Expert report: Risks to groundwater associated with the Narrabri Gas Project

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Introduction

I was requested by EDO, acting for their client, the North West Alliance (NWA), to prepare an expert report analysing groundwater-related issues associated with the proposed Narrabri Gas Project. I was asked to review all relevant materials – including the DPIE's recent Assessment Report and proposed conditions of consent – and provide my views as to whether these materials address concerns I have raised about the project's groundwater impacts in previous expert reports. NWA also asked me to provide my opinion on a series of relevant questions (provided at the end of this report) and to present to the IPC public hearing to discuss these matters.

The opinions outlined in this report are my own independent professional views, based on my expertise in hydrogeology and environmental engineering. I have not been asked to advocate any particular view about the project or approval outcome. I have prepared the report in accordance with Division 2, Part 31 of the *Uniform Civil Procedure Rules 2005* (**UCPR**) and the Expert Witness Code of Conduct (**Code of Conduct**) which states that:

> *"An expert witness is not an advocate for a party and has a paramount duty, overriding any duty to the party to the proceedings or other person retaining the expert witness, to assist the court impartially on matters relevant to the area of expertise of the witness."*

I have read Schedule 7 of these rules and agree to be bound by it.

My relevant expertise

I am an Associate Professor of environmental engineering in the School of Engineering at RMIT University. I received my PhD from Monash University, on the use of environmental isotopes and geochemistry to assess the sustainability of groundwater use and controls on groundwater quality in areas of intensive development. For the last nine and a half years at RMIT I have taught hydrogeology, geochemistry, and groundwater modelling to hundreds of environmental and civil engineering students, and supervised multiple Master and PhD projects in applied hydrogeology research. I have been awarded more than $1 million in research funding as a chief investigator on more than 12 grants, supporting projects examining groundwater sustainability and contamination issues. I have published more than 50 peer-reviewed international journal articles, which have been cited more than 1500 times, and served on the editorial board of the *Hydrogeology Journal* (the journal of the International Association of Hydrogeologists) from 2014 to 2018. I have acted as an independent expert witness examining groundwater impacts of mining activities, including the Victorian Parliamentary Inquiry into Unconventional Gas, the Northern Territory Scientific Inquiry into Hydraulic Fracturing, proceedings in the Land Court of Queensland, and other mining proposals examined by the NSW Independent Planning Commission. I have been reviewing and analysing technical documents and data relating to the Narrabri Gas Project, in response to requests from EDO, since 2013. My full CV is available on request.

Summary of my opinion

There are significant risks to groundwater quality and quantity associated with the Narrabri Gas Project, which have been outlined in expert reports I have previously prepared, and many other relevant submissions. The major risks, discussed below, are:

1. Groundwater, surface water and land contamination due to leaks and spills of CSG produced water – a saline fluid containing hazardous levels of salt, arsenic and other trace elements. This poses a threat to the quality of groundwater available for potable and irrigation usage and ecosystems in the area.

2. Cross-contamination of important shallow aquifers with methane and other hydrocarbons from deep in the Gunnedah Basin. This may result in bore pump failures, secondary impacts to groundwater quality (e.g. contaminant mobilisation) and - in extreme cases - explosion hazard.

3. Long term risk of depressurisation and leakage from key water supply aquifers – e.g. the Pilliga Sandstone and Namoi Alluvium - affecting the availability of groundwater for other users in a highly allocated and water-stressed system[1].

4. Risk of land and water contamination with hazardous salt and/or brine produced through treatment of coal seam gas produced water.

These risks were highlighted and analysed by the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining (IESC), in their review of the project EIS in 2017, and they were examined by the Water Expert Panel (WEP) appointed by DPIE during its recent assessment of the project. There is important new evidence which in my view increases the likelihood of certain impacts – particularly (2) and (3) above, some of which has not been considered by DPIE and the WEP (discussed below).

Based on my analysis of the relevant material, I believe the risks above are considerable, and in general they are likely to have been under-estimated in the EIS and other material produced by the applicant. Despite the above issues being raised by many concerned submitters, very little has been done by the applicant to:

a) further understand these risks – e.g., through additional field research programs, collection and analysis of more extensive monitoring data, and modification of assumptions in the groundwater modelling.

b) Modify the proposed plan of operations, to allow for mitigation of these potential impacts, and develop a comprehensive suite of baseline data and appropriate groundwater monitoring program.

As such, the applicant's capacity to respond to and address impacts that do arise will be hampered by lack of baseline data and understanding of key hydrogeological processes. Additionally, there are impacts which, even if detected by monitoring, may not be feasible to effectively mitigate, due to the inertia of major inter-layered aquifer systems, and difficulties of effective groundwater remediation once impacts have occurred.

The DPIE's assessment states that the project 'would not result in any significant impacts on people or the environment', which in my view is far from having been demonstrated and is not supported by all the available evidence. The WEP pointed out important uncertainties and knowledge gaps in relation to the risks above, but overall, believe the project can either be carried without significant water-related impacts, or that these can be managed with appropriate controls. While the panel provided sound analysis on many issues, in key areas it did not have access to, or did not consider, important relevant information and data - including recently published peer reviewed research[2] with significant findings regarding inter-aquifer connectivity.

Both DPIE and the Water Expert Panel believe that uncertainties regarding groundwater impacts (which the WEP point out are considerable in some areas) can be resolved after approval is given and the project commences, through subsequent collection of data and updating of the modelling.

With due respect to DPIE and the WEP, this is a flawed approach because:

1. Proper groundwater modelling must <u>first</u> incorporate careful development of correct geological conceptual modelling, supported by extensive field data and evidence (which are currently deficient in

[1] This issue was not extensively analysed in my previous expert reports, however NWA have asked me to examine it, and there is new evidence relevant to its assessment which has to date not been considered.
[2] E.g., Iverach et al., 2020.

key areas). Without the proper use of field investigations to develop a robust hydrogeological conceptualisation, any numerical modelling is likely to produce inaccurate and potentially misleading predictions. This is crucial in the context of DPIE's proposed conditions, which will rely on the groundwater model to estimate indirect water usage from the project, and thus determine the volume groundwater licenses required by the applicant.

2. If groundwater modelling has not incorporated a robust hydrogeological conceptualisation, based on adequate field data, decision makers and the public are not being presented with a full realistic range of potential impacts from the project at the assessment stage. They therefore cannot be reasonably expected to make informed decisions about the likely consequences, risks, and merits of the project.

In the following, more detailed analysis of the four risks outlined above is provided, drawing on relevant evidence considered by the DPIE, WEP and the applicant, as well as additional relevant data and research not considered in these assessments.

1. Groundwater, land, and surface water contamination with CSG produced water

As noted in DPIE's assessment report, several submissions raised the possible contamination of shallow groundwater, surface water and land in the area as a key concern, particularly in the context of:

a) the region's high quality, high yielding aquifers, which many people and ecosystems depend on.

b) a history of incidents of wastewater spills and leaks associated with CSG exploration in the region.

These concerns are justified. Extensive reviews and data compilations across a range of settings (e.g., Jackson et al., 2014; US EPA, 2016; Patterson et al., 2017) show that where they are carefully monitored and reported, spills and leaks of wastewaters are a common, if not inevitable, part of unconventional oil and gas production:

> "We assessed spill data from 2005 to 2014 at 31,481 UOG (unconventional oil and gas) wells in Colorado, New Mexico, North Dakota, and Pennsylvania. We found 2−16% of wells reported a spill each year." (Patterson et al., 2017).

While Patterson et al.'s review and others from the U.S. predominantly examine wells subjected to hydraulic fracturing (which is not proposed in the Narrabri project), their review and other relevant case studies of unconventional gas in the U.S. (e.g. Lauer et al., 2016), make clear that the majority of spills and leaks are not related to the hydraulic fracturing process and occur by mechanisms that apply to all gas wells, e.g., leakage from tanks, ponds, flowlines/pipelines and connection points for these. Produced water volumes in coal seam gas – including in the Narrabri area - are typically much greater than hydraulically fractured shale gas in the US (Kondash et al., 2018; Underschultz et al., 2018), and in this regard the potential for, and volume of, spills and leaks is heightened relative to shale gas (although risks at the well head associated with hydraulic fracturing are reduced – e.g. Fig. 1). It is unrealistic to expect the Narrabri gas project to be different from other unconventional oil and gas developments and be immune to issue of spills and leaks.

In the Narrabri project area, there are three factors which heighten the significance and potential adverse consequences of produced water spills and leaks:

1. The quality of groundwater in shallow aquifers is unusually high, and groundwater quality (and availability) is of great importance to water users.

2. The project area is within a recharge zone for a key Great Artesian Basin (GAB) aquifer (Pilliga Sandstone). As such, contamination incidents have wider significance than if they were to take place where recharge is limited and/or where the aquifer(s) are not extensively utilised.

3. The quality of produced water from the coal seams that will be extracted, transported, stored, and treated throughout the project area is particularly poor, containing unusually high concentrations of salts and trace

elements. For reference, average reported total dissolved solids content of Gunnedah Basin CSG produced water is more than five times the average from Surat Basin CSG operations (in Queensland), where DPIE conducted a field trip and consultations to assist in forming views about the project.

Rates of produced water spills and leaks vary depending on reporting requirements (which are variable in different jurisdictions) as well as the frequency of independent inspections by regulators, and mechanisms in place to detect these events (Patterson et al., 2017). Risk may be mitigated to an extent through technical and operating measures, and careful monitoring and oversight, but it not realistic to expect this will prevent spills and leaks entirely. Even if incidents occur at the low end of the range indicated by Patterson et al. and other studies, a significant number of spills and leaks would occur in the Narrabri project, given the proposal to drill more than 800 wells. For example, a 2.5% spill/leak rate would equate to approximately 20 incidents per year, which would have significant potential to compromise the quality of recharging groundwater and contaminate land in the area.

The Water Expert Panel noted the potential impacts of such incidents, but believe their wider significance will be limited:

> "Due to the salinity of the produced water, any spill of this water is likely to have significant impact on the local ecosystem, but given the likely volume, it is unlikely to have an impact on the regional groundwater system. There is also uncertainty about whether a spill could mobilise undesirable chemicals in the soil, leading to the appearance in surrounding bores of potentially toxic substances."

With respect, the view that leaks and spills will be localised and unlikely to affect regional groundwater quality is somewhat speculative - it is not based on any mass balance calculations, geochemical data, or modelling. If spills and leaks are not rapidly detected and mitigated, and their incidence and/or volume is significant - as has been documented in case studies of oil and gas operations from the US (e.g. Lauer et al., 2016, U.S. EPA, 2016), then widespread water quality impacts affecting a considerable area are possible (e.g. see Map 2).

The applicant and DPIE believe this issue can be managed, through:

> "collecting all saline water directly from the gas wells and conveying it in buried water gathering lines with leak detection systems to the Bibblewindi and Leewood facilities for storage and treatment;"
>
> and
>
> "storing all produced water, treated water and any associated wastes (brine and salt) in specially designed storages"

Storage of produced water is a key issue; the WEP believe the construction of wastewater storage ponds is of high standard, following a visit to the Leewood facility:

> "The WEP has reviewed Santos' proposed produced water treatment system in detail and concluded that it represents current best practice, and that any risks can be effectively managed subject to strict conditions."
>
> "Existing storage ponds at Leewood appear to be appropriately constructed. Adherence to the appropriate NSW Codes of Practice and close attention at the FEED stage to the requirement for environmentally safe operation, should ensure that any risks associated with storage of produced, treated and concentrated produced water are met"

Importantly, the data compiled by Patterson et al. indicate that a significant number (approximately half) of recorded wastewater spills in the US occur during the movement of wastewater via flowlines and temporary storage in tanks, as well as from storage ponds of the kind constructed at Leewood (see Figure 1 below). While the panel may be satisfied with wastewater storages at Leewood, it has not extensively analysed the risk from leakage at the well-head or flow-lines that will be used to collect and transport the produced water throughout the project area, nor the likely effects of aging and wear-and-tear of pond linings, gathering lines and other relevant infrastructure over a 25-year period. The panel noted that detailed plans regarding spill prevention and mitigation protocols are yet to be provided by the applicant (e.g., see recommendation 22), meaning the level of risk is contingent on future processes and information as yet unclear to the public.

While undoubtedly the applicant will endeavour to minimise leaks, spills and overflows of produced water in accordance with regulatory requirements, the data from Patterson et al. indicate that human error, equipment failure and unforeseen circumstances (such as extreme weather) are primary causes of these events, and the rates at which these occur remain considerable across a wide range of technical and regulatory settings. While the proposed management plan and recommended conditions may reduce the likelihood of incidents, the quality and significance of recharging shallow groundwater, and particularly poor quality of the produced water heighten the potential consequences.

Based on current infrastructure, there will be capacity to store approximately 600 ML of produced water and 300 ML of reverse osmosis concentrate at the Leewood plant – less than the projected yearly produced water volumes (approximately 1500 ML/year). There will thus be a need to continuously keep produced water and waste products from the treatment process moving through the transport, storage, and treatment cycle, and find end-uses for the water. The possibility of equipment failures, power outages and infrastructure damage/wear-and-tear create considerable risks in this context.

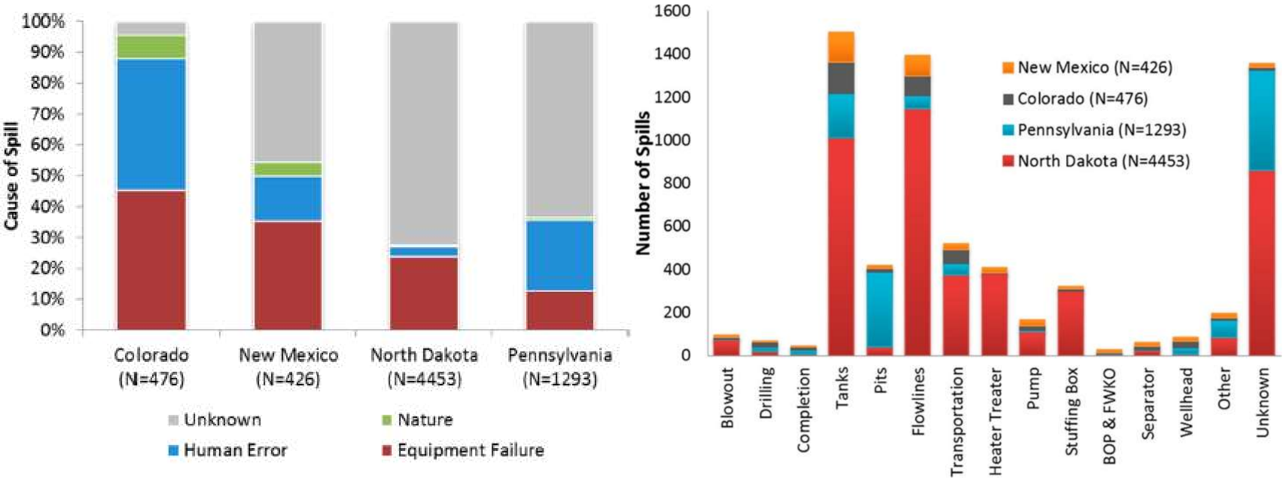

Figure 1 – Data reporting oil and gas wastewater spill and leak incidents and their identified causes from four US states where regulatory requirements compel unconventional oil and gas operations to report such incidents (reproduced from Patterson et al., 2017). A further map showing the correspondence of unconventional oil brine spills in North Dakota (where spills are particularly frequent) is provided at the end of this report (Map 2).

Multiple incidents of wastewater leakage and spills within the project area have already occurred during pilot CSG exploration and production activities in the Pilliga Forest (Cubby, 2012; Khan and Kordek, 2014; NSW EPA, 2014), affecting nearby groundwater quality. These incidents occurred when only a handful of wells were developed, producing small volumes of produced water and drilling fluid compared to the scale planned for the Narrabri project. There is evidence these incidents led to significant input of salts into nearby groundwater, as well as secondary changes in groundwater chemistry- i.e., mobilisation of contaminants from soils.

Significance of potential groundwater contamination in the project area

Groundwater in the Pilliga Sandstone – which outcrops at the surface in the project area – is of high enough quality to be used directly for drinking, and there is evidence the shallow groundwater in this aquifer supports groundwater dependent ecosystems (although, this is poorly documented due to the lack of a comprehensive field-based GDE study – see IESC, 2017).

Data included in the EIS Water Baseline Plan show the average electrical conductivity of Pilliga Sandstone groundwater is approximately 300 to 400 µS/cm, indicating an overall total dissolved solids content between

167 to 322 mg/L; well below the 600 mg/L guideline for drinking water aesthetic characteristics in the Australian Drinking Water Guidelines. Such high-quality groundwater is rare in Australian aquifers (e.g. Harrington and Cook, 2014).

In contrast, the reported CSG produced water chemistry contains numerous parameters exceeding drinking water, irrigation, and ecological guideline values. These include mean TDS contents between 14,668 and 23,800 mg/L, elevated sodium concentrations (approximately 90 times the average in the Pilliga Sandstone), mean arsenic concentrations ten times the safe drinking water guideline and mean fluoride concentration more than five times the guideline. The average TDS content of the produced water is approximately 5 to 7 times more concentrated than produced water from the Surat Basin (Underschultz et al., 2018). This significant contrast in quality between the potential contaminant (produced water) and receiving environment (Pilliga Sandstone aquifer) presents much greater groundwater quality risk than typical Australian CSG projects.

Water quality indicator	**Average for Pilliga Sandstone groundwater**	**Average for Narrabri produced CSG Water**
EC (field) µS/cm	303	22,613
EC (lab @ 25C) µS/cm	402	Not reported
TDS (range[3])	167 - 322	14,668 – 23,800
pH	6.2	9.4
HCO_3 alkalinity (as CaCO3) mg/L	164	12,994
Chloride mg/L	31.6	1,458
K	5.4	80.4
Na	76.8	7,059
SO4	2.7	42.7
Ca	5.5	7.46
Fluoride	0.35	7.64
Barium (mg/L)	0.3	3.35
Arsenic (ug/L)	Not reported	100
Cadmium (ug/L)	Not reported	20
Dissolved Organic Carbon	Not reported	196
Chemical Oxygen Demand (mg/L)	Not reported	44.1

Table 1 – Groundwater quality indicators in Pilliga Sandstone monitored bores and reported CSG produced water from gas wells in Narrabri area (data from: Santos EIS updated Water Baseline report, 2018)

The location of the project area, within a zone of recharge for a Great Artesian Basin aquifer, adds to the significance of possible contamination impacts. The WEP point out that the region is indeed a zone of recharge for the GAB, although they believe recharge rates are relatively low in comparison to the Warrumbungles, further south:

> "The project area, as with the entire region, is within a recharge area for the GAB. However, recent modelling by GISERA indicates that the project area is located within a comparatively low recharge zone (less than 5 mm per year), as the Pilliga Sandstone outcropping is limited in the area and rainfall is relatively low. Primary recharge in the region (more than 40 mm/yr) occurs via the Warrumbungles, located to the south of the project area, where higher rainfall and greater outcropping exists."

This analysis is not based on any detailed site-specific field studies, as would be required to demonstrate the extent to which groundwater recharge occurs at the appropriate scale. Neither Santos nor GISERA appear to have conducted field studies of groundwater recharge rates, mechanisms, and spatial and temporal variability within the project area. Such analysis requires multiple techniques, such as sampling for chloride in water table bores and/or soil moisture profiles, analysis of age-sensitive environmental tracers in groundwater (such as

[3] Based on the application of a conversion factor to electrical conductivity measurements, ranging between 0.55 and 0.8 (appropriate conversion factor is variable based on solution composition).

tritium) and analysis of water level fluctuations during rain events of different size and intensity (Scanlon et al., 2002; Healy et al., 2010; Hall et al., 2020). This is required to properly understand the spatial distribution – e.g. areas of higher/lower recharge potential, mechanism (e.g. focussed vs. diffuse, episodic vs. continuous) and rates of recharge, and their dependence on key factors such as soil permeability, vegetation and local hydraulic and topographic gradients.

Currell, (2017) provided calculations of recharge based on the chloride data reported in the project EIS, which suggested higher rates between 20 to 30 mm/year (though these are acknowledged to be uncertain in the absence of further data). The recharge rates estimated by GISERA are based on analysis of chloride data across the wider Namoi catchment as part of the Bioregional Assessment (Aryal et al 2018). Uncertainties in their method are acknowledged:

> "not accounting for the enhanced [chloride] deposition on forested areas leads to underestimating recharge."

In the context of typical rates of recharge in Australia, rates of 5 to 10 mm/year are still substantial. Irrespective of the rate, it is the potential for recharge to a key aquifer which is of most significance to the assessment of contamination risk, as this establishes a clear pathway for contaminants (e.g. CSG produced water spills and leaks) to enter the aquifer and compromise groundwater quality. Recharge to the GAB is known to be highly geographically restricted to specific zones in eastern Australia (Ransley and Smerdon, 2012) and as such, protection of the limited areas where it does occur is paramount to protecting the future quality of water in the system's aquifers. Currently, the Pilliga Forest has few (if any) potentially contaminating land-use activities occurring above areas of GAB aquifer outcrop, and as such an enhanced level of care and protection is warranted.

If indeed recharge rates are at the lower end of current predictions (e.g. 5 to 10 mm/year) this may heighten water quality risks from CSG produced water, as the dilution capacity of infiltrating water will be more limited than if recharge occurred at higher rates. Ultimately, the production, storage and movement of large volumes of poor-quality wastewater over an extensive footprint area (i.e., where well-heads, flow lines and the treatment plant infrastructure will be established), above a recharge area for a high quality aquifer presents major water quality risks.

Given the significance of this issue to assessment of future groundwater quality risks, as well as the groundwater modelling (see below) it is hard to understand why a thorough study of recharge, as well as flow paths and inter-aquifer connectivity, has not been conducted in the project area. This would have provided important information to understand the significance and consequences of potential contamination effects and more robust assessment of groundwater quality risk. Such work is also required for the development of a robust numerical model for predicting impacts on groundwater quantity (as well as quality - see section 3 below), as well as appropriate management and mitigation measures. Conducting such work after approval means it is not possible to gain a sound understanding of potential risk level and feasibility of impact mitigation.

Potential receptors and consequences

The major receptors who may be impacted by contamination resulting from CSG wastewater spills and leaks include:

- Groundwater users within the project area, particularly those with bores in the Pilliga Sandstone – e.g., accessing it for drinking water, stock, and irrigation.
- Additional groundwater users outside the project area, whose bores tap the shallow aquifers which may be impacted by migration of contaminants and/or changes to the quality or quantity of groundwater recharge entering the aquifer system (in the longer term).
- Groundwater dependent ecosystems (GDEs) – e.g. stygofauna and other ecological communities associated with Bohena Creek's alluvium, Hardys and Eather Springs (high-value GDEs).
- Surface water and associated ecosystems – such as Bohena Creek (e.g., if spills occur nearby)

The potential consequences include an inability for current (and future) water users to continue using groundwater for these purposes, and damage to the health and function of GDEs and riparian ecosystems.

Proposed mitigation/management strategies

DPIE believe that impacts associated with spills and leaks of produced water from the project can be mitigated by the draft conditions which:

"require Santos to:

- ensure the project causes no water pollution;
- locate all water-related infrastructure in accordance with the Field Development Protocol;
- treat all produced water to a suitable standard in accordance with the applicable guidelines;
- seek further approvals from the EPA prior to using any treated water for irrigation;
- meet strict criteria for any water discharges to Bohena Creek (volume, quality and temperature);
- comply with water performance measures; and
- prepare and implement a detailed Water Management Plan for the project, which includes monitoring and public reporting of any water impacts."

As discussed above, the empirical data (Patterson et al., 2017) show that most oil and gas wastewater spills and leaks relate to equipment failure and human error, and these can occur both during storage and processing of the water (e.g. at treatment plants) as well as during transport in flowlines and tanks – as outlined in the O'Kane Review's report (Fig 2). As noted above, it is optimistic to expect these issues will not occur in the Narrabri Gas Project, regardless of the conditions imposed, given its size and the number of wells proposed.

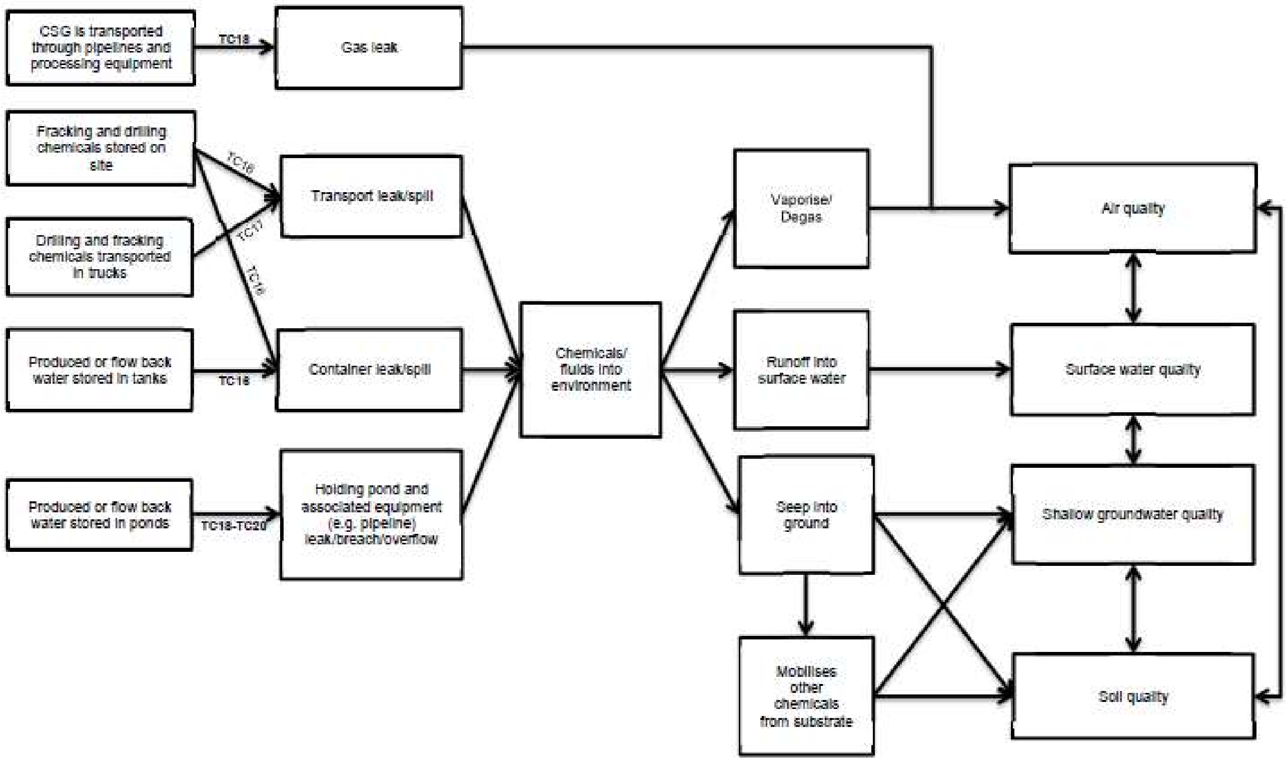

Figure 3: Risks and controls for spills and leaks
(For the list of technical controls (TC) see Appendix 1; for controls related to produced water solids see Figure 4)

Figure 2 – Pathways by which CSG produced water may contaminate the environment (reproduced from O'Kane, 2014).

Compliance with the stated aims of the recommended conditions will depend on the extent of the groundwater monitoring network and its ability to rapidly detect impacts, as well as the frequency and thoroughness of independent inspections by the regulator to verify compliance. The current monitoring network has been noted (by the IESC and WEP) to have significant gaps, which at present would not be adequate for the purpose.

Similarly, detailed plans for minimising and responding to spills and leaks are yet to be produced by the applicant (see WEP's report - recommendation 22), leaving considerable uncertainty in this regard.

Surface water discharges

The applicant proposes to discharge treated produced water to Bohena Creek, when it experiences high flow events - e.g., 100 ML/day, to assist with managing the produced water volumes generated by the project. DPIE and the WEP believe this can be done safely:

> "The WEP also concluded that the:
>
> - treated and amended water from the Leewood treatment facility would meet both the Australian Drinking Water standards and ANZECC guidelines for long-term irrigation; and
> - the water quality of any discharges to Bohena Creek in times of high rainfall would be "better than that measures in Bohena Creek, the Namoi River and local bores", but that some temperature matching should occur prior to any discharge."

The WEP did however note that concentrations of boron and zinc may be higher than current creek water based on current available data, which could result in ecological impacts. Generally, it is assumed lower concentrations of chemical species translate to 'better' water quality for ecological purposes. It is important to note that ecological communities are generally adapted to water quality within certain ranges of chemical and physical characteristics, and depending on specific ecological requirements, low concentrations of certain constituents (including salinity) may be detrimental to ecosystem health. A detailed analysis of ecological communities along Bohena Creek and their tolerance for different water qualities would allow for more meaningful assessments of this issue; however, this has not been conducted.

The IESC pointed to multiple problems with the applicant's assessment of potential ecological impacts resulting from discharge of treated produced water to Bohena Creek in its 2017 advice:

> "Further limitations of the risk assessment and direct toxicity assessment include:
>
> a. an absence of aquatic biota data used in the effects assessment (only data on mammals and birds were used to derive HQs)
>
> b. site-specific guidelines for boron and fluoride were derived incorrectly.
>
> This has resulted in more conservative values than if undertaken appropriately, although less conservative for boron than the current ANZECC/ARMCANZ (2000) guideline value."
>
> "The volume and duration limits (including proposed daily maximum discharge) of discharge events should be specified as this will alter the amount of contaminant dilution. These limits should be provided in daily and cumulative totals and as a proportion of total flows in Bohena Creek during discharge (e.g. ratio of discharge to natural creek water). This will be especially relevant on the falling limb of the Bohena Creek hydrograph where residual discharges and decreasing creek flows could result in a rise in contaminant concentration.
>
> "The proponent does not provide predictions of temporal variation in contaminants (e.g. ammonia, mercury, copper, boron, fluoride) to Bohena Creek. Contaminants percolating through the alluvial sediments and leaving residues behind can cause subsequent first flow pulses containing high contaminant concentrations that pose a potential water quality risk."

It remains unclear from the WEP report and applicant's responses whether these issues have been addressed - they are not discussed in detail in their report.

2. Cross-contamination of aquifers with methane and other hydrocarbons

The risk of cross-contamination of key water supply aquifers – e.g., the Pilliga Sandstone and Namoi Alluvium - with methane and other hydrocarbons in response to CSG extraction, has been raised by multiple submissions, including my previous expert reports. The issue is discussed by DPIE and the WEP as a key concern associated with the project:

> "Methane Migration: Submissions raised concerns about the potential for methane to migrate into surrounding strata, groundwater bores and other water supplies, as claimed in some high-profile cases in the US and in Queensland."

DPIE and the WEP's view is that the risk of methane contamination is relatively low, and can be managed:

> "Subject to the construction and maintenance of wells in accordance with the Well Integrity Code, the WEP considers that significant subsurface migration should not occur and is unlikely to result in significant impacts. The WEP also considered the potential for cross-contamination and other contamination of reservoirs and aquifers, which could occur from induced flows via a number of mechanisms including:
>
> - geological faults;
> - compromised gas well integrity;
> - coal seam gas well leakage, particularly in abandoned wells;
> - historical conventional gas wells and coal mining core holes; and
> - existing groundwater bores."
>
> And:
>
> "..the Gunnedah Basin where the Narrabri Gas Project is located has favourable geology and hydrogeology for coal seam gas development compared to several other jurisdictions, which reduces any risks considerably…the coal seam aquifers are physically separated from the shallower, better quality aquifers by thick layers of relatively impermeable rock (known as aquitards) which limits impacts to the shallow aquifers;"

The WEP also stated:

> "No geological structures were identified that are likely to adversely impact of gas production or groundwater movement."
>
> and
>
> "the hydraulic connectivity between the Gunnedah-Oxley Basin and the Great Artesian Basin is very low".

The applicant's response to submissions noted that seismic data collected throughout the region have been reviewed, showing "no evidence that faults extend into the overlying formations"; although, it did not present the data or any detailed interpretations in its EIS or response to submissions. As discussed below, there is data and evidence which contradicts this view.

<u>Key additional information not considered by DPIE and the WEP:</u>

The analysis by DPIE and the WEP did not consider recent peer-reviewed research conducted by a collaboration between UNSW and ANSTO (Iverach et al., 2020). This is probably due to the timing of publication (in late 2019) after much of the WEP's review was completed, although much of the geological data examined has been available for many years. The research drew upon water and gas isotope, hydrochemical and microbiological sampling, along with pre-existing geological literature and data – including the many seismic surveys carried out in the region. Importantly, the research indicates the presence of major geological structures in the Gunnedah Basin and overlying sequences, that are likely to enhance connectivity between deep and shallow geological units within and to the north of the project area (e.g., Fig. 3 and Fig. 4). Some of these surveys identify structures – e.g., faults and volcanic intrusions – which propagate from the deep coal-bearing layers of the Gunnedah Basin, through the intervening layers and into the GAB (contrary to the information reviewed by DPIE and the WEP):

> "The Wilga Park Anticline located 5 km to the south of Narrabri runs north-south, through our study area (Supplementary Fig. 1). A north-south seismic section along the axis of the anticline maps faults that cut into the Pilliga Sandstone and a volcanic plug that extends from the regional basement and passes upwards through the Maules Creek Formation and Hoskissons coal seam into the base of the Pilliga sandstone. The faults and plug contact zones are potential pathways for groundwater and gas to migrate. Additionally, structural subdivisions of the Gunnedah Basin (Hamilton et al., 1988; Tadros, 1995; ESG, 2004) show that there is a lineament running parallel to the Namoi River in our study area that may provide an additional pathway for groundwater and gas migration. (Gurba and Weber, 2001) mapped a number of igneous intrusions in the region and demonstrated that near these intrusions there is elevated CO_2 associated with gas migration from depth. The seismic surveys conducted by ESG (Eastern Star Gas) traverse some of these mapped igneous intrusions".
>
> "One of the seismic lines interpreted near Yarrie Lake, south-west of Narrabri (Supplementary Fig. 1) shows fault planes appearing in the east-west section that continue northwards, parallel to the thrust that is evident in Bellata seismic sections, 20 km north of Narrabri, in Tadros (1995). Some of these fractures in the ESG seismic section propagate into the top of the Purlawaugh Formation and into the Pilliga Sandstone."

Further, the research found areas where hydrochemical, isotopic, and microbiological data from shallow groundwater monitoring bores indicate input of methane from deep in the basin into the overlying aquifers (e.g., the GAB), and subsequent transport of this gas into the Namoi Alluvium via inter-aquifer leakage:

> "There is also a spatial trend with higher CH_4 concentrations in the south of the study area (labelled in Fig. 5). These areas coincide with the locations of important faults, igneous intrusions and permeable facies identified in the study area, as well as locations of wells drilled by ESG (Eastern Star Gas) for gas exploration."
>
> "Methane concentration data from ESG (2008–2011) show that there are extremely elevated concentrations of CH_4 in these deeper formations. Additionally, of the 25 samples collected from formations underlying the GAB, 21 had an isotopic signature indicating that the CH_4 had a microbial origin. The structures identified in Hamilton et al., 1988, Tadros (1995), and ESG (2004) present the most likely pathway for both the artesian discharge within the Pilliga Formation identified in Iverach et al. (2017b) and a potential migration pathway for CH_4 sourced from the underlying formations."

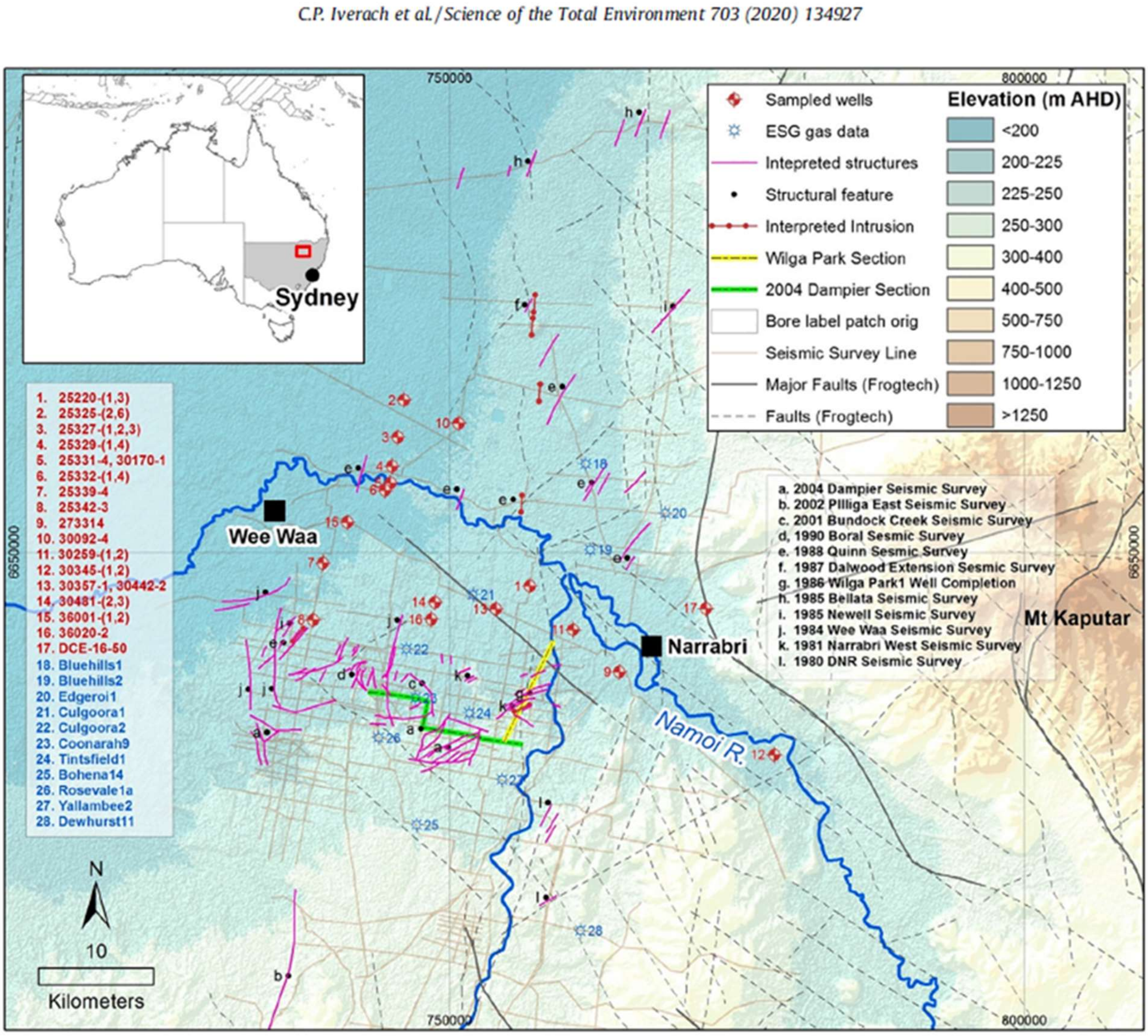

Figure 3 – Map of the study area examined in Iverach et al., 2020 showing location of geological structures interpreted from seismic data (and locations of survey sections) and monitoring bores sampled for hydrogeochemical indicators, including water and gas isotopes (reproduced from Iverach et al. 2020).

These findings are consistent with the same research team's earlier peer-reviewed study (Iverach et al., 2017) which indicated considerable inter-aquifer leakage of groundwater between the Great Artesian Basin and Namoi Alluvium occurring in areas north of the project area near the Namoi River, which has implications for assessment of water quantity impacts of the project (see section 3 below). Iverach et al., (2020) found that inter-aquifer leakage locally results in the transport of methane gas into the lower Namoi Alluvium:

> "Our results show that the resulting interconnection between hydrochemistry and microbial community composition affects the occurrence and oxidation of CH_4 within the alluvial aquifer, constraining the source of CH_4 in the groundwater to the geological formations beneath the alluvium."

These findings based on the geochemical and geological data are summarised in the figure below (reproduced from the published article). They contrast with assumptions made in the applicant's groundwater modelling and impact assessment, regarding the level of inter-aquifer connectivity, with respect to both gases and water:

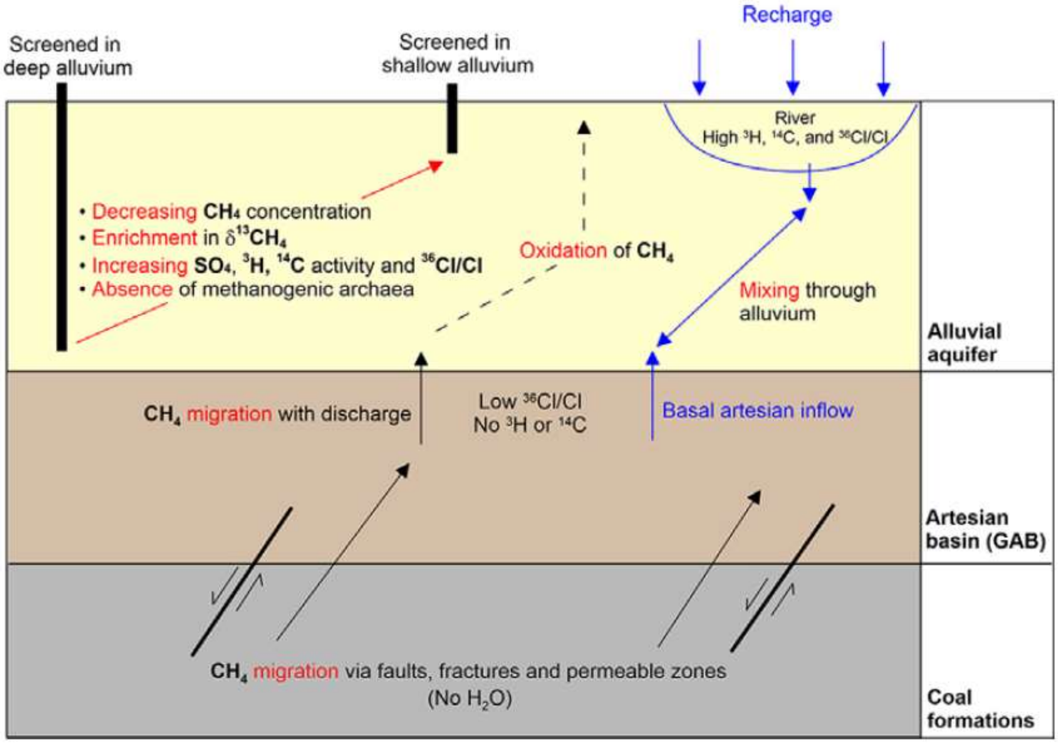

Figure 4 – Conceptual model of inter-aquifer connectivity, based on analysis of isotope tracers in gas and groundwater, and structural geology data from the region (reproduced from Iverach et al., 2020).

On this basis, the potential for cross-contamination between the coal seams targeted by the gas project and overlying aquifers appears to be greater than has been assumed. Due to the timing of the publication, the WEP were unfortunately unable to consider these findings. In its report, they noted key information gaps:

> "The number of wells currently available in Gunnedah sediments is limited and consequently in most areas, there is a high level of uncertainty attached to any extrapolations between wells. The cross sections provided in the NGP EIS are low resolution and not optimal for providing an indication of heterogeneity. This could be improved through high resolution seismic profiling or more drilling, or both"

The panel noted that faulting was not included in the groundwater modelling and only limited additional data were provided by Santos in response to their request (one interpreted seismic section). It thus appears that the full range of seismic and other geological data examined by Iverach et al. (2020), and interpretation of faulting patterns based on these data were not presented to or reviewed by the panel:

> "The NGP EIS does not provide any detailed cross sections or structure maps that might serve to clarify the fault pattern. Figure 4-11 in the EIS Appendix, does provide a map showing fault patterns, but at very small scale. Additionally, there are no seismic cross sections to illustrate the nature and magnitude of faults within the area of the NGP. The schematic of the hydrostratigraphy of the project area (Figure 6-12 of the NGP EIS) shows a simplistic 'layer cake' approach with no faulting indicated."

> "A number of submissions such as that of the North West Alliance, considered that there was insufficient information provided on faulting. The submission from the IESC recommended that further consideration of the scale and extent of faulting in the region was needed. It also recommended that there was a need to consider the likely impact on groundwater and on post-gas extraction, arising from the exclusion of faulting from the groundwater model."

Given the availability of data, it is hard to understand why further detail was not provided by the applicant in the EIS or in response to the IESC's advice or WEP's request. The WEP expressed concern regarding this issue and noted its importance for assessing possible cross-contamination, groundwater leakage and water quantity issues:

> "[the WEP] is concerned that the exclusion of faulting from the hydrogeological models, could have some impact in terms of predicting flow paths and that this needs further consideration"

> "The O'Kane Review was rightly concerned to ensure that "drilling is allowed only in areas where the geology and hydrogeology can be characterised adequately". Based on the information available to date, the WEP is not confident that the information provided in the NGP EIS on the structural setting of the NGP, meets the threshold of being "adequately characterised". The presence, or absence of faulting can have an impact not only on groundwater flow but also on the risk of gas migration and pollution of aquifers."

Given the significant amount of seismic data available, as well as studies of the geological structure of the region (e.g. Tadros et al., 1993; Gurba and Weber, 2001) the fact that such information was not extensively documented and discussed in the project EIS, or incorporated into the conceptual and numerical modelling (at the very least, in the form of an alternative hydrogeological conceptualisation) is concerning.

Nonetheless, DPIE concluded that the current groundwater model is 'fit for purpose'. The WEP recommended the applicant undertake more detailed assessments to examine the impact of excluding faulting from the groundwater model when determining gas well locations (Recommendation 6). However, their view is that in the meantime, the project could proceed without significant risks:

> "there is no evidence of any major geological structures that would adversely impact on CSG production but further work is required, as the project proceeds, to provide a more detailed assessment of the faulting at a resolution that meets modern petroleum industry standards"

With due respect to the panel's expertise, this is a highly risky approach (which is likely to be unsatisfactory to many stakeholders). The lack of detailed interrogation of relevant seismic and structural geology data mean that DPIE's, the WEP's judgements regarding inter-aquifer connectivity, and the risks of gas (and water) migration are based on incomplete information. The geological and geochemical data in Iverach et al., (2020) indicate there is considerable likelihood risks have been under-estimated in current modelling and impact assessment, which assumes all aquitards are continuous layers.

As discussed above, detailed understanding of inter-aquifer connectivity (with respect to gas transport) requires detailed field studies – such as surveys of the methane concentrations and carbon isotopic compositions throughout the different aquifer units, and their relationship to different features (such as geological structures). As the WEP pointed out, the EIS did not include baseline data showing distributions of methane concentrations in groundwater, and subsequent data in the updated water baseline report do not allow for assessment of the role of geological structures in gas transport, or associated risks.

This is a key issue with major implications for predictions of water quality (and quantity) risks of the Narrabri Gas Project. Leaving this unresolved at the time of an approval decision would mean current assessments of risk are based on an incomplete conceptual geological model and data sets. As such, decision-makers and the public are being asked to make judgements about the project's merits and risks without critical information incorporated into a robust assessment of the full potential impacts.

Implications for groundwater quality

Depressurising coal seams in the vicinity of geological structures that provide existing or potential pathways for gas transport would enhance the potential for further transport of hydrocarbon gases (predominantly methane) via these pathways (Fig. 5; Walker and Mallants, 2014). The wells sampled in Iverach et al.'s research are mostly to the north of the proposed gas development area (due to limited availability of suitable monitoring wells further to the south); however, areas where vertical transport of methane to shallow aquifers was identified are close to the northern boundary of the project area, and there is extensive evidence of geological structures – including faults - within the areas of proposed gas well development (Fig. 3). As such, there is direct relevance to the question of potential gas contamination of bores.

Negative consequences of methane contamination of groundwater can be significant, including:

- Water bores turning gassy, resulting in pump failure and in extreme cases, explosion risk (e.g. Bair and Tomastik, 2012). The Ground Water Protection Council's Stray Gas Forum (2012) recommended that dissolved methane concentrations above 7 mg/L – the typical lower solubility limit for methane - create a potential threat of fire or explosive risk. In one extreme case in Ohio, an explosion occurred in a house, and multiple water bores turned gassy in response to methane contamination related to unconventional gas development.

- Secondary biogeochemical changes in groundwater can result from the input of methane and other hydrocarbons into aquifers in which they are not naturally present, affecting groundwater quality. Cahill et al., (2017) showed that the introduction of methane into a shallow alluvial aquifer catalysed significant changes to groundwater quality, including mobilisation of trace metals. Van Stempvoort et al., (2005) documented biogeochemical changes occurring following gas contamination of groundwater from legacy oil and gas wells – including sulfate reduction (which can form harmful sulfides). These changes may result in enhanced risks to human health - where bores are utilized for drinking water - and/or the environment.

Based on the current available evidence, these risks are considerable in the Narrabri context. By the time drilling and gas extraction have commenced, enhanced connectivity related to geological structures - such as increased upward leakage of gas in response to decreasing pressures within the coal seams - will not be able to be feasibly reversed. While cross contamination with gases due to well integrity issues (see below) can in some cases be remediated through well repair works, stopping the migration of gas along geological structures is not practical. This means an 'adaptive' approach (post-approval), as is inherent in the recommended conditions of consent, leaves open a significant risk of major adverse outcomes which it may not be practical to mitigate.

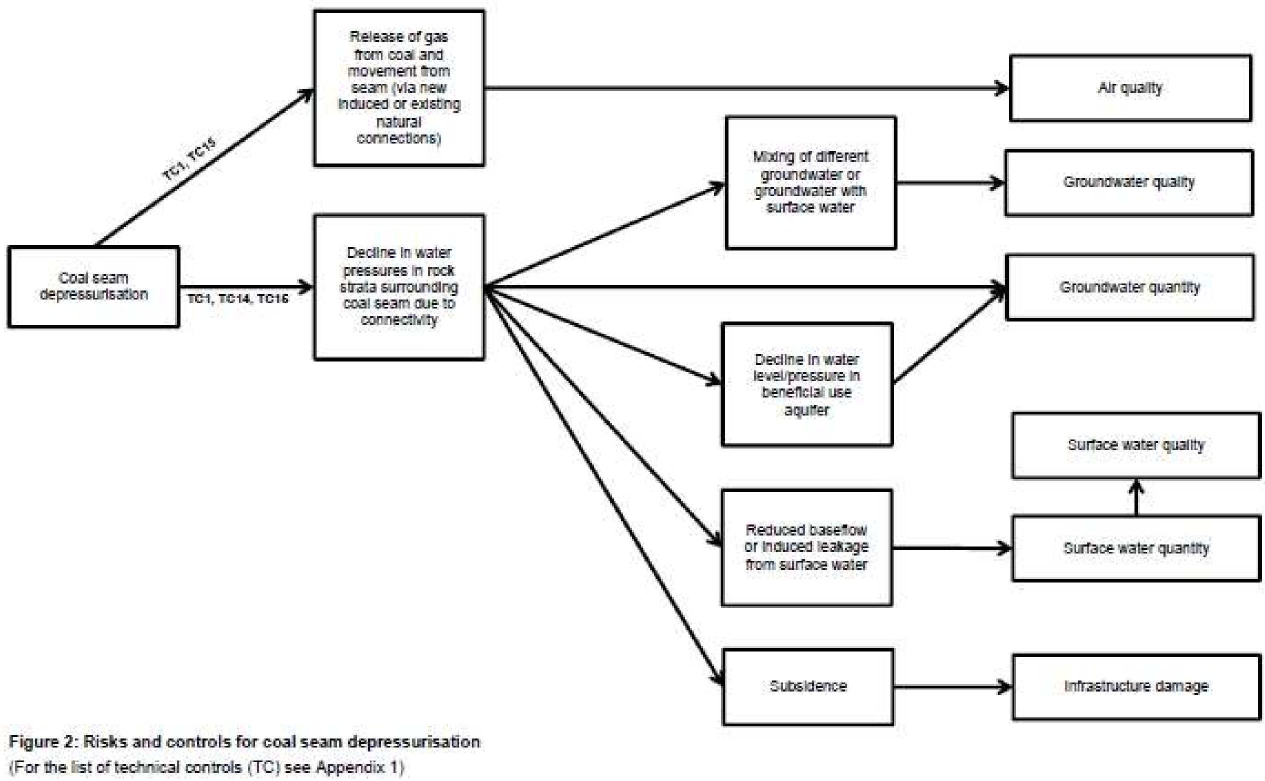

Figure 5 – Potential impacts associated with depressurisation of coal seams where pathways for inter-aquifer connectivity exist (Reproduced from O'Kane, 2014).

Well integrity
In addition to natural/geological pathways for fluid and gas cross-contamination, it is well documented that well integrity is a key consideration when assessing risks from both conventional and unconventional gas

development. This was considered by the WEP and DPIE and both believe well integrity issues can be managed through adherence to the CSG Well Integrity Code:

> "..the risks of the project can be reduced further by..ensuring that all gas wells are designed, drilled, operated, maintained and abandoned in strict accordance with the Well Integrity Code, which represents current international best practice and will be updated over time to incorporate any improvements in practice."

The WEP examined the issue; however, primarily focussed on the question of cross-contamination of saline fluids into shallow aquifers, which it believed (based on indicative calculations) to be unlikely. With respect to methane contamination, the panel observed:

> "The WEP considers pre CSG-activity baseline data will be helpful when assessing the levels of methane detected in groundwater at any time in the future. It considers the risk of methane leakage into groundwater is low provided the regulations are strictly adhered to"

Similar to the extensive data regarding typical incidence of wastewater spills and leaks associated with gas development (discussed in section 1), systematic reviews of oil and gas well integrity monitoring and compliance data indicate that in spite of best intentions and practices, problems are common throughout the lifecycle of oil and gas developments (Davies et al., 2014).

Davies et al. conducted a thorough review of available oil and gas well integrity data worldwide, incorporating hundreds of thousands of wells. Their analysis shows a wide range of rates of well barrier and/or integrity failure, ranging between 1.9% to 75% of the wells in a project/region (Fig. 6). Important factors include the age of wells, their depth, geology, construction materials, surrounding geochemical environment, and regulatory requirements around drilling, monitoring, and decommissioning. Again, based on these data it is optimistic to believe the Narrabri gas project will be different to other oil and gas projects, and not encounter some percentage of wells suffering barrier or integrity failures. A close analysis of shale gas wells in Pennsylvania by Considine et al. (2013) found:

> "Measurable concentrations of gas were present at the surface for most wells with casing or cementing violations."

The prospect of barrier or integrity failures leading to migration of methane into shallow groundwater (or the atmosphere) is therefore considerable and this will depend on a range of factors throughout the life of the gas project – including frequency of independent inspections and verification of well integrity (during and beyond the life of the gas project), level of corrosion encountered through the life of the wells, the extent to which the applicant and regulator have knowledge and oversight over legacy bores in the region, e.g. from prior coal and gas exploration, and the rigor of the groundwater monitoring program (details for which are as yet unclear).

Documented cases of methane contamination of groundwater due to unconventional gas development

Multiple high-profile cases of methane contamination of water wells are documented in the academic literature – particularly from the United States, where the unconventional gas industry is well established. Establishing causation for gas contamination of water wells is generally difficult, particularly as appropriate baseline data are often lacking in areas of gas development (e.g. Ground Water Protection Council, 2012). As such, these studies have required in-depth analysis of a range of forensic indicators – such as isotopes and noble gases in groundwater – to establish that the observed gas (or other contaminants) in water relate to unconventional gas activity, as opposed to natural or other causes. Jackson et al., (2013) and Darrah et al., (2014) found multiple instances of methane contamination of drinking water wells related to shale gas development, predominantly in two states (Pennsylvania and Texas), while Bair et al. (2010) and Bair and Tomastik (2012) documented a high profile instance in Ohio where contamination from a poorly cemented gas well led to a house explosion and contamination of multiple water wells in the region. Methane and benzene contamination of surface water from shale gas wells in Colorado was documented in COGCC (2004). These cases (and others) were reviewed in the U.S. EPA's assessment of the potential impacts of hydraulic fracturing for oil and gas on drinking water

(2016), which concluded that a combination of well integrity issues and natural pathways can lead to contamination of drinking water resources in areas of gas development:

> "These cases illustrate how construction issues, sustained casing pressure, and the presence of natural faults and fractures can work together to create pathways for fluids to migrate toward drinking water resources."

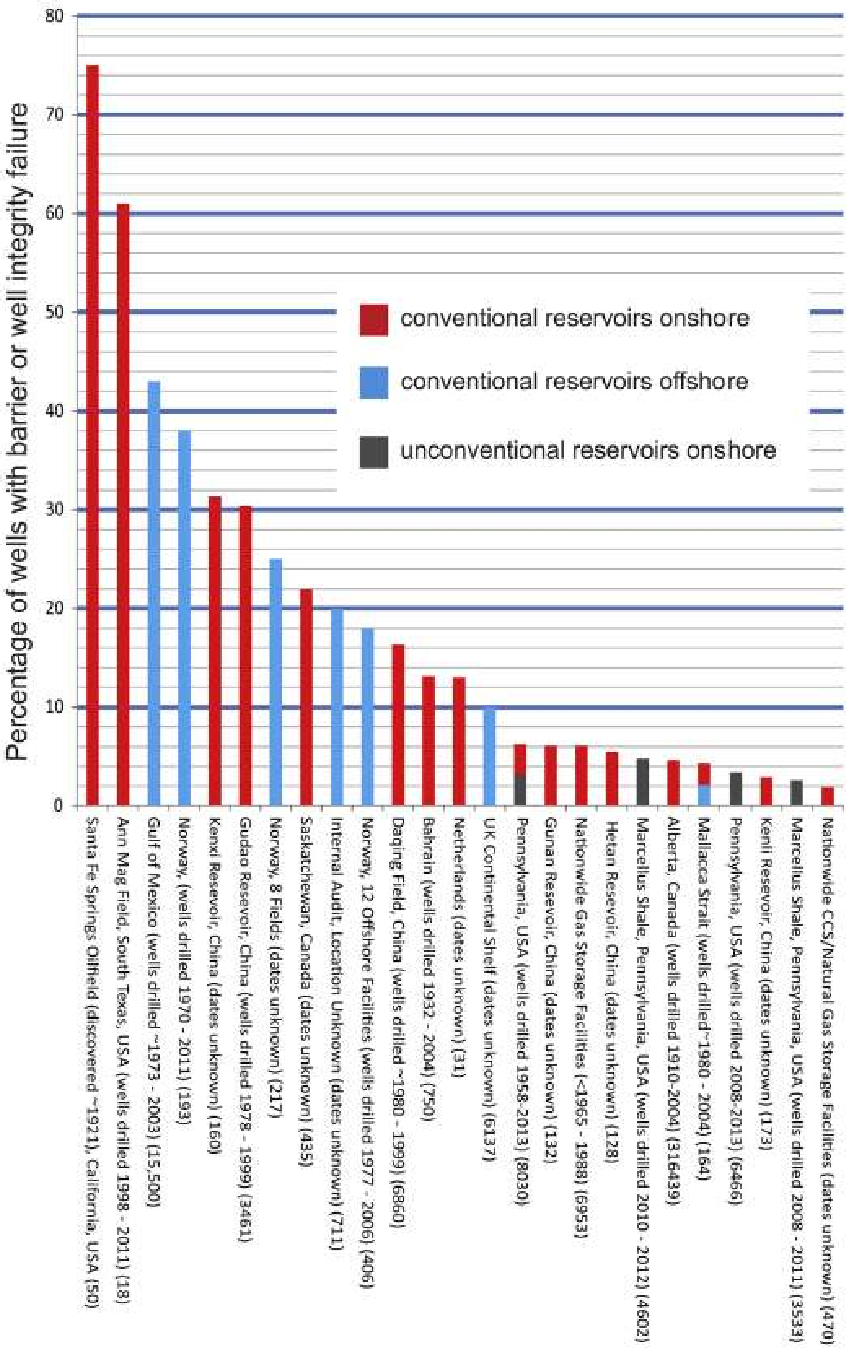

Figure 6 – Compilation of oil and gas well integrity data showing percentage of wells with barrier or well integrity failure (reproduced from Davies et al., 2014).

In the context of the data and findings of Iverach et al., 2020, and typical rates of well barrier/integrity issues (Davies et al., 2014), this finding is of high relevance to the Narrabri region, and the risks of cross-contamination of water bores are considerable.

3. Reduced groundwater levels and water availability in key aquifers

The potential for depressurisation of coal seams to impact groundwater levels and availability in key shallow aquifers – e.g., the Namoi Alluvium and Pilliga Sandstone – is another major potential risk - as highlighted in the IESC's advice. Concerns about this issue have been raised by many water users in the region. The two aquifers in question are extensively utilized for water supply; the Namoi Alluvium is one of the most utilized groundwater sources in Australia - with more than 100 GL of licensed extraction each year. Reductions in water allocations for irrigation have been negotiated and implemented over a period of many years to try to ensure the long-term sustainability of water usage in the system. There is also significant extraction within the GAB Southern Recharge groundwater source, and management rules and initiatives have similarly been developed following extensive consultations and technical work, to try to achieve sustainable extraction rates.

The current groundwater modelling (in the EIS), and additional modelling conducted in the wider Namoi Bioregion by the CSIRO (Sreekanth et al., 2017) predict that:

a) drawdown in these shallow aquifers is likely to be limited, and occur many years into the future, and

b) leakage rates will be relatively low in comparison to current usage rates in the aquifers in question.

This was noted by the DPIE and WEP, who compare modelled rates of leakage from the aquifers to overall current water usage rates:

> "For comparative purposes, the project would extract an average of 1.5 GL of saline water from the coal seams each year. The extraction of this water is predicted to result in the annual leakage of a maximum of 60 ML of water a year from the shallower aquifers (about 200-250 years from now), which is a low volume of water compared with the 165 GL of water currently being extracted from these aquifers by other water users each year"

As discussed further below, this type of comparison is in some respects misleading, as the area impacted by the gas project in the short to medium term would predominantly be localised (rather than spread across the whole Namoi system). It also ignores the significance of cumulative impacts in a system where allocations are at the maximum level considered to be sustainable (see further discussion below). Further, the peer-reviewed research by UNSW and ANSTO indicates that leakage rates may have been considerably under-estimated in the applicant's groundwater modelling.

The issue of inter-aquifer connectivity between the Gunnedah Basin and overlying GAB and Namoi Alluvium (discussed in section 2 above), is critical to determining whether the gas project is likely to result in significant drawdown and/or leakage, and thereby impact groundwater users and water budgets in these aquifers. As noted in DPIE's assessment report, coal seam gas extraction will result in drawdown of water levels within the targeted coal seams of hundreds of meters. This will cause the aquifer system to re-equilibrate, and as a result, pressures will re-distribute. As found in the EIS modelling, this will result in some proportion of water leaking from overlying units, causing accompanying drawdown. The extent of leakage and drawdown will depend on the level of hydraulic connectivity and properties of the intervening layers, as well as their thickness and extent.

The Great Artesian Basin sediments (including Pilliga Sandstone) occur above the target coal seams, with a sequence of intervening sedimentary and volcanic rocks in between. The Namoi Alluvium occurs above the GAB in the northern part of the project area – e.g., to the south of Wee Waa and west of Narrabri, as well as east of the project area (See Map 1 at the end of this report). These are both areas where the alluvium is extensively utilised for water supply. East of the project area, the Alluvium directly overlies Gunnedah Basin sediments – including locally, the Maules Creek Formation (the target for CSG extraction) – which outcrops near the Namoi River (as shown on Map 1). As such, intervening aquitards are likely to be considerably thinner or locally absent in this region. Based on the information provided in the groundwater impact assessment (e.g., Fig 6-12) it is unclear how consistent the representation of relevant unit thicknesses in the groundwater modelling is with geological mapping in the area (e.g. NSW government geological map sheets and studies by N.Z. Tadros in the 1990s), in key areas of interest – such as beneath the Namoi Alluvium.

The DPIE and WEP concluded that impacts to shallow aquifers are likely to be limited, as:

> "In the Namoi region there is a sequence of overlying aquifers and aquitards, so that while the pressure decline of the groundwater in the coal seam is predicted to be hundreds of metres, the pressure loss in the shallower productive zones is less than a few metres."

It is critical to note - as was pointed out by the WEP - that the modelling of drawdown and leakage from the shallow aquifers is currently based on the assumption that geological heterogeneity, including structures such as faults and intrusions, do not provide pathways for enhanced leakage of water between the shallow and deeper units in the system. No such structures were included in either the modelling conducted for the EIS or by the CSIRO (Sreekanth et al., 2017). Differences in hydraulic properties across the region, for example due to heterogeneity within the sedimentary sequence arising from different deposition characteristics, are also not represented. The modelling assumes that the aquitard layers between the coal seams shallow aquifers are continuous and will respond hydraulically in a uniform way across the region. The WEP noted – following the IESC's advice - that the effect of geological structures on inter-aquifer connectivity remains unclear (see discussion in section 2 above), and believe this should be addressed:

> "The WEP does not suggest that one model should be used for the NGP in preference to another. However, it is concerned that the exclusion of faulting from the hydrogeological models, could have some impact in terms of predicting flow paths and that this needs further consideration."

Nonetheless, they believed (on the evidence they reviewed) that significant connectivity from faulting remains unlikely:

> "Based on the evidence presented in the EIS, the WEP considers it unlikely that faulting constitutes a major risk to the NGP or is likely to have a major impact on groundwater flow"

However, as discussed above, Iverach et al., (2020) showed that the project area does contain major geological structures which cross between the deep coal seams targeted for CSG and the GAB, and that these impact the level connectivity between deep and shallow aquifers:

> "The Wilga Park Anticline located 5 km to the south of Narrabri runs north-south, through our study area (Supplementary Fig. 1). A north-south seismic section along the axis of the anticline maps faults that cut into the Pilliga Sandstone and a volcanic plug that extends from the regional basement and passes upwards through the Maules Creek Formation and Hoskissons coal seam into the base of the Pilliga sandstone. The faults and plug contact zones are potential pathways for groundwater and gas to migrate."

The geochemical and isotopic data collected in Iverach et al., (2020) and Iverach et al., (2017) indicate that:

a) Transport of methane gas between the deep Gunnedah Basin and overlying GAB occurs, and this is likely enhanced by the presence of geological structures (indicating a potential pathway for groundwater leakage as well)

b) The GAB locally provides substantial input of groundwater to the overlying Namoi Alluvium to the north of the Narrabri Gas project area, again most likely due to the presence of geological structures and heterogeneity that enhance upward leakage in certain areas (e.g. some wells in the alluvium show groundwater chemistry that essentially corresponds to GAB water characteristics).

As discussed above in section 2, these findings call into question the geological conceptualisation adopted in the project's numerical groundwater modelling as well as the accuracy of estimates of leakage induced by depressurisation of the coal seams. As such, the full range of potential drawdown and leakage impacts of the gas project is in all likelihood not presented in the applicant's assessment, in accordance with the stated objectives of the modelling (outlined in the EIS Groundwater Impact Assessment):

> "Identify and quantify potential groundwater loss or gain in each Water Sharing Plan zone due to intra- and inter-formational flows; and
>
> Identify those landholders who may potentially be impacted by coal seam gas activities and quantify the predicted impacts;"

The evidence of inter-aquifer connectivity documented in Iverach et al., (2017 & 2020) indicate considerable likelihood that the modelling has under-estimated leakage rates. Further issues which currently create significant uncertainties with respect to the modelling objectives (as detailed in the discussion of the modelling in the EIS) include:

- the lack of site-specific field data to inform values of hydraulic conductivity and specific storage in most geological layers in the system (in most cases, generic values have been assumed based on literature)
- uncertainty regarding the volumes of water that will be required to be dewatered from the coal seams to produce gas, and the associated drawdown this will cause in the coal seams across different areas,
- Lack of calibration data available to compare modelled and observed hydraulic head and/or flux levels, particularly in the deep parts of the basin.

Regarding the ability of the current model to meet its stated objectives, the IESC commented that:

> "The key risks of the project include impacts to landholder bores and GDEs utilising groundwater from the Namoi Alluvium, Pilliga Sandstone and the alluvium associated with Bohena Creek. These long-term risks are due to potential groundwater depressurisation propagating from target coal seams. **While the groundwater model has some degree of predictive capability in providing an early indication of the general location of impacts, it is not able to reliably indicate the magnitude of impact**." (emphasis added).

In this context, the DPIE's conclusion that the current groundwater modelling is 'fit for purpose' is highly questionable. This is critically important, as the determination of appropriate water allocation volumes - which the applicant will need to secure under the recommended consent conditions (see below) - is entirely dependent on the modelling (i.e., the fluxes of water from the shallow aquifers can't be directly measured and will be estimated using the model):

> "B28. Prior to the commencement of each Phase of the development, the Applicant must demonstrate that it has adequate water licences to account for the maximum predicted water take for the applicable Phase (including both short term and long term direct and indirect water take) to the satisfaction of the Planning Secretary.
>
> ***Note: The maximum predicted water take will be based on the most recent update of the ground water model.*"** (emphasis added).

The WEP highlighted uncertainties regarding the effect of the gas project on the groundwater levels and fluxes in the GAB and Namoi Alluvium aquifers:

> "The NGP EIS steady state groundwater model predicts a very small volumetric impact on flows between the GAB and the LNA. However, these flows are different to those published for the Lower Namoi Groundwater Source, which indicates some uncertainty in the NGP predictions."

The predictions referred to were developed based on a previous numerical model (Merrick, 2001), which indicated higher rates of inter-aquifer leakage between the two units than the applicant's model (between 7.9 and 10.1 GL/year) although the model domain areas are different making direct comparison difficult. The applicant's groundwater modelling concludes that 'induced groundwater flow at the base of the Namoi alluvium is predicted to be negligible'. However, the recent hydrochemical-isotopic data collected from the area by Iverach et al., 2017 (which is not referenced in the WEP's discussion of the issue or considered in the applicant's modelling) further indicate that the leakage volumes derived in the Merrick, 2001 may significantly underestimate the existing rates of leakage (and thus the level of connectivity) between the GAB into the Namoi Alluvium:

> "..we show that groundwater geochemistry can provide a more accurate evaluation of GAB contribution to the LNA. This is because the geochemical data can elucidate groundwater mixing processes and provide longer-term insights compared to the hydraulic head data. Multiple geochemical tracers reveal that boreholes in the north and west of the study area may be experiencing much more GAB inflow than has been inferred in catchment water balance models (Merrick, 2000; Kelly et al., 2007; CSIRO, 2007). This is most evident at sample 25342. It is not immediately apparent from the vertical heads in the hydrograph set at sample 25342 that there is any GAB inflow, yet based on the geochemical tracers this location is 100% GAB groundwater. The water balance model described in Merrick (2000) has GAB groundwater contributing 22% of all inflow into the LNA between Narrabri and Wee Waa (Fig. 1)." (Iverach et al., 2017)

The uncertainties identified by the WEP ultimately did not lead them to recommend further detailed work on this issue prior to approval and/or commencement of the project. With respect, this is likely to be highly unsatisfactory for concerned water users in the region, and not adequate for the purpose of assessing the overall sustainability of the water implications of the project. Proper analysis of this issue would require:

-More detailed study of inter-aquifer connectivity within the project area, using site-specific geophysical, geochemical and hydraulic testing of the relevant formations. This would need to utilize a network of nested monitoring bores across the relevant sequence of geological units, placed strategically in proximity to (and away from) geological structures and other key features that may impact inter-aquifer flows. The current seismic and other geological data are sufficient for the purposes of designing such a study; it is concerning that this has not been conducted to inform the groundwater modelling and impact assessment.

-A greater amount of in-depth analysis and data on typical water volumes required to produce CSG in the region and associated drawdown levels. While the modelling attempted to simulate water extraction from coal seams in accordance with historic production data from pilot CSG wells (e.g. Dewhurst and Bibblewindi), the reporting noted inconsistencies between water extraction rates and expected drawdowns based on gas reservoir modelling and the groundwater model, and made un-tested assumptions regarding the relationships between these.

-Incorporation of the findings of this work into groundwater modelling, capable of simulating the effect of geological structures and heterogeneity on inter-aquifer leakage rates, according to a robust range of possible hydraulic parameters and conceptual elements. Even based on current data, it should be possible to conduct alternative modelling simulations including indicative structures to simulate effects of these on leakage rates, giving preliminary indications of their potential effects on drawdown and leakage.

This is critical work on which impact assessment for the gas project must be based. Conducting this after approval and/or commencement of the project would mean that:

a) Analysis of the full possible range of impacts on groundwater quantity, based on a rigorous hydrogeological conceptualisation (including alternative hypotheses), is incomplete – affecting the validity of modelling predictions used to assess groundwater impacts in each Water Sharing Plan zone, and appropriate water licensing.

b) Unexpected impacts – e.g. greater than predicted propagation of drawdown or leakage in areas of gas well development – may occur. Once such impacts begin to manifest, it may be practically impossible to reverse them (as re-injection of water into the coal seams will not be feasible).

An 'adaptive management' regime is not well suited to the context, given the significant scale, depths and hydraulic inertia within the geological basins, which mean significant time-lags will characterise the response of the hydrogeological system to gas development (as is clear from the timings predicted for peak impacts to manifest in the current modelling). These lags will also make the timely identification of impact, and linking to specific processes difficult (or impossible), and will mean remedial action(s) taken to address impacts may require lengthy periods of time to take effect (e.g. Bredehoeft and Durbin, 2009), and may ultimately be ineffective. Pitfalls of an adaptive management approach in regional groundwater systems related to such time-lags are discussed in Thomann et al., (2020).

Impacts on groundwater users and proposed mitigation

As noted above, the IESC concluded the current groundwater modelling is not appropriate for quantifying rates of groundwater leakage from key aquifers arising due to the project. Nonetheless DPIE believes impacts on other water users will be minimal:

> "On the basis of the information available, the WEP considers the NGP EIS model to be fit for purpose and the predicted impacts minor. However, whilst the overall impact might be very minor, it is important to ensure that the impact on individual bores will not be significant or can be ameliorated to the satisfaction of the owner of the bore. This will need to be managed carefully by the Regulator and Santos."

Comparisons between total water volumes extracted in the project and total water usage in the Namoi sub-region (as cited by DPIE) are somewhat misleading (as discussed above), and the context of water usage in the area needs to be carefully considered. The Namoi catchment is one of the most water-stressed catchments in Australia, owing to high rates of irrigation usage and more recently – severe drought, and further cumulative impacts must be weighed in this context. The WEP examined the proposed groundwater extraction for the project in the context of groundwater usage and management rules in the system. As they pointed out, both the Upper and Lower Namoi Alluvial Groundwater sources are currently fully allocated. The WEP note that end-of-season groundwater levels are approaching the trigger level at which restrictions on access to groundwater may be applied by the regulator.

> "Added to this, the entitlement that Santos is seeking, or likely to seek for the Lower Namoi Groundwater Source, is large in comparison to the record of historic trading patterns provided by Aither (2017)."

Given that the work by Iverach et al., (2017) and Iverach et al., (2020) indicate a significant possibility of greater than predicted groundwater leakage from the alluvium, further questions should be asked about the feasibility of the gas project obtaining sufficient water, and more broadly the sustainability of its indirect water usage within the setting. If subsequent modelling, incorporating improved consideration of geological heterogeneity were to increase predicted rates of leakage from the shallow aquifers (as is likely), it is unclear how the applicant would secure the necessary additional water entitlements in a fully allocated system. Depending on the magnitude of leakage, obtaining such water may not be feasible. Again, leaving these uncertainties unresolved at the time of approval would be a considerable risk, and leave many water users in the region unclear about the project's water footprint and future implications. This is critical, as it is the modelling on which assessments of the indirect water usage resulting from the project will be based under the current recommended conditions of consent (see above).

In addition to water budget impacts of additional leakage, additional drawdown beyond what is currently predicted in the modelling (e.g. drawdowns of less than 0.5 m), particularly in regions where geological structures facilitate enhanced inter-aquifer leakage, is also a risk that is yet to be properly considered. Such drawdown may result in bore interference (e.g., reduced ability to pump water) or, in extreme cases, total loss of access to groundwater in some bores – particularly (in the short term) in relatively deep bores proximal to gas wells. Notably, sensitivity analysis in the EIS groundwater modelling showed that changing vertical hydraulic conductivity and specific storage values in aquitard layers (which are currently poorly constrained) can significantly increase the areas over which shallow aquifers experience drawdown. A further detailed study of inter-aquifer connectivity and its relationship to geological structures, and modelling of the drawdown and leakage implications for different water sources and current bores may yield quite different predictions, which may be considered unacceptable to water users and the regulator.

Impacts on GDEs

Possible impacts of the project on groundwater levels and flow also have the potential to affect the health of groundwater dependent ecosystems (GDEs). This issue was raised by the IESC, who pointed out that additional work was needed to properly characterise and assess risks:

> "Knowledge gaps, uncertainties and data limitations within the Environmental Impact Statement (EIS) have been identified by the IESC. In order to reduce associated uncertainties with these knowledge gaps, as soon as possible the proponent should consider:
> • providing a groundwater monitoring plan detailing a groundwater impact early warning monitoring system that includes management, mitigation and contingency measures.
> • identifying hydrogeological characteristics and source aquifers for Hardys and Eather Springs (identified as high priority GDEs by the NSW state government).
> • undertaking appropriate field assessment of further GDEs."
>
> Further:
>
> "Field sampling at each of these nominated Type 2 GDEs was inadequate to fully assess site specific potential impacts or to provide suitable baseline data for monitoring ecological responses due to altered groundwater regimes that may be caused by the project. Given that several of the nine Type 2 GDE sites were not sampled, the absence of important or threatened species has been inferred rather than verified from field assessment."
>
> "The identification of the source(s) of water to high priority GDEs (e.g. Hardys and Eather Springs) should include isotope and geochemical tracer studies. Field data on water level and/or flow to these spring GDEs should be obtained under baseline conditions along with estimated sensitivity to changes attributed to variable climatic conditions and/or CSG related impacts."
>
> "Riparian vegetation communities along Bohena Creek are stated to be GDEs. Potential impacts to this area should be represented and accounted for in the groundwater model or, preferably, in a separate smaller scale (daughter) model that enables time-variable localized impacts to be considered."
>
> And:
>
> "The proponent states that it is likely that shallow groundwater in the alluvium of Bohena Creek and Jacks Creek provides base flow during dry periods and is most likely a source of water to riparian vegetation and aquatic flora and fauna associated with pools in these creeks. However, no evidence is provided to support the subsequent claim that less than 0.5 metres drawdown in the shallow alluvium will result in no significant ecological impacts to low flows, the persistence of remnant pools, or groundwater levels adjacent to ephemeral creeks. In pools connected by subsurface flow along low-gradient stream beds (e.g. Bohena Creek and Jacks Creek), a drawdown of 0.2-0.5 metres may alter low flows and the persistence of pools connected by subsurface flow potentially impacting biota that rely on shallow refugial pools as drought refuges. To assess the likelihood and severity of these potential impacts, the proponent needs to undertake field analysis targeting locations identified by detailed hydrogeological and ecological conceptualisations that are likely to be inhabited by Type 2 GDEs."

Approximately three years after this advice, it appears (from the latest documentation) that these steps have not been taken. This means that a proper assessment of potential impacts of the project on GDEs – including the two high-value springs (marked on Map 1 at the end of this report), and development of appropriate monitoring and mitigation steps is incomplete. The applicant has argued against conducting the work recommended by the IESC on the following grounds:

> "Groundwater modelling indicates that there is an insignificant risk of impact to GDEs due to the large physical separation from the project water extraction, both vertically in the sub-surface and horizontally at the surface. This means there is a lack of connectivity between the target coal seams and aquifers supporting potential GDEs. As no impact is predicted, the Water Monitoring Plan does not propose to

> monitor at the GDE sites. Similarly, monitoring is not proposed at (potential) GDEs that are managed as farm dams for agricultural production."

On this topic, DPIE appear satisfied with the applicant's approach:

> "While the studies for the EIS did not identify any stygofauna in the project area, submitters noted That stygofauna have been identified in the Pilliga Sandstone and alluvial aquifers, and Santos acknowledges that further studies may identify stygofauna in the project area. Notwithstanding, Santos notes that the project is not expected to have any significant impacts on these groundwater units, and therefore is not expected to have any significant impact on stygofauna or other GDEs"

This rationale for neglecting to further investigate and monitor GDEs is highly questionable and contradicts statements that the applicant is taking a 'conservative' approach to assessment and management of groundwater impacts. As acknowledged by the applicant, the groundwater numerical modelling is currently only at confidence class 1 (under the Australian Groundwater Modelling Guidelines) and is therefore suitable for indicative impact prediction only (or, in the IESC's words, 'providing an early indication of the general location of impacts'). The new evidence demonstrating inter-aquifer connectivity discussed above means that additional drawdown in shallow aquifers within the project area is a significant possibility, and such drawdown may impact GDEs beyond the levels currently assumed.

The WEP noted that there are indications GDEs (including stygofauna) occur throughout the region and point out that these have not been surveyed in detail. However, they do not discuss the IESC's detailed advice regarding steps required to address potential impacts on GDEs above or analyse the extent to which the applicant has addressed these concerns.

To properly assess the likelihood of impacts on GDEs and detect these during the project, a comprehensive monitoring program identifying their key characteristics, source aquifer(s) and level of dependence on groundwater at particular levels and quality is required, along with sufficient baseline data to understand their relationship to flow rates and water levels in different aquifers. Waiting until after commencement of the gas project to conduct this work (or not doing it at all) will mean that unexpected effects on groundwater and GDEs will not be able to be adequately detected or characterised. The public and decision makers should have access to such information to make informed decisions regarding the likely levels of risk to GDEs (as with potential impacts to water users), prior to being asked to form an opinion about the project's merits and risks.

Gas extraction from the Hoskissons coal seam:

Extraction of a small proportion of the Narrabri project's total gas from the relatively shallow (~300 m depth) Hoskissons coal seam is proposed under the project plan. This coal seam is significantly closer to the GAB (and other shallow aquifers) than the deeper Maules Creek seams that will be predominantly targeted. This means that inter-aquifer leakage and drawdown related to water and gas extraction from this seam is likely to be greater than extraction from the deeper Maules Creek seams.

Specific information about the thickness and extent of the key intervening layers between the GAB and the Hoskissons seam – i.e., the Purlawaugh Formation, Digby and Napperby Formations - is not analysed in depth in the EIS or response to submissions. This may be important in consideration of groundwater impacts, in the context of the WEP's observation on this issue:

> "For example, in some areas, the Purlawaugh Formation, an aquitard, occurs at the base of the formation, but this is not the case everywhere, which in turn may have implications to connectivity"

The applicant has noted that the groundwater modelling includes a projected 5% of water extraction occurring from this seam, which is incorporated into the impact assessment. Detailed modelling and analysis of the specific drawdown and inter-aquifer leakage impacts associated with extraction from this coal seam (as distinct from the others) and field data relevant to assessing its potential risk in different zones has not been presented. The information regarding enhanced inter-aquifer connectivity discussed above is likely to have significant implications for this issue (as well as the wider impacts of water and gas extraction from the Maules Creek Formation).

It also remains unclear how the balance of gas extraction between the two formations will be determined. None of the recommended conditions of consent contain any specific requirements to limit extraction from this unit (for example, to prevent impacts on the overlying aquifers). If gas production from the Maules Creek coal seams is less than anticipated, and the applicant wishes to extract additional gas (and water) from the shallower Hoskissons seam – which is generally thicker and more regionally extensive – it is unclear whether additional approvals would be required and/or how the additional potential risk of leakage and drawdown would be estimated and accounted for in water licensing and other regulatory requirements.

4. Waste and salt management

The issue of how waste brine generated from the treatment of produced water will be managed is another issue of key concern for several submitters. If a safe disposal option for the waste cannot be identified, it will pose an ongoing potential land and groundwater contamination risk (by similar mechanisms to produced water, as discussed in section 1). The WEP believe the volumes are relatively small and the waste can be safely managed:

> "In relation to the production of wastes, the WEP noted that although average salt extraction rates would be high given the salinity levels of the produced water, total salt volumes (around 33,600 tonnes a year) would be relatively small compared to other coal seam gas projects in Australia and the Murray Darling Basin Authority's salt interception scheme, which generates about 500,000 tonnes of salt a year. The WEP found that the recovered salt would be comprised primarily of sodium carbonate and would be low in heavy metals and other undesirable components when compared to the EPA's Waste Classification guidelines. Consequently, the salt is likely to be classified as general solid waste which can routinely be disposed of at one of the 11 licenced waste facilities within 150 kilometres of the site. Nevertheless, the WEP noted that the salt may be suitable for beneficial reuse, and that Santos should be required to further investigate options for beneficial use prior to disposal. The Department has included this in the recommended conditions."

With respect, the comparison of salt volumes generated from the project with overall salt interception rates for the entire Murray Darling Basin – which incorporates fifteen different infrastructure projects, spaced over hundreds of kilometres – is quite misleading, as the salt will in this case be produced within a much smaller, concentrated geographic area. The WEP propose that the salt waste which is not re-used (e.g. for commercial purposes) may be disposed of at licensed landfill facilities within the region, however sufficient capacity to accommodate this volume of waste has not been demonstrated. The specific waste type (concentrated salt and/or brine) is also considerably different to normal municipal solid waste and would likely present significant additional management challenges – e.g. with respect to effective storage and leachate management – as the salt is highly soluble and would be a high risk of migration on contact with rain or groundwater.

The WEP pointed out some inconsistencies in the reporting of produced water chemistry in the EIS and water baseline report, which result in uncertainties regarding the total volumes of salt that will be produced, and its specific chemical composition. However mass balance calculations are used to estimate its composition for comparison to EPA waste classification guidelines for non-hazardous solid waste (p. 87 of the WEP report). These appear to show the waste would meet guideline values. One omission - as with the WEP's analysis of produced water chemistry - is arsenic, which was shown to be present within the produced water at an average concentration of 0.1 mg/L. The WEP also note that the concentrations of some compounds of interest in the produced water and their fate in the treatment process is not outlined in the EIS, and this may have implications for whether the material may need to be classed as hazardous waste.

I am not expert in the characterisation of salt material produced through distillation and other treatment processes, and as such cannot offer an opinion on the validity of calculations regarding the solid salt waste composition. Based on the data provided by the applicant in the water baseline report, the liquid brine produced as a result of reverse osmosis treatment at Leewood contains multiple constituents which exceed guidelines for water beneficial uses (drinking and irrigation) and as such any leakage or spills of this material (e.g. during storage or transportation) would create a significant risk of harm to any nearby soil, vegetation and shallow groundwater or surface water. Potential impacts of salt waste are similar in this regard to produced water – although, the salt is likely to be stored and managed over a smaller geographic footprint (e.g., confined within the wastewater treatment facility boundaries). Nonetheless the salt will be highly concentrated in certain chemical constituents, and the local environmental consequences of contamination incidents are likely to be severe. Compliance with the recommended condition to store all salt in weather-proof structures will mitigate risk to an extent; however, without more detailed information the full risk cannot be assessed.

Detailed plans regarding the plans for storage, transportation, and disposal of the tens of thousands of tons of salt/brine produced each year are yet to be outlined, resulting in residual risk in relation to this issue.

Monitoring, management, and mitigation of impacts

As discussed above and highlighted by the IESC, the current baseline data and monitoring network in the Narrabri gas project area contain significant deficiencies. The WEP pointed out problems in this regard:

> "..in the case of hydrogeological information, the current piezometer network is not sufficient either in plan position or vertically, to provide data for the groundwater flow models in order to predict future impacts of CSG activities particularly relating to water licensing considerations."

However:

> "Santos indicated that as the locations of the production wells are uncertain, a specific plan is not appropriate or possible at this stage. Rather, Santos proposes to negotiate a groundwater monitoring regime with the regulator after approval. This is a practical approach but provides little certainty to other stakeholders…The WEP considers that a generic monitoring plan that can be used to condition approval would be more appropriate"

DPIE believe this requirement can be addressed following a decision on approval of the project, through implementation of its recommended conditions of consent. These would (among other measures) require the proponent to develop a Groundwater Management Plan with additional baseline data to inform updated groundwater modelling and detailed plans for the location, timing, and frequency of groundwater level and quality monitoring, prior to construction of well pads and gas well drilling (e.g. Condition B38).

However, it is a reasonable expectation that the public see details of the proposed monitoring plan at the assessment phase (rather than after approval of the project), in order to better understand the degree to which possible local and regional-scale risks from the project are likely to be feasibly detected, mitigated and managed. Further baseline data and details of the proposed monitoring plan may be critical considerations in the public (and decision-maker's) evaluation of the project's risks and merits. Again, the current uncertainty and lack of data are likely to exacerbate concerns among stakeholders, as well as enhancing the risk of problems with future detection and attribution of groundwater-related impacts from the project.

A comprehensive monitoring network and baseline data are required not just to detect changes in groundwater condition rapidly and accurately (although this is one key objective). It is also required to generate sufficient understanding of the hydrogeological system – including key issues like inter-aquifer connectivity, recharge, flow paths and ground-surface water interaction - such that a full range of potential impacts can be assessed (using appropriate modelling and risk assessments) and future observed changes to groundwater quality, level and GDE health can be linked back to the relevant cause(s) and mechanism(s). The likelihood of this being achieved based on the current data, infrastructure and information is low.

The latter point is particularly important, because, under the recommended conditions of consent, the securing of water licences for the project – including for indirect take of water from the key shallow aquifers – will be based on the estimates of water usage derived from the groundwater model:

> **"Water Supply**
> B27. The Applicant must ensure that it has enough water for all stages of the development, and if necessary, adjust the scale of the development to match its available water supply.
>
> B28. Prior to the commencement of each Phase of the development, the Applicant must demonstrate that it has adequate water licences to account for the maximum predicted water take for the applicable Phase (including both short term and long term direct and indirect water take) to the satisfaction of the Planning Secretary.
>
> ***Note:*** *The maximum predicted water take will be based on the most recent update of the ground water model.*
>
> B29. The Applicant must report on water extracted by the development each year (direct and indirect) in the Annual Review, including water taken under each water licence.
>
> ***Note:*** *Under the Water Act 1912 and/or the Water Management Act 2000, the Applicant is required to obtain all necessary water licences for the development, including during rehabilitation and post closure."*

As discussed in section 3 (and the IESC advice), it is clear that the applicant's model is currently not able to accurately simulate indirect water usage in shallow aquifers resulting from the project, and has not incorporated sufficient field data to do so. To leave this unresolved at the time of project approval (as recommended by DPIE) presents significant risks, particularly given the context – i.e., full allocation of groundwater within the Namoi Alluvial water source, and the findings of Iverach et al., (2017 & 2020) which indicate a likelihood of significantly greater levels of leakage between aquifers. This leaves open the prospect that:

a) The modelling will not produce sufficiently accurate estimates of indirect water usage from key aquifers to determine the appropriate volumes of licensed usage required to be obtained and protect existing values.

b) Updating the modelling with improved field data (incorporating the issues discussed above) could result in significantly larger predictions of indirect water usage from the project than the public and decision maker are currently presented with.

c) Obtaining sufficient water licenses to account for more robust estimates of indirect groundwater usage – in a fully allocated system – may not be possible.

Alternatively, if the modelling continues to under-estimate indirect water usage via leakage from the overlying aquifer system (including GAB and Namoi Alluvium) following approval, then drawdown and water balance impacts of the project may be under-estimated in the licensing process, creating mis-match between the assumed and actual impact of the gas project, and further deterioration of the condition of an already stressed water resource.

This is critical to assessing the overall sustainability, risks, and merits of the project.

Further detailed information regarding the hydrogeological system and the proposed groundwater monitoring plan will also be required to implement the primary mechanism by which water users may be compensated for water-related impacts arising from the project under the recommended conditions:

> "B30. The Applicant must provide a compensatory water supply to any landowner of privately-owned land whose rightful water supply is adversely and directly impacted (other than an impact that is minor or negligible) as a result of the development, in consultation with DPIE Water, and to the satisfaction of the Planning Secretary.
>
> B31. The compensatory water supply measures must provide an alternative long-term supply of water that is equivalent, in quality and volume, to the loss attributable to the development. Equivalent water supply should be provided (at least on an interim basis) as soon as practicable after the loss is identified, unless otherwise agreed with the landowner.

B32. If the Applicant and the landowner cannot agree on whether the loss of water is to be attributed to the development or the measures to be implemented, or there is a dispute about the implementation of these measures, then either party may refer the matter to the Planning Secretary for resolution."

Due to the current lack of thorough understanding of the hydrogeological system (arising in part due to the lack of a comprehensive monitoring network, inadequate baseline data, and model uncertainty), there is potential for disputes to arise, which may not be able to be practically resolved under the above conditions.

In summary, DPIE's recommended conditions of consent will not in my view mitigate the considerable risks to groundwater outlined in this report, because:

a) Baseline data and current understanding of the hydrogeological system are insufficient to properly identify, characterise and mitigate the risks described in sections 1 to 4 of this report (above), and there are risks that are likely to have been considerably under-estimated,

b) The current monitoring infrastructure and groundwater modelling are inadequate to properly monitor and manage impacts, or develop robust estimates of the project's water-related impacts,

c) Enactment of appropriate measures to mitigate these groundwater impacts will depend on the ability to determine the extent to which these have been caused by the gas project (as opposed to other possible influences). Based on a) and b) above, this will be challenging if not impossible in some cases. This would likely lead to future conflict over the cause(s) of changes to water quality and availability, as well as the appropriate volumes water allocations required for the project.

d) In some cases, risks and impacts entailed in the gas project are essentially unavoidable consequences of unconventional gas development (e.g. spills, leaks and well integrity issues)

e) Hydrogeological systems are subject to significant time delays in response to activities which affect their water balance and flow regimes. In many instances, by the time an impact is first detected, remedial actions may come too late to effectively halt or reverse the impact (e.g. Thomann et al., 2020).

These are key issues which must be considered in the determination of an outcome for the project.

Key conclusions / responses to client's specific questions

The Environment Defenders Office's client – the North West Alliance – requested I address the following questions in my review of the relevant material on the Narrabri Gas Project's groundwater impacts:

a) In your opinion, have the concerns raised in your previous submission to the Project been adequately addressed, including through any recommended Conditions of Consent? If not, please provide information on any remaining issues of concern.

Answer: No. As highlighted above, concerns regarding groundwater contamination and quantity risks (e.g. drawdown and inter-aquifer leakage) have not been adequately addressed by the applicant or DPIE's review. My primary remaining concerns are the potential risk of produced water leaks and spills above a high-quality GAB aquifer, cross contamination of groundwater with hydrocarbons, and inter-aquifer leakage and drawdown of groundwater from important shallow aquifers. As discussed in the sections above, reliance on the recommended conditions of consent to address these issues post-approval would be problematic.

b) In your opinion, has the modelling for the Project adequately considered information obtained through the Dewhurst and Bibblewindi gas exploration projects?

Response: There is a substantial amount of geological data included in previous exploration and well completion reports by Eastern Star Gas – e.g., Dewhurst and Bibblewindi pilot projects – as well as other sources of data and literature (e.g. seismic surveys, the research by Iverach et al. and previous research studies by Tadros and others). These sources of information indicate geological structures occur throughout the sedimentary sequence in which gas development is proposed, and in some cases, enhance the potential for inter-aquifer connectivity, with important implications for both cross-contamination and leakage/drawdown impacts (see sections 2 and 3 above). Current groundwater modelling assumes that aquitard layers are continuous and will protect shallow aquifers from these impacts, i.e., geological structures and heterogeneity will not play a role. As such, the modelling is:

a) inadequate for estimation of the full range of possible impacts,

b) has considerable uncertainty, and

c) has likely underestimated key impacts.

c) In your opinion, has the Project assessment properly characterised the risks in relation to the potential to impact on any recharge areas for the Great Artesian Basin?

Response: No. An adequate study of groundwater recharge, flow paths and inter-aquifer connectivity – based on site specific field data - has not been conducted (as has been previously recommended to the applicant). Detailed plans for the monitoring network, spill and leak prevention, detection and response plans have not been provided. As such, the potential for the project to impact the quality (and quantity) of recharge entering the GAB aquifer in the project area – the Pilliga Sandstone - has not been properly characterised.

d) In your opinion, what, if any, is the risk of the Project triggering drawdown in the Namoi alluvium?

Response: Based on the recent research by Iverach et al., 2017 and Iverach et al., 2020, as well as other geological data, the risk of drawdown and inter-aquifer leakage in the Namoi alluvium is considerable, and likely to be greater than what has currently been modelled by the applicant. Current groundwater modelling assumes multiple layers between the coal seams and alluvium will respond uniformly as aquitards to depressurisation, preventing leakage. However, this is not well constrained or demonstrated using field data, and existing geochemical and geological data point to greater levels of connectivity than modelled. In the context of groundwater usage in the alluvium being at full allocation (under significant pressure from climate and irrigation water usage), this has significant implications for the sustainability of the project.

e) Provide any further observations or opinions which you consider to be relevant.

Response: See analysis of additional issues relating to groundwater in the preceding sections of the report.

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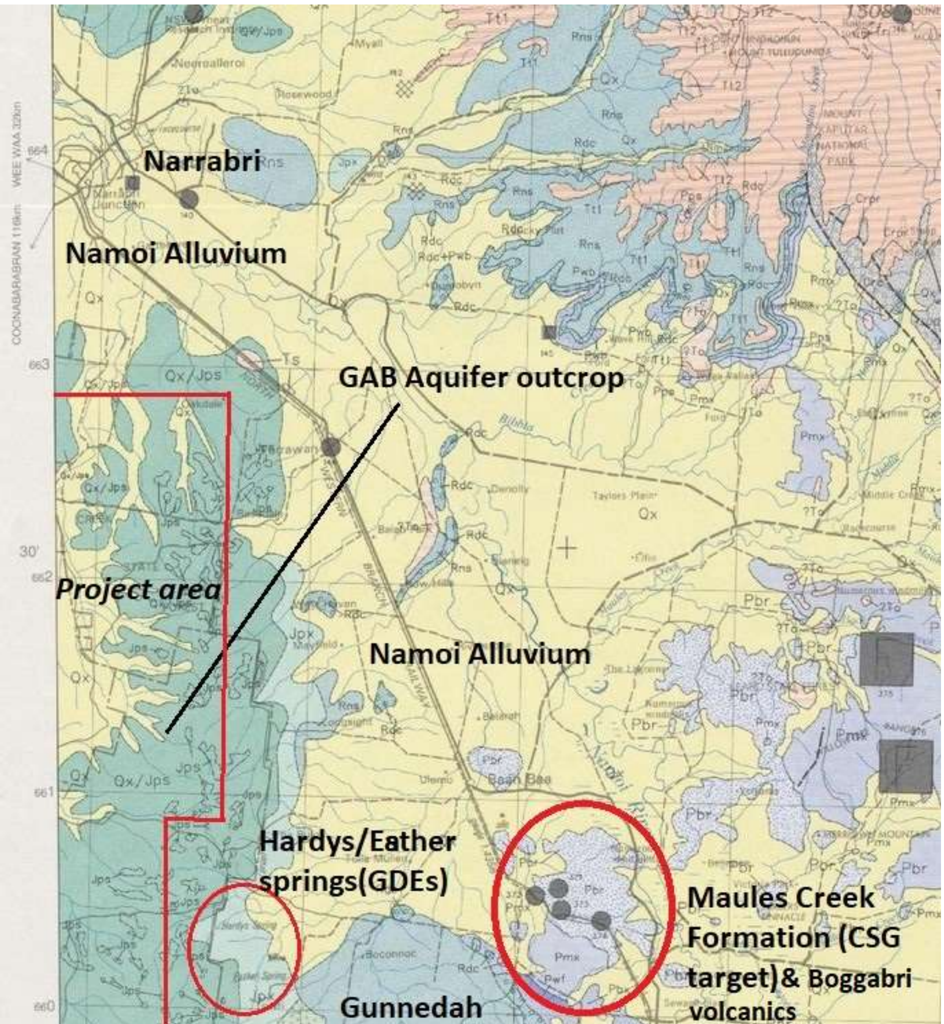
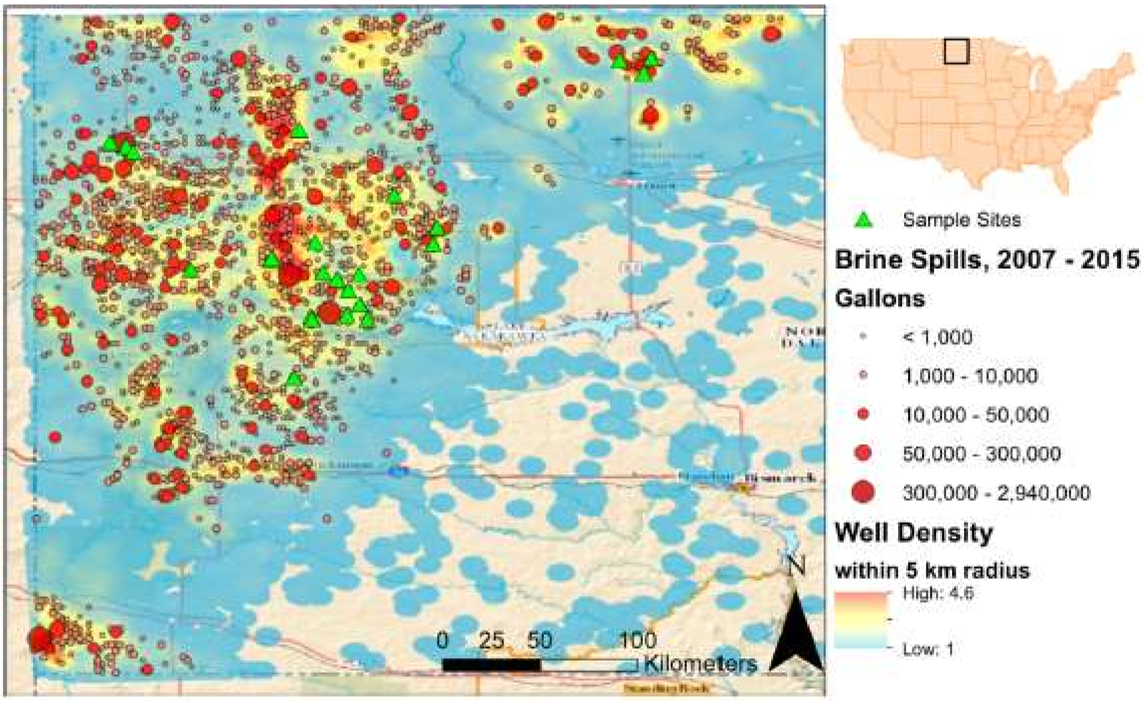


Map 1 – Geological map of the eastern part of the project area, with key hydrogeological features marked (modified from Manilla-Narrabri 1:250000 Metallogenic Map – NSW Government, 1992).



Map 2 – Incidence of Brine spills associated with unconventional oil development in North Dakota and correspondence with well density. Reproduced from Lauer et al., 2016.