Australia's National Science Agency

GISERA | Gas Industry Social and Environmental Research Alliance

Project Order

Short Project Title

Geochemical modelling and geophysical surveys to refine understanding of connectivity between coal seams and aquifers

Long Project Title	Integrating geochemical modelling and airborne geophysical surveys to refine the understanding of connectivity between coal seams and overlying aquifers
GISERA Project Number	W28
Start Date	01/07/2022
End Date	30/06/2024
Project Leader	Matthias Raiber

GISERA State/Territory

- ☐ Queensland
- ☒ New South Wales
- ☐ Northern Territory
- ☐ South Australia
- ☐ Western Australia
- ☐ Victoria
- ☐ National scale project

Basin(s)

- ☐ Adavale
- ☐ Amadeus
- ☐ Beetaloo
- ☐ Canning
- ☐ Western Australia
- ☐ Carnarvon
- ☐ Clarence-Morton
- ☐ Cooper
- ☐ Eromanga
- ☐ Galilee
- ☐ Gippsland
- ☐ Gloucester
- ☒ Gunnedah
- ☐ Maryborough
- ☐ McArthur
- ☐ North Bowen
- ☐ Otway
- ☐ Perth
- ☐ South Nicholson
- ☒ Surat
- ☐ Other (please specify)

GISERA Research Program

- ☒ Water Research
- ☐ Health Research
- ☐ Biodiversity Research
- ☐ Social & Economic Research
- ☐ Greenhouse Gas Research
- ☐ Agricultural Land Management Research
- ☐ Other (please specify)

1. Project Summary

CSIRO's GISERA has undertaken three projects on groundwater systems in the Gunnedah and Surat basins around Narrabri. Collectively, this body of work has generated important knowledge on the nature of these systems and potential for connectivity between primary target seams for coal seam gas (CSG) development and agricultural aquifers separated by approximately 300 – 700 m of inferred aquitards (Figure 1). CSIRO's research to date has found no *prima facie* evidence of strong connectivity between the target seams and agricultural aquifers, although some anomalous patterns of noble gases and dissolved methane concentrations in Surat Basin strata indicated that there may be potential localized connectivity. However, concern still exists among the community regarding potential drawdown at depth impacting on aquifer pressure in the confined Pilliga Sandstone aquifer and the adjacent alluvium. This proposed project will further improve our knowledge of these groundwater systems and refine the conceptual understanding of potential for hydrogeological connectivity pathways between shallow aquifers (including the Pilliga Sandstone and alluvial aquifers) and Gunnedah Basin formations (including the CSG target units) *via* a multi-disciplinary approach that combines existing data with targeted acquisition of new hydrochemistry, geochemistry, and geophysical survey data. The outcome of this project will include the generation of high-resolution 3D realizations of the subsurface that aim to represent continuous geological structures that will provide additional information on the potential for connectivity pathways between the CSG target units and adjacent groundwater systems.

The previous study by Raiber et al. (2022) suggested that the degree of connectivity/separation between the Gunnedah and Surat basins is spatially variable across different parts of the Narrabri Gas Project (NGP) area, with little or no connection inferred in the south and east and some limited data pointing to potential connectivity at depth identified at the north- and north-western margin of the current NGP petroleum leases. The acquisition of airborne electromagnetic (AEM) survey data will help to provide a more continuous 3D image and geological model of the upper approximately 400 m of the subsurface and close spatial gaps, ensuring that no major concealed structures have been missed by wider-spaced seismic surveys. To date hydrogeology modelling has largely focused on coal seams in the Gunnedah Basin and the impact of depressurization on fluid flow in these coal seams and adjacent deep saline aquifers. Less attention has been paid to developing a full understanding of the intervening stratigraphy to depths of 400 m between the top of the Gunnedah Basin formations and Surat Basin formations which contain confined agricultural aquifers. Improved understanding of the stratigraphy, hydraulic characteristics, connectivity and groundwater dynamics in these intervening layers will improve our ability to predict potential impacts of depressurization of the coal seams at depth. Rock samples and groundwater samples (e.g. from the Gunnedah Basin and Purlawaugh Formation) will be analysed for their hydrochemical and environmental tracer signatures, thus allowing to chemically and isotopically 'fingerprint' the different formations.

The existing and newly acquired data and knowledge will be integrated into a 3D hydrogeological and geochemical model framework that characterizes the geometry of the subsurface including stratigraphic layers and geological structures and groundwater dynamics. This will then provide the conceptual hydrogeological model and stratigraphic model structure to underpin future groundwater modelling studies, thus forming the basis for a comprehensive assessment of potential hydrogeological connectivity pathways and helping to answer the question whether the exclusion of geological structures from numerical groundwater impact models is warranted.

2. Project description

Introduction

In the Narrabri region (NSW) there are conflicting views on the presence and role of faults and other geological structures (e.g., igneous intrusions such as dykes and sills) on groundwater dynamics and potential hydrogeological connectivity between target coals seams and agricultural aquifers such as the Pilliga Sandstone and alluvial aquifers (Raiber et al., 2022).

In a recent explanatory draft note on the characterisation and modelling of geological fault zones prepared for the Independent Expert Scientific Committee (IESC) on Coal Seam Gas and Large Coal Mining Development, Murray and Power (2021a) noted that "*In some cases, faults can have little to no influence on groundwater flow, and in other situations faults can provide a barrier, a flow pathway or both that results in significant changes to water assets and GDEs*". Whether a fault (or another type of geological structure) forms a hydraulic barrier or conduit to groundwater flow (or more broadly fluid flow including gases such as methane) depends on many factors, including the juxtaposition (the degree of displacement) of aquifers versus aquitards across the faults, the hydrogeological properties of the fault zone, the regional stress regime and the orientation and magnitude of the hydraulic gradient in and around fault zones (e.g., Bense et al., 2013; Murray and Power, 2021 a, b).

To date, geological structures such as faults and igneous intrusions, and their associated hydraulic properties have not been represented in the groundwater models developed to predict potential impacts from the proposed Narrabri Gas Project (NGP) or subsequent groundwater models developed to predict cumulative impacts from CSG and coal mining activities in the Narrabri region (as discussed by Turnadge et al., 2018), as previous conceptualisations assumed that faults and structures are not relevant (NSW DPIE, 2020).

However, multiple recent studies and private or institutional submissions to the Independent Planning Commission (IPC) have suggested that additional work would be beneficial to confirm the role of geological structures on potential hydrogeological connectivity between CSG target coal seams and agricultural aquifers and confirm that their omission from groundwater models is warranted.

Submissions and recommendations from the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC, 2017), the Water Expert Panel (WEP) report (NSW DPIE, 2020), which formed part of the IPC approval process for the NGP, and others related to multiple major areas of hydrogeological research where additional work was recommended to reduce uncertainties, including the:

- refinement of the characterisation of geological structures in the NGP area;
- assessment of the spatial continuity of inferred aquitards such as the Purlawaugh Formation;
- collection of baseline hydrochemistry, methane and isotope data;
- confirmation that the omission of geological structures from groundwater models is warranted.

For example, in its advice on the NGP the IESC (2017) suggested that further "*characterisation of fault displacements and provision of fault and geological/stratigraphic analyses and data to support the geological conceptualisation are required*", including the collection of field-based groundwater data and provision of additional information on faults such as the presence or absence of gas shows in the Surat Basin strata (IESC, 2017). The IESC (2017) also recommended that a further assessment of the degree of faulting in the Narrabri region and the likely impact on aquifers during and post CSG development is necessary to justify omission of geological structures from the numerical groundwater model. This was also highlighted by the WEP (NSW DPIE, 2020).

The WEP in its final report (NSW DPIE, 2020) concluded that it is unlikely that faulting constitutes a major risk to the project based on evidence provided by Santos (the NGP proponent) since major faulting mainly displaces Permian and, to a lesser extent, Triassic strata, and that only minor displacements (5-40 m) are observed within the Surat Basin strata. This was also suggested by a recent study by Raiber et al. (2022), which did not identify evidence for significant vertical offsets of major formations within the Surat Basin. However, the WEP indicated that even a vertical displacement of only 40 m at a fault zone could potentially juxtapose different aquifers and result in impact on groundwater flow and flow paths that may not be recognised from the existing numerical groundwater models. They suggested that this may have an impact not only on groundwater flow but also on the risk of gas migration and pollution of aquifers and recommended that this needs further consideration.

Additional work recommended by the WEP includes characterisation of neotectonic activity in the NGP region, which could be a valuable addition to the existing structural data sets. This also relates to the variability and heterogeneity in the Surat Basin sedimentary sequence in which the Pilliga Sandstone aquifer lies, including the continuity of inferred aquitards such as the Purlawaugh Formation (which forms the base of the Surat Basin underneath the Pilliga Sandstone, the major GAB aquifer in this area). The WEP highlighted that the Purlawaugh Formation is not present everywhere (although it is likely considered to be continuous in groundwater numerical models developed to date), which may have some implications to connectivity. This is also in agreement with the recent study by Raiber et al. (2022), which suggested that the Purlawaugh Formation thins significantly from east to northwest and is locally absent at the north-western margin of the NGP area (Figure 1, discussed further in the section 'Prior Research').

Turnadge et al. (2018) also emphasised that additional work is required to characterise the spatial continuity of the aquitards and to determine if they are compromised by seal-bypass structures such as faults and igneous intrusions, and the IESC (2017) suggested that additional information on faults (e.g. the presence or absence of gas shows in the Jurassic sequence) and the sub-crop of strata should also be collected to further refine the hydrogeological conceptualisation of geological structures that may influence groundwater dynamics.

Further points raised by several public submissions to the IPC, by the IESC advice, the WEP and by the study by Raiber et al. (2022) are related to the availability of hydrochemistry, isotopes, and methane baseline data. For example, the IESC recommended that "*the collection and analysis of isotope data could provide more confidence in the overall water balance, mixing, and conceptual models of geology and associated connectivity*. *Should outcomes of this analysis indicate a larger role of geological features of different/various scales on groundwater flow in the region, further consideration could be given to geophysical methods to inform the conceptual and geological model*." Similarly, the WEP comments that some stakeholders suggested that the baseline data (including data relating to water quality/chemistry in the different aquifers and the methane concentrations of surface water and groundwater) collected to date for the NGP may be inadequate or incomplete. They also recommend that it is "*generally considered important to collect such baseline data, and to capture baseline readings accurately so that any future changes can be detected, and their causes identified*" and recommend that "*Santos investigate whether changes in groundwater chemistry over time could be used as a reliable means of detecting the migration of groundwater and dissolved salts from the lower aquifers to the GAB*". The availability of baseline hydrochemistry and environmental tracer data was also addressed in the recent study by Raiber et al. (2022), which showed that there is an overall good baseline understanding of the spatial variability of hydrochemistry and methane concentrations within the Pilliga Sandstone aquifer and hydrochemistry within the major CSG target Maules Creek Formation, whereas there are only limited data available from the Purlawaugh Formation and Gunnedah Basin formations such as the Digby Formation. The authors suggested that this poses uncertainties on the understanding of hydrogeological connectivity between Gunnedah Basin and major agricultural aquifers and highlighted the opportunity to close this knowledge gap by collecting samples from the new NSW DPIE/Water NSW water monitoring network for coal basins (NSW DPIE, 2019).

The research proposed by this project proposal relates closely to all points raised above by the IESC (2017), the WEP (NSW DPIE, 2020) and other stakeholders, as will be described in more detail in following sections. The proposed research involves four major tasks:

- Conducting an **airborne electromagnetic survey** to enhance the understanding of geological structures and the geometry of Surat and upper Gunnedah basins strata in the upper ~400 m (including identification of neotectonic features). This will significantly improve the understanding of neotectonics and potential connectivity pathways and form an additional safeguard to ensure that no significant geological structures were missed by previous assessments (which were based mostly on wider-spaced seismic surveys). It will also form the basis for the development of an improved 3D geological model that represents geological structures.

- Collection of baseline data, with a focus on collection of samples from bores in the Gunnedah Basin (using the new NSW DPIE/Water NSW groundwater monitoring bore network). It is generally acknowledged that **baseline hydrochemical and environmental tracer surveys** are a fundamental part of the fault zone characterisation and have the potential to reduce the conceptual uncertainty and identify "unknown unknowns" such as faults that may not be picked up in data sparse regions by limited geophysical surveys. This will build upon the work conducted by other authors (e.g., Cresswell, 2014; Santos, 2017a, b; Iverach et al. (2017, 2020), Suckow et al. (2019) and the recent study by Raiber et al. (2022)).

- **Mineralogical characterisation** of stratigraphic formations: this will help to assess the composition and the heterogeneity of major geological formations (Gunnedah Basin and Surat Basin). It will also involve age dating some of the igneous intrusions intersected within the NGP area to refine the understanding of the structural and tectonic history of the NGP area.

- **Geochemical modelling** to test some of the hydrogeological models of potential connectivity pathways presented in the recent study by Raiber et al. (2022).

This additional proposed research will directly address another point raised by the IESC (2017) and WEP (2020) on whether the exclusion of geological structures from groundwater models in the NGP area is justified. The proposed research will provide the conceptual hydrogeological models, 3D geological models and general baseline understanding that is required for the numerical assessment of the influence of geological structures, and this research can therefore directly inform such concurrent groundwater impact modelling exercises as proposed by Janardhanan (2022).

Prior Research

This proposed project builds on several previous studies (e.g. Cresswell, 2014; Iverach et al., 2017, 2020; Santos, 2017 a,b; Raiber and Suckow, 2018 and Suckow et al., 2019; Raiber et al., 2022).

The previous GISERA project 'Assessment of faults as potential connectivity pathways' (Raiber et al., 2022) assessed the influence of geological structures (e.g. faults and igneous intrusions) on the hydrogeological connectivity between the Gunnedah Basin (which hosts the CSG target units) and shallower aquifers (e.g. Pilliga Sandstone and alluvium) through integration of existing and newly acquired geophysical, hydrogeological, hydrochemical and environmental tracer data.

The assessment of the aquifer geometry and subsurface structure based on the integration of multiple data sources helped to identify several potential hydrogeological connectivity pathways (Figure 1) and to hypothesize where different pathways are likely to be present or absent. For example, the results indicated that there is likely only limited or no hydrogeological connectivity between Gunnedah Basin strata and the Pilliga Sandstone in the south and east of the NGP area, where groundwaters of the Pilliga Sandstone are very fresh (represented by low electrical conductivities in Figure 2). In contrast, the study suggested that there is some likely input from underlying hydrostratigraphic units into the Pilliga Sandstone groundwater in the north and north-west of the NGP area. This was indicated by the presence of basement highs identified in this region and the change of hydrochemistry from south and east towards the north- and north-west observed within the Pilliga Sandstone aquifer.

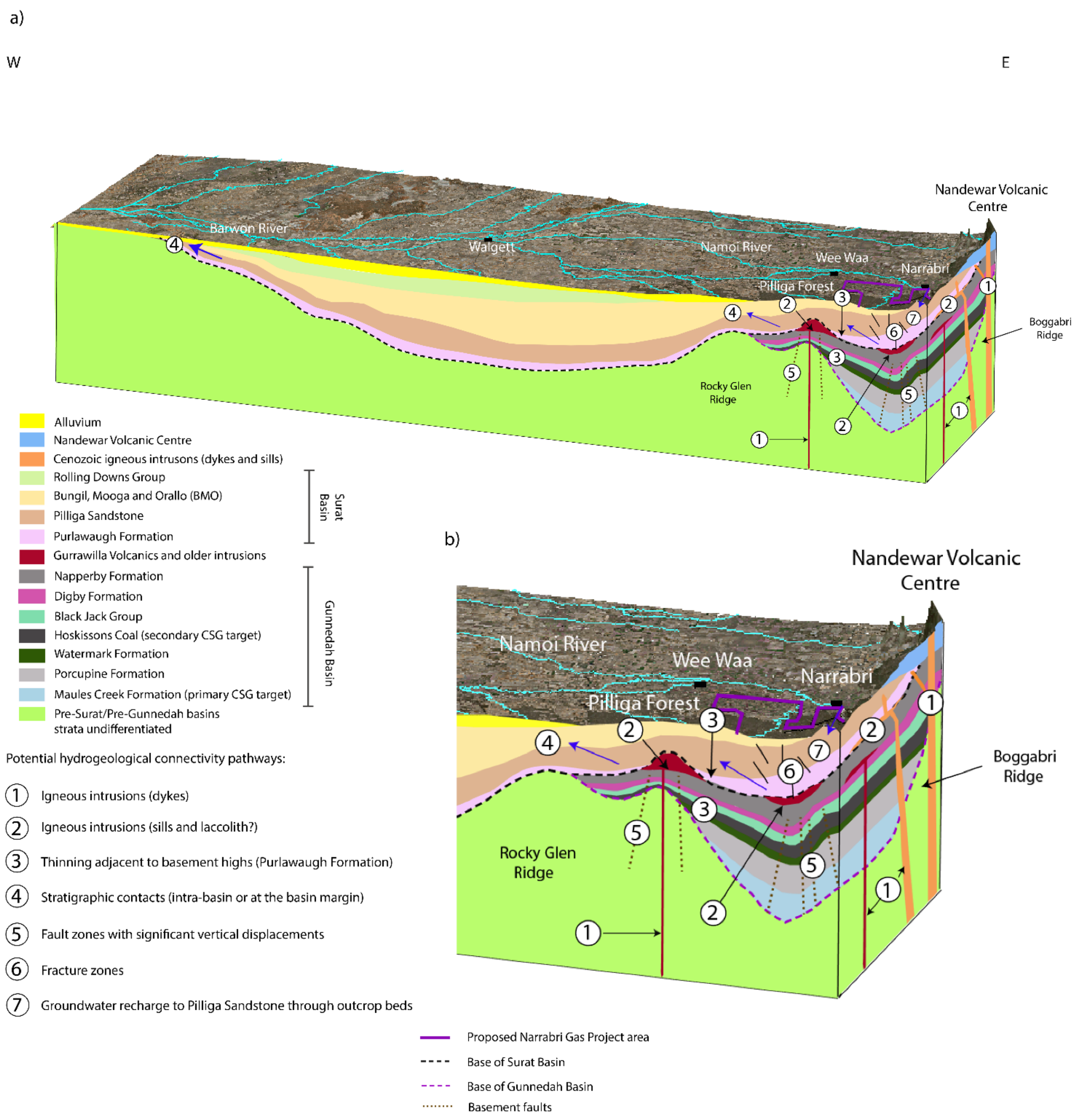


Figure 1 – a) Block diagram showing the conceptual hydrogeological connectivity pathways in the central/northern Coonamble Embayment (revised from Suckow et al., 2019); and b) zoom into the eastern part of the block model (Raiber et al., 2022).

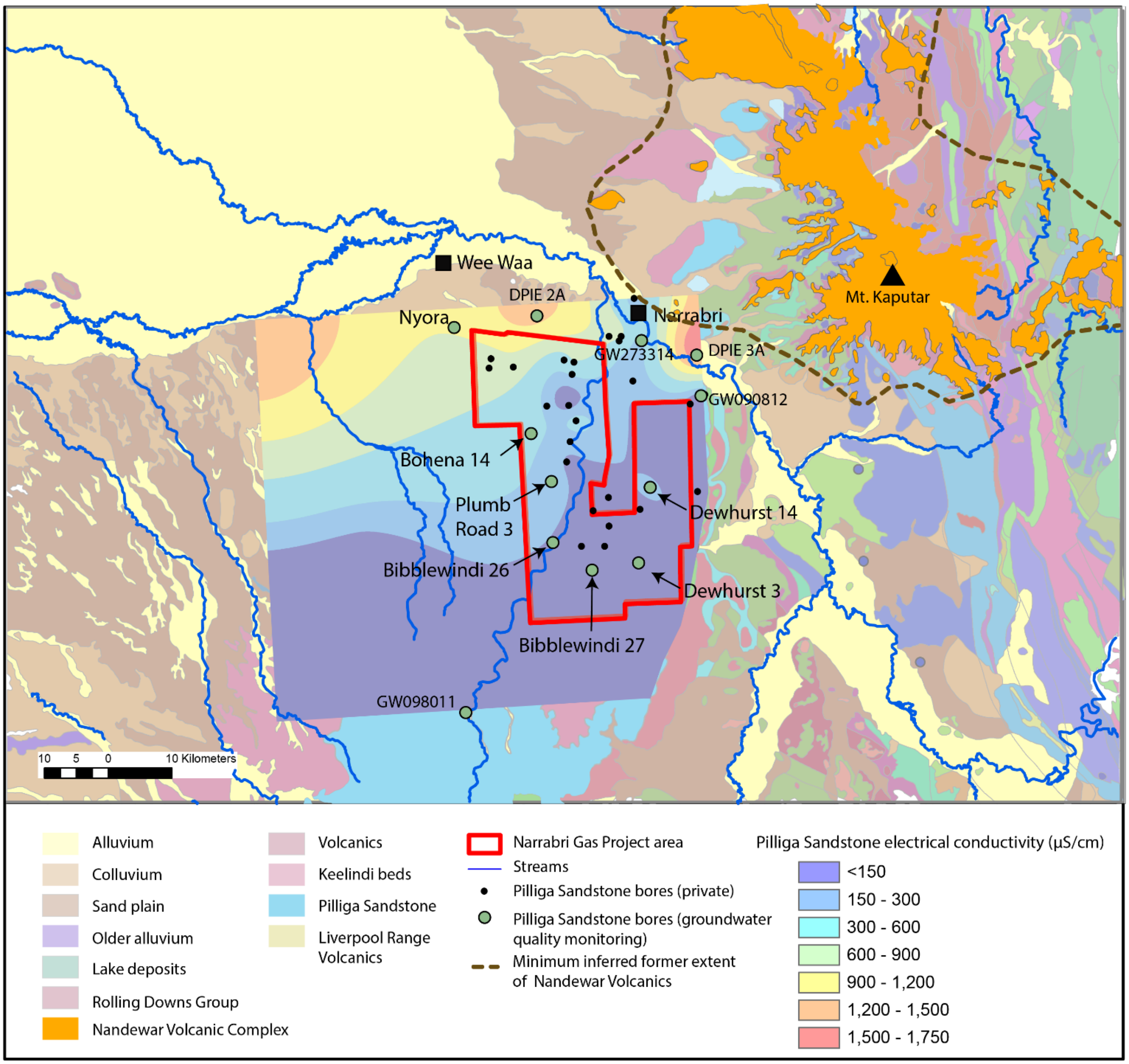


Figure 2 – Electrical conductivity (EC) of groundwater in the Pilliga Sandstone in the Pilliga area (Raiber et al., 2022).

Importantly, the assessment also identified on-going knowledge gaps, related to specific areas within the wider NGP area where the understanding on connectivity remains uncertain due to a lack of baseline data or geological complexity. The major knowledge gaps identified by Raiber et al. (2022) are:

- the increase of the electrical conductivity towards the north-west (Figure 2) indicates that there is likely a small admixture of more saline Gunnedah Basin groundwater to the Pilliga Sandstone aquifer. However, Raiber et al. (2022) also concluded that the change in hydrochemistry could also be at least partly explained by other processes such as ion exchange and mineral dissolution; the authors therefore suggested that additional baseline data (e.g. rock mineralogy and hydrochemistry and environmental tracer data from formations underlying the Pilliga Sandstone) and more comprehensive geochemical models are required to attribute these changes to different processes.

- Some lineaments have been identified in the south-west corner of the NGP area, and the inference of absence of major structures in the south and east of the NGP area ideally requires confirmation as it is currently primarily based on widely-spaced seismic surveys.
- The subsurface geometry in the western part of the NGP area is defined mostly based on relatively widely-spaced seismic surveys, with relatively little well control. The presence of igneous plugs and associated anticlines in the north and west is well documented (e.g., Eastern Star Gas, 2004), but their extent and the geometry of aquifers in between them can be further refined. To date, these anticlines and other geological structures have not been represented in groundwater models which form the basis for impacts assessments (Turnadge et al., 2018).
- The conclusions from the hydrochemical and environmental tracer assessment and end-member mixing models are currently based on a very small number of hydrochemical records from the Purlawaugh Formation (records from two groundwater bores available) and shallow Gunnedah Basin formations (records from three groundwater bores available), whereas significantly more hydrochemical records are available from the Pilliga Sandstone and Maules Creek Formation (primary CSG target). The lack of data available from multiple formations underlying the Pilliga Sandstone (e.g. Purlawaugh Formation and Digby Formation; Figure 1) results in on-going uncertainties of conceptual models and mixing calculations.

Relevant State/Territory Government independent reviews

As explained by NSW DPIE (2019), the NSW Chief Scientist and Engineer's Independent Review of Coal and Coal Seam Gas (CSG) Activities in NSW raised concerns on a lack of baseline data and the ability to accurately determine the impact of extractive industries. Amongst other things, these concerns led to the development of an expanded groundwater monitoring bore network, aiming to improve the understanding of groundwater dynamics and provide baseline water level and hydrochemistry/environmental tracer data to better assess the impact of extractive industries on water resources in coal basins in NSW. This investment has formed part of the NSW government's Water Monitoring Strategy for Coal Basins in NSW (NSW DPIE, 2019), which has been established in 2014 and was completed in 2020.

The proposed research directly relates to the concerns about the lack of baseline data. In two recent GISERA studies by Suckow et al. (2019) and Raiber et al. (2022), two of the first groundwater bores which were drilled within the NGP area as part of the NSW Water Monitoring strategy for Coal Basins were sampled at Plumb Road (Figure 3). Most bores were drilled between 2018 to 2020 and could therefore not be sampled by these previous GISERA projects. Raiber et al. (2022) highlighted the lack of baseline data from the Purlawaugh Formation and Gunnedah Basin strata (e.g. Digby Formation and Napperby Formation), and as shown in Figure 3, these new groundwater monitoring bores provide an excellent opportunity to close this gap, as they are screened mostly within the Gunnedah Basin strata and the Purlawaugh Formation.

It should be noted that NSW DPIE (2020) has already expressed support for CSIRO to sample these new bores as part of this proposed GISERA project.

The role of faults as potential connectivity pathways was also highlighted in multiple background papers commissioned in support of the independent review from the NSW Chief Scientist. For example, a report on the geology in support of the NSW Chief Scientist and Engineer's Independent Review of Coal and Coal Seam Gas (CSG) Activities in NSW highlights that the Gunnedah Basin and the overlying Surat Basin are likely to be hydraulically connected in some locations, but that there is currently only limited knowledge about where hydraulic connections between CSG target units and agricultural aquifers exist (Ward and Kelly, 2013).

A discussion on the potential presence of preferential flow paths through aquitards via geological structures was also presented in a report on the groundwater resources in relation to coal seam gas production (Anderson et al., 2013). In agreement with recommendations by the IESC (2017) and the WEP (NSW DPIE, 2020), a report of the NSW Chief Scientist also suggested that natural methane leaks through fault lines (more generally in coal basins rather than specifically relating to the Narrabri Gas Project area) raise the importance of both obtaining baseline measurements of methane over a period of time and raises the importance of using sophisticated monitoring techniques to be able to differentiate between different methane migration pathways (O'Kane, 2013). The challenge of obtaining representative baseline values for methane concentrations will also be addressed by this proposed research, as the study by Raiber et al. (2022) and a recent study by Banks et al. (2019) in the Gloucester Basin in NSW showed considerable differences in methane concentrations depending on sampling technique and depth of pump placement.

The review by O'Kane (2014) also recommended that conceptual models of the subsurface should be represented in 3D and represent "*hydrostratigraphic layers for flow models, map pathways of connectivity and map fault planes and fracture networks*". The document also references the report produced by Ward and Kelly (2013), which explains that 3D geological models considering faults and fracture networks for proposed CSG areas in NSW (including the NGP area) were limited at that point in time.

The final report from the NSW Chief Scientist recommended that "*more detailed knowledge of the structure and composition (especially regarding hydrogeology) of the sedimentary basins is needed to enhance productivity for the CSG industry through more precise resource characterisation and better subsurface and surface environmental management*" (O'Kane, 2014). Furthermore, it emphasized the need for commissioning of "*formal scientific characterisation of sedimentary basins starting with the East Coast basins and concentrating initially on integration of groundwater with the geological,* *geophysical and hydrological context. Viewing these integrated systems in models and in interpretation could be described as a 'Glass Earth' approach to understanding the dynamics of activities and impacts in the basins*" (O'Kane, 2014).

This proposed project will directly address all the recommendation from the NSW Chief Scientists' recommendations.

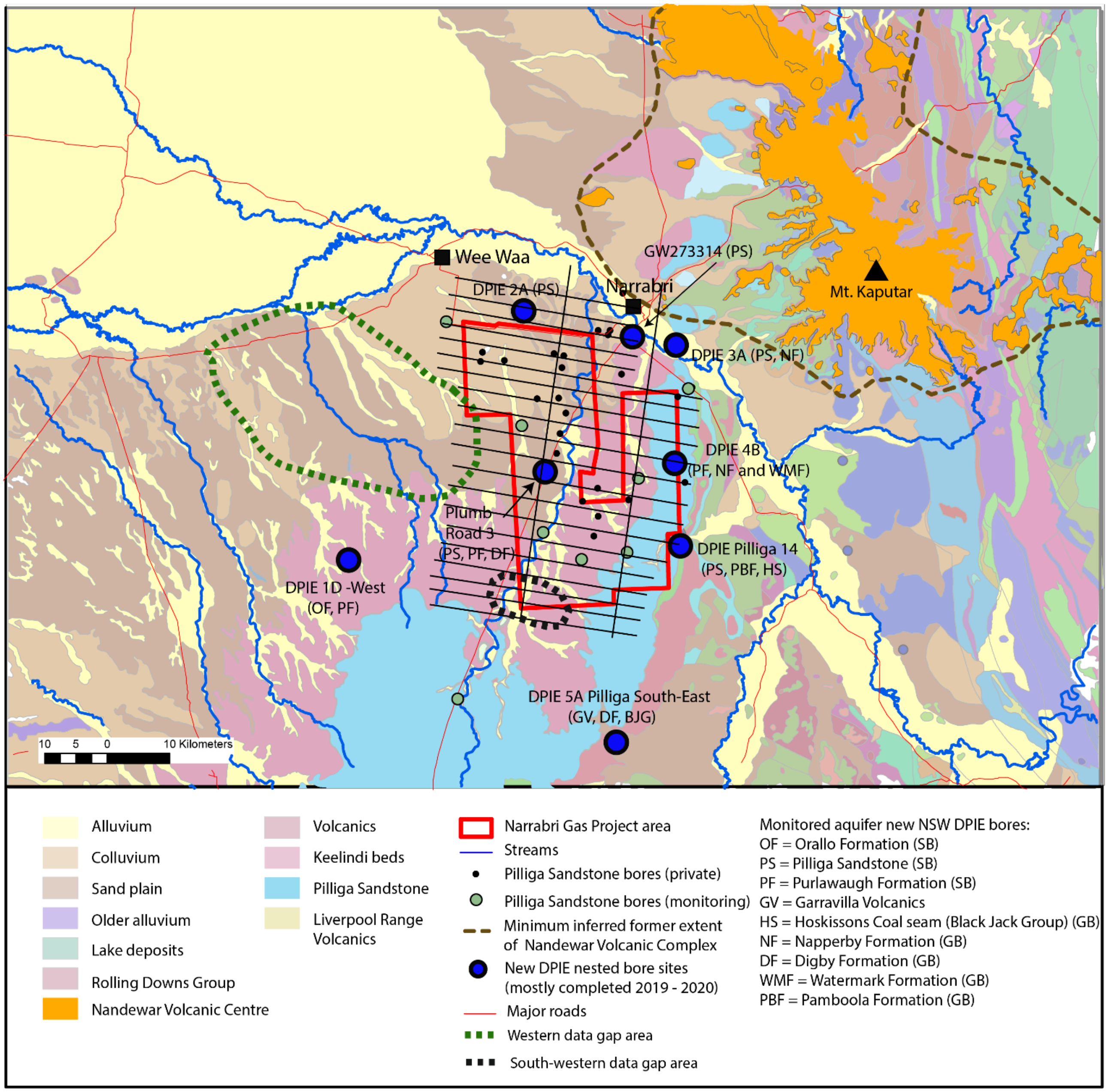


Figure 3 – New NSW DPIE groundwater monitoring bores (drilled mostly between 2018 and 2019) in the wider Narrabri Gas Project area available for sampling (Raiber et al., 2022) and a hypothetical grid of airborne electromagnetic (AEM) survey lines (black lines). SB refers to bores screened within the Surat Basin, and GB corresponds to bores screened within the Gunnedah Basin.

Need & Scope

In hydrogeological investigations where potential impacts of CSG developments on water resources (quality or quantity) are assessed, understanding the role of subsurface architecture and geological structure is very important. This includes the spatial representation of the lateral continuity and thickness of aquitards (or seals) and faults, the location of faults relative to the extraction wells, fault displacements, the hydraulic role of faults as either barriers or conduits to fluid migration and the composition and hydraulic properties of any fault zones (e.g., Raiber et al., 2016; Mallants et al., 2018; Underschultz et al., 2018; Murray and Power, 2021a, Murray and Power, 2021b).

In particular, understanding the integrity and continuity of aquitards is critical to identifying potential impacts of CSG activities on shallower groundwater resources. Whether aquitards form an effective seal depends on the presence and characteristics of fault zones (and other seal bypass features such as igneous intrusions) and the geometry of the geological compartments defined by the faults or fractures. If aquitards are compromised by a seal bypass (e.g. a fault or an igneous intrusion), the pressure change could be potentially transmitted at a higher velocity than the regional flow rate with potential impacts extending to the uppermost aquifers and surface water. Furthermore, it may be possible that prolonged depressurization may reactivate a fault zone, and thus create connections that were not active prior to the aquifer depressurization.

The geometry of the subsurface including aquifer and aquitard extent, thickness and heterogeneity and characteristics of seal bypass features are commonly described using a conceptual hydrogeological model. As shown by Raiber et al. (2022) and in studies by the Queensland Office of Groundwater Impact Assessment (e.g., OGIA, 2020), there is a need for, and value from, having an iterative approach in conceptual model development. Raiber et al. (2022) showed how the conceptual understanding of subsurface geometry in the Narrabri region has considerably evolved from previous studies, highlighting the value of combining existing geological, geophysical and hydrochemical/environmental tracer data with targeted and cost-effective acquisition of new geophysical survey and hydrochemistry/environmental tracer data. The study by Raiber et al. (2022) has also identified multiple on-going knowledge gaps (described in the section on *Prior Research*) that cannot be closed with the currently available data.

Conducting an AEM survey using a regular grid would provide extremely valuable insights into the subsurface to considerable depths (likely extending to depths beyond 400 m). These non-invasive AEM surveys are typically flown along regular transects (e.g., following a survey design similar to the hypothetical grid in Figure 3), and application of this technique would therefore provide a more continuous three-dimensional image and geological model of the upper 400 m of the subsurface than most ground-based geophysical techniques (which are constrained by the presence and access of roads and complicated by the dense vegetation within the Pilliga Forrest area).

The outputs of an AEM survey would support filling the following knowledge gaps identified by Raiber et al. (2022):

- in the north and west of NGP area: confirm the thinning and pinching out of the Purlawaugh Formation and consequently its confinement potential, which directly controls inter-aquifer connectivity (with overlying and underlying units), and further characterise the spatial distribution and geometry of anticlines associated with intrusions;
- in the south and east of NGP area: confirm the near absence of anticlines, the limited evidence for reactivation of major basement faults within the Surat Basin formations, and the lack of igneous intrusive activity inferred by the current assessment.

In addition, this proposed research would also provide critical hydrochemical and environmental tracer baseline data for specific formations where there is currently a lack of data. It will also make use of a new groundwater monitoring bore network, installed by NSW DPIE as part of the NSW Water monitoring strategy for coal basins (NSW DPIE, 2019). This groundwater monitoring bore network comprises 13 multi-level groundwater monitoring bores in the Purlawaugh Formation and Gunnedah Basin formations, which are the formations for which Raiber et al. (2022) have identified an on-going lack of baseline hydrochemistry and environmental tracer data (Figure 3). This highlights the value of emplacement of these new groundwater bores and the synergies between the NSW Water monitoring strategy and the proposed sampling campaign. The NSW DPIE has already indicated support for these groundwater bores to be sampled by the proposed project.

The integration of existing and new data will also help to underpin further groundwater model developments to test different conceptual hydrogeological models (and thus, help to reduce uncertainty of predictions) and provide the geological and hydrogeological understanding required for data analysis to assist with management decisions (e.g., placement of monitoring wells).

Objective

In order to determine if geological structures (or seal bypass structures) such as faults and igneous intrusions compromise the continuity and performance of seals/aquitards located between the shallow aquifers and the CSG target strata, and if they form actual pathways, integrated scientific approaches are required using aspects from both groundwater and petroleum system approaches (e.g., Underschultz et al., 2016; Mallants et al., 2018; Murray and Power, 2021a). A study by Raiber et al. (2022) provided a comprehensive assessment on the significance of seal bypass structures as potential hydrogeological connectivity pathways between the coal seams (hosted within the Gunnedah Basin) and the shallower aquifers (Pilliga Sandstone and alluvium) in the wider Narrabri region. Potential pathways identified by this study included faults and igneous intrusions (e.g., dykes, which are igneous intrusive bodies that are often near-vertical and cross-cut (intrude into) horizontal sedimentary formations along pre-existing faults or fractures). The study identified areas within the

NGP area where there (1) are unlikely to be any notable connectivity between the Gunnedah Basin strata and shallow aquifers, (2) where there may be some connectivity, and (3) where a lack of existing baseline data means that there is on-going uncertainty.

The overall objective of this project is to further test and refine the conceptual hydrogeological models of connectivity pathways presented by Raiber et al. (2022), as described in previous sections.

Methodology

The proposed project will follow a multi-disciplinary approach that integrates data from a wide range of different disciplines (e.g., geology, hydrogeology, geophysics, hydrochemistry and environmental tracers) (Figure 4). It will build upon the geoscientific evidence compiled as part of a study by Raiber et al. (2022), complemented with additional highly targeted data acquisition campaigns. Together, the currently available and newly acquired data will be integrated to refine the, or develop alternative, conceptual hydrogeological models of connectivity pathways.

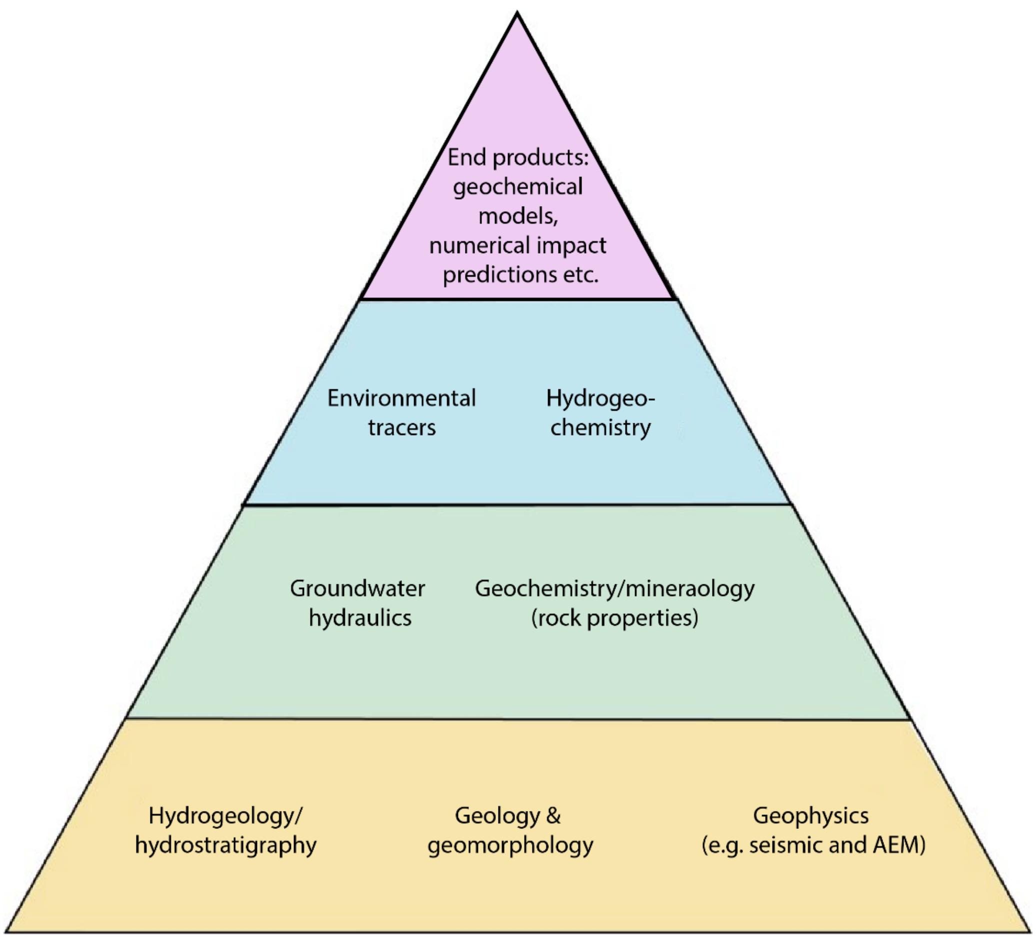


Figure 4 – Integrated approach for the assessment of presence and role of geological structures.

The major components of the proposed project area:

- **Collection of additional hydrochemistry and environmental baseline data (Tasks 1 and 4):** analysing additional samples from the Purlawaugh Formation and shallow Gunnedah Basin hydrostratigraphic units (e.g., Digby Formation and Napperby Formation and Hoskissons coal seam) would provide critical pre-CSG development data and reduce the uncertainty of geochemical mixing models. NSW DPIE have installed new monitoring wells throughout the region over the last few years (mostly developed between 2019 to 2020) as part of its NSW Coal Basins water monitoring strategy, with many of the bores screened within the formations inferred to interact with the Pilliga Sandstone (Figure 1). In addition to the suite of parameters collected for the 'Assessment of faults as potential connectivity pathways' project, external inputs from a project on the characterisation of microbiological parameters could help to confirm the source for methane observed in the Pilliga Sandstone or alluvial aquifers.

- **Collection of core samples for mineralogical analysis (Task 2):** To further understand the relative importance of inter-aquifer mixing and hydrogeochemical evolution from rock-water interactions, analysis of existing core samples (readily available from the NSW core library) from selected bores of key formations (e.g., Pilliga Sandstone, Purlawaugh Formation, Digby Formation and Early and Late Permian coal seams) for $^{87}Sr/^{86}Sr$ and mineral assemblage is considered necessary. Furthermore, our study (and other previous studies) highlighted the significance of igneous intrusions in this area; establishing the timing of these intrusions will assist in understanding when structural and tectonic activity and potential deformation has occurred. Analysing the age of selected intrusive rocks within the NGP area for their age and timing would further help to understand the structural history of this area.

- **Conduct an airborne electromagnetic (AEM) survey (Task 3):** the TEM surveys conducted during the Raiber et al. (2022) study confirmed that there is a lack of a conductive cover. This suggests that conducting an AEM survey using a regular grid would provide extremely valuable insights into the subsurface to considerable depths (likely extending to depths beyond 400 m). This would underpin the assessment of the aquifer framework presented in that study and importantly also allow to identify concealed structures that may be present in areas not covered by previous geophysical surveys. Unlike other geophysical techniques (e.g. seismic or ground-based TEM), non-invasive airborne geophysical techniques are not constrained by the presence and access of roads and complicated by the dense vegetation within the Pilliga Forrest area. However, pipelines and power lines ("cultural features") can cause interference, although the effects of this interference can be removed during inversion. It would be beneficial to conduct such a survey prior to commencement of emplacement of further infrastructure. A hypothetical example of how a grid of flight lines could be designed is shown in Figure 3.

- **Geochemical modelling to determine the relative contribution of admixture (discharge) from deeper formations versus mineral dissolution processes on the hydrochemical signature of the Pilliga Sandstone (Task 5):** Expanding the end-member mixing modelling conducted during this project to a comprehensive geochemical mixing model, including the selection of multivariate parameters and the assessment of uncertainty of end-members and potential hydrochemical reactions is considered the most reliable approach to further reduce the uncertainty of interpretations from the Raiber et al. (2022)study. This could build on all the data collected and compiled during the previous project and be combined with opportunities above, resulting in a comprehensive geochemical mixing model for the NGP area.

- **Data integration and conceptual model refinement (Task 6):** The data acquired throughout this project will be combined with data from previous projects.

3. Project Inputs

Resources and collaborations

Researcher	Time Commitment (project as a whole)	Principle area of expertise	Years of experience	Organisation
Matthias Raiber	68 days	Geology, hydrogeology and hydrochemistry (including environmental tracers)	18	CSIRO
Aaron Davis	85 days	Geophysics	20	CSIRO
Alec Deslandes	25 days	Environmental tracers	12	CSIRO
Henning Prommer	50 days	Groundwater- and geochemical modelling	30	CSIRO / University of Western Australia
Hydrogeologist/Hydrochemist	49 days	Geology, hydrogeology, and hydrochemistry (including environmental tracers)	7	CSIRO
Guangliang "Justin" Wu	80 days	Geophysics/geology	7	CSIRO

Subcontractors (clause 9.5(a)(i))	Time Commitment (project as a whole)	Principle area of expertise	Years of experience	Organisation
Dr. Dioni Cendón	N/A	Environmental tracer analysis	>25	ANSTO
Streamline Hydro (or similar environmental consultancy)	N/A	Hydrogeology	>10	As per first column
Geophysical company (AEM), provider to be confirmed	N/A	Geophysical surveys	>10	As per first column

Technical Reference Group

The project will establish a Technical Reference Group (TRG) aimed at seeking peer-to-peer technical advice on contextual matters and to discuss research needs as well as outputs as the project progresses. The TRG will include the project leader and a group of different stakeholders as appropriate which may include:

- Representative from NSW Department of Planning, Industry and Environment (DPIE)
- Associate Professor Bryce Kelly (University of New South Wales)
- Dr. Dirk Mallants, CSIRO Land and Water, Adelaide
- Dr. Harald Hoffman (University of Queensland)
- Santos representative (to be advised by Santos)
- Geoscience Australia representative (to be confirmed)

Budget Summary

Source of Cash Contributions	2021/22	2022/23	2023/24	2024/25	2025/26	% of Contribution	Total
GISERA	$0	$495,498	$347,140	$0	$0	80%	$842,838
- Federal Government	$0	$414,980	$290,730	$0	$0	67%	$705,710
- NSW Government	$0	$80,518	$56,410	$0	$0	13%	$136,929
Total Cash Contributions	**$0**	**$495,498**	**$347,140**	**$0**	**$0**	**80%**	**$842,838**

Source of In-Kind Contribution	2021/22	2022/23	2023/24	2024/25	2025/26	% of Contribution	Total
CSIRO	$0	$123,875	$86,785	$0	$0	20%	$210,660
Total In-Kind Contribution	**$0**	**$123,875**	**$86,785**	**$0**	**$0**	**20%**	**$210,660**

TOTAL PROJECT BUDGET	2021/22	2022/23	2023/24	2024/25	2025/26	-	TOTAL
All contributions	$0	$619,373	$433,925	$0	$0	-	$1,053,298
TOTAL PROJECT BUDGET	**$0**	**$619,373**	**$433,925**	**$0**	**$0**	**-**	**1,053,298**

4. Communications Plan

Stakeholder	Objective	Channel (e.g. meetings/media/factsheets)	Timeframe (Before, during at completion)
Regional community / wider public	To communicate project objectives and key messages from the research	Fact sheets (including development of one at commencement of project which will explain in plain English the objective of the project and one at the end of the project – these may be updated periodically as project progresses). Project progress reported on GISERA website to ensure transparency for all stakeholders including regional communities. Media release (optional)	From commencement of project and with updates as they come to hand. As required At completion
Government	To report on research being undertaken	Factsheets, newsletters, website or webcast	During
Gas Industry	Industry adopts methods for improving the baseline sampling methodologies, and uses the newly generated data, for example to inform placement of future groundwater monitoring bores	Presentation of findings at joint Gas Industry/Government Knowledge Transfer Session	At completion
Government	Advice provided to senior bureaucrats / ministers / policy makers	Presentation of findings at joint Gas Industry/Government Knowledge Transfer Session	At completion
Community stakeholders	Presentation of research findings	Presentation of findings through community forums or briefings	At completion
Regional community/wider public, government, scientific community and industry	To report on key findings	Public release of final report Digital interactive product and/or animation of the 3D geological and hydrogeological model to enhance and promote understanding of groundwater dynamics	At project completion At completion or soon after completion of project
Traditional Owner communities	To explore collaboration opportunities for information exchange.	Engagement with representatives of relevant land councils where appropriate to determine interest/availability in making information available to communities	Ongoing

5. Project Impact Pathway

Activities	Outputs	Short term Outcomes	Long term outcomes	Impact
Tasks 1, 2 and 4 - Hydrochemical and geochemical baseline sampling	Acquisition of critical baseline data sets; enhanced research collaboration with state government, gas industry and other stakeholders on issues of direct community & industry interest	Community's awareness about the environmental impacts of onshore gas development is improved; Industry knowledge is enhanced; Government regulators & policy makers are informed.	The integrated hydrogeological, geophysical and geological model and other outputs from this project will contribute to an informed, credible & collaborative engagement between industry, government & communities to address challenges & opportunities & develop solutions related to the gas development	The project will contribute to an improved land & groundwater quality under coexistence between gas and agriculture
Task 3 - Airborne electromagnetic (AEM) survey	A continuous 3D model of the upper 400 m of the subsurface (to be published)			
Task 5 - Geochemical modelling to test conceptual models	A detailed geochemical and hydrochemical model that assesses hydrogeological connectivity pathways		The project will contribute to an improved capacity to forecast & negate environmental, social & commercial risks	
Task 6 - Data integration and refinement of conceptual models	An integrated hydrogeological and geological model framework (to be published).			The project will contribute to sustainable Australian onshore gas industry
Tasks 7 and 8 – Reporting and communications	Research & community workshops, reports, factsheets and videos; - identification of knowledge gaps for the purpose of future research projects A 3D digital interactive product and/or animation of the 3D geological and hydrogeological model framework will be developed and published in collaboration with the GISERA communication team.	Community's awareness about the environmental impacts of onshore gas development is improved; Industry knowledge is enhanced; Government regulators & policy makers are informed.	The integrated hydrogeological and geological model and other outputs from this project will contribute to a more efficient and less disruptive placement & operation of CSG infrastructure. This will contribute to a greater trust between industry, government, community, and CSIRO	

6. Project Plan

Project Schedule

ID	Activities / Task Title	Task Leader	Scheduled Start	Scheduled Finish	Predecessor
Task 1	Hydrochemical baseline sampling (water)	Matthias Raiber	01/07/2022	23/12/2022	-
Task 2	Geochemical baseline characterisation (rocks)	Guangliang "Justin" Wu	01/07/2022	01/03/2023	-
Task 3	Airborne electromagnetic (AEM) survey	Aaron Davis	01/07/2022	01/09/2023	-
Task 4	Analysis of groundwater samples for environmental tracers	Matthias Raiber	01/09/2022	30/09/2023	-
Task 5	Geochemical modelling to test conceptual models	Henning Prommer	01/07/2023	31/1/2024	Task 1-3
Task 6	Data integration and refinement of conceptual models	Guangliang "Justin" Wu	01/10/2023	31/03/2024	Task 1-4
Task 7	Project reporting	Matthias Raiber	01/07/2022	30/06/2024	-
Task 8	Communicate findings to stakeholders	Matthias Raiber	01/07/2022	30/06/2024	-

Task description

Task 1: Hydrochemical baseline sampling (water)

OVERALL TIMEFRAME: 01/07/2022 to 23/12/2022

BACKGROUND**:** A previous GISERA project (‘Assessment of faults as potential hydraulic seal bypasses in the Pilliga Forest area, NSW’; Raiber et al., 2022) identified multiple potential hydrogeological connectivity pathways between the Gunnedah Basin (containing the targeted CSG formations) and the Surat Basin (including the Pilliga Sandstone, the major Great Artesian Basin aquifer in this region) (Figure 1).

The study showed that there is a distinct change in hydrochemistry from east to west and north-west within the Pilliga Sandstone in the NGP area. The interpretation of the observed patterns was that there is no or only limited connectivity between the Gunnedah Basin (including coal seams) and Surat Basin in the south and east of the NGP area. However, in some of the areas where there may be some connectivity, there remains significant ambiguity in the interpretations due to the lack of hydrochemistry and environmental tracer data from Gunnedah Basin strata and the Purlawaugh Formation, the deepest formation of the Surat Basin which directly underlies the Pilliga Sandstone.

To close these knowledge gaps, additional water samples from the Purlawaugh Formation and from shallow Gunnedah Basin hydrostratigraphic units (e.g. Digby Formation and Napperby Formation and Hoskissons coal seam) are required, thus providing critical pre-CSG development data and reduce the uncertainty of geochemical mixing models.

NSW DPIE have installed multi-level monitoring wells (screening different formations at the same site) throughout the region over the last few years (mostly drilled between 2019 to 2020) as part of its NSW Coal Basins water monitoring strategy (NSW DPIE, 2019), with many of the bores screened within the formations inferred to interact with the Pilliga Sandstone where there is a current lack of baseline data (Figure 2). However, so far, only basic water chemistry parameters have been analysed on groundwater samples collected from these bores. This new monitoring bore network provides an excellent opportunity to collect more baseline chemistry and tracer data prior to CSG development and close the knowledge gaps identified by Raiber et al. (2022).

TASK OBJECTIVES**:** Groundwater samples will be collected from at least 15 groundwater monitoring bores for a comprehensive set of hydrochemical and isotopic tracers (e.g. stable noble gases such as He, Ne, Ar, Kr, Xe, ^{222}Rn, dissolved methane (concentrations and isotopes), major and minor ion hydrochemistry, stable isotopes of water and strontium, tritium, carbon-14 and ^{36}Cl). Sampling sites will include primarily the new NSW DPIE groundwater monitoring bores in the Narrabri region (Figure 2), although samples from selected alluvial groundwater monitoring bores within the vicinity of the NGP area may also be collected.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: Collection of groundwater samples for a wide range of parameters from NSW DPIE groundwater monitoring bores and selected alluvial bores, and shipment of samples to laboratories (samples will be analysed at a wide range of laboratories in Australia and overseas (e.g. United States of America and New Zealand)).

Task 2: Geochemical baseline characterisation (rocks)

OVERALL TIMEFRAME: 01/07/2022 to 01/03/2023

BACKGROUND: A previous GISERA project ('Assessment of faults as potential hydraulic seal bypasses in the Pilliga Forest area, NSW'; Raiber et al., 2022) demonstrated that there is likely some groundwater mixing between the major GAB aquifer (Pilliga Sandstone) in the Narrabri region and underlying formations (and possibly also with the overlying Orallo Formation) in the north and north-western part of the NGP area. However, the assessment also showed that other hydrochemical processes (e.g., mineral dissolution and ion exchange) may also proceed in parallel and confirmed that with the currently available data, it is not possible to remove the ambiguity.

To further understand and quantify the relative significance of inter-aquifer mixing between coal seams (and more broadly, Gunnedah Basin formations) and aquifers (e.g. Pilliga Sandstone and alluvial aquifers) and hydrogeochemical evolution from rock-water interactions, analyses of existing core samples (readily available from the NSW core library) from selected bores screened within key formations (e.g. Pilliga Sandstone, Purlawaugh Formation, Digby Formation and Early and Late Permian coal seams) for $^{87}Sr/^{86}Sr$ and mineral assemblage (i.e. the presence and relative quantities of rock-forming minerals) are critical. The assessment of the $^{87}Sr/^{86}Sr$ ratio of both rocks and groundwater has proven to be very useful to determine connection of aquifers in the Surat Basin in Qld (Raiber et al., 2019)

Furthermore, the study by Raiber et al. (2022) (and other previous studies) highlighted the significance of igneous intrusion in this area. This suggested that in addition to faults, igneous intrusions such as dykes (dykes are igneous intrusive bodies that are often near-vertical and cross-cut (intrude into) horizontal sedimentary formations along pre-existing faults or fractures) and sills can also form potential hydrogeological connectivity pathways in the wider Narrabri Gas Project area.

It is very important to understand the timing when these igneous intrusions have occurred, as this will allow to refine the understanding on the structural history of the wider NGP area and help to determine whether the intrusions are present only within deeper formations or whether they are likely to intersect Gunnedah and Surat basins strata (thus, forming a potential connectivity pathway from the Gunnedah Basin to the Surat Basin).

TASK OBJECTIVES: The objective of this task is to provide baseline geochemistry data on the Pilliga Sandstone and under- and overlying formations (e.g., Purlawaugh Formation, Orallo Formation and Gunnedah Basin strata). When assessing connectivity between aquifers using geochemical modelling, it is important to characterise the different end members (e.g., the geochemistry of the rock and the hydrochemistry of different aquifers). To date, no such assessment has been conducted within the Narrabri region (or data are not publicly available). This assessment will include:

- analysis of 15 to 20 samples from different formations for their rock mineralogical assemblage using X-ray diffraction (XRD) and X-ray fluorescence (XRF).
- analysis of the $^{87}Sr/^{86}Sr$ ratio of selected rock samples (15 to 20 samples) from different stratigraphic formations.
- analysis of the age of selected samples (approximately five samples) from intrusive rocks to determine the timing of emplacement of the intrusions.

An initial screening confirmed that suitable samples are held by the NSW core library, and communication with the core library confirmed that these samples are readily available for collection and analysis.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: This task will provide a comprehensive understanding of the geochemical composition and isotopic signature of the Pilliga Sandstone as well as under- and overlying formations within the wider NGP area. The outputs will form a critical component of Task 5, representing the rock end member within the geochemical modelling.

Task 3: Airborne electromagnetic (AEM) survey

OVERALL TIMEFRAME: 01/07/2022 to 01/09/2023

BACKGROUND: The previous GISERA study by Raiber et al. (2022) assessed the subsurface architecture in the NGP area using newly collected data (ground-based transient electromagnetic (TEM) and AgTEM) together with the compilation of a vast amount of historic geological and geophysical data, followed by re-processing of a limited number of representative seismic sections. This has helped to hypothesise multiple potential hydrogeological pathways in the wider NGP area. Although this has significantly contributed to the understanding of connectivity between Gunnedah Basin and Surat Basin, the study has also highlighted on-going knowledge gaps and identified areas where additional data would be beneficial to further reduce the uncertainty.

The TEM surveys highlighted that there is a lack of a conductive cover, thus 'opening a window' into the subsurface. This suggests that conducting an AEM survey using a regular grid would provide extremely valuable insights into the subsurface to considerable depths (likely extending to depths beyond 400 m). This would underpin the assessment of the aquifer framework presented in this study and importantly also allow to identify concealed structures that may be present in areas not covered by previous geophysical surveys (e.g., areas such as the south and east of the NGP area where there is a lower density of seismic lines).

TASK OBJECTIVES: Acquisition of AEM survey data will provide new insights into the hydrogeological framework of the wider NGP region. The benefits of these surveys include that they provide a more comprehensive and continuous 3D model of the upper approximately 400 m of the subsurface than seismic surveys, as the surveys are conducted along regular grid lines (a hypothetical example of such a grid is shown in Figure 3). This will therefore help to

- further increase the confidence in the findings by Raiber et al. (2022) and other previous studies on the subsurface geometry
- confirm that no major concealed geological structures have been missed by seismic surveys (e.g., in areas where the spacing between the seismic survey lines is wider)
- determine the spatial extent of igneous intrusions
- provide the physical framework for future 3D geological and numerical groundwater models.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: Preparation and organisation of AEM survey, conducting AEM survey (via a contractor), inversion and electrical conductivity volume creation and preparation for layer-based 3D volume interpretation.

Task 4: Analysis of groundwater samples for environmental tracers

OVERALL TIMEFRAME: 01/09/2022 to 30/9/2023

BACKGROUND: This task is associated with Task 1, and it will involve the analysis of samples collected as part of Task 1.

TASK OBJECTIVES: Laboratory analysis of samples collected as part of Task 1 for parameters such as noble gas (He, Ne, Ar, Kr, Xe including $^{3}He/^{4}He$), ^{222}Rn, dissolved methane (concentrations and isotopes), other selected hydrochemical and isotopic tracers, including stable isotopes of water and strontium, tritium and carbon-14. Samples will be analysed at a wide range of laboratories in Australia and overseas.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: Analytical results of noble gases and other selected environmental tracers will be obtained, providing new evidence on the potential hydrogeological connectivity between the Gunnedah Basin (including coal seams) and shallow aquifers (e.g., Pilliga Sandstone and alluvium).

Task 5: Geochemical modelling to test conceptual models

OVERALL TIMEFRAME: 01/07/2023 to 31/1/2024

BACKGROUND: Raiber et al. (2022) identified different potential hydrogeological connectivity pathways, and their likelihood of forming actual hydrogeological connectivity pathways was assessed using multiple lines of evidence (i.e., geology, hydrogeology, geophysics, hydrogeochemistry and environmental tracers). This assessment suggested that some pathways are more likely to occur than others. The assessment showed that there is a distinct change in hydrochemistry within the major GAB aquifer in this region (Pilliga Sandstone) from east to west and north-west within the NGP area, with an increase of salinity towards the north and north-west indicating the potential of connectivity between the Pilliga Sandstone and underlying formations.

Simple two and three parameter mixing models were then used to test the conceptual models and further refine the understanding of hydrogeological connectivity pathways. Although such simple models are very useful to give an indication of mixing, there are also some uncertainties and limitations. This includes the uncertainty in representativeness of the available samples selected as end-members and the limited number of tracers considered (only two) for the calculations. Furthermore, as discussed in Task 1, although a good spatial distribution of hydrochemical records for the Pilliga Sandstone exists within the wider NGP area, there is only a small number of records available for the Purlawaugh Formation, Digby and Napperby formations and the Late Permian Gunnedah Basin coal seams (although there is a larger number of hydrochemical records available for the deeper Early Permian coal seams within the Maules Creek Formation, which are the primary CSG target unit).

Expanding the end-member mixing modelling conducted during this project to a comprehensive geochemical mixing model including both rock geochemistry and groundwater hydrochemical records as end-members and including the selection of multivariate parameters and the assessment of uncertainty of end-members and potential hydrochemical reactions is considered the most reliable approach to further reduce the uncertainty of interpretations from the current study.

TASK OBJECTIVES: The objective of this task is to develop a comprehensive geochemical mixing model for the aquifers within the NGP area, building on all the data collected and compiled during the previous studies (Creswell, 2014; Iverach et al., 2017 and 2020; Suckow et al. (2019) and Raiber et al., 2022) and combining with the newly acquired data from Tasks 1, 2 and 4. This will be conducted in PHREEQC (a public-domain geochemical and hydrochemical modelling software available from the United States Geological Survey, USGS). Hydrochemical modelling with PHREEQC provides the means to test concepts and a suite of proposed reactions to determine the degree of connection or separation between the Pilliga Sandstone and underlying or overlying formations. This will allow to refine the understanding of the different hydrogeological pathways presented in Figure 1 by means of identifying the reactions responsible for the hydrochemical evolution within the Pilliga Sandstone aquifer from south/east to north and north-west.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: A PHREEQC mixing model will be developed. This will allow testing and refinement of conceptual hydrogeological models and differentiate between different processes contributing to the change of hydrochemistry observed within the Pilliga Sandstone in the Narrabri region from south and east to north and north-west, and assess the significance of the following hydrochemical processes:

- mixing with other formations;
- silicate weathering reactions;
- dissolution of salts;
- precipitation of calcite, amorphous silica, and clay minerals;
- ion exchange reaction.

This will also allow to quantify the relative contribution of mixing between the Pilliga Sandstone and adjacent aquifers.

Task 6: Data integration and refinement of conceptual models

OVERALL TIMEFRAME: 1/10/2023 to 31/3/2024

BACKGROUND**:** Conceptual hydrogeological models form the basis of numerical models developed for impact predictions. The development of reliable conceptual hydrogeological models of potential hydrogeological connectivity pathways relies on the integration of multiple lines of evidence.

This includes geological and geophysical methods that characterise the geometry of the subsurface including identification of geological structures, and hydrochemistry, environmental tracers and geochemical modelling, which provide an independent line of evidence of how groundwater moves through the subsurface.

TASK OBJECTIVES**:** The data from previous studies and Tasks 1 to 5 will be integrated to test the conceptual models of hydrogeological connectivity pathways from CSG units to near surface environmental assets presented in Figure 1 (Raiber et al., 2022). The integration of data from multiple lines of evidence (geophysics, geology, geochemistry and hydrochemistry, environmental tracers and geochemical mixing models) will help to further reduce the uncertainty on the understanding of connectivity between aquifers and aquitards. The existing conceptual models will be updated, or new alternative conceptualisation of the hydrogeological system may be proposed if the newly acquired evidence shows that the present conceptual models are not accurate representations of the regional hydrogeological system.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: An improved conceptual hydrogeological model based on the integrated datasets from this study and previous studies. The project output will increase the confidence in the understanding of hydrogeological dynamics of the region and in particular the interaction between deep and shallow formations.

Two dimensional cross-sections and 3D geological representations will be used to represent the understanding of local geology, hydrostratigraphic layers and presence of geological structures derived from the geophysical surveys and the spatial distribution of environmental tracers, which may correspond to anomalies in proximity to and under the influence of geological structures. This will also involve the quantification of exchange fluxes between different formations and uncertainties associated with this assessment.

Task 7: Project Reporting

OVERALL TIMEFRAME: 01/07/2022 to 30/6/2024

BACKGROUND: Information from this project is to be made publicly available after completion of standard CSIRO publication and review processes.

TASK OBJECTIVES: To ensure that the information generated by this project is documented and published after thorough CSIRO Internal review.

TASK OUTPUTS AND SPECIFIC DELIVERABLES:

1) Preparation of a final report outlining the scope, methodology, scenarios, assumptions, findings and any suggestions/options for future research;

2) Following CSIRO ePublish review, the report will be submitted to the GISERA Director for final approval; and

3) Provide 6 monthly progress updates to the GISERA office.

Task 8: Communicate project objectives, progress and findings to stakeholders

OVERALL TIMEFRAME: Full duration of project

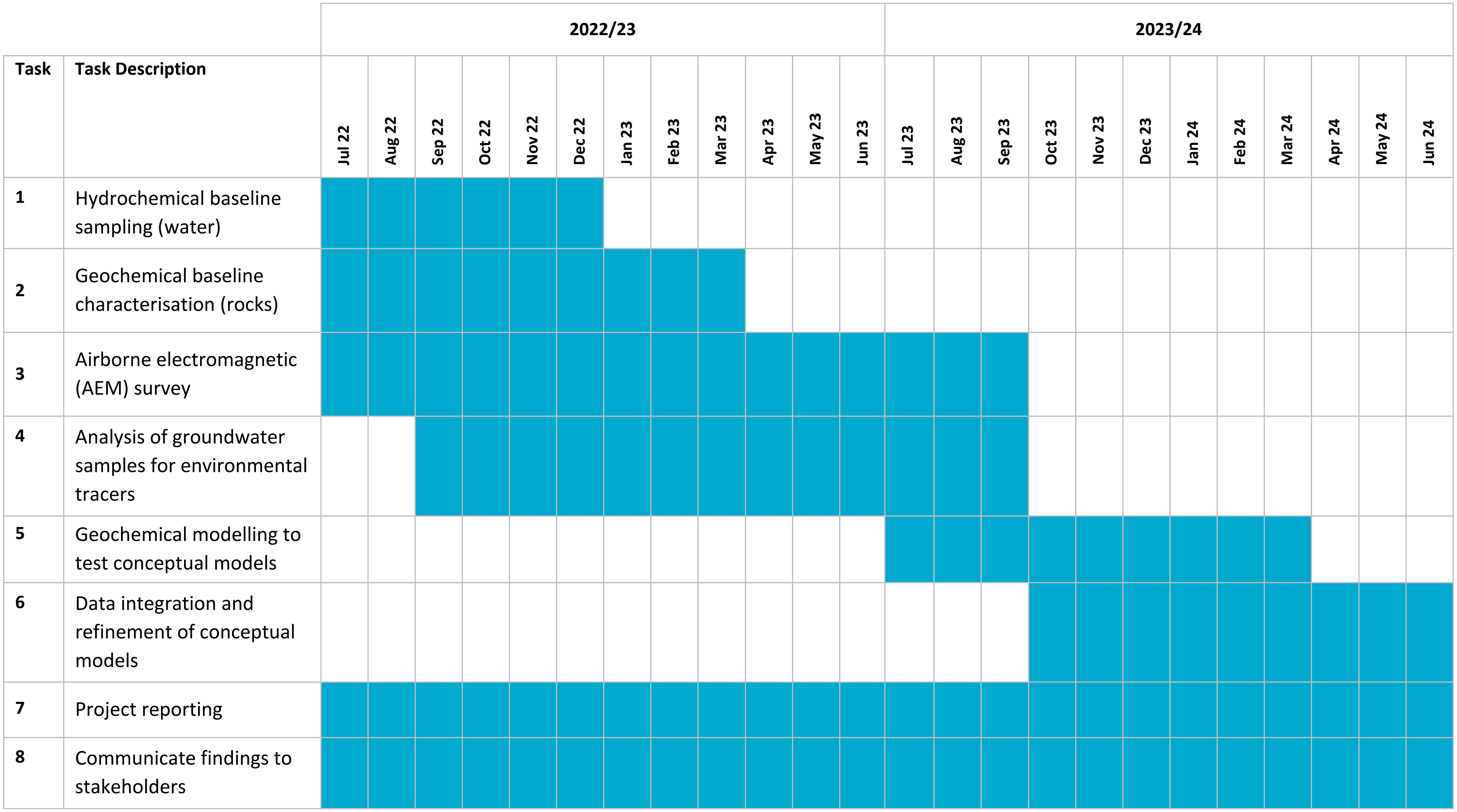
BACKGROUND: Communications of GISERA research are an important component of outreach and dissemination of findings to diverse audiences.

TASK OBJECTIVES: Communicate project objectives, progress and findings to stakeholders through meetings, knowledge transfer sessions, factsheets and journal articles, in collaboration with GISERA Communications officers. Develop a visualisation/animation of the 3D geological and hydrogeological model in collaboration with the GISERA Communications officers.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: Communicate project objectives, progress and results to GISERA stakeholders according to standard GISERA project procedures which may include, but not limited to:

1) Knowledge Transfer session with Government/Gas Industry
2) Presentation of findings to Community members/groups
3) Preparation of article for GISERA newsletter and other media outlets e.g. The Conversation
4) Revision of project factsheet to include final results (a factsheet is developed at project commencement, and another will be done at completion)
5) Peer reviewed scientific manuscript ready for submission to relevant journal
6) **Animation/visualization of 3D geological and hydrogeological model**

Project Gantt Chart



7. Budget Summary

Expenditure	2021/22	2022/23	2023/24	2024/25	2025/26	Total
Labour	$0	$223,873	$362,925	$0	$0	$586,798
Operating	$0	$125,500	$41,000	$0	$0	$166,500
Subcontractors	$0	$270,000	$30,000	$0	$0	$300,000
Total Expenditure	**$0**	**$619,373**	**$433,925**	**$0**	**$0**	**$1,053,298**

Expenditure per task	2021/22	2022/23	2023/24	2024/25	2025/26	Total
Task 1	$0	$76,405	$0	$0	$0	$76,405
Task 2	$0	$59,651	$0	$0	$0	$59,651
Task 3	$0	$376,342	$91,216	$0	$0	$467,558
Task 4	$0	$66,907	$15,809	$0	$0	$82,716
Task 5	$0	$0	$129,997	$0	$0	$129,997
Task 6	$0	$0	$104,427	$0	$0	$104,427
Task 7	$0	$16,534	$53,530	$0	$0	$70,064
Task 8	$0	$23,534	$38,946	$0	$0	$62,480
Total Expenditure	**$0**	**$619,373**	**$433,925**	**$0**	**$0**	**$1,053,298**

Source of Cash Contributions	2021/22	2022/23	2023/24	2024/25	2025/26	Total
Federal Govt (67%)	$0	$414,980	$290,730	$0	$0	$705,710
NSW Govt (13%)	$0	$80,518	$56,410	$0	$0	$136,929
Total Cash Contributions	**$0**	**$495,498**	**$347,140**	**$0**	**$0**	**$842,638**

In-Kind Contributions	2021/22	2022/23	2023/24	2024/25	2025/26	Total
CSIRO (20%)	$0	$123,875	$86,785	$0	$0	$210,660
Total In-Kind Contributions	**$0**	**$123,875**	**$86,785**	**$0**	**$0**	**$210,660**

	Total funding over all years	Percentage of Total Budget
Federal Government investment	$705,710	67%
NSW Government investment	$136,929	13%
CSIRO investment	$210,660	20%
Total Expenditure	**$1,053,298**	**100%**

Task	Milestone Number	Milestone Description	Funded by	Start Date (mm-yy)	Delivery Date (mm-yy)	Fiscal Year Completed	Payment $ (excluding CSIRO contribution)
Task 1	1.1	Hydrochemical baseline sampling (water)	GISERA	Jul-22	Dec-22	2022/23	$61,124
Task 2	2.1	Geochemical baseline characterisation (rocks)	GISERA	Jul-22	Mar-23	2022/23	$47,721
Task 3	3.1	Airborne electromagnetic (AEM) survey	GISERA	Jul-22	Sep-23	2023/24	$374,046
Task 4	4.1	Analysis of groundwater samples for environmental tracers	GISERA	Sep-22	Sep-23	2023/24	$66,173
Task 5	5.1	Geochemical modelling to test conceptual models	GISERA	Jul-23	Jan-24	2023/24	$103,998
Task 6	6.1	Data integration and refinement of conceptual models	GISERA	Oct-23	Mar-24	2023/24	$83,542
Task 7	7.1	Project reporting	GISERA	Jul-22	Jun-24	2023/24	$56,051
Task 8	8.1	Communicate findings to stakeholders	GISERA	Jul-22	Jun-24	2023/24	$49,984

8. Intellectual Property and Confidentiality

Background IP (clause 11.1, 11.2)	**Party**	**Description of Background IP**	**Restrictions on use (if any)**	**Value**
				$
				$
Ownership of Non-Derivative IP (clause 12.3)	CSIRO			
Confidentiality of Project Results (clause 15.6)	Project Results are not confidential.			
Additional Commercialisation requirements (clause 13.1)	Not Applicable			
Distribution of Commercialisation Income (clause 13.4)	Not Applicable			
Commercialisation Interest (clause 13.1)	**Party**		**Commercialisation Interest**	
	CSIRO		N/A	

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