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Surat Basin Carbon Capture and Storage Project

Advice to the Queensland Department of Environment and Science

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Contents

Summary

The State of Queensland acting through the Department of Environment and Science (DES) requested CSIRO provide technical advice on the Environment Impact Statement (EIS) and Groundwater Modelling and Management report for the Carbon Transport and Storage Corporation (CTSCo) Pty Limited – Surat Basin Carbon Capture and Storage (CCS) trial project located approximately 44 km southwest of Moonie in southern Queensland.

The technical advice, in the form of a written report to DES, addresses questions posed by DES to amend the environmental conditions of Environmental Authority (EA) EPPG00646913 for greenhouse gas (GHG) exploration permit EPQ10 to authorise the carrying out of CO_2 (i.e. GHG stream) injection testing in EPQ10. The review comments and recommendations are categorised by a level of concern varying in significance from major (level 1), to moderate (level 2), and minor (level 3).

A key weakness of the EIS is that risks are not identified and presented in a structured way. It is recommended that a systematic risk assessment is used to connect identified hazards with potential impacts and the monitoring techniques needed to detect these potential impacts. The review identified major concerns related to the assessment of exposure pathways for potential impacts due to 'water extraction in the Hutton or Precipice Sandstones close to West Moonie-1 Injection Well'. It is recommended that the assumptions and range of parameter combinations used for particle tracking modelling be revised to rule out potential impacts beyond the modelled plume that considers all possible water resource development scenarios. Additional recommendations include:

1 Groundwater and geological assessments

- Address uncertainties due to limited baseline data using alternative conceptual (and numerical) models to explain groundwater salinities, connectivity pathways, and flow velocity estimates.
- Additional details to support the adopted 3D geological (static) model, reservoir models, and numerical groundwater models better to characterise geological structures.

2 Numerical groundwater modelling

- Broaden the parameter uncertainty analysis to better define likely bounds of the dissolved CO_2 plume extent in the case of a new groundwater extraction well in the Precipice Sandstone aquifer.
- Re-evaluate the influence of thermal changes to clearly recognize potential impacts near the GHG injection well on geomechanical stresses.

3 Exposure pathway assessment

- Additional interpretation of new 3D seismic survey and collection of passive seismic monitoring is recommended to update knowledge of local faults in the geological structural model.

4 Human use assets

- Systematic assessment of the 6 Environmental Values related to human use using conservative modelling approaches considering all possible water resource development scenarios.

5 Monitoring, mitigation, and remedial measures

- Evaluate and present in a structured way the logic used to select monitoring technologies, detailing the logic and sensitivity behind selected monitoring technologies.
- Examine probability distributions for hazards, encompassing best and worst-case scenarios, and transparently document the logic used to set hydrochemical and water quality trigger values.

1 Introduction

1.1 Scope

The State of Queensland acting through the Department of Environment and Science (DES) requested CSIRO provide technical advice on the Environment Impact Statement (EIS) and Groundwater Modelling and Management report for the Carbon Transport and Storage Corporation (CTSCo) Pty Limited – Surat Basin Carbon Capture and Storage (CCS) trial project located approximately 44 km southwest of Moonie in southern Queensland.

The EIS was prepared to meet the requirements of the approval conditions for Environmental Authority (EA) EPPG00646913 for greenhouse gas (GHG) exploration permit EPQ10 covering approximately 3,664 km^2. Approval was initially granted on 9 December 2019, to explore the potential for GHG storage. The EIS is required to amend the environmental conditions of the EA to authorise the carrying out of CO_2 (i.e. GHG stream) injection testing in EPQ10.

The detailed scope of works provided by DES asked CSIRO to review information provided and provide a concise written technical report that included expert scientific advice on the presented EIS information and an independent assessment of the potential environmental risks associated with the proposed project, including an evaluation of proposed management strategies, geophysical methods and the conclusions reached in the EIS. The scope of the CSIRO review was to:

> *'Undertake a detailed technical (scientific) adequacy review and risk assessment of the submitted EIS and recommend any further necessary works to describe any potential impacts to Environmental Values (EVs) and any necessary mitigation measures and monitoring required to adequately protect those EVs'.*

1.2 Structure

The technical review is organised in 5 sections based on the questions as set out by DES in their detailed scope of work and summarised below:

1. Groundwater and geological assessments

Q1. *Does the EIS suitably present representative, reliable, appropriate, and verifiable conclusions and commitments for the identification and assessment of potential impacts and risks, including their predicted duration, spatial extent, containment, and magnitude of impacts (plume, dissolved phase, plume movements, inter-aquifer containment and water quality changes) for the proposed pilot project?*

Q2. *Does the EIS suitably present representative, reliable, appropriate, and verifiable conclusions and commitments for the presented hydrogeological characterisation, geophysical techniques, methods, and conceptualisation*?

2.2 Numerical groundwater modelling

Q3. *Does the EIS suitably present representative, reliable, appropriate, and verifiable conclusions and commitments for the assumptions, limitations, uncertainty analysis and calibration of models used to predict potential environmental impacts*.

Q4: *Do the EIS numerical groundwater models (including the plume migration and geochemical models) suitably present the assumptions, variables, input data, uncertainty analysis and interpretation of outputs and conclusions on potential impacts from the proposed project?*

2.3 Exposure pathway assessment

Q5: Is the exposure pathway assessment to existing local abandoned wells intersecting the Precipice Sandstone aquifer and the potential for geological structures (e.g., fracturing or faults zones) to open new pathways to potential receptors to overlying aquifers, and users of groundwater within the region, from the injection of the supercritical greenhouse gas stream adequate?

2.4 Human use assets

Q6: Is the assessment of existing, authorised, and future human use assets and whether sufficient information is provided to support conclusions regarding these assets and the spatial extent, magnitude and duration of likely impacts stated in the EIS adequate?

2.5 Monitoring, mitigation, and remedial measures

Q7: Are the proposed mitigation measures, management strategies, monitoring and verification techniques to be implemented by the proponent adequate?

1.3 Information and documents received

The CSIRO technical team met with representatives of DES on 26 May, 19 July, 22 August, and 20 September 2023. A final meeting with DES, CTSCo and CSIRO is planned for 6 October 2023.

The information received from DES and CTSCo is summarised in Table 1. Throughout this document, reports are referred to by the number in Table 1 using square brackets: []. Page numbers are the page number in the document (not the page number printed on the page). This enables consistent referring to page numbers, even when a document has several appendices, each with their own page numbering. For example, Table 1-1 Summary of proponent details in Chapter 1 of the EIS would be cited as 'Table 1-1 (p 3 in [1]).'

Table 1 Information received

Nr	Title – Date	'Label' – Filename	Author	Source
1	Introduction including appendices (Terms of Reference checklist) – Chapter 1	01+Introduction+(final+221124).pdf	CTSCo	DES
2	Proposed Project Description – Chapter 2	02+Project+Description+(final+221108).pdf	CTSCo	DES
3	Approvals – Chapter 4	04+Approvals+(final+221108).pdf	CTSCo	DES
4	Geology – Chapter 8	08+Geology+(final+221122).pdf	CTSCo	DES
5	Groundwater – Chapter 9	09+Groundwater+(final+221108).pdf	CTSCo	DES
6	Geology – Appendix 08A Well Completion Reports	Appendix+08A+Geology,+Well+Completion+Reports+(final+221108).pdf	CTSCo	DES
7	Groundwater – Appendix 09A Groundwater Impact Assessment Technical Report	Appendix+09A+Groundwater+Impact+Assessment+Technical+Report+(final+221108).pdf	CTSCo	DES
8	DES1231304 - Submission attachments complied	DES1231304 - Submission attachments complied.pdf	DES	DES
9	Great Artesian Basin Strategic Management Plan	GAB strategic-management-plan.pdf	DCCEEW	DES
10	Queensland Murray-Darling and Bulloo River Basins | Groundwater Environmental Values and Water Quality Objectives	Qld-Murray-Darling-basin-Bulloo-River-basin.pdf	DES	DES
11	Introduction and final ToR – Appendix 01A	Appendix+01A+Introduction+Final+ToR+(final+221108).pdf	CTSCo	DES

1.4 Review methodology

Review comments and recommendations are categorised by level of concern according to Table 2.

Table 2 Categorisation of review recommendations

Level of concern	Description
Level 1: **Major issues**	Potential to **significantly** underestimate impact and/or risk Improper, unverified, or poorly justified model assumptions and statements potentially leading to conclusions that underestimate risk and/or impact
Level 2: **Moderate issues**	Potential to **moderately** under- or over-estimate impact and/or risk Improper, unverified, or poorly justified model assumptions potentially leading to conclusions that under- or over-estimate risk and/or impact Limited transparency, unclear description of assumptions, model choices, parameters and/or results
Level 3: **Minor issues**	**Minimal** or no effect on impact and/or risk Assumptions and model choices not relevant to quantity of interest Editorial issues (typos, missing references, etc)

2 Technical review

This section is organised based on the scope of the technical advice as outlined in 1.1. Recommendations are summarised by level of concern (Table 2) for each review question in the blue boxes and discussed in greater detail in the text.

This review follows the guiding principles and information needed to assess whether a groundwater model and uncertainty analysis are fit-for-purpose as outlined in the updated explanatory note on uncertainty analysis for groundwater modelling (Peeters and Middlemis, 2023), including these key concepts:

1. Fit-for-purpose: means that the results of the model are **usable** – relevant to the decision-making process; **reliable** – demonstrate that the range of model outcomes is consistent with the system knowledge and honours historical observations; and **feasible** – considering trade-offs due to budget, time and technical constraints
2. Quantity of interest (QoI): means model outcome from a specified model scenario, with a predefined spatial and temporal setting, that is relevant to assessing the likelihood and consequence of a causal pathway element representing a hazard. An alternative term is 'key prediction'.

2.1 Groundwater and geological assessments

2.1.1 Potential impacts and risks for the proposed pilot project

This section addresses '*Q1: Does the EIS suitably present representative, reliable, appropriate, and verifiable conclusions and commitments for the identification and assessment of potential impacts and risks, including their predicted duration, spatial extent, containment, and magnitude of impacts (plume, dissolved phase, plume movements, inter-aquifer containment and water quality changes) for the proposed pilot project?*'

The EIS assesses 5 exposure pathways that provide a comprehensive framework for the evaluation of potential impacts on the Hutton or Precipice Sandstone aquifers due to migration of the injected GHG stream plume.

Level of concern: 1

The limited sensitivity and uncertainty analysis mean that potential impacts on water users in the Precipice Sandstone aquifer due to new groundwater extraction near the GHG stream injection well cannot be ruled out. It is recommended that the range of parameter combinations used for particle tracking modelling be revised to rule out potential impacts beyond the modelled plume due to groundwater extraction from the Precipice Sandstone aquifer.

Level of concern: 2

Review recent environmental tracer data analyses for the Surat Basin to determine upper bound estimates of flow velocity for the proposed injection area.

Section 6 of Appendix 09A Groundwater Impact Assessment Technical Report (p 170-200 in [7]) identifies potential impacts associated with release of gases (or containment of GHG stream), changes to groundwater pressure, groundwater quality, and cumulative impacts. The cumulative impacts associated with the geology, hydrogeology, water quality, aquatic ecosystems and groundwater dependent ecosystems, and groundwater water supply and users are identified and discussed in Section 6.4 (p 196-198 in [7]). The groundwater-related environmental values associated with the Precipice Sandstone aquifer in the Eastern Central Area of the Basal Zone of the GAB identified in the report (Section 4.5, p 97 in [7]) include:

- Aquatic Ecosystems
- Water supply (includes Irrigation, Farm supply/use, Stock water, Drinking water, Industrial use)
- Cultural, spiritual and ceremonial values.

A base case scenario and 4 alternative exposure pathway scenarios were used to consider potential impacts on the Hutton or Precipice Sandstone aquifers. The assessment for the 'Caprock integrity pathway' (p 180-186 in [7]) finds migration of the injected GHG stream plume through shallower barriers (aquitards) is unlikely to occur. This is consistent with the regional-scale screening model estimates (~150 m) developed for the Cooper Basin (Geological and Bioregional Assessment Program, 2021) and used to rule out potential impacts associated with compromised aquitard integrity. This effectively rules out potential impacts on aquatic ecosystems and cultural, spiritual and ceremonial values associated with shallower aquifers. Therefore, potential impacts are limited to receptors associated with the Hutton or Precipice Sandstone aquifers.

The reported exposure pathway scenarios are consistent with causal pathways associated with geological carbon storage isolated by an intact barrier and include:

- Compromised subsurface integrity (includes faults, fractures, overpressure, localised pathways)
- Compromised well integrity (includes via the annulus, blow outs, cement integrity, casing integrity)
- Deep groundwater injection (includes changes to horizontal and vertical hydraulic gradients)
- Deep groundwater extraction (includes changes to horizontal and vertical hydraulic gradients).

The 5 exposure pathways provide a comprehensive framework for the evaluation of potential impacts on the Hutton or Precipice Sandstone aquifers due to migration of the injected GHG stream plume:

1. Base case – '*injected GHG stream plume in supercritical state remains in place in the near-field environment around the well and does not migrate more than approximately 500 m away from the injection location, owing to a lack of driving pressure gradient*' (p 171 in [7])
2. Caprock integrity – includes faults, fractures, overpressure reactivation of existing structures, and localised pathways
3. Well integrity – includes improperly constructed injection and monitoring wells, existing domestic and industrial wells, abandoned historical water and petroleum wells within the Project site, and future drilling activities at the site
4. Mining and other underground activities – groundwater extraction alters hydraulic gradients, causing GHG stream plume to migrate to water extraction location.
5. Water management – aquifer injection alters hydraulic gradients, causing GHG stream plume to migrate to water extraction location.

Level of concern: 1

Potential impacts associated with '*water extraction in the Hutton or Precipice Sandstones close to West Moonie-1 Injection Well*' were not evaluated. Instead, the report states '*Currently no water abstraction takes place in the Hutton Sandstone or Precipice Sandstone close to operational lands which makes this scenario unlikely. This is due to the significant depth of these formations in this southern part of the Surat Basin (over 2 km deep), making them economically unviable for water supply*' (p 190 in [7]).

The submission from AgForce notes '*A water supply bore in the Precipice Sandstone within 10km of the injection site is licensed and is being constructed, which is expected to change how any plume will propagate*' (p 5 in [8]). This scenario is not directly assessed in the EIS. Instead, this review uses the 5 reported particle tracking sensitivity analysis scenarios (Table 48, p 146 in [7]), particle tracking plots (Appendix C, p 255-259 in [7]) and particle tracking heads (Appendix D, p 260-269) to consider whether the parameters for the 5 reported EIS particle tracking scenarios could address this water extraction scenario.

For the particle tracking sensitivity analysis, modelled particles are released on the corners of a 750 m x 750 m square with the injection well in the centre (Figure 50, p 149 in [7]). This coincides with the edge of the modelled plume, located about 375 m from the injection well. Conservative estimates of plume migration via advection and dispersion are created by selecting upper bound estimates of the hydraulic gradient and aquifer transmissivity, and lower bound estimates of aquifer storativity and the dispersion coefficient. These parameters were varied parameter by parameter in the 5 sensitivity analysis scenarios:

- Scenario 2.1 considers high hydraulic gradients
- Scenario 2.2 considers high hydraulic gradients and high aquifer transmissivity values
- Scenario 2.3 considers low hydraulic gradients once pumping stops in year 3
- Scenario 2.4 considers low porosity values (low storativity)
- Scenario 2.5 considers high aquifer transmissivity values.

Particle movement beyond the modelled plume was predicted to be 15-20 m over 1000 years for 4 of the 5 cases. The exception was Scenario 2.4 with low storativity, when porosity was reduced from 13.5% under the base case to 4.5%, where particle movement was estimated to be 50 to 60 m beyond the modelled plume.

Plume migration predicted by the particle tracking scenarios include hydraulic gradients associated with the GHG stream injection and 1000 ML/year water extraction from the Moonie oil field. However, the limited sensitivity and uncertainty analysis used in the assessment [7] mean that potential impacts on water users in the Precipice Sandstone aquifer due to new groundwater extraction near the GHG stream injection well cannot be ruled out based on the reported sensitivity analysis scenarios. The parameter values used for the sensitivity analysis appear to be suitably conservative but the limited parameter combinations tested and contextual information provided limit confidence extrapolating impacts beyond the 5 sensitivity analysis scenarios.

Recommendation: Review and revise the range of parameter combinations used for particle tracking modelling to rule out potential impacts beyond the modelled plume due to groundwater extraction from the Precipice Sandstone aquifer.

Level of concern: 2

Estimates of flow velocity made using environmental tracers in the northern part of the Surat Basin, are in the range 0.8 to 1.5 m/y (Suckow et al., 2018). The flow velocity in the project area is likely to be less than these estimates due to the greater depth. Hofmann et al. (2022) presented new environmental tracer data for the southern Surat Basin, which have not been discussed in the EIS documents (see 2.1.2).

Recommendation: Review previous environmental tracer analyses for the Surat Basin, including Suckow et al. (2018) and Hofmann et al. (2022), to assess if tracers can be used to determine upper bound estimates of flow velocity relevant to the proposed injection area in this part of the Precipice Sandstone aquifer.

2.1.2 Hydrogeological characterisation and conceptualisation

This section addresses '*Q2: Does the EIS suitably present representative, reliable, appropriate, and verifiable conclusions and commitments for the presented hydrogeological characterisation, geophysical techniques, methods, and conceptualisation?'*

Level of concern: 2

Conceptual model uncertainties exist in the West Moonie model area due to limited baseline data. To address these uncertainties, it is recommended that additional alternative conceptual (and numerical) models are used to explain observed groundwater salinities and possible connectivity pathways. Further, additional details are needed to support the adopted 3D geological (static) model, reservoir models and numerical groundwater models. This includes any geological structures interpreted in the models and findings of the planned/recently acquired 3D seismic survey to support the statement that '*no faulting is present around the West Moonie-1 Injection Well location*'.

Level of concern: 2

Conceptual model uncertainties

The West Moonie model area is relatively data poor, having limited baseline water chemistry and groundwater level data for the different aquifers (p 34 in [5]). This lack of data means there are some conceptual uncertainties with regards to groundwater flow directions within the Precipice Sandstone, groundwater chemistry and the presence or absence of faults.

The higher groundwater salinity observed in the Precipice Sandstone in the Moonie region is '*attributed to the location in the deeper part of the basin, further from the recharge areas, and in an area where there is no throughflow*' (p 38 in [5]). However, Raiber and Suckow (2017) suggested that elevated groundwater salinities in the Precipice Sandstone further north in the Surat Basin may be due to faults acting as connectivity pathways with adjacent units. The elevated salinities observed in the northern part of the Surat Basin occur near geological structures with similar salinities as those observed in the Precipice Sandstone in the Moonie region.

Hydrocarbons have been developed from the Precipice Sandstone in the nearby Moonie oil field for many years. However, the Precipice Sandstone is not the hydrocarbon source rock, suggesting that fault-induced connectivity with hydrocarbon source rocks in the underlying Bowen Basin occurs within the broader regional area over geological time scales.

The report would be improved by addition of a qualitative uncertainty analysis table (Peeters 2017) to summarise detailed technical information in a more accessible and concise way. The table lists the main assumptions and model choices and scores the potential impact on the QoI based on whether the assumption or model choice is driven by data availability, time and budget available for the project, or technical challenges. '*The most important score, however, is the perceived effect of the assumption on the model outcomes'* (Peeters and Middlemis, 2023).

Recommendation: Explicitly consider alternative conceptual models to explain observed groundwater salinities and connectivity pathways that may alter the conclusions of the assessment. Clearly document the main assumptions and model choices and evaluate the potential impact of each on the QoI.

The analysis of hydrochemistry and environmental tracer data from the Precipice Sandstone aquifer to support the conceptual model development presented in the EIS documents is limited (pp 77-83 in [7]) and relies mostly on Rodger et al. (2020) and OGIA (2021). It does not reference or include any data or interpretations from the more recent hydrogeological and isotopic assessment of the southern Surat Basin by Hofmann et al. (2022) relevant to the West Moonie model area. These limitations are highlighted in submission comments – *'the original work by Rodger et al. (2020) but the interpretation as presented is too simplistic and the inferences are unjustified; this is particularly the case for dD-d18O, 14C and 36Cl/Cl]'* (p 87 in [8]).

Recommendation: Review the data and interpretations by Hofmann et al. (2022) and integrate all information to confirm or refine existing conceptual models (and discuss associated uncertainties and limitations).

Geological (static) modelling

The geological (static) model forms the basis for reservoir and numerical models, including subsurface structures, such as faults that can compartmentalise groundwater flow. The project description notes that '*existing seismic data interpretation has shown that no faulting is present around the West Moonie-1 Injection Well location*' (p 29 in [2]). However, this is not supported by Figure 8-3 [4], which shows very few wells or seismic lines are located within or near the West Moonie model area.

Given the sparsity of seismic data in the West Moonie model area, the 3D seismic survey appears to be a very important piece of work to confirm the absence of faults near this site. It would be useful to provide some additional information on the design of the 3D seismic survey (which, according to the document, may have already happened by now).

Recommendation: Provide additional information on the design and findings of the recent 3D seismic survey to support statement that '*no faulting is present around the West Moonie-1 Injection Well location*'.

The adopted modelling workflow for the geological (static) model aims to '*create the 3D grid model with internal zonation derived from the 2D structural surfaces and fault surfaces*' (p 24 in [4]). However, many of the reported cross-sections (Figures 8-9, 8-11, 8-12, 8-14 in [4]) do not show any fault displacements even though the subsurface geometry in these cross-sections indicates possible presence of such features.

Recommendation: Clarify if the geological model includes any subsurface structures.

2.2 Numerical groundwater modelling

2.2.1 Model assumptions, limitations, uncertainty analysis and calibration

This section addresses '*Q3: Does the EIS suitably present representative, reliable, appropriate, and verifiable conclusions and commitments for the assumptions, limitations, uncertainty analysis and calibration of models used to predict potential environmental impacts'* and makes the following recommendations to improve confidence in the modelling:

Level of concern: 1

- Future groundwater extraction bores: revise modelling of potential impacts of a new groundwater extraction bore, including all assumptions, limitations and conceptualisations.
- Extent of dissolved CO_2 plume: additional analysis to rule out plume migration due to a new groundwater extraction well installed in the Precipice Sandstone aquifer

Level of concern: 2

- Model parameter uncertainty: additional analysis to encompass a greater range of possible conceptual and parameter uncertainties
- Monitoring data: outline how monitoring data collection will reduce uncertainty in future modelling
- Effect of thermal changes on geomechanical stress: update assessment to explicitly acknowledge the effect of thermal changes near the GHG stream injection well on geomechanical stresses.

This section of the review is presented by level of concern and includes consideration of the following aspects as outlined in the detailed scope of works provided by DES:

> *'The review should also include technical appraisal of modelling predictions of vertical and horizontal greenhouse gas plume spatial extent, dissolved phase plume spatial extent, plume behaviour and associated effects, water quality changes and pressure or level changes to all relevant EVs associated with the Precipice Sandstone aquifer and any other overlying aquifers. NOTE: The EIS uses the following the working interchangeably: plume, GHG plume, CO2 plume, predicted plume areas, plume perimeter, plume extent, plume position).'*

Level of concern: 1

Future groundwater extraction bores

A key weakness identified by many of the IESC submissions [8] is that the EIS assumes that potential impacts due to future development of groundwater extraction in the Precipice Sandstone are not possible for economic reasons (p 190 in [7]).

> *'The other mechanism which may affect the future evolution of the system studied is water extraction in the Hutton or Precipice Sandstones close to West Moonie-1 Injection Well. Complete migration pathways can be assumed if hydraulic head is reduced in the Hutton Sandstone due to future water management/usage. Currently no water abstraction takes place in the Hutton Sandstone or Precipice Sandstone close to operational lands which makes this scenario unlikely. This is due to the significant depth of these formations in this southern part of the Surat Basin (over 2 km deep), making them economically unviable for water supply.'*

Given the available model (revised to take account of the conceptual and parameter uncertainties), it should be straightforward to examine potential impacts on a water well drilled outside of the predicted CO_2 plume boundary, at a radius between 1 and 50 km of the GHG stream injection well. This would greatly increase confidence in the accuracy of the predictions of potential impacts on other operations.

The additional modelling should be properly documented in the EIS, so that the assumptions and limitations of the analysis are clearly expressed, alongside the evidence for the parameter choices, and an explanation of the process that will be followed to the update the modelling.

Recommendation: Update modelling and analysis to rule out impacts from a new water extraction bore scenario in the EIS, including clear documentation of all assumptions, limitations and conceptualisations.

Extent of dissolved CO_2 plume

The numerical models used for the assessment follow standard approaches that have been validated in CCS modelling at other sites. The geological modelling makes use of the limited available data to produce a best estimate of the subsurface conditions at the location of the proposed GHG stream injection. The combination of multi-phase hydrodynamic modelling with tNavigator^{TM} software for the plume migration, reactive transport modelling and groundwater flow modelling is a powerful combination of techniques that covers all the necessary aspects of the evolution of the subsurface in response to CO_2 injection.

The predictions made by the models are broadly reasonable for the vertical and horizontal extent of the plume (Figure 55 in [7]) and compare well with simple theoretical estimates. The predicted extent of the dissolved plume is likewise reasonable, since initially it follows the distribution of the gas phase, and subsequently the slightly denser fluid with dissolved CO_2 will sink towards the bottom of the aquifer shown in the plot of dissolved gas after 100 years shut-in (Figure 55 in [7]). There is some uncertainty about the long-term movement of the dissolved CO_2, since it could be impacted by future developments such as new water supply wells drilled into the Precipice Sandstone, and there is an underlying uncertainty about the direction of water flow in the aquifer unit prior to injection. As discussed below, this uncertainty should be quantified by additional modelling and uncertainty analysis. The scenario should model the effects on GHG stream spatial extent if a new water extraction well was drilled near the predicted CO_2 plume. This would provide information of the maximum boundary of a lateral 'exclusion zone' for access to future water resources.

Recommendation: Explicitly model the extent of the dissolved CO_2 plume in the scenario of a new groundwater extraction well installed in the Precipice Sandstone near the GHG stream injection well.

Level of concern: 2

Model parameter uncertainty

The West Moonie model area is in a part of the basin and in a reservoir interval where there is very little well-based data. This is favourable for a CCS project because it corresponds to a much lower chance of impact on existing users, such as water extraction bores. However, the limited site-specific data means the numerical modelling needs to encompass a greater range of conceptual and parameter uncertainties, and model calibration is harder. Key uncertainties to explore include parameters related to the top seal geometry, groundwater flow direction, absolute permeability, and how the main predictions (e.g. plume extent) are sensitive to these uncertainties (Bagheri et al., 2021; La Force et al., 2018). This analysis is crucial for increasing confidence that the range of possible environmental impacts has been thoroughly understood and fairly assessed.

The numerical models of plume behaviour test variations in the ratio of vertical to horizontal permeability. However, other important factors, such as absolute permeability, heterogeneity, seal geometry, groundwater flow directions, far-field boundary conditions, that could influence the predictions are not considered. The EIS modelling should be extended to encompass a greater range of possible uncertainties. Results of plume extent should be presented in standard spatial probabilities (such as P10, P50, P90). Parameter sensitivities should be presented in a standard way, such as a tornado chart. This would increase confidence in the maximum estimate of the CO_2 plume extent, the likelihood, and the long-term consequences of evolution of that plume, which is crucial for estimating risks on groundwater near the GHG stream injection well.

Recommendation: Expand the model sensitivity and uncertainty analysis to encompass a greater range of possible conceptual and parameter uncertainties, include parameters related to the top seal geometry, groundwater flow direction, and absolute permeability.

Recommendation: Expand presentation of spatial and parameter uncertainties using different spatial probabilities and plots.

Monitoring data

It is unclear how and when new monitoring data will be used to reduce model conceptual and parameter uncertainties. For example, the baseline 3D seismic survey can improve the characterisation of the seal geometry, which is a key element of the predictions of the direction and extent of CO_2 plume migration.

Another critical element is the overall permeability of the reservoir interval. The standard way to test this is a water production or injection test, which can give a good estimate of the reservoir permeability on a scale of hundreds of metres, and potentially detect any near-field barriers such as sub-seismic faults.

Recommendation: Outline how and when new monitoring data will be used to refine numerical modelling to improve confidence, including explicit links between monitoring techniques and modelling components.

Effect of thermal changes on geomechanical stress

Thermal impacts of CO_2 injection are negligible in the EIS – '*As the GHG stream will enter the injection zone at the same temperature as the Precipice Sandstone there will be no thermally induced fracturing*' (p 78 in [5]). The EIS states there will be no impact because the CO_2 will equilibrate with the rock around the wellbore as it is being injected. However, there is extensive theoretical and field experience which indicates that CO_2 injection at the proposed rate, about 300 tonnes/day (Table 9-3 in [5]), will cool the reservoir near the wellbore by an appreciable amount, say 10-20°C. Analyses for similar injection schemes indicate that the thermal changes near the well affect the geomechanical stresses. The net result is that the threshold for the maximum allowable injection pressure will be reduced. Given the highly permeable nature of the target formation, this is unlikely to have a material impact on the GHG stream injection plan. However, explicit consideration of additional geomechanical stresses due to thermal changes should be explicitly addressed in the assessment.

Recommendation: Explicitly acknowledge the effect of thermal changes near the GHG stream injection well on geomechanical stresses.

2.2.2 Plume migration and geochemical modelling

This section addresses '*Q4: Do the EIS numerical groundwater models (including the plume migration and geochemical models) suitably present the assumptions, variables, input data, uncertainty analysis and interpretation of outputs and conclusions on potential impacts from the proposed project?'* and makes the following recommendations to improve confidence in the modelling:

Level of concern: 2

The plume migration and geochemical modelling approaches used for the EIS are broadly appropriate. However, additional modelling is recommended to expand the model sensitivity and uncertainty analysis to encompass a greater range of possible conceptual and parameter uncertainties.

Level of concern: 2

The plume migration and geochemical modelling approaches reported in the EIS and supporting appendices ([5, 7]) are broadly appropriate. The predictions of plume migration and the geochemical impact of the CO_2 plume in the Precipice Sandstone aquifer are comparable to predictions and field experience in other CCS projects for aquifer storage. For example, at the Otway International Test Centre in Victoria, CO_2 was injected into an open brine saturated sandstone aquifer (Ennis-King et al., 2016). Model predictions and field sampling showed dissolution commences within hours of injection (Haese et al., 2013). Field seismic and pressure tomography monitoring data showed that residual trapping contributed to plume stabilisation, with up to 50% of the plume dissolved within months of injection (Jackson et al., 2022). These experiments showed that residual trapping can effectively immobilise a GHG stream plume and dissolution is effective as the front migrates away from an injector. This has been observed in large-scale international industrial projects as well (Doung et al., 2019; Tawiah et al., 2020).

However, in the modelling presented in the EIS document there is a lack of explicit attention to the uncertainties in key parameters, and the sensitivity of the model predictions to these uncertainties. The geochemical modelling is also subject to additional parameter uncertainties related to water composition and assumed reactions rates. Peeters and Middlemis (2023) recommend that the design, execution and review of an uncertainty analysis carefully consider these aspects:

1. What is the QoI to the decision-maker?
2. What are the main sources of uncertainty to the QoI?
3. How do system knowledge and historical observations constrain or condition the QoI (the key prediction(s) for informing decisions)?

Recommendation: Expand the model sensitivity and uncertainty analysis to encompass a greater range of possible conceptual and parameter uncertainties. Additional modelling should:

- Quantify the uncertainty in key flow modelling inputs: e.g. absolute permeability, heterogeneity, seal geometry, groundwater flow directions, far-field boundary conditions
- Quantify the uncertainties in key geochemical modelling inputs: e.g. water chemistry, mineralogy, reactions rates.
- Quantify the sensitivity of the model predictions to the uncertainties in the key parameters e.g. through a tornado diagram and spatial probability plots.
- Examine the effect of the predicted CO_2 plume on future water supply development.
- Clearly document how future monitoring data, such as 3D seismic survey and well tests, will improve the models by reducing conceptual and parameter uncertainties.
- Clearly document the assumptions, parameters and limitations of the modelling process.

2.3 Exposure pathway assessment

This section addresses '*Q5: Is the exposure pathway assessment to existing local abandoned wells intersecting the Precipice Sandstone aquifer and the potential for geological structures (e.g., fracturing or faults zones) to open new pathways to potential receptors to overlying aquifers, and users of groundwater within the region, from the injection of the supercritical greenhouse gas stream adequate?'*

Potential impacts associated with compromised well integrity are unlikely to occur and the proposed monitoring technologies identified in the EIS are adequate. Exposure pathway for *'users of groundwater within the region, from the injection of the supercritical greenhouse gas stream adequate*' are addressed in the responses to Q1, Q3 and Q6.

Level of concern: 2

Additional information is needed to support the statement that '*no faulting is present around the West Moonie-1 Injection Well location*'. This should include additional interpretation of the new 3D seismic survey and collection of passive seismic monitoring.

Well integrity

There is confidence in the information provided in the EIS that existing local abandoned or operating wells do not form potential pathways for the leakage of CO_2 or formation water into shallower aquifers. The EIS identifies 5 abandoned wells within a 20 km radius of the West Moonie-1 injection well (p 186 in [7]) that are beyond the 525 m radius of the predicted maximum CO_2 plume extent (59 in [5]) and are unlikely to be impacted by pressure changes from the CO_2 injection.

The highest risk to the containment of the injected CO_2 is a mechanical failure, for example due to improperly placed cement, cement degradation or casing corrosion of the West Moonie-1 injection well or the West Moonie-2 monitoring well. This risk is addressed by adopting best practice well drilling and completion standards in accordance with 'Code of Practice for the construction and abandonment of petroleum wells and associated bores in Queensland' (p 203 in [7]). Monitoring technologies for early leakage detection identified in the EIS, including continuous annulus pressure measurements, pulsed neutron and carbon oxygen logging, temperature and pressure measurements, seismic surveys, and water sampling are adequate (p 201 in [7]). In addition, the proposed mitigation measures are adequate to sufficiently reduce the risks of any leakage and detrimental impacts on water resources or surface environmental receptors due to compromised well integrity are unlikely to occur.

Exposure pathway assessments for *'users of groundwater within the region, from the injection of the supercritical greenhouse gas stream adequate*' are addressed in the responses to Q1, Q3 and Q6.

Level of concern: 2

Caprock integrity

In the modelled scenarios, the base case and all but one of the sensitivity cases show the modelled GHG stream to become immobile within the Lower Precipice Sandstone due to the permeability contrasts within the reservoir. Thus, the plume isn't expected to reach the base of the caprock seal as free gas. Therefore, risk of exposure to caprock fractures is considered a low level of concern. The geomechanical modelling and leak-off testing reported in the EIS (p 183 in [7]) support the conclusion that anticipated bottomhole injection pressures for the planned injection rates are safely below fracturing pressures for the Precipice Sandstone.

Based on the available 2D seismic survey data, no naturally occurring open fracture zones or faults were identified by the proponent in the vicinity of the West Moonie-1 injection well. The models investigate a low gradient regional dip of the reservoir confirmed by the Formation Micro-Imager (FMI) Logs that show the geological and petrophysical properties near the well bore. Increased pressures created by the GHG stream injection could potentially open cemented fractures or re-activate sub-seismic or previously unidentified faults. Additional information on the design and findings of the recent 3D seismic survey to support the statement in the EIS that '*no faulting is present around the West Moonie-1 Injection Well location*' (p 29 in [2]) is needed to confirm assumptions and models underpinning the assessment for this exposure pathway.

Recommendation: Incorporate additional seismic monitoring techniques to enhance confidence in the assessment, including interpretation of the new 3D seismic survey to update the numerical model predictions of the extent of the modelled CO_2 plume. Compare the newly acquired 3D seismic survey data with the FMI logs to update the structural framework for the static and dynamic models as appropriate.

Recommendation: Consider using passive seismic monitoring to record micro-seismic events and to identify the early onset of fracturing and fluid migration.

2.4 Human use assets

This section addresses '*Q6: Is the assessment of existing, authorised, and future human use assets and whether sufficient information is provided to support conclusions regarding these assets and the spatial extent, magnitude and duration of likely impacts stated in the EIS adequate?'*

The EIS identifies 6 Environmental Values (EVs: Aquatic ecosystems, Irrigation, Farm supply/use, Stock water, Drinking water, Industrial use, Cultural, spiritual and ceremonial values) related to human use associated with the Basal Great Artesian Basin. Another 5 EVs (Aquaculture, Human consumption, Primary recreation, Secondary recreation, and Visual recreation) are not associated with this zone.

Level of concern: 1

Potential impacts associated with '*water extraction in the Hutton or Precipice Sandstones close to West Moonie-1 Injection Well*' were not evaluated. Instead, the EIS assumes that potential impacts do not occur based on the depth of extraction, water quality and absence of existing wells. It is recommended that each of the 6 EVs related to human use associated with the Basal Great Artesian Basin Zone are systematically assessed using conservative modelling approaches that consider all possible water resource development scenarios.

This review considers the assessment of 'any human uses' as required under the Environmental Protection (Water and Wetland Biodiversity) Policy 2019 and section 9 the EP Act (Section 9.4.1 Water quality – a critical matter in Appendix 01A, p 24 in [11]):

> *'identify the environmental values of surface waters and groundwaters within the proposed project area and immediately downstream or downgradient (or influenced by the zone of potential water quality of impacts) that may be affected by the proposed project, including* ***any human uses*** *and cultural values of water'.*

Under the *Water Act 2000 (Qld),* Water Plans, prepared as part of a consultative process on a catchment-by-catchment basis, outline the Environmental Values (EVs) relevant to the waterbodies (surface water and groundwater) in the plan area. '*EVs for water are the qualities of water that make it suitable for supporting aquatic ecosystems and human water uses*' (p 8 in [10]). '*Water Plans are developed to balance water allocations (that is, human use) with environmental flows (that is, leaving water in a watercourse or aquifer to maintain natural processes)'* (p 9 in [5]). This technical review does not address the assessment of the risks posed to human health and well-being, amenity or wildlife.

The EVs associated with the Basal Great Artesian Basin Zone (Plan GWQ4168) are relevant to the West Moonie-1 Injection Well.

> *'This division represents the lowest beds in the GAB, mainly the Evergreen aquitard and underlying Precipice Sandstone. It also includes members of the Bundamba Group in the Clarence Moreton Basin. The GABORA equivalents are the Precipice Unit, and the Evergreen Fm. from the Hutton Unit. The division is absent from the southwest of the QMDB. Six zones have been defined, based on lithology, and limited water quality data. The groundwater is generally moderately saline, dominated by HCO_3 with either Na, or mixed cations in northern outcrop area near basaltic remnants. Instances of high fluoride have been recorded in the central Surat area.'*

There are 6 EVs related to human use associated with the Basal Great Artesian Basin Zone listed in Table 9-21 (p 41 in [5]):

- Protection of cultural and spiritual values, including Traditional Owner values of water
- Suitability for crop irrigation
- Suitability for drinking water supplies
- Suitability for farm supply/use
- Suitability for industrial use (including mining, minerals refining/processing)
- Suitability for stock watering.

Another 5 EVs (Aquaculture, Human consumption, Primary recreation, Secondary recreation, and Visual recreation) are not associated with the Basal Great Artesian Basin Zone.

Level of concern: 1

The comparison of key features of existing GHG injection projects to the CTSCo proposed project is useful (Table 9-3 in [5]) but could be expanded. For example, the 'Storage' column could be expanded to better describe groundwater salinity, including the minimum, maximum, and mean values of the host formations. The target formation for carbon storage, Precipice Sandstone aquifer, is classified as a 'Saline Formation' (as are most other formations listed here). However, in the regional context of the Surat Basin and the Great Artesian Basin, the Precipice Sandstone is considered an aquifer and groundwater within the Precipice Sandstone in this area is at the lower end of the 'Brackish' groundwater range (Table 9-10 in [5]) rather than what would normally be considered a saline groundwater resource in Australia.

Further, the groundwater in the Precipice Sandstone at the West Moonie model area is described as '*unsuitable for livestock consumption due to the high fluoride concentrations*' (p 43 in [5]) and

> *'A comparison of the groundwater quality sampled from the Precipice Sandstone aquifer via West Moonie-1 Injection Well, with the WQOs for the listed EVs is discussed below. Generally, the water quality at West Moonie-1 Injection Well indicates that the aquifer is naturally not consistent with the WQOs for the identified EVs. Additionally, the depth to the aquifer would be a limiting factor for most users. Shallower aquifers with better water quality would be used instead as a source of water.'* (p 41 in [10])

Consequently, the assessment does not consider future treatment or mixing with other water sources, as noted in the EIS submission comments [8] and by ruling out groundwater extraction for human use, it does not properly assess potential impacts from future water extraction for human use.

Recommendation: Provide a systematic assessment for each of the 6 EVs related to human use associated with the Basal Great Artesian Basin Zone that considers all possible water resource development scenarios, including water extraction for human use from the Precipice Sandstone aquifer.

2.5 Monitoring, mitigation, and remedial measures

This section addresses '*Q7: Are the proposed mitigation measures, management strategies, monitoring and verification techniques to be implemented by the proponent adequate?'*

Level of concern: 1

A key weakness of the EIS is that risks are not identified and presented in a structured way. It is recommended that a systematic risk assessment is used to connect identified hazards with potential impacts and the monitoring techniques needed to detect these potential impacts.

Level of concern: 2

The following recommendations are made to improve confidence in the adequacy of the proposed mitigation measures, management strategies, monitoring and verification techniques:

- explore plausible probability distributions, including models representing the best and worst case for identified hazards
- clearly document logic used to select monitoring technologies, including the sensitivity of these techniques to the hazards they are designed to mitigate
- revise and clearly document rationale used to set trigger values for hydrochemical parameters and discuss whether trigger values for additional water quality parameters are warranted.

Systematic risk assessment

Experience in CCS demonstration and industrial-scale projects has shown that it is essential to link monitoring clearly to risk. A monitoring method should be part of mitigating a specific risk. These comments focus on the subsurface risks associated with CO_2 storage, especially the impact on groundwater. These are not the only environmental risks that need consideration – there are risks associated with the surface equipment, for example, the pipeline – but these are not considered here.

In standard terminology, a 'risk' is defined as the effect of uncertainty on objectives (AS/NZS ISO 31000:2018). This involves assessing the potential consequences and likelihood of impacts to environmental and human values that may stem from an action, under the uncertainty caused by variability and incomplete knowledge of the system of interest. A 'hazard' is an event or process that has the potential to cause harm; there is a likelihood that a hazard will occur with a consequent impact. Often an ordinal scale – a ranking – is used to identify the most serious risks, where both the likelihood and the consequence or impact are large. The familiar risk matrix tabulates likelihood against consequence and populates cells with hazards; this is just one method of identifying and managing risks. The 'bow tie' is a related method that lays less stress on probability, although it is implicit in the method.

The requirements and recommendations for the capture, transportation and geological storage of CO_2 streams is described in ISO 27914:2017. In addition, numerous 'best practice' guides have been developed to monitor CCS projects that explain and justify these concepts. A recent example, with clear discussion of the links to monitoring techniques, is a guide for developing a Measurement, Monitoring, and Verification (MMV) plan for geologic storage of carbon dioxide (IOGP, 2022). Other relevant reviews of carbon storage monitoring technologies include Jenkins et al., (2015) and Jenkins (2020).

The EIS format does not encourage the presentation of risk management in structured forms. Alternative scenarios were developed based on an existing Feature Event Process (FEP) database developed '*to support the long-term safety and performance of a storage system during and after GHG stream injection (version 2, (Quintessa, 2014))* (p 42 in [7])'. However, the assessment describes these alternative scenarios as implausible, stating

> *'There are no current data or interpretations to support any of these scenarios occurring, and section 6.1.3 describes how implausible they are. In this regard, these alternative scenarios are highly improbable, and only consider hypothetical situations.' (p 173 in [7]).*

Risks are reported throughout the documents, mainly in [5] and [7] but are not systematically linked to monitoring techniques. Further, there is no clear definition of what it means for hazards to be considered 'likely' or 'unlikely'. In addition, if a hazard is not identified, it is unclear if it has been forgotten or discounted because it is unlikely or because the impact is considered negligible.

Overall, the hazards identified in the EIS are plausible, as is the assessment of their likelihood. If we accept the proponent's assessment of the impacts, the proposed monitoring plan is comparable to those approved in the USA under Class II rules for oilfield disposal operations and Class VI rules for saline aquifer storage. Annual reports for carbon storage facilities in the USA are available from the US EPA website[1]. However, the level of detail in this EIS is insufficient to form a rigorous judgement on the suitability of this monitoring plan. It is recommended that a structured risk management plan following international best practice that

[1] https://www.epa.gov/ghgreporting/subpart-rr-annual-monitoring-reports

includes explicit links to identified risks and how potential impacts can be mitigated is used to revise the proposed monitoring plan.

Recommendation: Evaluate and present in a structured way the identified hazards, identifying and connecting them clearly to impacts and the monitoring that is part of mitigating these impacts.

Level of concern: 2

Likelihoods

Sites for geological storage of CO_2 are selected to be free of leakage paths. It is thus difficult to attribute likelihoods to mechanisms of leakage which are ruled out by site selection. The probability of residual hazards can be ranked, informed by expert judgement and using numerical modelling. However, it is critical for this reasoning to be clearly and systematically documented to provide confidence in the proposed mitigation and management strategies. A critical element to building confidence is documenting the logical links between proposed monitoring techniques and the identified risks.

In this EIS, the primary leakage mechanisms considered are a breach of the seal, most probably via an undetected transmissive fault, or leakage up a wellbore where zonal isolation has failed. A surrogate for the level of risk is the size of the final plume, as the bigger it is, the more of the seal it will probe (although at a reduced column height of buoyant CO_2).

The proponent's assessment of the likelihood for these risks for the alternative exposure pathway scenarios is considered plausible (p 181-190 in [7]) but should be explained more fully. Specifically –

- Since there is not yet any detailed seismic imagery of the storage site, it is recommended that the roles of faults and seal continuity is assessed using analogies with areas with more data.
- What do modern data on leakage along wellbores tell us about the risk in this case? A recent study of North Sea wellbores (UK Government) is informative. It is recommended that migration of CO_2 due to movement of contaminated groundwater along wellbores is included in the assessment.
- The main output of the hydrodynamic modelling of the GHG stream plume is to predict its size and duration. It is recommended that the sensitivity of the modelled plume extent to these metrics is assessed for a range of uncertain petrophysical quantities, primarily kv/kh, porosity and permeability. Probing the role of heterogeneity (informed by geological narratives about the depositional environment) is also warranted.

Recommendation: Establish the likelihood of the identified hazards, either by Monte Carlo simulation using plausible input probability distributions for poorly known parameters, or by establishing 'bookend' models for best and worst case for critical hazards.

Impacts

A challenge for this assessment is balancing the competing needs of different resource development activities (oil field, groundwater extraction and carbon storage). The Precipice Sandstone aquifer is managed under multiple acts, policies and regulations: under the *Petroleum and Gas (Production and Safety) Act 2004* (*Qld*) at the Moonie oil field approximately 30 km from the model area; under the *Water Act 2000 (Qld)* in relation to stock, domestic, industrial and agricultural groundwater extraction activities; and under the *Greenhouse Gas Storage Act 2009* in relation to geological carbon storage. In addition, all industrial, resource or intensive agricultural activities with the potential to release contaminants into the environment are managed under the *Environmental Protection Act 1994 (Qld).* These resource development activities are included in the 6 EVs related to human use associated with the Basal Great Artesian Basin Zone (p 41 in [5]).

Targets for groundwater monitoring in the Precipice Sandstone aquifer will differ depending on the intended use. Impacts associated with the Moonie oil field are principally related to changes in groundwater levels due to water extraction (or 'drawdown'). '*Predicted impacts in the Precipice Sandstone are associated with the Moonie oil field where production started in 1964 and is now in a declining phase, nearing end of life'* OGIA (2021). Groundwater extraction from the Precipice Sandstone aquifer is approximately 2225 ML/y for stock, domestic and industrial uses, in addition to 1000 ML/year water extraction from the Moonie oil field (OGIA, 2021). Potential impacts from groundwater extraction are principally related to groundwater drawdown.

However, CO_2 injection for carbon storage will change both groundwater levels and water chemistry, meaning that the parts of the Precipice Sandstone aquifer contained within the CO_2 plume are not suitable for water extraction. The EIS states that '*Injection of the GHG stream is not likely to result in a deterioration in the environmental values of the receiving groundwater outside of the predicted GHG plume*' (p 8 in [3]). For these reasons, it is recommended that the proposed monitoring plan clearly document explicit links between identified risks to groundwater levels and water chemistry, as well as how to detect and mitigate deviations from predicted plume behaviour using different monitoring techniques.

Recommendation: Clearly document the motivations and rationale used to select the proposed monitoring technologies in the EIS, including an explanation of the sensitivity of each monitoring technique to the hazards they are designed to mitigate.

Monitoring techniques

A suite of methods of monitoring are proposed to address the risks that have been identified:

- **Seismic imagery, using permanent-installed sources** is used to detect the extent of the CO_2 plume, and possibly also detect leakage into an overlying aquifer. However, no detailed calculations are presented of the sensitivity of the proposed method. Building on the experience of the Otway Stage 2C and 3 experiments, detailed calculations should be presented that justify the proposed role of seismic imagery. These calculations will need input on repeatability at the site from the baseline seismic surveys. These are scheduled but not yet done or analysed.
- **Pulsed neutron logging** is a well-established method to detect CO_2 near (m) the wellbore; and was used successfully at the Otway site. Calculations showing the feasibility and sensitivity for the aquifer conditions near the West Moonie-1 injection well are recommended.
- **Groundwater sampling** for hydrochemistry and environmental tracer samples is needed during injection. However, while the spatial extent of predicted impacts associated with the proposed injection is expected to be extremely small and null results (no change in hydrochemistry) are difficult to interpret, the monitoring provides public assurance. Any sampling will build on previous work to better understand groundwater flows in the Precipice Sandstone and other aquifers (Rodger et al. 2020, OGIA, 2021, Hofmann et al. 2022).
- **Downhole pressure and temperature** methods are fundamental to understanding the plume's behaviour and have been widely used elsewhere. However, much more detail would be needed to assess their likely effectiveness for this project, such as
  - Where will pressure be measured, and what questions should the data answer?
  - Will above-zone monitoring be undertaken, and how sensitive is it?
  - Will earth tides be measured?
  - Will distributed temperature sensing be used, and if so, how will it monitor well integrity?

Overall, the suite of proposed monitoring technologies is broadly consistent with other carbon storage projects worldwide, but it is unclear if it is optimum or fit-for-purpose.

Recommendation: Clearly document the logic used to select monitoring techniques, explaining why each specific method was selected to manage a specific risk.

Trigger values

The proposed Precipice Sandstone aquifer trigger values for TDS (5,000 mg/L), Arsenic (1 mg/L) and Lead (10 mg/L) as outlined in Table 9-30 in (p 84 in [5]) are high when compared to ambient groundwater quality and are not adequately justified within the documents. Furthermore, trigger values are only defined for a limited number of hydrochemical parameters, and no trigger values have been defined for most major and minor anions and cations. This omission was highlighted in many of the EIS submission comments, including by the IESC (p 8 in [8]), DES (p 70 in [8]) and Harrington (p 86 in [8]).

Recommendation: Revise and set appropriate trigger values for hydrochemical parameters based on a robust assessment of groundwater quality baseline data within the southern Surat Basin (such as Hofmann et al. 2022; OGIA 2021). Clearly document reasoning for selection of trigger values (such as in the context of geochemical modelling conducted as part of the EIS) and discuss if trigger values for additional parameters (such as other metals) are required.

3 References

AS/NZS ISO 31000:2018. Risk management – *Guidelines*. Standards Australia, Sydney.

Bagheri M, Dance T, Jenkins C, Paraschivoiu E, Glubokovskikh S, Barraclough P (2021). Uncertainty analysis and probabilistic approach to address CO2 injection issues - A case study from CO2CRC Otway Stage 3 project. In: Proceedings of the 15th Greenhouse Gas Control Technologies Conference 15-18 March 2021

Duong C, Bower C, Hume K, Rock L, Tessarolo S (2019). Quest carbon capture and storage offset project: Findings and learnings from 1st reporting period. International Journal of Greenhouse Gas Control, 89, 65-75.

Ennis-King J, Paterson L, Dance T, Freifeld B, Zhang Y (2016). Field-scale residual CO2 saturation: analysis of pressure and temperature data from CO2CRC Otway Residual Saturation and Dissolution test. International Journal of Greenhouse Gas Control.

Geological and Bioregional Assessment Program (2021) Compromised aquitard integrity: Stressor node description for the Cooper GBA region, accessed 02 August 2023

Haese R, La Force T, Boreham C, Ennis-King J, Freifeld B, Paterson L, Schacht U (2013) Determining residual CO2 saturation through a dissolution test - Results from the CO2CRC Otway Project. Energy Procedia, vol. 37, pp. 5379-5386.

Hofmann H, Pearce JK, Rodger I, Golding SD, Hayes P (2022) Regional hydrogeology of the southern Surat Basin project 7-0918-C316 published by University of Queensland for Australian National Low Emissions Coal Research & Development (ANLEC R&D), source link: https://anlecrd.com.au/projects/regional-hydrogeology-of-the-southern-surat-basin/

IOGP (2022) Recommended practices for measurement, monitoring, and verification plans associated with geologic storage of carbon dioxide. Report 652. International Association of Oil and Gas Producers, London (2022).

ISO 27914:2017. Carbon dioxide capture, transportation and geological storage — Geological storage. International Organization for Standardization.

Jackson S, Gunning J, Dance T, Bagheri M, Barraclough P, Pevzner R, Ennis-King J, Jenkins C (2022) Time-lapse pressure tomography of a migrating CO2 plume at the Otway Stage 3 site. Proceedings of the 16th Greenhouse Gas Control Technologies Conference (GHGT-16) 23-24 Oct 2022, Available at SSRN: https://ssrn.com/abstract=4296215 or http://dx.doi.org/10.2139/ssrn.4296215.

Jenkins C, Chadwick A, Hovorka SD (2015) The state of the art in monitoring and verification—ten years on. *International Journal of Greenhouse Gas Control*, *40*, 312-349.

Jenkins C (2020) The State of the Art in Monitoring and Verification: an update five years on. *International Journal of Greenhouse Gas Control*, *100*, 103118.

LaForce T, Dance T, Ennis-King J, Paterson L, Cinar Y (2018) How Good is Good Enough in CO_2 Storage Modelling? Looking Back Over Three Generations of Models for the Otway Stage 2C Project. 14th Greenhouse Gas Control Technologies Conference Melbourne 21-26 October 2018 (GHGT-14), Available at SSRN: https://ssrn.com/abstract=3365566

Office of Groundwater Impact Assessment (OGIA) (2021) Underground Water Impact Report for the Surat Cumulative Management Area, Queensland Department of Natural Resources, Mines and Energy, State of Queensland.

Peeters LJM (2017) Assumption hunting in groundwater modeling: find assumptions before they find you. *Groundwater*, 55(5): 665–669. Available [online]: https://10.1111/gwat.12565

Peeters LJM, Middlemis H (2023) *Information Guidelines Explanatory Note: Uncertainty analysis for groundwater modelling*, A report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of Climate Change, Energy, the Environment and Water, Commonwealth of Australia. Available from https://www.iesc.gov.au/publications/information-guidelines-explanatory-note-uncertainty-analysis.

Quintessa (2014) Generic CO_2 FEP Database, Version 2.0., Quintessa Limited, Henley-on-Thames, United Kingdom.

Raiber M, Suckow A (2017) Hydrochemical assessment of the Hutton and Precipice sandstones in the northern Surat Basin. CSIRO, Australia. https://gisera.csiro.au/wp-content/uploads/2018/03/Water-6-Milestone-3.1-Report.pdf

Rodger I, Pearce JK, Hoffmann H, Golding, SD, Hayes P (2020) Hydrogeology of the Southern Surat Basin: Memo report 2, The University of Queensland.

Suckow A, Raiber M, Deslandes A, Gerber C (2018) Constraining conceptual groundwater models for the Hutton and Precipice aquifers in the Surat Basin through tracer data. Final Report. CSIRO, Australia.

Tawiah P, Duer J, Bryant SL, Larter S, O'Brien S, Dong M (2020) CO2 injectivity behaviour under non-isothermal conditions–Field observations and assessments from the Quest CCS operation. International Journal of Greenhouse Gas Control, 92, 102843.

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