Review of Santos final submission to IPC hearing: Narrabri Gas Project

Dr Matthew Currell
Associate Professor (Environmental Engineering)
RMIT University
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I was requested by EDO on behalf of North West Alliance to prepare this report in response to Santos' final submission to the IPC on the Narrabri Gas Project (on 10th of August 2020). My advice was requested particularly in relation to a peer reviewed research paper by Iverach et al. 2020, which was cited in submissions to the IPC (including my previous expert report), and which is discussed in some detail in Santos' submission. I was asked to assess the accuracy and validity of claims made by Santos about this research and its relevance to the assessment of groundwater impacts of the Narrabri Gas Project. I was also asked to respond more broadly to any new information raised in the submission with respect to the potential groundwater impacts of the Project, including the evidence from Richard Lancaster SC (included as Appendix B of the submission).

Summary of my opinion

Santos' submission argues that their groundwater impact assessment and modelling are robust and provide a conservative estimate of groundwater impacts of the project, and that evidence regarding groundwater presented to the IPC (including my expert report) does not call this into question. The submission argues that evidence regarding the potential connectivity between shallow and deep geological layers in the region (e.g., the study by Iverach et al., 2020) is either of limited relevance and/or contains weaknesses, and that the assumption that aquitards are continuous and will prevent impacts on shallow aquifers (on which Santos' groundwater impact assessment is based) is sound. Santos also down-play other concerns regarding groundwater impacts outlined in submissions to the IPC, such as evidence regarding the likelihood of groundwater contamination from wastewater spills and leaks, and the importance of the region as a recharge area for the Great Artesian Basin. Ultimately Santos (and DPIE) believe there is no risk of significant harm to groundwater from the project and any impacts can be managed under the proposed conditions.

My view is that:

- Santos have failed to incorporate key peer-reviewed scientific evidence relevant to the assessment of groundwater impacts of the project, e.g., the study by Iverach et al., (2020),
- Criticisms of Iverach et al., 2020 in Santos' submission are unfounded and not supported by appropriate peer-reviewed data and evidence,
- Because of the failure to incorporate the findings of this research, and other deficiencies in the groundwater impact assessment (e.g., outlined in my previous evidence), Santos' assessment is missing key elements, and is unlikely to capture the full range of potential groundwater impacts of the project (consistent with the IESC's advice on the project).
- In this sense, the groundwater impact assessment is not conservative (as has been argued by Santos and DPIE), and there is a risk of significant damage to the groundwater system and the users and ecosystems dependent on it, beyond what is currently predicted.
- The recommended conditions of consent and Adaptive Management approach proposed to manage groundwater impacts are not well suited to managing potential long-term impacts of the project on groundwater users and ecosystems (as was argued in my previous evidence), and some of these impacts may be irreversible.

Section 9.2.1: New studies said to prove faults connect target coal seams with shallow aquifers

In this section of their submission, Santos argue that the findings of Iverach et al. 2020 do not indicate additional risk of groundwater impacts associated with inter-aquifer connectivity, e.g., due to the existence of faulting, beyond what is presented in their EIS, arguing:

a) that the findings of Iverach et al., 2020 are of limited relevance to this topic and to assessing groundwater impacts of the Narrabri Gas Project, and;
b) there are possible weaknesses in the study's interpretations and its proposed model of methane transport, and alternative hypotheses that could explain the data.

Santos question some of the paper's research findings, suggest an error in the data presented (and conclusions drawn on its basis), and put forward alternative explanations/hypotheses to explain some of the data reported in the paper. The suggestion of alternative interpretations and hypotheses regarding transport of methane in the aquifer system is not problematic in itself; however, it is important to note that the suggested alternative hypotheses are not supported by substantive peer-reviewed data or modelling results. The claim in Santos' submission that data reported in Iverach et al., 2020 is erroneous also appears to be false - this was verified through review of publicly available data (see Appendix A of this report). Aspects of the proposed alternative hypotheses put forward by Santos are also problematic (see below).

Overall, the nature of the analysis presented in Santos' submission is somewhat concerning from the standpoint of proper peer review process. The Iverach et al. paper has been through the normal rigorous process of academic peer review prior to publication. Professor Peter Cook, of the Water Expert Panel (WEP), referred to the paper as a 'fine piece of science' in discussion between the IPC and the WEP on 28 July 2020. The journal in which the paper is published is a highly ranked outlet with an editorial board made up of international experts. In this context, counterclaims and/or suggestions of error made by Santos about the paper need to be carefully scrutinised, so as not to mislead the IPC. This is the context in which I was asked to provide the analysis below.

Significance of the issue

The relevance and rigor of the Iverach et al., 2020 study is an important topic, as the current modelling and groundwater impact assessment for the Narrabri Gas Project assume there is minimal connectivity between deep and shallow aquifers (with respect to both gas and groundwater flow), and that geological structures such as faults, fractures or volcanic intrusions do not enhance this connectivity. As Santos note in their submission, some submissions to the IPC argued that findings from Iverach et al. 2020 indicate that contrary to Santos' working model of the aquifer system, there is evidence of pathway(s) for gas (and potentially groundwater) to move between deep and shallow layers, and that this may be facilitated/enhanced by geological structures such as faulting.

This finding could have significant implications for the future risk of methane contamination of groundwater during coal seam gas development, as additional methane will be liberated from the coal seams during dewatering, and some of this may migrate along existing pathways, contaminating the overlying groundwater. It is also relevant to the assessment of groundwater drawdown and leakage impacts related to the Project. Flow of groundwater between layers may be enhanced by faulting and other structures, if these provide connectivity between the coal seams and shallow aquifers (Bense et al., 2013), and this is not currently captured in the groundwater impact assessment.

In my opinion, the Iverach et al., 2020 paper calls into question aspects of the current groundwater impact assessment, as well as the claim that impacts on groundwater have been assessed using 'conservative' assumptions. The Iverach et al. 2020 paper is one line of evidence which indicates that the full potential range of groundwater quality and quantity impacts is unlikely to have been fully captured in the current groundwater impact assessment, and greater levels of impact or harm to groundwater than are currently predicted may occur. A more detailed discussion of these issues, including analysis of the significance of the Iverach et al. 2020 paper to questions of methane contamination and inter-aquifer leakage, was included in my previous report[1].

Aims, scope and findings of the paper, and relevance to the Narrabri Gas Project

It is important to stress that an analysis of the impacts of the Narrabri Gas Project on groundwater was not the aim of Iverach et al., 2020, and a full examination of inter-aquifer connectivity in the region is beyond the scope of their research. The focus of the Iverach et al. 2020, paper was examining potential methane sources and transport pathways in the Narrabri region's aquifers, with particular focus on the Namoi Alluvium and Great Artesian Basin along the Namoi Valley (immediately north of the Narrabri Gas Project area). While the relevance of the research to gas migration and inter-aquifer leakage risks associated with the Narrabri Gas Project should therefore not be over-stated, the paper is relevant to consideration of these topics. It presents new data and findings regarding inter-aquifer connectivity within the geologic setting of the Narrabri Gas Project, in close proximity to the Project area.

The data and analysis in Iverach et al. 2020 appear to indicate that methane migration into the Great Artesian Basin (GAB) and Namoi Alluvium occurs from underlying geological units in the sedimentary sequence. It is hypothesised, based on the available data, that the most likely source of this gas is the coal seams of the Gunnedah Basin. One plausible explanation for this, which is explored to the extent possible (based on the available data), is that vertical gas transport is facilitated by the presence of geological structures (e.g. faults), which transmit gas from the Gunnedah Basin into the overlying GAB. Further inter-aquifer leakage of groundwater from the GAB into the Namoi Alluvium is proposed to explain the occurrence of methane in the alluvial groundwater. As discussed below, there is considerable evidence presented in the paper that is consistent with gas transport occurring via this mechanism (although all aspects of this cannot be proven beyond doubt). My reading of the geochemistry, isotope and microbiological data is that the author's hypothesised model is sound, and nothing in Santos' submission contradicts it.

If indeed the paper's main hypothesis proves correct and applies more widely within the region, this has implications for assessing the risk of gas migration in response to de-pressurisation of the coal seams, under the influence of coal seam gas extraction. Methane solubility is influenced by pressure (e.g. Ground Water Protection Council, 2012), and pressure in the coal seams would decline significantly during de-watering for coal seam gas (CSG), liberating methane into the free-gas phase. This may lead to enhanced movement of such liberated gas into shallower aquifers along existing pathways (such as geological structures), depending on groundwater and gas flow rates, pressures, and permeability (e.g., Cahill et al., 2017). If Santos has further data and analysis that is inconsistent with the findings and proposed mechanisms outlined in Iverach et al., 2020, then these should be made public and subjected to a similar process of peer review, to inform a comprehensive assessment of this risk.

Specific comments & analysis of claims made by Santos in its submission

Santos states (on p. 20 of the submission) that: "Multiple lines of evidence indicate most known faulting within the Project area is of small scale and does not extend into the overlying formations."

Comment: No detailed supporting data have been provided by Santos in the EIS, Response to Submissions or submissions to the IPC to support claims about the nature and extent of faulting in the region. The Iverach et al., 2020 study was not an in-depth analysis of the structural geology of the Narrabri Gas Project area (this was beyond the scope of the paper); however, their analysis of publicly available structural geology information, in support of their research aim (see above), is

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[1] Included in the NW Alliance's submission to the IPC

more detailed on this topic than the information or supporting data presented in the Narrabri Gas Project EIS. Elements of the analysis of structural data in Iverach et al. 2020 also appear to contradict Santos' claim about the extent of faulting, e.g.:

> "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."
>
> "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."

One of the cross sections Iverach et al. 2020 refer to is reproduced below, showing significant faulting and a volcanic intrusion crossing from the lower coal formations of the Gunnedah Basin into the Pilliga Sandstone in the vicinity of the Wilga Park 1 well (which is within the Narrabri Gas Project area):

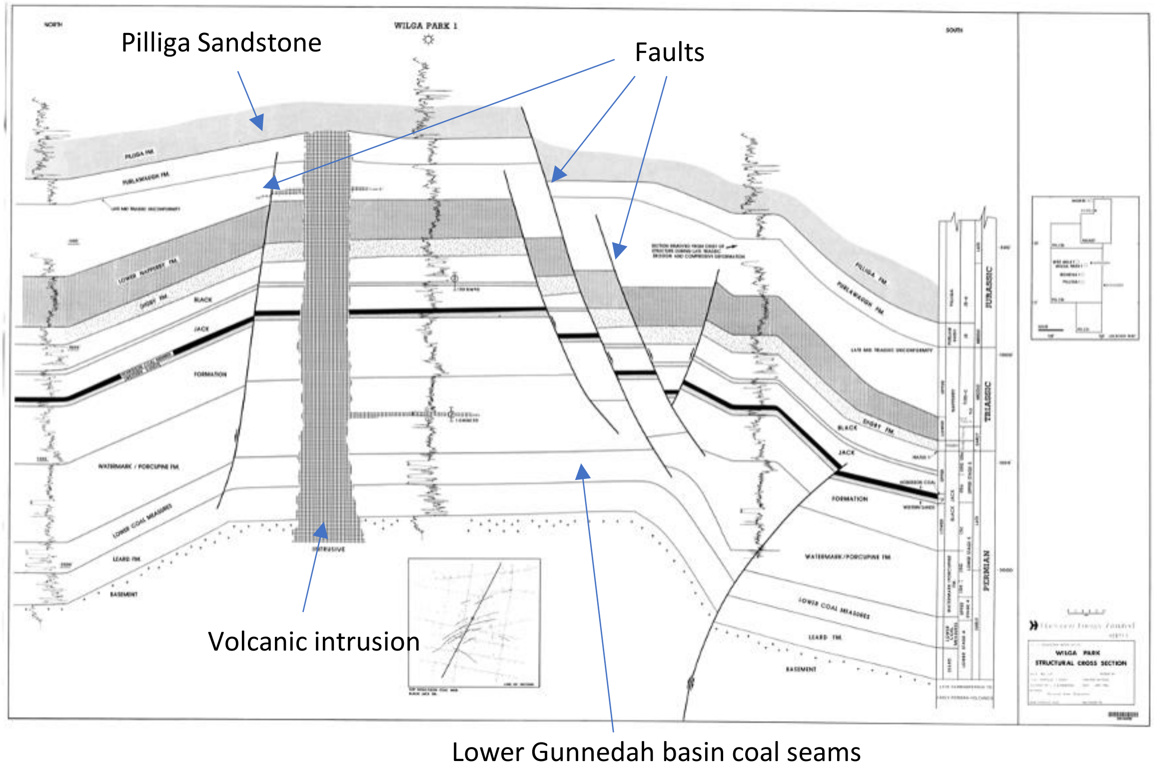

Fig 1 – Interpreted cross section from Wilga Park well completion report (Short & Harris, 1986), available at: https://search.geoscience.nsw.gov.au/report/R00017088. (Annotations added)

Given the potential significance of this finding for inter-aquifer connectivity, it is reasonable to expect Santos to present supporting data, and carry out more detailed research, specifically aiming to address the question of how geological structures impact methane transport and groundwater flow in the vicinity of faults in the Narrabri Gas Project area (consistent with the IESC's recommendation in 2017).

On p. 20, Santos states: "Potential impacts to groundwater flow due to faulting is highly unlikely at the local and regional scale. As referred to in the NGP EIS Response to Submissions (5-16, 6-90), Santos has undertaken an in-depth review of the existing data that supports its findings on fault characterisation."

Comment: This information (i.e., the full dataset underpinning the 'in-depth review') has not been made public or included in the EIS, Response to Submissions or evidence presented to the IPC (to my knowledge). No in-depth analysis showing that testing has been done to examine the effect of faulting on groundwater and/or gas transport in the system has been presented. Such analysis can be conducted using a range of techniques, as outlined in Bense et al., (2013):

1. Outcrop mapping and interpretations of geological structures based on drilling and/or geophysical data (e.g. mapping fault and fracture locations, extents, and orientations),
2. Fault rock mineralogy and geochemistry studies (e.g., to examine evidence of fluid flow, and estimate permeability of material in the fault zone),
3. Collection and analysis of geochemical and isotopic data in groundwater near faults, e.g. age-sensitive environmental tracers, and other isotope data relevant to the assessment of inter-aquifer connectivity across fault zones,
4. Detailed water level monitoring on either side of faults to examine potential barrier/conduit effects,
5. Hydraulic testing (e.g. pumping tests) to examine barrier/conduit behaviour across fault zones.

Santos' groundwater impact assessment does not include detailed studies of this kind and does not include analysis of the possible effect of faulting within the groundwater modelling simulations. This could have been conducted by testing alternative hydrogeological conceptualizations in the modelling, which included faulting with various barrier/conduit properties (e.g. Bense et al., 2013).

Faults may provide pathways for significant rates of fluid and gas flow (e.g., groundwater and/or methane) between aquifers, even where these are separated by aquitards (Bense et al., 2013). As such, observing the effect of faulting on drawdown and leakage predictions (incorporating field data of the type outlined above) would represent a truly conservative approach to groundwater impact assessment, helping to mitigate uncertainty as to how faulting and other structures may influence groundwater-related impacts of the project.

Such work, and the presentation of relevant supporting data, was recommended by the IESC in their advice in 2017:

> "Characterisation of fault displacements and provision of fault and geological/ stratigraphic analyses and data to support the geological conceptualisation are required. Further consideration is needed with respect to the scale and extent of faulting in the region and the likely impact on groundwater during and post CSG extraction to justify excluding faulting from the groundwater model." (IESC, 2017).

The WEP also expressed concerns about the effect of faulting not having been explored in the groundwater modelling and impact assessment. As such, there is residual risk of greater than anticipated impacts associated with interactions between groundwater, gas, and faulting (and/or other geological structures), that is not captured in the current groundwater impact assessment.

On p. 20 Santos states: "The inferred fault data presented by Iverach et al. (2020) is not new."

Comment: The authors of the study do not claim the data are new, and they have cited all data sources and information used to develop Figure 2 (their map of faults and other structures), which are verifiable and published (through the NSW Government's DIGS database). The absence of detailed presentation or analysis of these in the Narrabri Gas Project EIS is, in my opinion, a key weakness of the groundwater impact assessment.

On p.20 Santos states: “While the evidence presented in the Iverach et al. (2020) paper is consistent with very small volumes of gas migrating over geological time scales into the Namoi Alluvium, other reasonable and competing hypotheses for the presence of methane are equally probable.”

Comment: The timescale of gas migration under current or natural conditions (i.e., geological or otherwise) could not be determined in the Iverach et al. 2020 study – this is beyond the scope of the work. However, the timescales can to some degree be constrained by the age-sensitive environmental tracer data (e.g. radiocarbon, tritium and chlorine-36) and the isotopic data from the sampled gas in the paper (and in Iverach et al., 2017). The idea that migration of methane to the shallow aquifers occurs over geological timescales, such as ‘millions of years’, as suggested by Professor Cook in the recent meeting between the IPC and WEP is, in my opinion, unlikely. If gas transport was occurring at such slow rates, degradation of the methane (in the presence of oxygen) would be expected to effectively remove it within (or en route to) the shallow aquifers. Substantial modification of gas isotopic compositions would also be likely to occur if the migration were occurring on such long timescales. As discussed further below, there is strong similarity between the isotopic composition of the deep methane (i.e., from the Gunnedah Basin coal seams) and the methane in groundwater sampled from the GAB and alluvium, consistent with relatively rapid transport (albeit with evidence of minor isotopic modification due to oxidation). A conservative approach to groundwater impact assessment would not discount the possibility of rapid migration, as this is consistent with data reported in the paper.

One of the key findings of importance of the Iverach et al. 2020 study is that it strongly suggests the existence of a pathway for methane to reach shallow aquifers (including both the GAB and the Namoi Alluvium) from deeper parts of the basin, including in areas where geological structures are known to occur. For example, sample site 13 - a groundwater monitoring bore in the Great Artesian Basin at 106-109m depth - is located adjacent to a mapped fault (see Fig. 2 of Iverach et al., 2020), and the groundwater was found to contain a significant methane concentration (approximately 2700 ppm), with isotopic values of $\delta^{13}C_{CH4}$ = -67.6 ‰ and $\delta^{2}H_{CH4}$ = -249 ‰. This isotope signature is within the range of reported isotope signatures from coal seam gas exploration wells from the Project area, as reported by Eastern Star Gas (included as supplementary material in the paper). Median isotope values in methane from the gas wells identified in the paper are -66.5 ‰ and -248 ‰, almost identical to the isotope signature observed in the GAB groundwater at this site. This is consistent with vertical transport of gas from the Gunnedah Basin coal seams into the GAB. The lack of apparent isotopic modification of the methane is consistent with rapid transport as opposed to long-term migration (although a precise timeline cannot be deduced). The fact that a fault zone has been mapped immediately adjacent to this bore provides a logical pathway for the methane transport. These data are thus all consistent with the proposed model outlined above.

As discussed further below (in response to point 3 below), further migration of methane into the Namoi Alluvium, via inter-aquifer flow of groundwater from the GAB to the lower part of the aquifer, is also suggested by multiple lines of evidence, while alternative hypotheses are currently speculative and not supported by substantive datasets.

On this basis, there are strong indications of a pathway for gas transport in the system from deep to shallow levels, which is not currently captured within Santos’ existing conceptualisation of the hydrogeology, or risk assessment with respect to gas migration and inter-aquifer leakage. As noted above, depressurisation of coal seams will liberate additional gas, as methane becomes less soluble with declining pressure, and this has the potential to increase methane migration rates (as free gas) to shallower aquifers via any existing high permeability pathways. Hence, while current observed concentrations in shallow groundwater are relatively low, this may significantly increase if the coal seams are depressurised. A rigorous assessment of such potential pathways, using further data of the kind reported in Iverach et al. 2020 from within the Project area, would allow for comprehensive understanding of this issue, consistent with a conservative approach to groundwater impact assessment.

On p. 20-21 of the submission Santos provides a list of 'issues' with respect to the conclusions and relevance of Iverach et al. 2020:

"1. The area of study is located outside the Project area. The paper considers evidence of connectivity in shallow aquifers located to the north of the Project, not within the Project footprint. Drawdown impacts in the target coal seams due to the Project are not expected to extend more than 5 km beyond the tenement. The area of relatively high fault density studied will not be affected by Project activities. The Project area avoids high density fault areas and also areas of locally intrusive volcanic rock."

Comment: While it is true the bores sampled in Iverach et al., 2020 are to the north of the Narrabri Gas Project area, most of the bores are close to the northern Project boundary (e.g., some are within 5 km of this boundary), and the groundwater modelling and other lines of evidence indicate that impacts on groundwater will not be confined to entirely within the Project boundary (as is standard for any major de-watering activity). The deep geological layers from which gas is proposed to be extracted - as well as the intervening geological sequence below the Namoi Alluvium - continue from within the Narrabri Gas Project area into the study area where Iverach et al.'s sampling was conducted. Importantly, some of the geological information (e.g. interpreted seismic data) shown in Fig. 2 of the paper indicate faulting and other geological structures that do occur within the Narrabri Gas Project area. Hence, findings related to the potential for structures to enhance inter-aquifer connectivity are of relevance to the project area (noting that further groundwater sampling, isotope and microbiological analysis within this area would be required to confirm that the mechanisms of gas transport are analogous).

Even if CSG extraction wells avoid zones of extensive faulting (it is not clear how this would work in practice under the current proposed conditions of consent), the current groundwater modelling indicates depressurization of the coal seams will occur throughout (and beyond) the Project area. Thus, impacts associated with enhanced connectivity – such as migration of gas and/or groundwater along structures – may occur irrespective of the location of individual gas wells. Drilling wells away from specific fault zones would thus be unlikely to mitigate the associated risks of preferential gas or water flow along structures, particularly in the long term, as drawdown will spread throughout the coal seams and would be expected to reach many such structures.

p.20: "2. The paper's characterisation of faults relies on a qualitative assessment of lineaments and does not adequately describe or characterise faults with any rigour (e.g. fault length, depth, orientation, throw, stress regime, age, formation mechanism, etc.). Based on the information reported in the paper (e.g. a low-resolution and highly stylised geological cross section; uninterpreted seismic data and coarse-scale maps of 'inferred' fault locations), it is not clear whether an adequate and appropriate peer review could have been undertaken regarding geological structures. Cited references do not provide the detail nor supporting investigations to validate the inferences made in the paper regarding fault characterisation and their potential effect on hydrogeological connectivity."

Comment: While it may be true that the structural interpretations shown on Figure 2 of Iverach et al. 2020 have not been independently scrutinized in fine detail, and these may not be perfect representations of faulting in the study area, the paper has been through the standard, rigorous process of academic peer review, and its findings have been found to be robust. The research studies and data sources cited (which include journal articles, government reports and a PhD thesis by N.Z. Tadros) are all published and have also presumably been subject to peer review. Gas exploration well completion reports, which were also used in to support the interpretations, were produced by other gas companies (e.g. Eastern Star Gas), obtained from the NSW DIGS database and the data can be readily verified (e.g., Appendix A).

The issue again highlights the question as to why - if Santos has conducted an in-depth review of faulting - these data or analysis has not been made public, or presented and analysed in the project documentation. As noted earlier, the Iverach et al. 2020, study is not a detailed structural geology study; this was beyond the scope of their work.

p. 20-21: "3. The geochemistry data do not confirm that the low concentrations of dissolved methane observed in the Namoi Alluvium is sourced from the coal seams of the GOB [Gunnedah Oxley Basin]. There are other reasonable and competing hypotheses not presented by the paper that may explain how the observed methane has migrated from other sources"

Comment: Firstly, the significance of this issue in the context of the Narrabri Gas Project needs to be carefully considered. The comment relates to the transport of methane into the Namoi Alluvium – i.e., the shallowest aquifer in the region. As noted above, there is reasonably strong evidence that methane sourced from the Gunnedah Basin coal seams (GOB) transports into the Great Artesian Basin (GAB) aquifer, e.g., as indicated by their similar isotopic compositions. This is a significant pathway, with implications for potential methane contamination of the GAB under coal seam gas development, which is not incorporated into Santos' current conceptual hydrogeological model and impact assessment. Potential enhanced migration of methane into the GAB is an important issue in itself, as many water users utilise this source.

Secondly, with respect to the Namoi Alluvium, multiple lines of evidence in Iverach et al., 2020 – discussed below – are consistent with upward transport of methane from deeper in the basin into the aquifer, and the Gunnedah Basin coals are considered a likely source of this gas (although it is not possible to verify this beyond doubt). The proposed mechanism(s) of methane transport and analysis of the data have been accepted and considered robust by the peer-review process. The alternative explanation for occurrence of methane in groundwater in the Namoi Alluvium is that it is instead generated 'in situ' – e.g. by degradation of organic matter within the alluvium itself, rather than migrating from below[2]. This does not appear to be likely based on the evidence reported in the paper or any new information in Santos' submission.

Groundwater in the Namoi Alluvium is generally oxygenated, and most samples contain significant concentrations of sulfate (see Fig. 4, reproduced below). The generation of methane by degradation of organic matter typically does not occur in such conditions, as it requires a reducing (low oxygen) environment in which competing electron acceptors are absent (e.g. Zhang et al., 1998; Whiticar, 1999). Unless there is evidence of extensive organic matter deposits and reducing conditions within the Namoi Alluvium, the environment is unlikely to support extensive in-situ methanogenesis.

Due to the predominantly oxygenated environment in the GAB and Namoi Alluvium, it is likely any methane which reaches the aquifer from deeper levels would undergo some degree of degradation by oxidation. This would be expected to result in:

a) Decreasing methane concentrations moving from deep to shallow layers
b) Increasing carbon isotopic signatures in the methane (from more negative to less negative $\delta^{13}C_{CH4}$ values).

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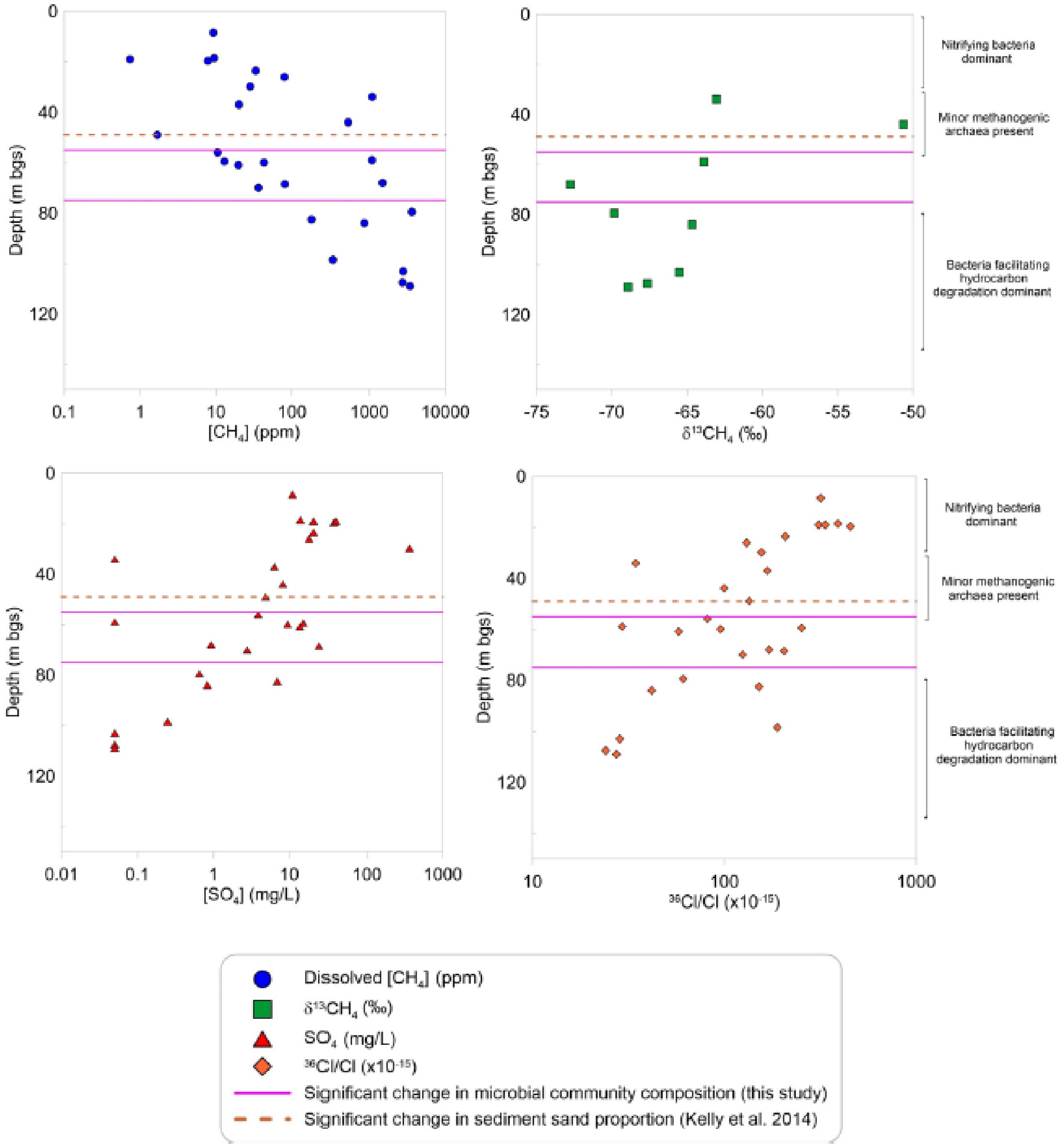
[2] There is a remote possibility methane in the shallow groundwater could be the result of an un-related contamination source (e.g. gas pipeline, landfill, wastewater plant), but there is also no evidence of this.

As shown in the plots below (reproduced from the article) both phenomena are indeed observed in the data:

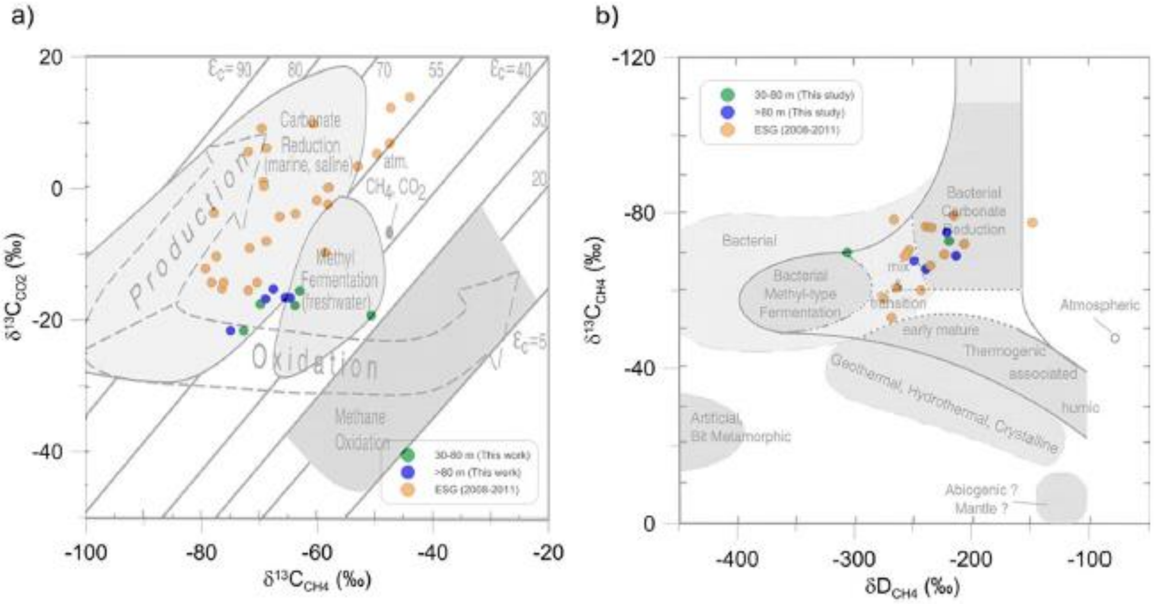
C.P. Iverach et al. / Science of the Total Environment 703 (2020) 134927



[**Figure 4** of Iverach et al., 2020 – reproduced from the published article]

Additionally, the microbiological community analysis, based on extracted DNA analysis presented in the paper (Fig. 3) show that methanotrophic bacteria are present in the water sampled from the Namoi Alluvium, suggesting oxidation of methane is indeed a significant process.

As shown in Fig. 7b of Iverach et al., 2020 (reproduced below), the isotopic values of the methane in groundwater from both the GAB and Lower Namoi Alluvium are similar to those in the gas wells sampled from the Gunnedah Basin – albeit with some evidence of modification due to oxidation. These data, along with the pattern of decreasing methane concentrations from deep to shallow wells, are consistent with input of methane to the shallow aquifers via upward transport of a common source of the gas (e.g., the Gunnedah Basin coal seams below, which contain high methane concentrations), as opposed to discreet, in-situ methanogenesis within each geological layer.



[**Figure 7**, of Iverach et al., 2020, reproduced from the published article. Orange points are gas isotope compositions from Gunnedah Basin gas exploration wells (from reports in the NSW DIGS database) while blue and green points are gas isotope compositions for methane extracted from GAB and Namoi Alluvial groundwater, respectively]. Note the considerable overlap, consistent with a common source.

The degree to which methane migrates as free phase gas (i.e., in bubble form, which can move along pressure and concentration gradients independent of groundwater flow - see Cahill et al., 2017) as opposed to dissolved phase flow in groundwater, is unclear and beyond the scope of the paper. However, this is an important consideration with respect to future methane contamination risk from coal seam gas development in the area. The potential for methane migration as free-phase flow (as opposed to dissolved) does not appear to have been extensively discussed or considered in the groundwater impact assessment, or the WEP's analysis.

p. 20 "a. No data are presented describing dissolved gas isotope signatures of the Pilliga Sandstone or any other aquifers or aquitards of the GAB which are alternative potential sources of methane in the region (e.g. Herzeg & Torgeson, 1991; DMR, 2002)."

Comment: As noted above, observed isotopic signatures of methane extracted from the GAB groundwater in a number of wells are reported in the paper, and these are similar to the reported isotopic signatures of methane from gas wells in the Gunnedah Basin, consistent with this being the source of the methane (although other sources within the basin can't be ruled out beyond doubt). Some level of 'in situ' production of methane within the GAB (as opposed to transport from the Gunnedah Basin), and upward transport of this gas into the Namoi Alluvium is one potential alternative hypothesis for the methane occurrence in the Namoi Alluvium; however, this is considered unlikely without further compelling evidence. Groundwater in the Pilliga Sandstone (the main GAB aquifer) in the region is generally oxygen rich, and it is thus unlikely significant in-situ methane production occurs within it (e.g. Schlesinger and Bernhardt, 2013).

p.20-21 "b. There is an absence of supporting groundwater chemistry data to support the conclusion that faults are responsible for upward migration of dissolved methane from the GOB. For example, given there is a natural upward hydraulic gradient (i.e. deeper units are under greater pressure than shallower units) changes in water quality such as increased chloride would be expected because the deeper aquifer units and coal seams of the GOB are far more saline than shallow aquifers."

Comment: As noted above, the gas may transport as a free-phase (i.e., not necessarily dissolved in groundwater), which would not result in increased salinity in overlying groundwater. Due to the high concentrations of methane in the Gunnedah Basin coal seams, this mechanism of transport is plausible. Methane solubility depends on pressure, and typically decreases from deep to shallow depths within a sedimentary sequence, meaning input from below may occur as a free gas phase (e.g. bubbles) as opposed to, or in addition to, transport via groundwater in the dissolved phase. Cahill et al., (2017) showed that free-phase migration of methane (independent of groundwater flux) was a significant process in a controlled methane injection experiment in a sedimentary aquifer with similar characteristics to the Namoi Alluvium in Canada. Due to the relatively high permeability of the GAB and Namoi Alluvium in the study area, localised input of saline water from inter-aquifer flow would also be likely to be relatively difficult to detect due to dilution with fresh groundwater flowing through these units.

As discussed above, an absence of detailed geological, geochemical and hydraulic gradient data from the region (including in the Narrabri Gas Project EIS) does mean that the precise pathway(s) of methane transport into shallow aquifers – e.g., free gas migration vs. dissolved phase transport in groundwater, fault/fracture or other pathway - cannot be verified without further in-depth research. However, evidence presented in the paper (described above) is consistent with upward transport of methane via preferential pathways such as faults, fractures, intrusions, or zones of heterogeneity (e.g. the sample adjacent to a fault in the GAB with similar gas isotope compositions to those reported in gas exploration wells). This should therefore be considered a plausible pathway when assessing risks of methane contamination of shallow groundwater.

"c. The paper estimates that the concentration of methane in underlying formations that would be required to explain the changes in methane isotopic signatures in the alluvial sediments is 4,062ppm. Iverach, et al. report (in Table 1b) methane concentrations in the formations underlying the GAB are 800,000ppm and explain that this supports a hypothesis of upward gas migration. However, this appears erroneous, as the data presented appears to have been transcribed incorrectly and actual concentrations are up to 800ppm (i.e. 800,000 µg/L). Hence the reported evidence shows a decrease in methane concentration at depth, not the increase in concentration as described."

The suggestion of an error in the methane concentration data reported in the paper is false. Review of the relevant data – which are publicly available through the NSW Government's DIGS database (attached below as Appendix A) - shows that the original numbers cited in Iverach et al. 2020 are correct – e.g., the methane concentration reported for the Culgoora-2 well was 789,900 ppm (not 800 ppm). As highlighted above (e.g., Fig. 4 of the paper), the data clearly show a decline in methane concentrations from deep to shallow levels in the system, consistent with upward transport of certain amounts of the methane from deep in the Gunnedah basin (where it occurs in high concentrations) into the shallow aquifers, with some loss due to oxidation and/or dilution as it moves upwards.

p.21 "d. Irrigators on the Namoi Alluvium extract groundwater from the underlying Pilliga Sandstone to irrigate crops. Excess water infiltrates and adds to the alluvium groundwater, hence introducing water with a "GAB signature" into the local alluvial groundwater. This complicates the process of quantitatively assessing the natural flux between the GAB and the alluvium in this region based on water chemistry alone."

Comment: The relevance of this to the topic of assessing the source of methane in the alluvium is questionable, and the mechanism not supported by any data. If indeed return flow of irrigation water from the GAB (containing methane) was a significant process contributing to the observed methane in the Namoi alluvial groundwater, then presumably higher concentrations of methane would be observed at shallow (as opposed to deep) levels, which is contradicted by Figure 4 (above). The majority of irrigation water in the area where sampling was conducted is sourced from the Namoi Alluvium and Namoi River (with significantly less extracted from the GAB) (e.g., see groundwater usage data reported in the NSW Water Register). This means that the contribution of GAB water in any recharge water via irrigation return flow is likely to be small and have minimal impact on geochemical signatures. Irrigation return flow is also highly unlikely to penetrate to depths of more than 50 meters and reach the lower Namoi Alluvium on the required timescale for this hypothesis to hold true.

If the comment relates to the question of inter-aquifer leakage between the GAB and Namoi Alluvium – as discussed in Iverach et al., 2017, then again, the mechanism proposed seems questionable. Groundwater extraction is significantly greater in the Namoi Alluvium than it is in the GAB, and the locations where GAB-type water are observed in the alluvium have upward hydraulic gradients (Iverach et al., 2017). The significance of this wider topic is beyond the scope of this report, but it was discussed in my earlier evidence submitted to the IPC.

"e. Gas isotopes presented for the alluvial groundwaters outline a distinct signature, separate from the Gunnedah Basin groundwaters (Figure 7a in Iverach, et al., 2020), with the former exhibiting a relatively heavier carbon signature in methane for a given carbon dioxide value, reflecting a methyl fermentation origin and not the methane oxidation origin proposed in the paper."

As noted above, Figure 7b of Iverach et al., 2020 (reproduced above) indicates strong similarity between the methane isotopic values of the Gunnedah Basin groundwater and the methane isotopic signatures in the sampled GAB and Namoi Alluvium groundwater. The difference in the carbon isotopes of CO_2 between the alluvial groundwater and gas exploration wells, which the comment refers to (as shown in Fig. 7a above) is explained in Iverach et al. 2020 as being likely associated with the oxidation of methane during transport into and/or within the Lower Namoi Alluvium from below:

> "The instances of 13C-enrichment in some shallow alluvial samples is most likely associated with oxidation. The general trend of 13C-enrichment in CH4 coupled with 13C-depletion in CO2 (Fig. 7a; Supplementary Table 1a), suggests that the CO2 is a product of the oxidation of CH4. Additionally, the isotopic values from the formations underlying the GAB (ESG, 2008–2011) show a 13C-depletion in CH4 with an enrichment in CO2 (Supplementary Table 1b). This suggests that the CH4 in the formations underlying the GAB has migrated upwards through the GAB and into the alluvium, and as it has migrated into groundwater with different biogeochemical conditions, the CH4 has been oxidised (thus becoming more 13C enriched), producing CO2 that is 13C-depleted. This explains why our alluvial samples have a more 13C-depleted d13C-CO2 signature than the ESG samples and provides further evidence that mixing between the two primary inputs to the LNA has a significant effect on CH4 distribution and oxidation in the alluvium.

This conclusion is consistent with the presence of methanotrophic bacteria in the alluvial groundwater (See Fig. 3 of the paper) as well as the other lines of evidence discussed above (e.g. presence of increasing sulfate concentrations and redox potential from deep to shallow levels). Modelling of the expected change in isotopic composition during oxidation was conducted and reported in the paper (Fig. 8), and this is consistent with the interpretation above.

The methane which occurs within the Gunnedah Basin coal seams may be derived from reduction of carbon dioxide and/or acetate fermentation – however this is largely irrelevant to the question of assessing whether the source of methane in the Lower Namoi Alluvium is from deeper layers of the sedimentary basin or from in-situ generation. Both mechanisms may apply in coal-rich sediments (e.g. Grundger et al., 2015). As discussed above, the hypothesis that methane is produced in-situ in the Namoi Alluvium (e.g. via methyl fermentation) cannot be conclusively ruled out, but currently there is no strong evidence to support it, or invalidate the proposed interpretations of methane transport that are outlined in the paper.

p. 21 "Based on the evidence presented, conclusions that can be drawn from the paper are:
1. There is likely connectivity between the Namoi Alluvium groundwaters and the underlying groundwaters of the Great Artesian Basin.
2. Biogenic methane in deeper layers of the alluvium likely undergoes oxidation as it rises to the surface.
3. Where there is elevated sulphate and/or oxygen, methanogenesis is inhibited.
4. Gas may be migrating over geological time scales from deep coal seams, but there is no evidence to support significant connectivity through faults."

The first three conclusions are indeed all supported by the paper and the data analysis; none of them contradict the hypothesis that there is a pathway for gas to transport from deep in the basin (e.g. from the Gunnedah Basin coals) to shallow aquifers – GAB and Namoi Alluvium, and that this transport may be facilitated by faults or other geological structures.

With respect to point 4, as discussed above, determining the timescale of migration was beyond the scope of the Iverach et al. 2020 study. However, as discussed above, rapid transport (i.e., on modern, as opposed to geological timescales) cannot be ruled out, and there are data which are more consistent with rapid transport – e.g., via faulting and/or other preferential pathways (e.g. at Site 13 which is adjacent to a mapped fault), as opposed to gradual migration on long timescales.

In summary:
a) The data and findings in Iverach et al., 2020 are rigorous and stand up to peer-review.
b) Counterclaims presented by Santos in their submission to the IPC are not supported by substantive evidence or data which contradict the proposed interpretations in the paper.
c) There are unresolved questions about the connectivity (with respect to gas and groundwater flow) between the coal seams of the Gunnedah Basin and overlying shallow aquifers, and the potential role geological structures play in enhancing connectivity between these layers.
d) Comprehensive analysis of these issues should have formed part of the Narrabri Gas Project's groundwater impact assessment and may have a significant impact on the level of risk of methane contamination and inter-aquifer leakage resulting from the proposed gas project.

As outlined above, the presence of one or more pathways for gas to transport from deep in the Gunnedah basin to the shallower aquifers has implications for the assessment of methane contamination risk from the Narrabri Gas Project. Depressurisation of the coal seams will reduce methane solubility in these, and this may liberate additional gas which may transport via existing pathways into shallow groundwater more rapidly than currently (potentially leading to contamination of bores). A conservative assessment of groundwater impacts would incorporate potential migration of gas according to the hypothesised pathway and mechanism(s) outlined in Iverach et al., 2020, until conclusive evidence to the contrary is established.

More broadly, if structures result in locally enhanced connectivity between aquifers, facilitating enhanced rates of inter-aquifer flow of groundwater, then risks associated with aquifer depressurisation may also be heightened relative to Santos' current groundwater impact assessment. Greater than predicted drawdown impacts than are currently captured in the modelling thus cannot be ruled out and would be captured in a conservative groundwater impact assessment.

Other groundwater-related issues in the Santos submission:

9.1 Water access licenses:

The estimates of groundwater leakage (flux) resulting from the Project, which are quoted for the different groundwater sources (in the table provided on p. 19) are based on the current EIS numerical modelling. The IESC made clear that this modelling is not fit to quantify the level of impact (including quantitative estimates of drawdown and leakage):

> "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." (IESC, 2017)

As such, these figures may not be accurate, and the reality may vary considerably. The capacity for Santos to secure additional volumes of water (for example, through water trading) beyond what is presented in the table if these model predictions in fact underestimate the true volumes is unclear.

The use of the groundwater model to estimate the volume of licenses required prior to gas development (as proposed under the recommended conditions of consent) is problematic, given the current level of uncertainty in the modelling (as discussed in my previous report). These volumes will be difficult to independently verify - direct measurement of leakage volumes is not feasible - and as such, the current proposed mechanism to account for the take of water, particularly in the shallow aquifers, entails significant risk.

One future scenario that should be considered plausible would be:

- The groundwater modelling under-estimates the rate of leakage from the GAB and/or Namoi Alluvium resulting from coal seam gas development (based on the current state of the modelling, this is a significant possibility),
- Future updates to the modelling do not reduce the level of uncertainty regarding these leakage volumes to the extent that they can be analysed with a high level of accuracy (this is also a significant possibility, see below),
- The modelling is used to set the volume(s) of licensed water allocation Santos are required to secure from these aquifers, but the volumes under-estimate the true take of water caused by the project
- The additional leakage caused by the gas project (not accounted for in the license volumes) causes additional drawdown of groundwater in the aquifers, which isn't accounted for in the overall licensing and setting of water allocations throughout these aquifers.
- The regulator may not attribute the observed drawdown impacts to the gas project or not have adequate information to establish the cause,
- Existing water users may in turn suffer from reduced access to groundwater, and they may not be compensated under 'make good' arrangements, as the link between the impact (drawdown) and the cause of the impact (coal seam gas project) is not properly established or accounted for in the modelling or licensing process.

Future modelling upgrades may or may not result in the estimates of leakage volumes reaching a level of confidence which is appropriate for accurate estimation of appropriate license volumes. The model is complex, and subject to a range of sources of uncertainty, some of which may not be able to be effectively reduced through proposed strategy of future transient calibration and updating of model parameter values accordingly. Residual uncertainty following calibration of complex numerical models is typical in complex systems of this kind (e.g. Doherty and Moore, 2019). As such, the current proposed conditions (involving future model updates) leave open residual risk in relation to drawdown and water balance impacts of the project.

9.2.2 Impacts to water bores of the Gunnedah Oxley basin

The statements about extent of impact on bores within the Gunedah Oxley Basin (GOB) are again based on the assumption that the extent of drawdown in this layer is accurately represented by the current groundwater modelling, which is questionable (see above). If (for example) hydraulic conductivity has been under-estimated in this unit, drawdown impacts may extend further than currently predicted. The current values of hydraulic parameters in the modelling are not based on a substantial body of field-based testing. Relying on the monitoring program to detect impacts into the future is also potentially problematic, especially as peak impacts may be many years into the future (potentially after CSG extraction in the project area has finished).

9.2.3 Assertions that aquitards in the groundwater model were not adequately characterised or conceptualised

While the data and analysis reported by Turnadge et al., (2018) regarding vertical hydraulic conductivity of aquitards in the Gunnedah Basin are robust, the conclusion that this work indicates that Santos' existing modelling conservatively captures the full potential behavior of aquitards in the system is not (in my view) fully supported by the evidence. The IESC noted that the work by Turnadge et al. indicated potential differences in the behaviour of aquitards compared with what is included in Santos' modelling; in some cases, indicating more rapid an extensive drawdown in response to depressurisation:

> "The groundwater model adopted hydraulic conductivity values for aquitards at the low end of the range of previous modelling studies. However, Turnadge et al. (in press; 2017) report a method which up-scales aquitard core permeability tests using wireline logs of bores across the project area and also accounts for spatial variability. Turnadge et al. (2017) report shorter timeframes for the propagation of depressurisation and greater medians of maximum drawdowns in localised areas using this method. Consideration should be given to these and similar methods, including the collection of site-specific data, in assessing the effects of changing permeability and storativity, particularly in areas with overlying sensitive receptors." (IESC, 2017).

It is also important to stress that the findings of Turnadge et al. are predominantly derived using point-based measurements of permeability (based on laboratory testing of core-holes from the study area), with up-scaling carried out using interpolation of these measurements using well geophysical data (wireline logs). They do not represent full site-specific characterisation of the geological strata of the project area, or bulk vertical hydraulic conductivity of the aquitards under the influence of regionally extensive drawdown (noting that such behavior is difficult to characterize at both local and regional scales).

Santos compare the median values of vertical hydraulic conductivity estimated by Turnage et al. in each aquitard unit to the values selected in their groundwater modelling, and contend that these are similar (or slightly lower), providing justification for the values used in the modelling and supporting the argument that drawdown predictions are conservative. This appears to be not entirely consistent with the IESC's comment above (although I am unable to review whether or not there is a substantial difference in the version of the Turnadge work seen by the IESC and the published version).

Santos' conclusion also over-simplifies the findings of the work and relevance to the assessment of the Narrabri Gas Project's drawdown impacts. Turnadge et al. indicated that significant heterogeneity occurs within the aquitards – particularly the Watermark Formation, which returned permeability estimates from core samples that varied by six orders of magnitude (Fig. 8 of Turnadge et al., 2018). This level of potential variation in vertical hydraulic conductivity is currently not reflected in the groundwater modelling or uncertainty analysis, which utilised single, fixed values for the aquitards (with modification by one order of magnitude during sensitivity analysis).

There are also two important limitations when considering upscaling the laboratory-based permeability measurements and assuming that these are representative of wider aquitard properties and behaviour in the region (which are acknowledged in Turnadge et al. 2018):

1. The core-holes collected in the study do not provide sufficient spatial coverage to assess the full range of thicknesses, heterogeneity and continuity of aquitards in the Project area (particularly in the vicinity of fault zones or intrusions, where aquitards may thin and/or be truncated). The authors are careful to acknowledge this, and explain that the presence of geological structures or other zones of local scale weakness that were not sampled in the coreholes could create pathways that essentially bypass the estimated bulk permeability values derived from their methodology:

> "Our analysis of seal properties, however, is limited in being based largely on the core-scale properties of sealing sequences. The ultimate goal for any assessment of risk levels to seals is the definition of the three dimensional (3-D) architecture of the seal combined with a full description of the sealing properties in 3-D, in the context of past and present-day stress regimes. This includes a description of heterogeneities on any observable scale. The most vulnerable parts of a seal are, by definition, those that can act as fluid-migration pathways, i.e., the most permeable connected routes with the lowest capillary threshold pressures. A major challenge is to identify and predict these routes using a combination of geophysical (including 3-D seismic interpretation), petrophysical, and geological data." (Turnage et al., 2018)

They go on to explain that faults and intrusions (both of which are mapped within the Project area, as discussed in the first section of this report) are two common structural features which may result in preferential leakage across otherwise relatively uniform, low-permeability aquitards, enhancing rates of leakage and drawdown (potentially, by considerable amounts).

2. Corehole-based assessments of vertical hydraulic conductivity may not capture the behaviour of aquitards at the regional scale under conditions of stress (e.g. during significant drawdown of underlying layers). Schulze-Markuch et al., (1999) and others have shown that hydraulic conductivity is highly scale-dependent and point-based measurements often under-estimate regional-scale permeability of aquifers and aquitards, by orders of magnitude. While a range of models have been used in Turnadge et al., 2018 to assist in upscaling the point-based measurements, the issue of scale-dependence may be significant and a full assessment of vertical conductivity would utilise independent hydraulic conductivity estimation methods – such as pumping tests – to cross compare values derived from the field and laboratory.

As discussed in the first section of this report, there is evidence that faulting and other geological structures occur within specific regions of the Project area. It is well known that such zones and other types of heterogeneity can enhance vertical hydraulic conductivity (Bense et al., 2013). The fault zones in the study area have not been sampled or analysed in detail to determine their effect on vertical hydraulic conductivity or inter-aquifer connectivity, which may be a significant influence on inter-aquifer flow, and be a significant control on the system's response to coal seam gas development. Bianchi et al., (2011) and many others have shown that a high proportion of the flow between different parts of an aquifer system can occur within small zones of high permeability, which allow preferential flow of water at significantly greater rates than is typical elsewhere.

The current proposed mitigation approach for this issue, of avoiding drilling coal seam gas wells near highly faulted zones (e.g. the area of intensive faulting identified in the north of the study area, noted in Santos' submission) will be unlikely to mitigate preferential flow along such zones in the long term, as drawdown in the coal seams will ultimately be regional (irrespective of individual gas well locations) and extend to within such zones.

9.2.4 The timing of updates to the groundwater model

As discussed above (and in my previous report), there are clear deficiencies in the current groundwater modelling and impact predictions, and lines of evidence which indicate the potential for groundwater impacts beyond those which are currently predicted and presented in the groundwater impact assessment.

Waiting until after approval of the Project to further update the modelling in light of these deficiencies would mean that a full, robust range of potential groundwater impacts, considering plausible alternative hypotheses regarding inter-aquifer connectivity and a wide range of potential hydraulic parameters, would not be made clear to the public and decision makers prior to a Project determination. This would run contrary to a precautionary approach. Proceeding with the Project under current assumptions about the groundwater system's behaviour and its response to gas extraction would risk significant potential harm to groundwater (beyond what is currently predicted) and its related uses and values.

As outlined in my first expert report, the significant time-lags involved in groundwater system behaviour at the scales relevant to the Project (e.g. Cook et al., 2003; Rousseau-Gueutin et al., 2013) mean that an adaptive management approach (as proposed under the recommended conditions of consent) has significant associated risks and may not mitigate long-term damage to groundwater users and ecosystems. Currently, there is no guarantee that future updates to the modelling will result in adequate reduction of uncertainty in order to effectively mitigate potential impacts of the project that are beyond current predictions (see further discussion in relation to Appendix B below).

9.2.6 Uncertainty analysis

It is true that some level of uncertainty analysis has been conducted by Santos and by the CSIRO, which has allowed a degree of assessment of potential variability of groundwater drawdown and leakage impacts. However, importantly, at no stage has the issue of conceptual uncertainty – e.g. related to the geological set-up and structure of the model's layers – been assessed. As highlighted above, there is significant evidence (e.g. the field data collected by Iverach et al., 2020) which suggests geological structures play a role in controlling the connectivity between aquifers, which has at no stage been considered in the modelling by Santos (or the CSIRO). A robust uncertainty analysis would assess how such conceptual elements may alter predictions of drawdown and leakage as a result of the project, incorporating a significantly greater amount of field data (as has been recommended by the IESC, see further discussion below).

9.2.7 Leakage from the Namoi Alluvium

This issue was discussed in my previous expert report and is covered above. It is my opinion that current estimates of leakage from the alluvium are highly uncertain and it is plausible that such leakage has been underestimated to a significant degree, based on the current available information.

9.2.8 Risk to aquifers from loss of containment (contamination)

This issue was also discussed in my previous expert report. The use of spills/leak data from the U.S. is considered appropriate, as there is a substantially greater history of unconventional gas development, and a much wider range of jurisdictions from which spill and leak data have been reported (e.g. in comparison to Queensland). As noted in my first expert report, the significance of spills in the Narrabri Gas Project area will be heightened relative to Queensland, as the produced water will be significantly poorer quality, and the shallow groundwater is generally of higher quality than is typical within the Queensland CSG fields. The track record of spill and leak incidents from within the Narrabri Gas Project area during gas exploration and appraisal activity – involving multiple uncontrolled spills and leaks – indicates that this is not merely an abstract risk, but one for which the likelihood and consequences can be considered significant.

9.2.9 Assertions that the Project is located in a major recharge zone for the GAB

As discussed in my expert report, the fact that the area is within a zone of recharge for the GAB is not in dispute (as pointed out by the WEP). Santos appears to be arguing as to whether the rate(s) of recharge are 'significant' or 'major' in the context of the region's water balance.

While areas of higher recharge into the GAB indeed occur to the south of the Project area (where currently no gas development is proposed), it is clear that the Pilliga Sandstone GAB aquifer does outcrop and sub-crop over a significant part of the Narrabri Gas Project area - whereas, over much of the Australian continent it is buried beneath a significant thickness of overlying sediment. As such, there is a clear pathway for spills and leaks of CSG wastewater to recharge the GAB groundwater, creating a risk of harm to groundwater quality and associated users and ecosystems. This is currently not being fully acknowledged by Santos in its assessment of groundwater contamination risk.

Appendix B – Evidence from Richard Lancaster, SC

In **paragraphs 21 and 24** of his evidence, Mr Lancaster cites evidence from Mr Kitto regarding the likelihood of significant groundwater impacts, as the basis for his views on whether the Precautionary Principle is triggered with respect to groundwater impacts. In particular, Mr Lancaster notes Mr Kitto's opinion that the expert evidence on the topic of groundwater does not indicate a risk of 'significant and irreversible harm'.

Firstly, my view (which is consistent with other groundwater expert evidence, such as that provided by the IESC and Dr Hayley – see below), is that there is a potential risk of significant, irreversible harm to groundwater, there is a lack of full scientific uncertainty as to that harm, and the current level of scientific investigation, modelling and understanding of the system is insufficient to rule out significant irreversible harm.

Secondly, as was outlined in my previous advice on the topic of Adaptive Management (AM), contrary to Mr Kitto's opinion, an AM approach currently proposed by DPIE is poorly suited to managing the potential groundwater impacts of the project, as:

> a) impacts are likely to arise on a relatively long timescale (e.g., compared to the timeline of the gas project),
>
> b) certain groundwater-related impacts are essentially irreversible - e.g., once the coal seams are depressurized by gas development, it is not practically feasible to re-pressurise them to mitigate adverse outcomes such as methane contamination and/or loss of access to groundwater which may harm ecosystems or water users.

> c) significant time-lags in the response of groundwater systems to impacts which could arise as a result of the Narrabri Gas Project (e.g. Cook et al., 2003; Rousseau-Gueutin et al., 2013) mean that linking observed changes in groundwater conditions to specific activities (e.g. aspects of the gas development process) can be difficult without sound *a priori* understanding of the aquifer system's dynamics (as is currently the case). Such time lags also mean that implementation of mitigation steps is likely to be ineffective and/or impractical (e.g. Thomann et al., 2020).

In **Paragraph 56:** Mr Lancaster states the following:

"I am instructed that anticipated groundwater and surface water impacts of the Project have also been assessed over a number of years by three separate independent expert bodies, namely the:

(a) CSIRO (GISERA);

(b) Water Expert Panel; and

(c) Commonwealth Independent Expert Scientific Committee;

each of which has determined that the Project would not have a significant impact on groundwater and surface water having regard to the proposed comprehensive suite of conditions to be imposed on the Project."

Comment: This is not an accurate reflection of the views of these expert bodies with respect to the groundwater impacts of the Narrabri Gas Project, particularly in the case of the IESC. The IESC should be considered the eminent authority on groundwater-related impacts of coal seam gas and coal mining development - the committee has scrutinized more than 100 coal and coal seam gas projects since its inception in 2013, and was specifically created by the Federal Government to examine groundwater-related impacts of projects of the type being proposed by Santos. In its advice in 2017, the IESC noted the following potential groundwater-related impacts associated with the Narrabri Gas Project:

> "The key potential impacts of the project include:
>
> - long-term release of salt to the environment and the ongoing management of brine and salt waste. There is uncertainty in the quantities of salt that will be produced. There is also limited information in relation to the location and process for storage, and the containment and monitoring measures at the point of disposal.
> - declines in groundwater level in landholder bores as a result of depressurisation and drawdown in the medium- to long-term (greater than 10 years).
> - reductions in water availability to springs and other GDEs as a result of groundwater depressurisation and drawdown. These reductions may also impact surface water and groundwater connectivity, particularly along Bohena Creek.
> - changes in surface water flow as a result of proposed discharges into Bohena Creek and uncertainties in the management of water during project operations in the short term (less than 10 years).
> - changes to surface water and groundwater quality as a result of inappropriately stored or unintentional release of chemicals or untreated co-produced water." (IESC, 2017)

These impacts are consistent with those identified as being major potential risks of the Narrabri Gas Project in my expert report(s) submitted to the IPC. With respect to the likelihood of such impacts and the supporting evidence available to assess these, the IESC pointed out a number of deficiencies in Santos' assessment, and as such, their advice is not consistent with the information provided to Mr Lancaster above (i.e., that the Project "would not have a significant impact on groundwater and surface water"). For example, the IESC stated:

> “Baseline groundwater information has been collected to inform the environmental impact assessment for this project. However, the IESC considers that further data is required to determine the full range of potential impacts to groundwater resources and associated users.”
>
> And,
>
> “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. The use of small scale ‘daughter models’ in areas of particular concern could be considered to address this limitation. While the current modelling indicates a low likelihood and severity of impact to most receptors, further verification of model inputs (including suitability of imposed extraction rates) and other refinements of the model are needed to improve confidence in model predictions.

Note that the quote above refers to Santos’ EIS modelling (which has remained unchanged since the time of the IESC advice) - i.e., the IESC are stating that the proponent’s EIS model predicts a low likelihood and severity of impacts (not that this is their view), and that a significant amount of further information needed to be collected and incorporated into the modelling in order to fully understand the full nature and magnitude of the potential groundwater impacts. Their recommendation to produce ‘daughter models’, as well as the need for more thorough baseline data and analysis of other groundwater-related information have (to my knowledge) not been adopted by Santos since the time of the advice (more than three years ago).

The IESC also stated that:

> “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 detail on the reservoir modelling, including confirmation that gas extraction will be limited to 5% from the Hoskissons seam and 95% from the Maules Creek Formation.
> - 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.
> - clarifying the nature of long and short term salt storages, including associated monitoring and management measures.”

They also outline a range of additional measures that should be taken to improve confidence in the modelling, such as more thorough characterization of faulting (e.g., “Further consideration is needed with respect to the scale and extent of faulting in the region and the likely impact on groundwater during and post CSG extraction to justify excluding faulting from the groundwater model”), the use of probabilistic modelling, and collecting more field data to improve the conceptual model. In relation to these issues, they noted that:

> “Uncertainties associated with each of these aspects have the potential to result in different predicted impacts to those presented in the EIS.”

Again, to my knowledge, none of the IESC's recommendations regarding the need for more detailed baseline data and modification of modelling methods and assumptions have been acted on in a substantive way. This means that residual uncertainty regarding groundwater impacts, and the possibility of significantly greater groundwater drawdown, contamination, and GDE health impacts pointed out by the IESC, remain significant. This is inconsistent with the information provided to Mr Lancaster as per the above quote.

Regarding the CSIRO's opinions on the groundwater impacts of the project, as Dr Hayley's evidence noted, the modelling and uncertainty analysis by Sreekanth et al., (2017) indicated that when a wider range of plausible aquifer parameters in the system are incorporated into modelling, this results in some modelled scenario results which predict greater leakage rates from the Great Artesian Basin in response to CSG development –which can be considered 'significant'. Again, it is important to stress that this modelling did not consider the potential impact of faulting and other geological structures, which my evidence (as well as the IESC's) highlighted as being a key potential deficiency, which, (when properly considered) may result in substantially greater impacts on groundwater than are currently predicted.

In **Paragraph 57**, Mr Lancaster states:

"I have been asked to consider whether, assuming that the following statements provide an accurate description of the substance of the SSD application in relation to groundwater, it is open to the IPC to consider that the proposed monitoring and adaptive management approach for the Project meets the description in *Speleological Society*: (a) the potential impacts to groundwater sources have been rigorously assessed and found to be negligible. The model used to predict future impacts has been described as "world class" and "fit for purpose" by an independent peer review conducted by CSIRO. It will continue to be enhanced with further field monitoring data;

(b) although some level of uncertainty will always remain with respect to the modelling of groundwater impacts, an "adaptive management" approach has been adopted, as is widely accepted for resources projects, whereby there will be ongoing monitoring of water levels and pressures and water quality via a Water Management Plan;

(c) the baseline conditions are known to the extent that they can be through the groundwater model,26 which will be continuously updated;

(d) remaining knowledge gaps can only be closed out by commencing the Project, updates to the groundwater model and through implementation of the Water Management Plan.27 In addition, the water management performance measures prescribe performance measures for water impacts and on the aquifers, riparian and aquatic ecosystems, well integrity, produced water, irrigation and beneficial reuse management, Bohena Creek water discharges, salt management and chemical and hydrocarbon storage,28 and through the collection of ongoing monitoring data;

(e) the Water Management Plan (which includes multiple sub-plans dealing with all aspects of water management) is to be developed in consultation with several key agencies and stakeholders and approved by the Planning Secretary. It incorporates an early detection system to ensure that any changes in groundwater which were not predicted are actioned well before there are any impacts to water users; and

(f) a Water Technical Advisory Group is being established to provide ongoing advice on all aspects of the project water-related management issues, including the groundwater model, Water Management Plan and the Field Development Plan.29"

Comment: Again, this is not consistent with current evidence (and expert opinion) regarding the rigor of the modelling, and current state of knowledge of the groundwater system and its baseline conditions. The IESC recommended (more than three years ago), that significant additional baseline data be collected "as soon as possible" to characterise groundwater dependent ecosystems in the project area and validate current baseline groundwater level, pressure and quality conditions, and that the groundwater monitoring plan, including an early warning monitoring system, management and mitigation measures be provided (IESC, 2017). Their opinion was that:

> "The model is not capable of robustly determining the full range of the magnitude of potential local impacts on GDEs and landholder bores, limiting its ability to be used as a tool for risk assessment under the *EPBC Act 1999* and the NSW Aquifer Interference Policy (AIP) (DPI, 2012).

As such, Mr Lancaster's evidence regarding the risk of significant impacts to groundwater, and the ability for proposed future data collection and adaptive management to mitigate these, does not thoroughly consider the critical residual uncertainties identified by the IESC and my previous expert evidence. My opinion is that there remains a considerable risk of significant harm to groundwater and water users and ecosystems dependent on it as a result of the gas project, and that the proposed Adaptive Management approach is not well suited to protection against such impacts. Santos' final submission to the IPC does not contain new evidence or information that changes or invalidates these conclusions.

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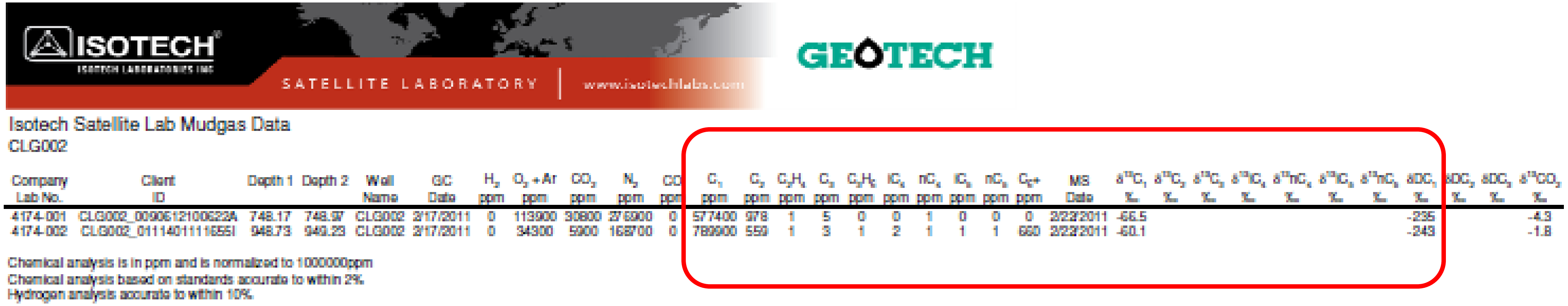
Appendix A – Well completion report from Culgoora-2 gas exploration well in the Gunnedah Basin (methane concentration and isotope composition highlighted – these are reported accurately in Iverach et al., 2020, contrary to Santos’ submission).



Isotech Satellite Lab Mudgas Data
CLG002

Company Lab No.	Client ID	Depth 1	Depth 2	Well Name	GC Date	H_2 ppm	O_2 + Ar ppm	CO_2 ppm	N_2 ppm	CO ppm	C_1 ppm	C_2 ppm	C_2H_4 ppm	C_3 ppm	C_3H_6 ppm	iC_4 ppm	nC_4 ppm	iC_5 ppm	nC_5 ppm	C_6+ ppm	MS Date	$\delta^{13}C_1$ ‰	$\delta^{13}C_2$ ‰	$\delta^{13}C_3$ ‰	$\delta^{13}iC_4$ ‰	$\delta^{13}nC_4$ ‰	$\delta^{13}iC_5$ ‰	$\delta^{13}nC_5$ ‰	δDC_1 ‰	δDC_2 ‰	δDC_3 ‰	$\delta^{13}CO_2$ ‰
4174-001	CLG002_00906121006223A	748.17	748.97	CLG002	2/17/2011	0	113900	30800	276900	0	577400	978	1	5	0	0	1	0	0	0	2/22/2011	-66.5							-235			-4.3
4174-002	CLG002_01114011116551	948.73	949.23	CLG002	2/17/2011	0	34300	5900	168700	0	789900	559	1	3	1	2	1	1	1	660	2/22/2011	-60.1							-243			-1.8

Chemical analysis is in ppm and is normalized to 1000000ppm
Chemical analysis based on standards accurate to within 2%.
Hydrogen analysis accurate to within 10%.