Final report of Activity 3 of the Healthy HeadWaters Coal Seam Gas Water Feasibility Study. Department of Natural Resources and Mines, Toowoomba.

Casey, J.A. et al. 2015. Predictors of indoor radon concentrations in Pennsylvania, 1989-2013. *Environmental Health Perspectives* 123: 1130-1137.

Caulton R., et al., 2014. Towards a better understanding and quantification of methane emissions from shale gas development. *Proceedings of the National Academy of Sciences USA*, 111(17): 6237-6242.

Crosbie, R., Jolly, I.D., Leaney, F.W., Petheram, C. 2010. Can the dataset of field based recharge estimates in Australia be used to predict recharge in data-poor areas? *Hydrology and Earth System Science* 14: 2023-2038.

Crosbie, R., Morrow, D., Cresswell, R., Leaney, F., Lamontagne, S. and Lefournour, M., 2012. New insights to the chemical and isotopic composition of rainfall across Australia. CSIRO Water for a Healthy Country Flagship, Australia.

Currell, M.J. 2015. Groundwater: the natural wonder that needs protecting from CSG. Published May 20, 2015. http://theconversation.com/groundwater-the-natural-wonder-that-needs-protecting-from-coal-seam-gas-41978

Currell, M.J., Banfield, D., Cartwright, I., Cendon, D.I., 2016. Geochemical indicators of the origins and evolution of methane in groundwater: Gippsland Basin, Australia. *Environmental Science and Pollution Research* (in press, doi: 10.1007/s11356-016-7290-0)

Darrah TH, Vengosh A, Jackson RB, Warner NR, Poreda R. 2014. Noble gases identify the mechanisms of fugitive gas contamination in drinking-water wells overlying the Marcellus and Barnett Shales. *Proceedings of the National Academy of Sciences.* www.pnas.org/cgi/doi/10.1073/pnas.1322107111

Day, S., Dell'Amico, Fry, R., Javanmard Tousi, H. (2014). Field Measurements of Fugitive Emissions from Equipment and Well Casings in Australian Coal Seam Gas Production Facilities. CSIRO, Australia.

Fensham, R., Ponder, W., Fairfax, R. 2010. Recovery plan for the community of native species dependent on natural discharge of groundwater from the Great Artesian Basin. Report to Department of the Environment, Water, Heritage and the Arts, Caberra. Queensland Department of Environment and Resource Management, Brisbane.

Ground Water Protection Council (2012) A white paper summarizing the stray gas incidence and response forum. GWPC, October 2012.

Hamawand I., Yusaf, T., Hamawand, S.G., 2013. Coal seam gas and associated water: A review paper. *Renewable and Sustainable Energy Reviews* 22: 550-560.

Harrington, N., Cook, P. 2014. Groundwater in Australia. National Centre for Groundwater Research and Training, Australia.

Healy, 2010. Estimating groundwater recharge. Cambridge University Press, 245pp.

Herczeg, A.L., 2008. Background report on the Great Artesian Basin. A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO, Australia.

Herczeg, A.L., 2011. Groundwater. *In* Water: Science and Solutions for Australia (Chapter 4). CSIRO, Australia.

Howarth, R.W. (2014). A bridge to nowhere: methane emissions and the greenhouse gas footprint of natural gas. *Energy Science & Engineering* 2: 47-60.

Humez, P., Mayer, B., Ing, J., Nightingale, M., Becker, V., Kingston, A., Akbilgic, O., Taylor, S., 2016. Occurrence and origin of methane in groundwater in Alberta (Canada): Gas geochemical and isotopic approaches. *Science of the Total Environment* 541: 1253-1268.

Iverach, C.P., Cendon, D.I., Hankin, S.I., Lowry, D., Fisher, R.E., France, J.L., Nisbet, E.G., Baker, A., Kelly, B.F.J. 2015. Assessing connectivity between an overlying aquifer and a coal seam gas resource using methane isotopes, dissolved organic carbon and tritium. *Scientific reports:* DOI: 10.1038/srep15996

Jackson RB, Vengosh A, Darrah TH, Warner NR, Down A, Poreda RJ, Osborn SG, Zhao K, Karr JD. 2013a. Increased stray gas abundance in a subset of drinking water wells near Marcellus shale gas extraction. *Proceedings of the National Academy of Sciences* 110(28): 11250-11255.

Jackson RE, Gorody AW, Mayer B, Roy JW, Ryan MC, Van Stempvoort DR. 2013b. Groundwater protection and unconventional gas extraction: the critical need for field-based hydrogeological research. *Ground Water* 51(4): 488-510.

Jackson, R.D., et al. 2014. The environmental costs and benefits of fracking. *Annual Reviews in Environment and Resources* 39: 327-362.

Jacobs, 2015. Gippsland Region groundwater sampling and characterisation for hydrocarbons. Report for the Onshore natural gas water science studies, June 2015.

Khan S and Kordek G (2014) Coal seam gas: produced water and solids. Report prepared for the office of the NSW Chief Scientist and Engineer (OCSE).

Kort EA, Frankenberg C, Costigan KR, Lindenmaier R, Dubey MK, Wunch D. 2014. Four corners: the largest US methane anomaly viewed from space. *Geophysical Research Letters* doi: 10.1002/2014GL061503.

Leaney, F. et al. 2011. Recharge and discharge estimation in data poor areas: Scientific reference guide. CSIRO: Water for a Healthy Country National Research Flagship.

McJeon H, et al. (2014) Limited impact on decadal-scale climate change from increased use of natural gas. *Nature* 514: 482-485

Melbourne Enery Institute (2016). A review of current and future methane emissions from Australian unconventional oil and gas production. Report commissioned by The Australia Institute, October 26, 2016 (90p).

Pacific Environment Ltd. 2014. AGL Fugitive methane emissions monitoring program – technical report. Job No. 7081E, 5th February, 2014.

Parliament of Victoria, 2015. Inquiry into onshore unconventional gas in Victoria. Final Report: EPC Report No. 3, 58th Parliament.

Paulik, L.B., et al. (2015). Impact of natural gas extraction on PAH levels in ambient air. *Environmental Science and Technology* 49: 5203-5210.

QGC (2012) Approval conditions 49 to 52: Stage 2 CSG Water Monitoring and Management Plan. Brisbane, Australia: Queensland Gas Company.

Stamford, L., Azapagic, A. 2014. A fractured truth. *The Chemical Engineer* 881: 26-30.

Van Stempvoort, D., Maathuis, H., Jaworski, E., Mayer, B., Rich, K. 2005. Oxidation of fugitive methane in ground water linked to bacterial sulfate reduction. *Groundwater* 43(2): 187-199.

Vengosh, A. et al. 2014. A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. *Environmental Science and Technology* 48: 8334-8348.

Vidic, R.D., et al, 2013. Impact of shale gas development on regional water quality. *Science* 340, 1235009.

Walker, G.R., Mallants, D. 2014. Methodologies for investigating gas in water bores and links to coal seam gas development. CSIRO, Australia

Warner NR, Christie CA, Jackson RB, Vengosh A (2013). Impacts of shale gas wastewater disposal on water quality in western Pennsylvania. *Environmental Science & Technology* 47: 11849-11857.