Narrabri Gas Project: Review of baseline and ongoing groundwater data requirements under conditions of approval

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8th July, 2021

Executive Summary

This report outlines my expert opinion regarding the specifics of additional data and analysis required to meet the conditions of approval relevant to groundwater (B41 and B39) for the Narrabri Gas Project. It outlines both minimum and best practice requirements to address these conditions.

Key data and information required (as a minimum) in order to meet the baseline data requirements, which have not been addressed to date, include a need to expand the groundwater monitoring bore network within the Great Artesian Basin and Gunnedah Oxley Basin, and collect a minimum of three years of baseline water level and quality data from key areas where to date such data are missing. This is fundamental to future impact assessment, and to align with the requirement (in condition B41) to characterise aquifer and aquitard health, baseline groundwater levels and quality. The expanded monitoring network should address current gaps in bore coverage, the most important of which are:

a) A lack of existing bores and data to characterise groundwater levels and quality in the Great Artesian Basin in two key areas/zones. Firstly, along the eastern margin of the project area where the Pilliga Sandstone outcrops, and where both groundwater recharge potential, and possible interaction with Groundwater Dependent Ecosystems, is highest. Secondly, the north-western corner of the project area, where the concentration of landholder bores in the GAB is highest and there are to date no baseline data.

b) A lack of bores and data to characterise baseline levels and quality in the Gunnedah Oxley Basin (GOB) units within the project area – e.g., there are only two existing sites within the project boundary in the south of the petroleum lease. This is critical for protection of bores accessing groundwater from the GOB, documenting aquifer conditions in areas likely to experience significant changes in level and/or quality and informing future groundwater modelling and impact assessment.

c) Limited groundwater quality monitoring within the Bohena Creek alluvium – an area that is particularly vulnerable to contamination from surface spills of CSG produced water, and where there is potential for occurrence of groundwater dependent ecosystems.

d) Missing elements within the baseline water quality monitoring program, including key constituents (arsenic, ammonia, organic carbon, iron) which are elevated in CSG produced water and which will pose an ongoing groundwater contamination risk.

The expanded groundwater monitoring network and sampling program should include at least 7 or 8 additional bores in the Great Artesian Basin, and at least 6 additional sites in the Gunnedah Oxley Basin (to address areas currently lacking data). All new bores should be monitored for levels and quality for at least the three year baseline period specified in condition B41, prior to any coal seam gas production. Water level data should be presented both as hydrographs and potentiometric contour maps of each aquifer at different monitored time periods, capturing seasonal/climatic variability. There should also be a focus (during the necessary expansion of the bore network) on construction of nested monitoring sites, to allow for analysis of vertical hydraulic gradients and inter-aquifer connectivity in the system. Detailed lithological logging of the new bores, covering the full profile from the surface to the lower GOB (e.g. Maules Creek Formation) should be conducted to address the requirements of condition B39 to improve geological characterisation, particularly in areas where geological structures may occur (based on previous drilling, geophysical and geochemical data). Aquifer testing (i.e., pumping tests), to complement desktop assessments of aquifer hydraulic parameters and core-based analysis of aquitards (previous work by the CSIRO) are also needed to address condition B41.

Utilising additional bores constructed in the Pilliga Sandstone in the eastern part of the project area, and appropriate field-based techniques, an analysis of groundwater recharge rates and their dependence on soils, hydrogeological and climatic influences, is also fundamental to characterise aquifer health, analyse water budgets and fluxes, and inform future groundwater modelling.

There is also a need for a detailed survey of water levels and quality – including sampling for dissolved and free methane – in all registered irrigation, stock and domestic supply bores, using appropriate sampling methodologies, and covering periods of different standing water level (e.g. pumping/non-pumping periods) and accounting for the baseline variability of dissolved gas concentrations in groundwater (typically higher than non-gaseous constituents).

To address significant deficiencies in the assessment and monitoring of groundwater dependent ecosystems (springs, stygofauna and vegetation), identified by multiple independent reviewers, and to align with condition B41, additional field-based studies of groundwater dependent ecosystems are required - as per the IESC's 2017 advice, and submission to the IPC from Dr Peter Serov. This includes a need to visit, sample and monitor groundwater and spring levels and quality at Hardys and Eather springs, additional surveys for stygofauna – targeting the Bohena Creek Alluvium, GAB and Namoi Alluvium in the north of the project area, and a need to characterise these GDEs' level of dependence on groundwater quantity/quality in different aquifers.

In order to address the requirement of condition B39, such that the groundwater modelling aligns with Class 3 confidence level, a significant amount of additional field data will be required, to:

a) Improve the conceptualisation of the hydrogeology of the system (which is the basis of the model), including more robust estimates of hydraulic parameter ranges, and mapping of geological/structural features and any other relevant data concerning inter-aquifer connectivity

b) Calibrate the model in transient mode and conduct thorough sensitivity and predictive uncertainty analysis.

For confidence class 3, the calibration datasets must include both water level timeseries (hydrographs) from monitoring bores in multiple aquifers covering the project area (including the zones where such data are currently absent), and measured groundwater fluxes (flow) data, e.g., monitored groundwater discharge rates to springs, streams or other surface features. Both types of data (water level and flux) are needed to meet class 3 confidence level.

Best practice methods to meet the groundwater conditions B39 and B41 would involve the additional construction and monitoring of bores required to adequately cover the GAB and GOB (outlined above) plus further monitoring bores to map groundwater flow patterns, gradients and quality at higher resolution. Best practice would also involve environmental tracer studies, to improve the conceptualisation and understanding of groundwater recharge, flow and inter-aquifer mixing rates throughout the aquifer system. This would encompass stable and radiogenic isotopes in groundwater and methane from nested bore sites throughout the project area, and characterising groundwater recharge, flow and inter-aquifer connectivity for both water and gases. The isotopic study should be targeted towards:

a) Better quantification of groundwater recharge rates to the GAB, and understanding of recharge mechanism(s)
b) Understanding inter-aquifer connectivity between different aquifer units in the system and quantifying fluxes (e.g. through end-member mixing analysis)
c) Full isotopic characterisation of dissolved methane in each aquifer unit, as well as the gas-bearing unit(s), to enable future assessment of the cause(s) of any observed changes in methane concentrations in groundwater during ongoing monitoring.

These isotopic studies should build upon the published studies conducted by the University of New South Wales and ANSTO (Iverach et al., 2017 and 2020), utilising a similar approach and expanding the coverage of groundwater and gas isotope data throughout the project area.

Introduction and scope

I was requested by Lock the Gate Alliance Ltd. to prepare a report outlining my expert opinion regarding what specific types of data and analysis would be required to meet the Conditions of Approval for the Narrabri Gas Project. In particular I was asked to address the following:

1) What would be needed to meet the detailed baseline data required in the Groundwater Management Plan (B41)

2) In general, what would be required for Santos to meet the requirements set down in condition B39, to update the groundwater model 'to be generally in accordance with the feature of a Class 3 confidence level model'

3) Provide any other advice in relation to the groundwater conditions and additional surveys and/or data collection that I consider is needed to implement them.

4) Relevant timeframes in terms of the length of data collection required to meet the specifications in each case.

In the case of 1) and 2), I was asked to provide an opinion on the minimum requirements I believe necessary to address these conditions, factoring in existing data and work already completed by the project proponent, as well as what would constitute the best practice (i.e., most comprehensive) way of addressing the conditions.

Qualifications

I received my PhD in Geoscience from Monash University in 2011 after completing a Bachelor of Science (Hons) in Environmental Earth Sciences in 2006. For the past decade, I have lectured hydrogeology at RMIT University to environmental and civil engineering students, and supervised numerous applied research programs examining groundwater systems in Australia and the Asia-Pacific region. I have served on the editorial board of the Hydrogeology Journal and the Victorian committee of the International Association of Hydrogeologists and have received multiple awards for my teaching and research in hydrogeology. My full academic CV is available upon request.

My opinion

According to Narrabri Gas Project Condition B41, the Groundwater Management Plan (GMP) which must be prepared by the proponent must include:

"detailed baseline data of hydrogeology and groundwater levels, formation parameters (such as hydraulic conductivity, storage and yield) and quality for groundwater resources potentially impacted by the development (based on at least 3 years of monitoring data), including:

- aquifer and aquitard health;
- subsidence and seismicity, including a topographic baseline survey using interferometric synthetic aperture radar (or similar method as agreed by the Planning Secretary);
- groundwater supply and quality for other water users;
- natural methane leaks and accumulations, including in privately-owned bores and monitoring bores; and
- groundwater dependent ecosystems"

The minimum data needed to meet these baseline and ongoing monitoring requirements are analysed below, falling into 8 categories:

1. Baseline groundwater level data

Meeting condition B41 will require monitoring of baseline groundwater levels, presented as time-series hydrographs and potentiometric maps of flow patterns (i.e., water level contour maps) for each aquifer between the target coal seams and the surface. To meet the requirement of characterising 'aquifer and aquitard health', the monitoring network would need include data from sufficient bores in each aquifer, monitored frequently enough to document the variability in groundwater levels across the project area in response to seasonal and multi-year climate variability, and any existing anthropogenic influences (e.g. seasonal groundwater extraction for irrigation). As stated in the condition, the baseline data (prior to any gas development) must cover a period of at least three years. Monitoring bores should be constructed with appropriate screened intervals, which target the specific aquifer in question (i.e., not spanning multiple formations), and groundwater level data should be reported as elevations relative to the Australian Height Datum (AHD).

Existing water level data and further minimum requirements

The Narrabri Gas Project EIS water baseline reports (including the updated version in Santos's Response to EIS Submissions in 2018), include water level hydrographs from 50 bores in the region, some of which are within, and some outside, the gas project area. This includes 9 bores from Gunnedah-Oxley Basin (GOB), 25 from the Great Artesian Basin (GAB), and 16 from the Namoi Alluvium. Most (though not all) of these bores have been monitored for a period of three years. Importantly, there are substantial areas within and surrounding the gas project boundary, where there is no monitoring bore coverage or existing baseline data in these units. As such, additional bores need to be constructed and monitored for a minimum three-year period.

Major gaps which require addressing in order to align with the GMP requirements include:

- ***Gunnedah Oxley Basin:*** Only two existing GOB monitoring bore sites for which baseline data have been reported in the Water Baseline Reports are within the project boundary (Figure 1). Additional bores thus need to be installed spanning the full project area, including sites both on the western and eastern half of the petroleum lease. Additional locations where monitoring bore data are urgently needed to address the current gaps are marked in Figure 1 below.

- While generally there is comparatively less existing groundwater extraction for irrigation supply within the GOB (i.e., compared to the GAB and Namoi Alluvium), the construction of additional groundwater monitoring bores in the GOB is critical. Many landholders have water bores drawing supplies from within the Gunnedah-Oxley Basin units for domestic, potable and stock usage, and are highly dependent on these. These bores are likely to be particularly vulnerable to impacts from CSG, due to their depth and relatively close proximity to the gas-bearing formation(s) and baseline data are also critical to protection of these bores.

- Further, the data obtained from GOB monitoring bores will be the primary method to understand water level impacts of gas development deep in the aquifer system (i.e., within or close to the depth of water and gas extraction for CSG) and provide early information about the extent of drawdown impacts modification. This was highlighted in the IESC in their advice on the project in 2017:

  > "The monitoring network should include…monitoring bores within the Triassic units of the Gunnedah Basin, in particular within the Napperby and Digby Formations and targeted in areas of early development, to provide early warning triggers of the timing and extent of groundwater depressurisation." (IESC, 2017).

  Comprehensive baseline groundwater level data from bores in the GOB is also necessary to understand potential vertical leakage impacts in the aquifer system (as specified in the subsequent parts of condition B41) and inform improved groundwater modelling, in line with condition B39 (see below).

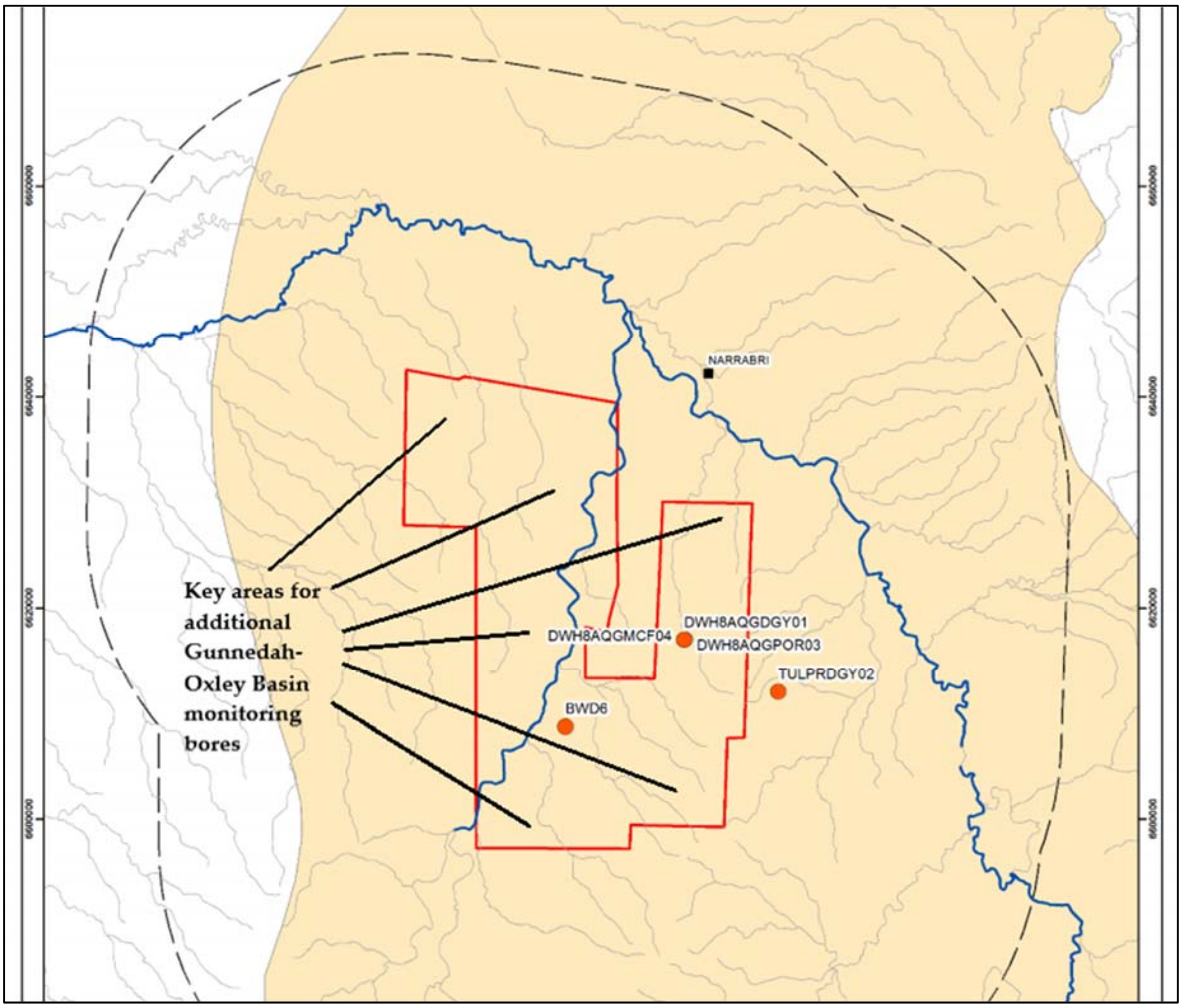

Figure 1 – Indicative locations where additional groundwater monitoring bores and baseline data are required to characterize aquifer health in Gunnedah-Oxley basin. Modified from Narrabri Gas Project EIS Water Baseline Report (2018).

- ***Great Artesian Basin****:* In the current baseline groundwater datasets, while there are a greater number of monitoring bores in the GAB compared to other units, the monitoring bores are limited or missing in key areas within the project boundary. In particular, monitoring bores and baseline data are needed where the Pilliga Sandstone - the key GAB water supply unit in the area, outcrops along the east of the project area (marked in pink on Figure 2 below). It is critical that this zone, where groundwater recharge potential into the GAB is highest, is equipped with monitoring bores, to collect level (and quality) data, and properly understand groundwater recharge rates, mechanism(s) and quality. This is fundamental to characterization of aquifer health (in accordance with B41), water balance and flow patterns. Bores in this region are also vital for the characterization of GDEs, their source aquifer(s) and interactions with the aquifer system, including the springs identified as having high ecological significance by the IESC (2017) – i.e., Hardys and Eather Springs (see section 8 on GDEs below).

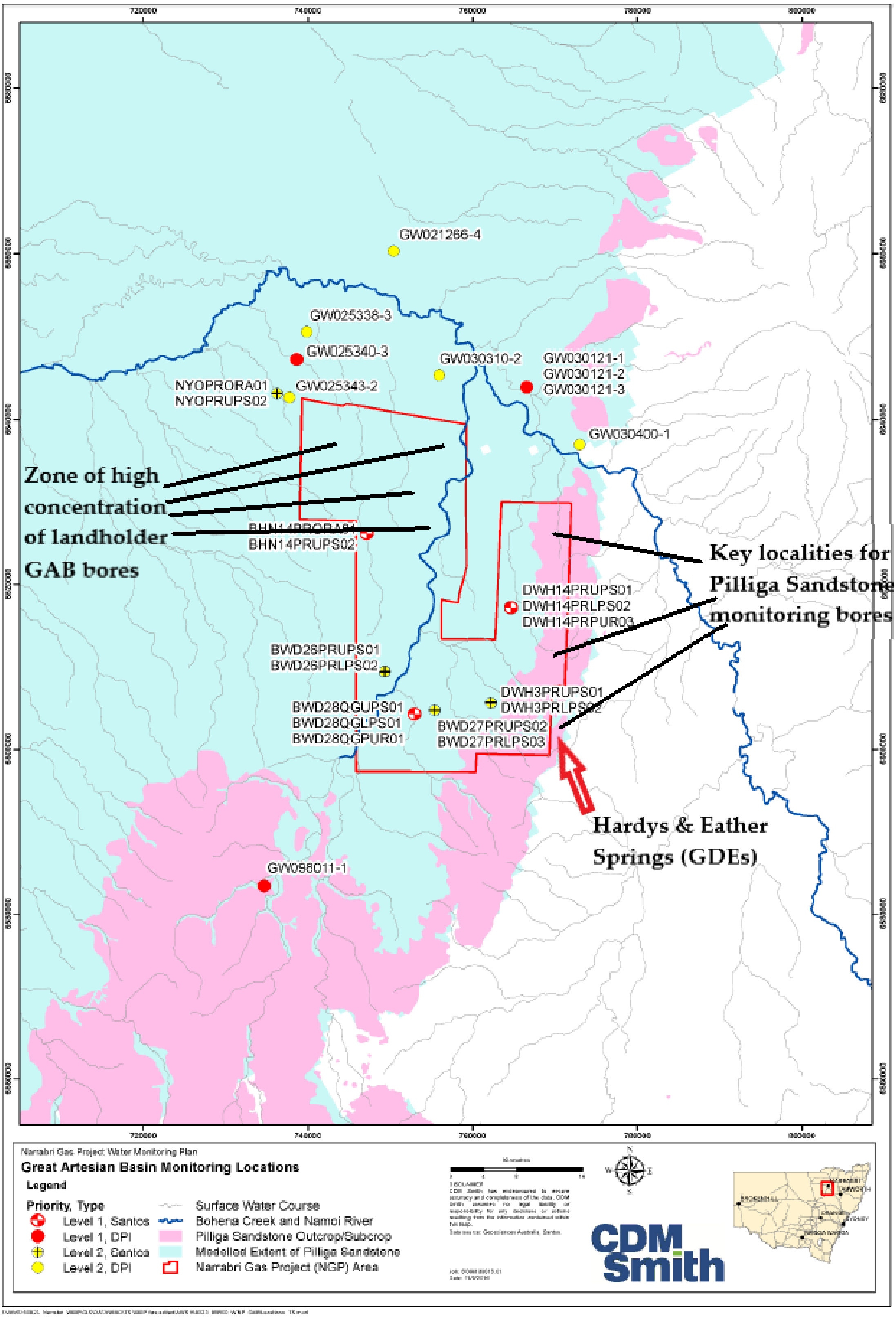

Figure 2 – Locations of existing GAB monitoring bores, and sites where additional groundwater monitoring bores and baseline data are required to characterize water levels, flow patterns and aquifer health in the Great Artesian Basin. Areas of outcrop of the Pilliga Sandstone, near key GDEs, and the area of high concentration of landholder bores in the northwest of the project area all require additional monitoring bore coverage and baseline data for at least three years. Modified from Water Baseline report (EIS Response to Submissions Appendix D).

- In addition to the eastern GAB outcrop/recharge areas, there is also a large area of the northwestern part of the project area with no GAB monitoring bore coverage, where a significant number of landholder bores within the GAB occur (see Figure 3 below). Multiple bores should be installed in this region to properly characterize groundwater levels and aquifer health in this key area of GAB water supply:

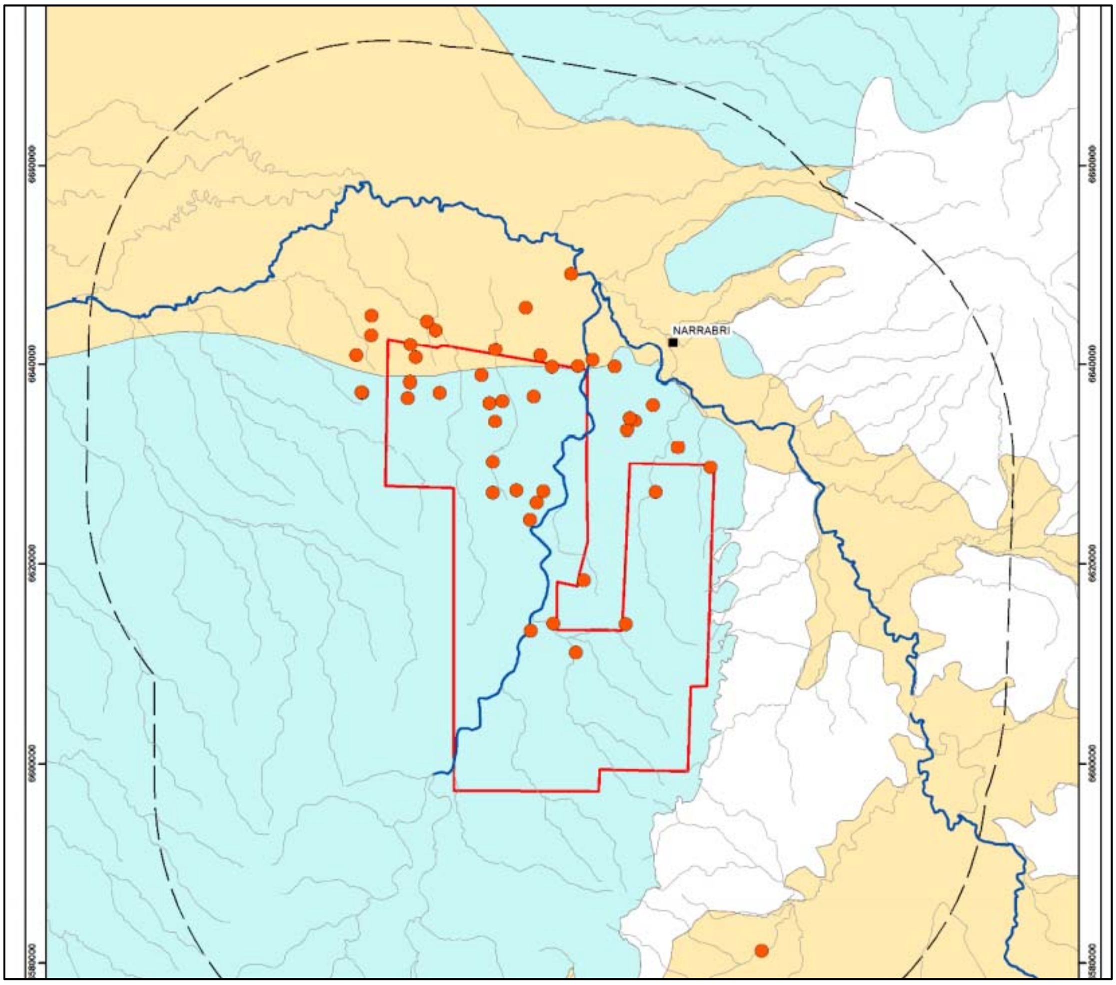

Figure 3 – Identified landholder water supply bores in the GAB and alluvial aquifers (from EIS Response to Submissions Water Baseline Report). The area with highest concentration of bores is currently not covered by the monitoring bore network outlined in the Narrabri Gas Project Water Baseline Report (2018).

Based on the gap analysis above, an additional 7 to 8 GAB monitoring bores and at least 6 GOB monitoring bores would be required to complete the minimum coverage needed for characterization of groundwater levels, flow patterns and aquifer health in these units, as per condition B41. Best practice/maximum requirements would include additional sites beyond this number to map out flow patterns and gradients in further detail.

Nested groundwater monitoring sites: Monitoring bores must (in order to properly characterize aquifer and aquitard health and allow for monitoring of inter-aquifer leakage) include nested sites, screening multiple aquifers at a given locality. This should include (as a minimum) the upper and lower Gunnedah Oxley basin coal bearing units (Black Jack and Maules Creek Formations), Digby and Napperby Formations, the upper and lower GAB units (Purlawaugh Formation and Pilliga Sandstone) and, where present, the Namoi or Bohena Creek Alluvium. Collecting groundwater level data at such nested sites is necessary to monitor vertical interaction between the aquifers prior to, and under the influence of, water and gas extraction for CSG production. This point was made clear in the IESC's review of the project EIS:

> "targeted groundwater monitoring wells at adequate depths and spatial variation, close to areas of early gas extraction to monitor the early propagation of groundwater depressurisation during production. This should also include monitoring of hydraulic head directly above and below the tightest formations (i.e. aquitards) to provide realistic observations of hydraulic gradients (refer to paragraph 6b)."

As a minimum, there should be four nested monitoring sites (in the Northwest, Southwest, Northeast and Southeast zones of the project area) with each site equipped with a dedicated monitoring bore in each of the units noted above, to be monitored contemporaneously for levels and quality. Best practice would involve additional nested sites beyond this number (e.g., 8 fully equipped nested monitoring sites). This would allow targeted reduction in groundwater modelling uncertainty and greatly improved ability for early detection of the propagation of impacts from coal seam gas extraction into overlying aquifers.

Groundwater contour mapping: Mapping groundwater flow patterns and gradients (as potentiometric contour maps), is also fundamental to characterizing aquifer and aquitard health, understanding recharge, discharge and potential inter-aquifer connectivity, and determining baseline influences on groundwater levels. So far, the mapping of baseline groundwater level data in each aquifer has yet to be presented in the EIS or responses to submissions. Contour maps of groundwater levels in each aquifer must clearly show groundwater flow patterns (based on interpolation between monitoring data), and be presented for multiple periods of time, to allow for identification of areas with increasing/decreasing groundwater level trends, and characterize flow paths and hydraulic gradients (which may be impacted by gas development). Such mapping is necessary to enable full assessment and de-coupling of the extent of impacts on water levels due to CSG development, as distinct from other influences such as climate and seasonal water extraction.

Monitoring time period/frequency: As outlined in B41, all bores (both existing and new) require at least three years of baseline data. In the new bores required to characterize groundwater levels and aquifer health in the GAB and GOB discussed above, baseline monitoring would need to begin as soon as the bores are constructed and continue for a three-year period prior to CSG development. Best practice would involve collection of data for a potentially longer period of time, in particular if the three year period does not encompass climatic conditions that are representative of the full range of wet/dry conditions in the region (e.g., if the three years of monitoring all occur during a relatively wet phase, the baseline aquifer health would not be comprehensive as this may be significantly affected during dry/drought periods).

The length of time for which baseline data have already been collected from existing monitoring bores is variable. In most existing bores, monitoring commenced in 2014 and continued into 2017, providing three years of data. Continuing the monitoring in these existing bores to coincide with monitoring events in the new bores in the GAB and GOB would be essential for interpretation of these data – e.g., water level contour mapping. Such mapping requires levels from bores in each aquifer to be monitored contemporaneously; hence, previous data (from 2014-17) should not be mapped together with new monitoring data.

The monitoring frequency in all bores should be at least monthly (if conducted by manual dipping), or greater than monthly in units where the existing data indicate the aquifer is highly sensitive/responsive to climate or other influences through time – e.g. with continuous hourly or twice-daily logging. In general, shallow aquifer units, such as the alluvium and Pilliga Sandstone, will require more frequent monitoring to characterize baseline variability than deeper bores (e.g. those in the Gunnedah Oxley Basin). The minimum frequency in deeper bores should be monthly; however, this could be reduced to quarterly if variability in levels (and/or quality) over time is observed to be minimal in the first year of data collection. Best practice would involve monitoring all bores continuously (e.g. twice daily or hourly) using telemetered loggers that are periodically checked through manual readings and maintained/replaced upon detection of any faults.

Additional geological characterization: As outlined in condition B39 f(iii) and f(iv), additional characterization of the geology of the aquifer system, encompassing geological structures, will be required to address uncertainty regarding inter-aquifer connectivity, and improve the groundwater modelling. The primary method of addressing these requirements will be detailed geological logging of all new monitoring bores drilled at the additional GAB and GOB sites (including nested sites) described above, reaching down to the Maules Creek formation within the GOB.

These lithology logs should include both a raw description of each rock/sediment type encountered throughout the geological profile during drilling, plus identification/attribution of these lithological types to the known stratigraphic units of the sedimentary basins (to enable correlation between bores, and identification of faulting and other structures). The logs should also identify any structural features (such as fracturing or discontinuities) encountered within each bore and include textural and grain size analysis. Using sonic or other non-destructive drilling technique would enable the best characterization of the geology of each borehole and any borehole-scale structural features.

The geological logs should (as a minimum) be correlated with any existing bore log records available in the NSW DIGS database and data held by the proponent, and these should be used to construct detailed geological/stratigraphic cross sections. Best practice would involve the use of additional geophysical techniques – e.g., seismic surveys – which can be correlated with multiple bore logs along each cross section.

2. Groundwater quality

Baseline monitoring of groundwater quality is also a key component of Condition B41. The regular sampling of the existing network of monitoring bores, plus the additional bores required to complete the coverage in the GAB and GOB (outlined above) should, as a minimum, provide reasonable coverage to characterize baseline groundwater quality in each aquifer. However, additional shallow (water table) monitoring sites also need to be installed near any significant infrastructure used to store and/or transport produced water from CSG development – such as holding ponds and major produced water gathering pipelines. A detailed discussion of the importance of such groundwater quality monitoring is included in my expert report submitted to the IPC in 2020 (Currell, 2020). Notably, the analysis of produced water quality (presented in the updated Water Baseline Report in 2018) from ponds at the Leewood Plant indicates that the water from the target coal seams is poor quality (e.g., in comparison to produced water extracted from the Surat and Bowen Basin gas fields), characterized by high TDS, organic carbon, and concentrations of trace elements (such as fluoride, barium, arsenic and other heavy metals). As such, the groundwater pollution risk associated with spills and leaks of produced water is heightened, and attention should be given to the monitoring baseline shallow groundwater quality in areas where significant volumes of this fluid are produced, stored and transported. Particular attention should also be given to the eastern part of the project area, where the Pilliga Sandstone (GAB) outcrops or occurs at shallow depth, as any produced water leaks or spills occurring in these areas have a relatively higher risk of contaminating recharging water for this important aquifer.

Existing groundwater quality data in the EIS water baseline reports includes sampling from 42 bores (3 GOB, 19 GAB, 13 Namoi alluvium, 4 Bohena Creek alluvium). Additional quality sampling should (as a minimum) include the additional 7-8 GAB and 6 GOB bores indicated above (section 1). Groundwater quality sampling should be conducted at quarterly frequency (as a minimum) with monthly or more frequent monitoring conducted in areas of relatively high risk - e.g. shallow monitoring bores near areas of CSG produced water storage and transport, areas of Pilliga Sandstone outcrop and Bohena Creek alluvium. Sampling should, as a minimum, encompass the analytes already reported in the updated (2018) water baseline report (e.g. Table 4.3 to 4.7), plus these additional elements, which were overlooked/excluded in the initial baseline groundwater monitoring but which are essential to proper baseline water quality characterisation:

- Iron (as both total and dissolved iron, and both Fe^{2+} and Fe^{3+})
- Arsenic and other heavy metals excluded from tables 4.3 to 4.7 (Cd, Cr, Hg, Pb, Cu, Ni, Zn)
- Aluminium
- Ammonia, Nitrate and total N
- Dissolved and Total Organic Carbon
- Hydrogen sulfide
- Uranium, Thorium & other radionuclides (e.g. ^{222}Rn, radium)
- Sulfate reducing bacteria (and other microbiological characteristics associated with produced water)
- Petroleum hydrocarbons

These constituents are typical water quality parameters associated with groundwater monitoring near oil and gas developments, and a number of these are elevated in the produced water analysis reported in the 2018 Water Baseline report. A full baseline of their concentration levels is thus required from monitoring bores across the project area in each aquifer prior to CSG production.

Groundwater quality sampling should also involve the collection of field parameters at each monitored site, including pH, EC, Temperature, Dissolved Oxygen and redox (as ORP and/or Eh). Redox state in groundwater is particularly important in areas of hydrocarbon development, as changes in this may be an early indicator of possible contamination with hydrocarbons and/or produced waters. Such changes may catalyse secondary reactions that mobilise heavy metals – e.g., Cahill et al., (2017); Whyte et al., (2021).

Most existing monitoring bores have reported at least three years of groundwater quality data (e.g. tables 4.3 to 4.47 in the updated Water Baseline Report (2018)); however, this excludes the constituents listed above, meaning an additional period of baseline sampling would be required in all existing bores (sufficient to determine baseline levels of these elements), as well as three years of data from the new GAB and GOB bores. In some cases – e.g. many of the Namoi Alluvium bores – groundwater quality monitoring was last conducted more than 20 years ago, and up-to-date water quality monitoring is required, as there may have been substantial changes in groundwater quality since last monitoring.

Also, groundwater quality monitoring in the Bohena Creek Alluvium only appears to have taken place during one or (at most) two sampling events in 2013. A full three-year monitoring period is required to characterize groundwater quality at multiple sites in this unit. This is critical for establishing aquifer and GDE health, noting that the IESC identified the Bohena Creek Alluvium as a key potential area for groundwater dependent ecosystems and an area potentially significantly impacted by gas development through produced water discharges.

Characterising the quality of water entering the aquifer system in the recharge area(s) and the evolution of groundwater quality along flow paths - e.g., due to water-rock interaction, inter-aquifer mixing and any existing anthropogenic influences - is also fundamental to characterizing aquifer health (as per B41). This could (as a minimum) be achieved through the sampling of major and minor elements in the updated groundwater monitoring network outlined above, in conjunction with the groundwater level monitoring outlined in section 1. Best practice monitoring for groundwater quality and aquifer health would include the program described above, plus sampling for additional environmental tracers, e.g. stable isotopes of oxygen, deuterium and carbon, plus radioisotopes such as tritium and radiocarbon, to enable improved conceptualization of the groundwater recharge, flow, inter-aquifer mixing and discharge pathways within the aquifer system (Clark, 2015).

3. Groundwater recharge

While not explicitly mentioned in condition B41, the quantification of groundwater recharge amount and quality is also fundamental to the characterization of aquifer health (e.g., Scanlon et al., 2002; Healy, 2010). Currently, the rates, locations, mechanisms and quality of groundwater recharge are poorly understood in the project area, and largely based on desktop assessments. As noted in section 1 above, there are currently no monitoring bores within the outcropping areas of the Pilliga Sandstone, where recharge potential to the GAB is highest. As a minimum, analysis and quantification of minimum and maximum recharge rates based on two independent/complementary field techniques should be undertaken in this unit, utilizing the additional GAB monitoring bores indicated on Figure 2, e.g., using Chloride mass balance and Water Table Fluctuation (Scanlon et al., 2002). Best practice for characterizing groundwater recharge would involve the use of further lines of evidence to quantify recharge, including the above techniques plus other environmental tracers (e.g. tritium and radiocarbon), soil moisture monitoring and/or other geochemical/geophysical techniques (e.g. Cartwright et al., 2017; Hall et al, 2020).

4. Groundwater supply and quality for other users

In order to comply with this aspect of condition B41, the proponent would need to conduct a bore baseline survey in the region, identifying and sampling water from all registered irrigation, stock and domestic bores in the project area and its radius of potential impact. All bores in the survey need to be monitored for standing water level across a minimum of two different climate/water use periods (e.g., during two events that capture the approximate minimum and maximum standing water levels, accounting for seasonal climate and groundwater pumping). Sampling would also be needed to characterise water quality in these bores, in accordance with the minimum requirements outlined in section 2 above. Quality sampling would need to cover (as a minimum), two events corresponding with minimum/maximum standing water level conditions. Best practice would involve regular (e.g. twice yearly) sampling and ongoing monitoring of registered bores for all landholders who wish to participate in the baseline and ongoing monitoring program, with additional monitoring conducted by the proponent upon request (e.g. if a landholder detects a change in normal bore operation or water quality).

5. Natural methane leaks and accumulations including in privately owned and monitoring bores

In conjunction with the baseline bore survey and baseline groundwater quality monitoring of the updated bore network (described above), analysis of methane in groundwater, as both dissolved and free gas, must be conducted to meet the requirements of condition B41. It is well known that unconventional gas development can lead to changes in the concentrations and behaviour of methane in aquifer systems, and potentially result in accumulations of the gas in water supply bores, increasing the risk of explosions or pump failures, and/or causing secondary changes in groundwater quality (e.g. Groundwater Protection Council, 2012; Cahill et al., 2017; Whyte et al., 2021).

All groundwater quality monitoring events, including from the monitoring bore network and landholder bores, should include sampling for methane, using appropriate methodologies - e.g. those outlined in Groundwater Protection Council, (2012) and/or Walker and Mallants, (2014). It should be noted that baseline methane concentrations in groundwater are known to vary significantly through time, due to (among other influences) changes in hydraulic gradients and heads within an aquifer system (impacting methane solubility equilibrium), changes in temperature and barometric pressure, and changes in the level of activity of sub-surface microbial communities (e.g., methanogens) (Humez et al., 2016). Variability would be expected to be greater than for most of the other water quality constituents indicated above in section 2. As such, methane sampling should be conducted as frequently as is required to characterise a stable timeseries with minimum/maximum, mean/median values and a reasonable standard deviation, under baseline conditions (see Humez et al., 2016, for further guidance). An initial period of relatively frequent analysis of methane in key bores where there is detection of significant dissolved methane (e.g. >1 mg/L) in the early baseline sampling should be carried out to allow for effective determination of a reasonable baseline range of concentrations. Methane sampling in landholder bores should (as a minimum) encompass the approximate minimum/maximum standing water level conditions discussed above in section 4, and further ongoing sampling (e.g. twice yearly, or greater in bores with significant variability in methane concentrations over time established using the methodology above).

As a best practice approach to the analysis of methane occurrence and behaviour in the aquifer system and to allow for more conclusive analysis of the cause of any observed changes in groundwater methane concentrations, a full study of the isotopic composition of methane within the monitoring bore network should be carried out, including analysis of isotopes of deuterium and carbon in methane ($\delta^{13}C_{CH4}$ and $\delta^{2}H_{CH4}$), and $\delta^{13}C$ in groundwater dissolved inorganic carbon (e.g. Currell et al., 2017). Baseline isotopic compositions of methane in the groundwater monitoring network should encompass multiple bores in each major aquifer unit, to establish end-member isotopic compositions (e.g., Jackson et al., 2013).

The methane isotopic study should (as best practice) be conducted in conjunction with sampling for other complementary isotopic tracers (e.g., carbon-14, chlorine-36, stable isotopes of water and carbon-13), along with major/minor element data, to explore potential mixing between both water and gases within the aquifer system in different locations - utilising the nested bore monitoring sites discussed above in section 1. An approach that utilizes the methodology outlined in Iverach et al., (2020), and which builds upon the existing methane isotopic and other environmental tracer datasets reported in that study (but with a significant additional number of wells located within the project area), would align with best practice. Upon commencement of CSG extraction, determination of the isotopic composition of the produced gases and produced water from the target units would be required, in order to conduct a comparison with isotopic compositions for any methane observed in groundwater bores (i.e., the monitoring bore network and supply wells covered in the baseline program). This approach would allow for not just an assessment of changes in concentrations of methane in the aquifer system and landholder bores in response to CSG development, but an understanding of the causes and mechanism of any such changes.

6. Aquifer and aquitard parameters, storage and yield

Currently, the proponent's groundwater modelling (and additional modelling conducted by CSIRO during the Bioregional Assessment program) relies on approximate/averaged values of hydraulic parameters (e.g., hydraulic conductivity and specific storage) in each aquifer/aquitard, applied uniformly across each layer within the model domain. Currently it is unclear whether this approach provides an adequate conceptualization to model the behavior of the aquifer system under the influence of CSG development, and/or to assess the risks associated with more extensive inter-aquifer connectivity – an equally plausible conceptualisation (e.g., Groundwater Solutions, 2020).

The approach outlined under condition B39 will be to update these hydraulic parameter values in response to calibration performance of the model and any additional relevant field data, during future groundwater model updates. This approach may lead to reduction in uncertainty in model predictions over time; however, given the number of layers and complexity of the aquifer system, and the general lack of site-specific testing of aquifer and aquitard parameters to date, there are likely to be significant limitations in the ability of model calibration (in itself) to reduce model predictive uncertainty (see discussion of this issue in Doherty and Moore, 2019). As such, additional field-based testing of hydraulic parameters, along with further geological investigation to characterize faulting and other structures, will need to be conducted. The IESC emphasized this point also:

> "Primary data collection of aquifer hydraulic parameters through pump testing should also be undertaken to verify parameterisation in the model, with a particular focus on hydraulic conductivity and storativity. The measurement for realistic variations of storativity in the model, based on scaling up of in-situ measured storativity (Acworth et al. 2017, David et al. 2017) is particularly important as these values are a source of uncertainty in the model that has the potential to affect the magnitude and timing of drawdown."

This will also generate information that can improve the conceptual model of the aquifer system, including obtaining a greater understanding of inter-aquifer connectivity in key areas, to further enable more targeted and effective groundwater level and quality monitoring to protect existing groundwater-related values.

Pumping tests designed and run in accordance with the relevant Australian Standard should be conducted to establish hydraulic parameters and identify any inter-aquifer leakage during groundwater extraction from the GOB (gas bearing units). Generally, this would require pumping for a period of at least 72 hours, and monitoring of both drawdown responses and recovery (following cessation of pumping), in multiple observation bores in the target and overlying aquifer/aquitard units – although this needs to be assessed based on the quality of data collected during ongoing pumping test monitoring. Pumping tests should target key knowledge gaps relevant to ongoing analysis of the impacts of gas development, namely:

- Tests involving bores within the Gunnedah-Oxley Basin, with monitoring bores installed both within the pumped GOB unit(s), and immediately above in the overlying aquitard(s) – e.g. Pumping/monitoring wells in the Maules Creek/Black Jack formation, and monitoring wells in the Digby and/or Purlawaugh Formation. Monitoring should also be conducted during pumping tests conducted within the Pilliga Sandstone and (where it is present) Namoi Alluvium, to determine if there is any noticeable impact of deep groundwater pumping on levels in these aquifer units.
- These pumping tests should target areas where potential inter-aquifer connectivity (with respect to water and/or gas) have been identified – e.g., the zone where there are significant geological structures (volcanic dykes and faulting) in the northwest/north central part of the project area – as described in Iverach et al., (2020), as well as zones where the aquitards are more extensive (e.g., informed by seismic data and the study by Turnadge et al., 2018).
- Additional pumping tests should target the Pilliga Sandstone aquifer (to improve understanding of its transimissivity, storativity and level of confinement in different regions), and further examine connectivity between the GAB and overlying Namoi Alluvium in the northern part of the study area. This is critical due to the large number of water supply bores in this region, and current uncertainty regarding the degree of flux/leakage between the GAB and Namoi alluvium. This uncertainty is evident in the contrasting estimates of GAB-Namoi alluvium inter-aquifer flows in groundwater modelling for the region, and the environmental tracer-based analysis published by Iverach et al., (2017) (see further discussion of this issue in the Response to Submissions, 2018 and Water Expert Panel report, 2020).

Data and analysis focused on characterizing aquitard vertical hydraulic, conductivity by the CSIRO during the Bioregional Assessment of the Namoi sub-region (Turnadge et al., 2018) provides some guidance on appropriate aquitard hydraulic parameters in the Purlawaugh, Napperby, Watermark and Porcupine formations. This should be incorporated into updated groundwater modelling conducted under the requirements outlined in condition B39. This core-based permeability analysis should however also be supplemented with pumping test analysis to elucidate more clearly the hydraulic behavior (i.e., aquitard leakage) under conditions of stress, allowing for improved understanding of inter-aquifer connectivity. Pumping tests in key areas - such as those where geological structures have been previously identified (see Iverach et al., 2020) or where these are newly discovered during drilling of the additional nested monitoring bore sites (outlined in section 1 above) would provide information to further constrain estimates of inter-aquifer flux during CSG production (as per condition B39).

7. Subsidence and seismicity

I am not an expert in the field of monitoring techniques for land subsidence and seismicity. The requirements outlined in condition B41 appear to be relatively self-explanatory, indicating that a detailed topographic baseline survey will be required. LiDAR is one interferometry technique which is now commonly used to obtain high resolution topographic elevation data, and a baseline and repeated LiDAR surveys could be one method to allow for the monitoring of subsidence associated with water and gas extraction. Monitoring for subsidence can also be conducted using a combination of in-situ sensors, e.g. borehole extensometers, and remote sensing techniques.

8. Groundwater dependent ecosystems

To accord with condition B41, as a minimum, baseline monitoring and characterisation of Groundwater Dependent Ecosystems (GDEs) needs to provide clear descriptions and field data from all known and potential GDEs within and surrounding the project area. This should involve an updated (and more comprehensive) GDE survey. This survey must address the methodological issues and gaps identified in the IESC's advice on the project, and the submission to the IPC by Dr Peter Serov in 2020. The survey should be based on direct observation, i.e., visiting and collecting appropriate groundwater, surface water and ecosystem condition data from all known and potential GDE sites.

The proponent should also (as a minimum) develop a conceptualisation of any GDEs and their dependence on groundwater - e.g., which aquifer(s) support the ecosystem, and to what extent, the recharge and discharge pathways for groundwater to reach the GDE, and baseline data to show how the GDEs vary in response to current (pre-development) changes in groundwater conditions through time, covering seasonal and inter-annual climate variability.

Existing characterisation of GDEs: The EIS and follow-up studies included limited information about GDEs within and surrounding the project area. It was noted by independent reviewers (including the IESC) that no direct field surveys of two springs identified as high priority GDEs by the NSW government - Hardys and Eather Springs – located to the immediate east of the project boundary was conducted (see locations on Figure 2 above). The IESC highlighted multiple other deficiencies in the GDE assessment methodology in the EIS, and recommended specific methodologies to address these:

> "In contrast to recommended approaches (e.g. Richardson et al. 2011; Serov et al. 2012), desktop analyses were used to exclude most of the Type 2 and Type 3 GDEs from field assessment. The GDE assessment was further limited as the risk assessment assigned low ecological values to many potential GDEs within the project area, based on scant or no field data collected by the proponent. Therefore, the risk assessment potentially under-estimates the potential impacts on GDEs in the project area."

With respect to stygofauna, the IESC noted that one field survey had been conducted, but highlighted its limitations and gaps, concluding that further data collection is still required:

> "The limited field sampling (from five shallow pits and nine bores that were sampled only once, Table 4 in EIS, Appendix C of Appendix G1) in the project area yielded no stygofauna. As stated by the proponent, stygofauna generally occur in low densities and the lack of animals does not conclusively indicate their absence from the site. At least 7 taxa of stygofauna have been collected from 15 monitoring bores in the Namoi River alluvial aquifer near Wee Waa, approximately 50 km west-northwest (and downstream) of Narrabri (Korbel 2012). Further

stygofaunal sampling should be undertaken, especially in the hyporheic zone of Bohena Creek and associated alluvium."

I am not aware of any subsequent field-based GDE surveys conducted in response to the IESC's or other experts' advice. The submission to the IPC in 2020 by ecologist Peter Serov (whose methodology was recommended in the IESC advice) also indicated that the lack of field-based GDE surveys remained a serious oversight in the impact assessment.

As a minimum, the proponent should therefore conduct the following further field surveys:

- Conduct a repeat and expanded stygofauna survey, including a wider number of bores, and targeting the Bohena Creek alluvium and Namoi Alluvium to the north of the project (as per IESC advice).
- Visit the two high value springs (Hardys and Eather springs), gauge groundwater and wetland/surface water levels and discharge rates from these, establish their source aquifer, and monitor the relationship between groundwater levels and spring hydrological and ecological conditions (see p. 2 of the IESC advice).
- Conduct a dedicated field-based survey of potential GDEs in the Bohena Creek area, ensuring the repeat stygofauna survey(s) covers multiple bores in the alluvium, and analyses alluvial groundwater discharge to the creek during different climatic periods (low flow and high flow).
- Develop conceptual models for any identified GDEs based on these field surveys
- Monitor baseline groundwater levels and their relationship to ecosystem health indicators at all identified GDEs.

For maximum/best practice requirements, detailed environmental isotope and other tracer studies of groundwater recharge, flow and discharge (as outlined in sections 2 and 3 above) along with tracer-based studies of ground-surface water interaction should be conducted in areas of identified/potential GDEs in order to improve conceptual models of GDEs and aid their monitoring and management. The use of multiple techniques (including environmental tracers) to characterize the source aquifer and flow pathway(s) to springs would follow a multiple-lines of evidence approach, as outlined in case studies of GAB springs in areas of coal seam gas development in Queensland – e.g. Flook et al., (2020).

Groundwater management and monitoring system

Condition B41 also specifies that the groundwater management plan should include:

> "a detailed description of the groundwater management and monitoring system, including a monitoring network that is capable of:
>
> - characterising temporal and spatial variations of all potentially affected water sources; − verifying actual direct and indirect water take;
> - providing an early warning of any impacts to potentially affected water sources, at varying depths in the geological profile;
> - providing data to improve the confidence level class of the groundwater model as soon as reasonable and feasible; and
> - integrating with any government monitoring networks in the area;"

These requirements should be met by ongoing monitoring using the infrastructure, data collection methods and monitoring frequencies outlined above for baseline characterisation of groundwater levels, quality, aquifer and aquitard health and GDEs (sections 1 to 8). Further, condition B41 requires that the GMP includes:

> "detailed performance criteria, including trigger levels for identifying and investigating any potentially adverse impacts associated with the development, on:
>
> - regional and local aquifers and aquitards (alluvial and hardrock);
> - ground subsidence and seismicity;

- ➢ groundwater supply and quality for other water users, including all potentially affected privately owned licensed groundwater bores;
  - ➢ groundwater dependent ecosystems; and
  - ➢ aquatic habitat and stygofauna;
- a program to monitor and evaluate:
  - ➢ compliance with the relevant performance measures listed in Table 7, and the performance criteria established above;
  - ➢ groundwater flows, quality and yield in regional and local aquifers and aquitards (alluvial and hardrock),
  - ➢ ground subsidence and seismicity;
  - ➢ geological fracturing and heterogeneity;
  - ➢ water loss/seepage/leakage from water storages and project related infrastructure into the groundwater system;
  - ➢ potential cross-contamination of aquifers, including migration from lower aquifers to the GAB; − sub-surface leakage of methane, drilling fluids and saline groundwater;
  - ➢ groundwater inflows, outflows and storage volumes to inform the Site Water Balance; − the effectiveness of the groundwater management systems;
- reporting procedures for the results of the monitoring program (including timely public reporting); and
- a plan to respond to any probable or actual exceedances of the groundwater performance criteria, and repair, mitigate and/or offset any adverse groundwater impacts of the development;"

Again, the additional infrastructure, sampling and monitoring activities outlined in sections 1 to 8 of this report should provide an adequate basis with which to address these aspects of the groundwater management plan. Note that in some cases, the appropriate trigger levels and performance criteria will need to be developed following the completion of (additional) baseline data collection, as performance criteria are typically based on statistical measures – e.g. specified level of variability compared to the mean or median values determined in baseline monitoring. A full discussion of these performance criteria is beyond the scope of this report.

Groundwater modelling

Condition B39 outlines the requirements (including additional data) for improvement and updating of the groundwater modelling completed for the Narrabri project to date. My primary expertise is in hydrogeology, geochemistry and environmental tracers in groundwater systems. While I have some familiarity and a basic level of expertise in groundwater modelling, I am not an expert groundwater modeller. As such, my comments with respect to these requirements are relatively brief.

The extract from Table 2-1 in the Australian Groundwater Modelling Guidelines (below) makes clear what is required for a Class 3 numerical groundwater model. Note that many of the requirements listed under 'Data' in this table align with the minimum baseline data requirements outlined in the earlier sections of this report. For example, the gaps identified above in the GAB and GOB monitoring bore networks require addressing, to obtain adequate spatial and temporal distribution of groundwater head observations (as per the first point in column 1). Aquifer-testing (as described in section 6 of this report) would also be required to define key aquifer parameters (Column 1, bullet point 5). Detailed quantification of current groundwater extraction volumes from each of the major aquifers would also be required to meet this confidence class.

A transient groundwater flow model (as required under condition B39) will require time-series water level data in each major aquifer unit to be collected and included as calibration datasets in future groundwater model runs. This requirement would be partially satisfied by the collection of additional baseline groundwater level data from the expanded monitoring network as outlined in section 1 of this report. In order to calibrate the model for the primary prediction(s) of interest – i.e., changes in groundwater levels and flux within and between the GAB and alluvial aquifers, this should include groundwater level timeseries from multiple bores within these units as well as in the Gunnedah-Oxley Basin, as this is the unit which will be most significantly and rapidly affected by drawdown due to coal seam gas extraction.

To meet the requirement of being a Confidence Class 3 model, calibration must also include both groundwater level (head) data, and flux data collected from the field (measured rates of groundwater discharge). The calibration data must therefore encompass both the baseline groundwater level monitoring hydrographs discussed above, and datasets reporting the flow/flux of water out of the aquifer system (e.g., volume of outflow per unit time at various locations). This could take the form of groundwater extraction volume data from each aquifer, water production volume data collected during pilot gas development and, particularly for shallow aquifers, monitoring of groundwater discharge flows from springs and/or into surface water bodies (e.g. using spring flow gauging, streambed seepage meters and/or complementary environmental tracer-based methods).

Determining the sensitivity of model predictions to key aquifer parameters (such as aquifer and aquitard vertical hydraulic conductivity and storage coefficients) should also guide future data collection and calibration efforts, as per the Australian Groundwater Modelling Guidelines (2012).

Table **Error! No text of specified style in document.**-1: Model confidence level classification—characteristics and indicators

Confidence level classification	*Data*	*Calibration*	*Prediction*	*Key indicator*	*Examples of specific uses*
Class 3	• Spatial and temporal distribution of groundwater head observations adequately define groundwater behaviour, especially in areas of greatest interest and where outcomes are to be reported. • Spatial distribution of bore logs and associated stratigraphic interpretations clearly define aquifer geometry. • Reliable metered groundwater extraction and injection data is available. • Rainfall and evaporation data is available. • Aquifer-testing data to define key parameters. • Streamflow and stage measurements are available with reliable baseflow estimates at a number of points. • Reliable land-use and soil-mapping data available. • Reliable irrigation application data (where relevant) is available. • Good quality and adequate spatial coverage of digital elevation model to define ground surface elevation.	• Adequate validation* is demonstrated. • Scaled RMS error (refer Chapter 5) or other calibration statistics are acceptable. • Long-term trends are adequately replicated where these are important. • Seasonal fluctuations are adequately replicated where these are important. • Transient calibration is current, i.e. uses recent data. • Model is calibrated to heads and fluxes. • Observations of the key modelling outcomes dataset is used in calibration.	• Length of predictive model is not excessive compared to length of calibration period. • Temporal discretisation used in the predictive model is consistent with the transient calibration. • Level and type of stresses included in the predictive model are within the range of those used in the transient calibration. • Model validation* suggests calibration is appropriate for locations and/or times outside the calibration model. • Steady-state predictions used when the model is calibrated in steady-state only.	• Key calibration statistics are acceptable and meet agreed targets. • Model predictive time frame is less than 3 times the duration of transient calibration. • Stresses are not more than 2 times greater than those included in calibration. • Temporal discretisation in predictive model is the same as that used in calibration. • Mass balance closure error is less than 0.5% of total. • Model parameters consistent with conceptualisation. • Appropriate computational methods used with appropriate spatial discretisation to model the problem. • The model has been reviewed and deemed fit for purpose by an experienced, independent hydrogeologist with modelling experience.	• Suitable for predicting groundwater responses to arbitrary changes in applied stress or hydrological conditions anywhere within the model domain. • Provide information for sustainable yield assessments for high-value regional aquifer systems. • Evaluation and management of potentially high-risk impacts. • Can be used to design complex mine-dewatering schemes, salt-interception schemes or water-allocation plans. • Simulating the interaction between groundwater and surface water bodies to a level of reliability required for dynamic linkage to surface water models. • Assessment of complex, large-scale solute transport processes.

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