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Australia's National
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Bravus (Carmichael)

Advice to the Queensland Department of Environment and Science

Final report

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Summary

The State of Queensland acting through the Department of Environment and Science (DES) requested CSIRO and Geoscience Australia (GA) to provide technical advice on groundwater reports required under the State environmental authority conditions for the Bravus Mining and Resources (Bravus) – Carmichael Coal Mine located in the Galilee Basin, approximately 160 km northwest of Clermont in Central Queensland. The technical advice, in the form of a written report to DES, addresses questions posed by DES in relation to the following groundwater reports:

1. Groundwater Management and Monitoring Program/Plan (GMMP) Review report
2. Hydrogeological Conceptual Model report
3. Groundwater Model report.

The review found the groundwater model is unable to support a robust uncertainty analysis and therefore confidence in the range of predicted impacts is low. Major issues that limit confidence in the model are:

1. **Parameter sampling**: the sampling of parameter combinations for the predictive ensemble is not consistent with the hydraulic properties and does not account for spatial correlation between hydraulic properties, which underestimates the range of potential impacts
2. **Convergence**: number of possible model realisations that meet the acceptance thresholds for convergence in the ensemble of model predictions is limited by numerical instability
3. **Sensitivity analysis:** critical for demonstrating that the parameters important for impact predictions are effectively constrained by observations and not affected by numerical instability
4. **Surface water – groundwater interactions**: Carmichael River is simulated to be a gaining rather than losing stream, which limits confidence in modelled groundwater levels and fluxes
5. **Tertiary aquifer**: groundwater levels and mapped extent of the Tertiary aquifer, connecting the mine area with the source aquifer for the Doongmabulla Springs Complex, do not match observations.

Recommendations to address the major issues identified by the technical review relate to:

1. **Groundwater model report**: improve the representation of the hydrogeological conceptual model in the numerical model and the methods for model parameterisation and uncertainty analysis. A groundwater modelling workflow to improve the model methodology is recommended.
2. **Groundwater Management and Monitoring Program**: improve confidence in the method used to detect and manage impacts on groundwater levels and how observations are used in the model.
3. **Rewan Formation Connectivity Research Plan**: ensure the updated hydrogeological conceptual model is consistently implemented in the numerical groundwater model.
4. **Great Artesian Basin Springs Research Plan:** clarify field and laboratory analytical methods and engage a team of experts to re-evaluate the hydrochemistry and environmental tracer database.

The review finds that the groundwater model report does not meet the requirements of condition E4a of the Queensland Environmental Authority (EPML01470513).

1 Introduction

1.1 Scope

The State of Queensland acting through the Department of Environment and Science (DES) requested CSIRO and Geoscience Australia (GA) to provide technical advice on groundwater reports required under environmental approval conditions for the Bravus Mining and Resources (Bravus) – Carmichael Coal Mine located in the Galilee Basin, approximately 160 km northwest of Clermont in Central Queensland.

The CSIRO and GA were engaged to review and assess information supplied by Bravus and provide concise technical advice, in the form of a written report to DES, in response to 19 questions posed by DES. DES provided CSIRO and GA with the 3 reports listed in Table 1: the Groundwater Management and Monitoring Program/Plan (GMMP) Review report [1], the Hydrogeological Conceptual Model report [2], and the groundwater model report [3]. Note, in the questions posed by DES, the terms 'GW Review report' refers to the groundwater model report [3] and the 'DSC' to the Doongmabulla Springs Complex.

The final Groundwater Management and Monitoring Program (GMMP) was prepared to meet the requirements of the approval conditions for Environmental Authority (EA) EPML01470513 for the Mining Leases (ML) 70441, 70505 and 70506, initially granted on 2 February 2016 and further amended in September 2019, July 2020 and most recently April 2022.

The technical review and response to each question is organised in 4 sections:

2.1 Groundwater model

Q1: Does the uncertainty analysis presented in the GW Review report meet the IESC guidelines and will it provide an acceptable/realistic range of potential impacts?

Q2: Is the methodology used to model the impacts of long wall mining under the SEIS B scenario adequate and appropriate, particularly with respect to prediction of impacts to the DSC?

Q3: Has the use of pilot points resulted in a more accurate representation of parameters instead of using one parameter value per layer?

Q4: Is the model cell size of 500 m in the mining areas appropriate especially with respect to identifying impacts from residual voids post mining?

Q5: Do the initial heads determined in the history matching process adequately represent the observed groundwater heads and groundwater system. In particular:

- *Does the model represent the pre-mining groundwater lows observed north of the Carmichael River in the Bandanna Formation, Colinlea Sandstone and Joe Joe formation? Does the model incorporate findings from the conceptualisation?*
- *Do the initial heads and simulated groundwater levels in the Carmichael River alluvium adequately represent that aquifer and if not, how might this affect the understanding of surface water-groundwater interaction? Has the use of dry bores north of the river affected the process?*

Q6: Has the use of many more head change targets than absolute heads in the history matching process resulted in poorer matches between simulated initial heads and observed heads?

Q7: Has the modelling approach which does not include landholder water use from bores, in particular the Joe Joe to the south of the lease, resulted in predicted mining impacts in this area that match the head change targets?

Q8: Does the modelling of the open cut mining only scenario (including parameters used and methodology of the uncertainty analysis) provide an appropriate level of confidence in the predicted impacts to DSC?

Q9: What matters must be addressed to the model methodology prior to undertaking an Optimisation model of mining activities to ensure no greater than 0.2m drawdown at DSC?

2.2 Groundwater Management and Monitoring Program

Q10: Does CSIRO/GA support the use of GW thresholds based on the open cut only model scenario?

Q11: The GMMP Review report, Appendix A now includes predicted drawdowns in Joe Joe formation bores in the Mellaluka Springs area of between 60 and 80 m for the open cut only scenario. This is an increase from previous predicted drawdowns (under the 2013 SEIS model) which were less than 1 m for these same bores. Are these increases realistic? Have they been influenced by the lack of landholder water use being included in the model in this area?

Q12: Are the initial heads in the Tertiary sediments and Weathered zone representative of the observed groundwater system in these units? Has the use of dry bores in the Weathered zone affected the process?

Q13: Do you support the Bravus proposed additional monitoring bores and locations? Do you support DES recommendations for additional bores? Any additional bores?

Q14: What action should be taken if the actual monitored rates of groundwater drawdown are faster than predicted?

Q15: To address ongoing and upward trending water quality trigger exceedances – what do you recommend as an appropriate action?

Q16: Please provide advice on the suitability and reliability of the use of VWP monitors.

2.3 Rewan Formation Connectivity Research Plan

Q17: What additional geological work with respect to the extent of the Clematis Sandstone and Dundas Beds is required to improve the confidence in the modelling outputs for the optimisation model?

2.4 Great Artesian Basin Springs Research Plan

Q18: Has sufficient isotopic work been undertaken to advance our understanding of the source aquifer? GAB Springs Research Report 1.

Q19: Have all the additional works as recommended by CSIRO/GA in 2019 been addressed (whether completed or not) to your satisfaction in particular to support the identification of the source(s) aquifer(s)?

1.2 Information and documents received

The CSIRO and GA technical teams met with representatives of:

- DES on 1, 10 and 27 February 2023, and 17 March 2023
- Bravus, EMM Consulting and DES on 3 March 2023.

The information received 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 pdf document (not the page number printed on the page). This allows for consistent referring to page numbers, even when a document has several appendices, each with their own page numbering.

Table 1 Information received

Nr	Title – Date	'Label' – Filename	Author	Source
1	Groundwater Management and Monitoring Program – Final Review Report Carmichael Coal Mine and Rail Project – January 2023	'GMMP review' – GMMP Review Report 2022_finalv1.pdf	EMM	DES
2	Carmichael Coal Mine Report No 1: Data review and conceptualisation report – February 2023	'Hydrogeological conceptual model (HCM)' – E210818_RP1_HCM_v4.pdf	EMM	DES
3	Cover Note: Updated Numerical Groundwater Model Report – Carmichael Coal Mine Report No2: Numerical groundwater flow model report – 8 February 2023	'Groundwater model' – E210818_model_calib_v2_1_bravus cover letter.pdf	Bravus/EMM	DES

1.3 Review methodology

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

Table 2 Categorisation of review comments

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.

2.1 Groundwater model

This section addresses questions from DES related to the groundwater model report [3], which '*contains the outcomes of the review of the Numerical Groundwater Model developed for Carmichael coal mine project. This model is required to be reviewed during 2022 and further on a five-yearly basis into the future in accordance with our Environmental authorisation*' (p 1 of [3]). The original groundwater model was developed by GHD in 2013 and reported in Appendix K1 of the original Supplementary Environmental Impact Statement (SEIS). '*The updated model constitutes a complete rebuild from the 2013 SEIS model and includes an updated 15-layer representation of the groundwater system based on available geological data and new structural surfaces'* (p 5 of [3]).

The assessment undertaken by CSIRO and GA identified several major issues with the groundwater model. These can broadly be grouped in 2 categories: (1) representation of the conceptualisation in the numerical model and (2) parameterisation and uncertainty analysis.

2.1.1 Uncertainty analysis

This section reviews 'Q1: *Does the uncertainty analysis presented in the GW Review report meet the IESC guidelines and will it provide an acceptable/realistic range of potential impacts?'*

The review finds that the groundwater model does not meet the IESC guidelines. The model is unable to support a robust uncertainty analysis and therefore confidence in the range of predicted impacts needed to support regulatory decision making is low.

The review identified 3 major issues that limit confidence in the model:

1. Parameter sampling: the sampling of parameter combinations for the predictive ensemble does not accurately represent the available information on hydraulic properties or take into account spatial correlation between hydraulic properties, which leads to an underestimate of the range of potential impacts
2. Convergence: numerical instability limits the number of possible model realisations that meet the acceptance thresholds for convergence in the ensemble of model predictions
3. Sensitivity analysis: needed to demonstrate that the parameters important for impact predictions are effectively constrained by observations and not affected by numerical instability

Level of concern: 1

Future groundwater modelling should address the following recommendations:

- generate parameter values accounting for spatial correlation and available information
- address the reasons why the model fails to converge to provide confidence that the model provides an acceptable/realistic range of potential impacts
- perform a sensitivity analysis to assess whether predictions of the quantities of interest (QoI) are compromised by model convergence issues
- address all 9 questions in the checklist in the IESC guidelines on uncertainty analysis

- include all QoI relevant to the approval conditions in predictive scenarios
- use a robust uncertainty analysis, including sensitivity analysis for quantities of interest, to support the optimisation of future operational underground mine plans
- resolve the reasons for numerical instability before further model calibration and prediction
- revise the model to address the reasons why the model fails to converge to provide confidence that the model provides an acceptable/realistic range of potential impacts
- justify rationale used to define threshold values for the Monte Carlo simulations
- justify how systematic deviations in modelled and observed values affect impact predictions
- justify spatial patterns of modelled hydraulic properties in relation to geological information
- perform a sensitivity analysis to assess whether predictions of the QoI are sensitive to boundary conditions
- improve report transparency for parameter ranges and distributions, how targets are derived, and parameter variability within a single realisation or an ensemble of realisations.

Level of concern: 1

The uncertainty analysis in the groundwater model report [3] does not meet the '*IESC guidelines'* or more specifically the IESC Explanatory Note on uncertainty analysis (Middlemis and Peeters, 2018)[1]. The 2018 IESC guidelines state that '*A robust uncertainty analysis will ensure that management options and approaches are commensurate with the level of risk and the likelihood of any particular impact*'.

The 3 key guiding principles for any uncertainty analysis in the IESC guidelines are:

- *'the model used must be fit for the purpose of providing information about uncertainty in a way that allows decision-makers to understand the effects of uncertainty on project objectives, and the effects of potential bias*
- *uncertainty must be considered and addressed at the problem definition stage (when deciding on the approach to groundwater modelling and what questions that modelling will address) and at each subsequent stage of the workflow*
- *engagement with regulatory agencies (noting the IESC is not a regulator) is required, to discuss and agree on the methodologies and understand the implications of the results.'*

This review uses the following terminology from the updated version of the IESC Explanatory Note on uncertainty analysis for groundwater modelling:

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'.

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[1] The IESC Explanatory Note on uncertainty analysis for groundwater modelling is under revision and the updated version (Peeters and Middlemis, 2023) will replace the 2018 version (Middlemis and Peeters, 2018). While the revised version has been available for public consultation since August 2022, this review will only refer to Middlemis and Peeters (2018) as this was the authorative version at the time of preparation of the groundwater model report [3].

Table 3 in Section 12 of the IESC guidelines (Middlemis and Peeters, 2018) sets out a fatal flaws checklist – see detailed answers below. The groundwater model report [3] addresses or partly addresses 5 of the 9 questions in the checklist for uncertainty analysis (Table 3, p.30) and fails to adequately address the remaining 4 questions – see discussion below.

The second part of the question is if the uncertainty analysis provides an acceptable/realistic range of potential impact. This requires that the uncertainty analysis presents a range of model outcomes, relevant to decision makers, that corresponds to a range of parameter values, consistent with available data and knowledge.

Confidence is low that the range of potential impacts presented meets these criteria. The main issues are (1) the sampling of parameters, (2) numerical stability of the groundwater model, and (3) lack of sensitivity analysis. These are detailed below. This is considered a level 1 issue as it directly affects the predicted impact and leads to an underestimate of the predicted range of potential impacts.

The workflow for uncertainty analysis described in the groundwater model report [3] is:

1. Obtain a base realisation of parameter combinations that provide an optimal fit to the history-matching targets, consisting of 239 hydraulic head targets, 11,202 head-change targets and 2 flux targets. The PESTPP-IES algorithm is used to minimise the objective function.
2. The ensemble for prediction of 500 parameter combinations is generated *'…with a Gaussian distribution centred on base realisation pilot point values where one standard deviation is equal to one order of magnitude.'* (p 73 in section 4.1.3.ii in [3]). Analysis of the parameter values in the spreadsheet provided shows this is not an accurate description of the sampling. It appears that standard deviation is chosen such that the 90th percentile confidence interval (i.e between the 5th and 95th percentile) covers 2 orders of magnitude, or 1 order of magnitude each side of the mean. This corresponds to a standard deviation of approximately 0.5. It also appears that values that are outside the bounds have been replaced with the bounds of the parameter interval. This is not mentioned explicitly in the report.
3. The parameter combinations that result in scaled root mean squared error values below the acceptance thresholds for initial head (SRMS: 12.5%), transient head (SRMS: 8%) and transient head-change (SRMS: 3.5%) are included in the predictive ensemble, provided they result in a converging model for the post-mining simulations. Of the 500 possible model realisations, only 105 (21%) meet the acceptance thresholds for convergence in the ensemble for predictions (Table 3).

The sampling protocol described in point 2 is not consistent with the available hydrogeological conceptualisation and parameterisation information. The Hydrogeological Conceptual Model report [2] provides estimates for the ranges and distributions of the parameter groups. These are used for the initial parameterisation and to inform the parameter bounds. However, this information is not used and is replaced by an arbitrarily chosen parameter distribution that is normal in log10-transformed space, centred on the values from the history-matching model runs and a 90th percentile confidence interval spanning two orders of magnitude. In the absence of other information or data, this is often an appropriate approach. In this case however, it does not use readily available information in the Hydrogeological Conceptual Model report [2].

A second issue with the sampling protocol is that each parameter is sampled independently from the range of possible values. This sampling approach means that 2 points located next to each other could be represented in the model using the extremes of the range of possible values, causing model parameters to lack any spatial coherence or relationship to the hydrogeological conceptualisation. It is very unlikely that the hydraulic properties at scale are not spatially correlated. The results of the history-matching model runs show the opposite, a strong spatial correlation, with extensive areas having similar values (Figure 4.3 on p 75 in the groundwater model report [3]). Ignoring spatial correlation in the sampling of parameter values leads to an underestimate of the range of effective hydraulic properties. This is exacerbated by replacing any sampled values from out of bounds by the minimum or maximum of the range.

The sampling protocol appears to underestimate the range of model predictions. This is of greatest concern where the pilot point locations are close together, such as in the vicinity of the mine and the Doongmabulla Spring Complex.

Recommendation: Generate the initial ensemble of parameter values in a way that accounts for spatial correlation and is consistent with the prior information on parameter distributions, such as data and information contained in the Hydrogeological Conceptual Model report [2].

'*A crucial practical requirement is a stable groundwater model that converges over a wide range of parameter values. This requires careful design, testing and review of the model(s)*' (Middlemis and Peeters, 2018). The large number of parameter combinations that fail to converge in the transient, post-mining simulation (Table 3) indicates that the groundwater model is not numerically stable.

Table 3 Overview of the convergence and acceptance of realisations in the uncertainty analysis

Description	Number	%
Initial number of realisations	500	100
Number of realisations that converged in steady state simulation (7 runs removed)	493	99
Number of realisations that converged in steady state and meet the acceptance thresholds for summary statistics (231 runs removed)	262	52
Number of realisations that converged in transient, post-mining simulations, with estimation of impact due to future mining operation (157 runs removed)	105	21
Number of realisations included in the ensemble for predictions	105	21

Information on which parameter combinations cause non-convergence is not presented or discussed. Non-convergence of a model over part of its parameter range does not necessarily mean the resulting range of predictions is compromised. The convergence issues suggest structural issues with the model that need to be resolved before a robust uncertainty quantification can be carried out.

Such a model can still be used for a valid predictive uncertainty analysis, provided it can be demonstrated that the parameter combinations for which the model fails to converge are (a) unrealistic parameter combinations, i.e. at the extremes of the ranges consistent with prior knowledge or resulting in large mismatches between observed and simulated values, and (b) parameter combinations for which the predictions are not sensitive and the ensemble of converging parameter combinations provides a comprehensive sampling of the parameters to which predictions are sensitive. Based on the information provided, the model appears to fail to converge for parameter combinations that are realistic. This means the model is not fit for the purpose of a robust uncertainty analysis as it cannot simulate predictions associated with these realistic parameter combinations and therefore that the range of predictions of potential impact is underestimated. It is also possible that the random sampling of parameter values without spatial correlation results locally in large contrasts in hydraulic property values in the model, causing large gradients in pressure, creating numerical instability.

Recommendation: Identify, document, and address the reasons why the model fails to converge to provide confidence that the model provides an acceptable/realistic range of potential impacts.

The material presented does not provide a sensitivity analysis or any other information discussing which parameters are important to match historical observations and which parameters are important for the prediction of impacts. Without this information it is not possible to evaluate if the range of predictions is constrained by the observations or if the parameter combinations causing numerical instability are compromising the range of predicted impacts. The groundwater model report [3] does not discuss the sensitivity of predicted impacts to boundary conditions.

Recommendation: Perform a sensitivity analysis to identify the parameters important to reproduce historical observations, the parameters important to simulate impacts and the sensitivity of impact predictions to boundary conditions.

The issues identified above are discussed in more detail as part of the 9 questions posed in '*Table 3—Fatal flaws review checklist for uncertainty assessment*' in the IESC Explanatory Note on uncertainty analysis (Middlemis and Peeters, 2018). Out of the 9 questions, 5 were partly or adequately addressed and 4 were not adequately addressed.

Recommendation: Address all 9 questions in the checklist in the IESC guidelines on uncertainty analysis

☐ *1. Is there evidence of engagement between project proponent and regulatory agencies?*

Yes. The groundwater model report [3] addresses requirements of Condition E9 of the environmental approval conditions for the Carmichael Coal Mine. On-going engagement between the project proponent (Bravus) and the Queensland government regulator (DES) is evident in the relevant plans and reports prepared to meet relevant approval conditions, Bravus commitments and to address recommendations from DES. This review includes relevant discussion related to the regulatory issues relevant to the purpose of the groundwater model report [3] identified in Condition E9, including:

- updated groundwater monitoring data, measured mine dewatering volumes, observed groundwater levels, groundwater flow rates to surface water, hydrogeological conceptualisation, predicted impacts, water balance and model assumptions
- transient calibration and additional model layers below the D seam of the Colinlea Sandstone
- changes in predicted groundwater levels for a range of scenarios
- documentation and justification of changes to the model and its outputs, including data
- evaluation of the accuracy of the predicted changes in groundwater levels, groundwater flow rates to surface water and recommended actions to improve the accuracy of the model predictions.

☐ *2. Does the modelling and uncertainty analysis provide information for decision makers on the effects of uncertainty on the project objectives?*

Partly. Quantitative uncertainty analysis is only reported for groundwater drawdown for the open-cut only scenario. '*Two additional scenarios were developed to predict the effects of underground mining and associated fracturing; however predictive uncertainty analysis was not undertaken on these*' (p 5 of the groundwater model report [3]). Quantitative uncertainty analysis for other QoI identified in the approval conditions, such as changes in groundwater flow rates to surface water, are not reported. For the open-cut scenario, the report includes water balance predictions and changes in baseflow to the Carmichael River. Changes in flux at the springs are not reported. The confidence intervals for the reported fluxes are not presented.

Recommendation: Expand the set of model predictions included in the uncertainty analysis to include all flux and drawdown estimates relevant to the QoI identified in the approval conditions.

The groundwater model report [5.1 in 3] describes 3 prediction scenarios:

- Scenario 1- Open cut only
- Scenario 2- SEIS with previous fracturing assumptions
- Scenario 3- SEIS with updated fracturing assumptions.

Model predictions of drawdown for scenarios 2 and 3 that include underground mining operations are deterministic and uncertainty on those predictions is not presented. This was agreed with the regulator to enable the mining plans for the underground mining operations to be optimised in the future to minimise potential impacts.

Recommendation: Use a robust uncertainty analysis, including sensitivity analysis for the QoI, for future groundwater modelling to support the optimisation of operational underground mine plans.

☐ *3. Are the adopted conceptual model, complexity-simplicity balance, and applied modelling capabilities commensurate with the overall risk context and the model's purpose of investigating the uncertainty / risk issues?*

Partly. The risk profile of this project is high. The conceptual hydrogeological model is comprehensive, and most aspects of the conceptual model are adequately represented in the numerical model. However, issues related to the representation of boundary conditions (western constant head boundary, surface water-groundwater interactions, landholder bore pumping) have been identified and are discussed in greater detail in sections 2.1.5 and 2.1.7.

The model is complex. The modellers have chosen to use a very large number of parameters in the parameterisation to represent this complexity in the uncertainty analysis. The benefits and drawbacks of applying this parameterisation scheme are discussed in greater detail in section 2.1.3 in response to the DES question on the pilot points.

The model is not numerically stable enough for the predictive scenario. The high structural complexity and large number of parameters make it difficult to diagnose the cause of numerical instability. The numerical instability compromises the ability of the model to quantify the predictive uncertainty and means that the groundwater model is not suitable for a robust uncertainty analysis needed to support regulatory decision making.

Recommendation: Identify, document, and revise the model to address the reasons why the model fails to converge to provide confidence that the model provides an acceptable/realistic range of potential impacts.

☐ *4. Has the uncertainty assessment and modelling methodology been designed and implemented using all the available data?*

Partly. The modelling team has incorporated a large amount of new information through the updated conceptualisation and numerous observations for history matching.

The ranges for hydraulic properties documented in the Hydrogeological Conceptual Model report [2] are however not used in generating the ensemble for predicting impacts.

For example, section 2.1.7 outlines where historical pumping by landholders is used to explain variations in observed groundwater levels, especially in the Joe Joe formation. This pumping is however not represented in the numerical model, which will require parameters to compensate for this missing boundary condition, leading to biased parameter estimates.

The geometry and extent of the Tertiary aquifer (refer section 2.2.3) and Clematis Sandstone (refer section 2.3.1) directly affect the predicted drawdown, especially in the case where the eastern extent of both aquifers intersects the mine lease. However, supporting documentation for how these stratigraphic units are mapped is limited.

Recommendation: Identify, document, and justify why any model conceptualisations, parameterisations or predictions are inconsistent with available hydrogeological conceptualisations or observation data.

☐ *5. Where history-match condition calibration is undertaken, has it minimised non-uniqueness and error variance? Is an acceptable level of model-to-measurement mismatch defined for the conditional calibration?*

Yes. The ensemble approach to history matching through PESTPP-IES minimises non-uniqueness and error variance. Threshold values for model-to-measurement mismatch have been defined for the subsequent Monte Carlo simulations. The rationale for the choice of these thresholds is not documented.

It is important to note that using PESTPP-IES in combination with pilot point parameterisation does not provide any safeguard against parameters compensating for incorrectly specified boundary conditions, which may lead to biased parameter values and biased predictions. Many parameter values in the base realisation are at their bounds. This generally indicates that parameters are compensating for boundary conditions, such as in the parameter histograms in Appendix B and in the spatial distribution of parameter values presented in Figure 4.3 (horizontal hydraulic conductivity in Clematis Sandstone), Figure 4.6 (vertical hydraulic conductivity upper Rewan formation), Figure 4.7 (vertical hydraulic conductivity lower Rewan formation), Figure 4.10 (horizontal hydraulic conductivity in AB Coal seam) and Figure 4.11 (horizontal hydraulic conductivity in D Coal seam) of the groundwater model report [3]. This is discussed in greater detail in section 2.1.3.

Recommendation: Document and justify rationale used to define threshold values for model-to-measurement mismatch for the Monte Carlo simulations.

☐ *6. Are all simulations consistent with all relevant information/data?*

No. The base realisation provides the best fit to the objective function and the parameter combinations retained in the ensemble used for prediction where all meet the predefined objective function thresholds. However, the flux targets, i.e. the estimated spring flow from field data at Joshua Spring and other Doongmabulla springs Figure 1, are not used to constrain the predictive ensemble. The groundwater model report [3] mentions that springflow estimates are not used as acceptance criteria as they are more uncertain. While this is correct, it leads to the inclusion of parameter combinations in the predictive ensemble that result in springflow estimates that are more than twice as large as those estimated for the other Doongmabulla springs and less than half of what is estimated for Joshua Spring.

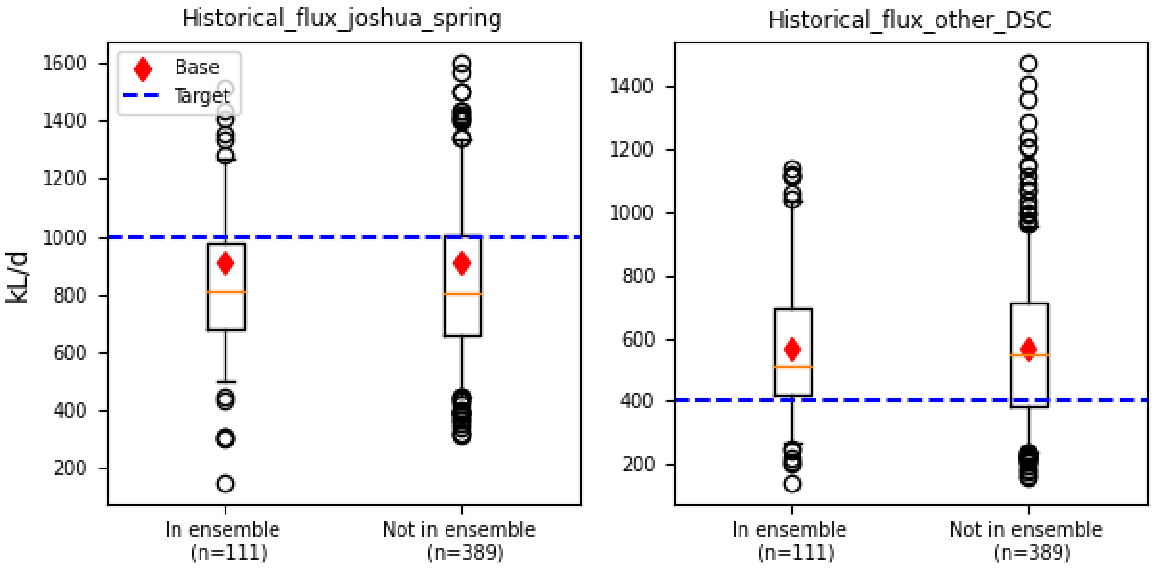

Figure 1 Simulated flux at Joshua Spring and at other springs in the Doongmabulla Spring Complex. ***[Figure created by CSIRO]***

The scatterplots of observed to simulated values (Figure 4.12 on p 86 and Figure 4.13 on p 87 in the groundwater model report [3]) and the hydrographs (Appendix C of [3]) identify many areas with large systematic deviations from the observed values. Of particular concern is the systematic overestimation of groundwater levels in the vicinity of the Carmichael River and the Doongmabulla Spring Complex. This results in the model predominantly predicting groundwater inflows to the river or a gaining system, instead of a losing system as reported in the Hydrogeological Conceptual Model report [2]. This compromises the ability of the model to simulate any drawdown at these receptors and is discussed in detail in 2.1.5.

There is no discussion in the groundwater model report [3] on whether the spatial distribution of hydraulic properties inferred using PESTPP-IES is consistent with the geological information.

Recommendation: Discuss and justify systematic deviations between observed and simulated values and how this may affect the predictions of impact.

Recommendation: Discuss and justify the spatial patterns of hydraulic properties inferred using PESTPP-IES and how they relate to available geological information.

☐ *7. Has the model been submitted to stress testing with extreme parameter combinations?*

No. There is no mention in the groundwater model report [3] on testing the robustness of the model. EMM Consulting provided a dataset after an information meeting with DES, CSIRO and GA on 3 March 2023. The updated information on the convergence status of each model realisation used for the predictive ensemble (Table 3) was provided by email on 31 March 2023 and reduced the number of realisations included in the ensemble for predictions from 111 to 105. Figure 2 was prepared using original dataset and was not updated.

Out of 500 model realisations, including the base case, 7 failed to converge in steady state, 231 converged in steady state but failed to meet acceptance thresholds for history matching, and 157 failed to converge in the post-mining predictive scenario. The predictive ensemble includes 105 parameter combinations, or 21% of the 500 possible realisations. There are no impact predictions for the 395 parameter combinations, or 79% of the 500 possible realisations, that failed to converge or to meet the acceptance thresholds.

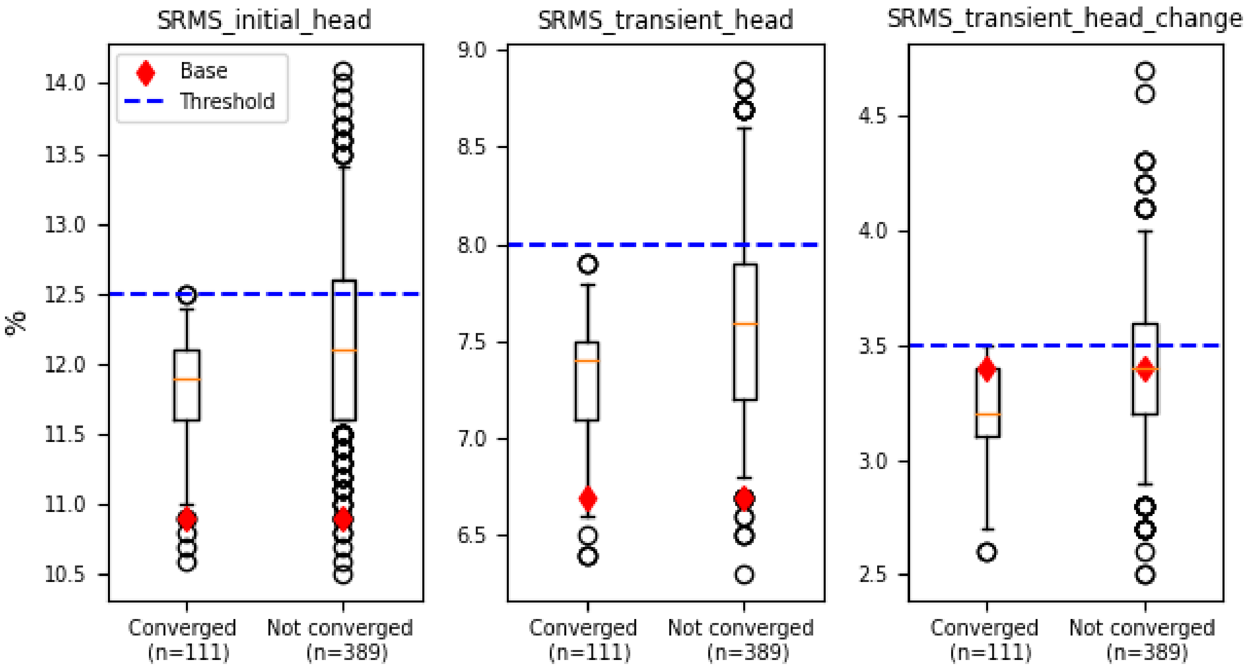

Figure 2 Boxplots of summary statistics with their acceptance thresholds for converging and non-converging parameter combinations, showing initial heads in left plot, transient heads in middle plot, and transient head changes in right plot. The red diamond indicates the summary statistics for the base case parameter combination and orange line shows the median of the parameter combinations for each class. ***[Figure created by CSIRO]***

Figure 2 shows the summary statistics for the converged and not converged parameter combinations. While the median values for the summary statistics for non-converging parameter combinations are higher than those for converging parameter combinations, most non-converging parameter combinations meet at least one of the acceptance thresholds. Table 4 highlights that only 40% (105 out of 262) of parameter combinations that meet all acceptance thresholds result in a converging model for the future scenario.

Table 4 Overview of number of realisations that meet convergence and acceptance criteria

Description	Meets all acceptance thresholds	Does not meet all acceptance thresholds	Total
Converged – historical and future	105	0	105
Failed to converge future	157	231	388
Failed to converge historical	NA	NA	7
Total	262	238	500

The base case parameter set results in low summary statistics, but not the minimum. For the SRMS_transient_head_change the base case parameter set is close to the maximum of the converging set.

Inspection of the parameter combinations associated with converging model runs and those associated with non-converging model runs did not indicate specific parameter ranges or combinations that cause numerical instability. Other possible causes of numerical instability sources to be considered include structural issues with the model or the independent sampling of pilot point parameters.

Recommendation: Investigate, identify, and resolve the reasons for numerical instability before further model calibration and uncertainty analysis.

☐ *8. Has a parameter sensitivity analysis and/or parameter identifiability analysis been completed to identify which parameters can be constrained by the available observations and which parameters affect the simulations the most?*

No. This is a major shortcoming of the groundwater model report [3]. To have confidence in groundwater model predictions, it is not sufficient to demonstrate that the model is able to reproduce historical observations. It needs to be demonstrated that reproducing historical observations means that the parameters that are important to the predictions have been constrained. The groundwater model report does not provide a sensitivity analysis on which parameters are important to reproduce observations, or on the parameters that are important to the predictions of drawdown or flux. This is crucial information. Without this information, it is not possible to evaluate whether parameters compensating for boundary conditions will result in biased predictions.

The dataset provided to CSIRO by EMM with the parameter values, observation targets and selected predictions for each of the 500 realisations allows the sensitivity of observation targets to parameters and the sensitivity of predictions to parameters to be investigated. There is however a very large number of parameters: 516 pilot point locations with different values across 4 parameter groups (Kx, Kz, Ss, Sy) and 15 hydrostratigraphic units, which results in 30,960 parameters representing spatial variability. In addition, there are 25 parameters representing boundary conditions and properties of boundary conditions (such as recharge and drain conductance). A single parameter will have very limited impact on any of the summary statistics or any of the predictions. The ensemble of 500 realisations, due the large number of parameters and independent sampling, is not suited for sensitivity analysis. Identifying which parameters are important to the predictions is further hampered because predictions are only available for the 105 parameter combinations that resulted in a converging simulation for the future predictive scenario.

Recommendation: In addition to a parameter sensitivity analysis, perform a sensitivity analysis to assess whether predictions of the QoI are sensitive to boundary conditions. The western boundary represented by a constant head boundary and the boundary conditions representing surface water-groundwater interactions along the Carmichael River are of greatest concern. The maps of simulated groundwater levels clearly show the effects of these boundary conditions (e.g. Figure 4.15 on p 89 and Figure 4.16 on p 90 in the groundwater model report [3]). A formal investigation of how the location of boundary conditions and the level assigned to the boundary condition (constant head or drainage base) affects model calibration and predictions is warranted. This is discussed in more detail in section 2.1.5.

☐ *9. Have all reports been prepared in an open, honest and transparent way?*

Bravus has engaged with DES and the CSIRO/GA the review team in an open, honest constructive way. This included providing additional detailed groundwater model information in a timely manner. The IESC guidelines (Middlemis and Peeters, 2018) identify key elements for reviewers to look for, including:

- *'clear definition of the required model outcomes*
- *justification of the methods and assumptions*
- *open, transparent and logical documentation of methods and results in a way that is amenable to scrutiny*
- *evidence of consultation and communication between proponent and regulator'.*

No. The groundwater model report [3] does not satisfy the key elements identified by the IESC guidelines needed for reviewers to assess whether the uncertainty analysis is suitable and therefore if the model is fit-for-purpose. Issues in reporting that would improve the transparency of the report are:

1. Justification for parameter ranges and distributions with explicit links to the Hydrogeological Conceptual Model report [2]
2. More detail on how the available observations of groundwater level are used to derive targets for history matching, especially how head change targets are computed and how conflicting observations between loggers and manual measurements are dealt with
3. Presentation of parameter values of the ensembles. The report mixes two sources of variability: (1) the spatial variability within a single realisation (base realisation) and (2) the variability within different realisations. For example, in Figure 4.2 on p 74 of the groundwater model report [3], the blue histogram, with frequency on the right-hand side y-axis, corresponds to the values of the pilot points shown spatially in Figure 4.3. The grey histogram in Figure 4.2, with frequency on the left-hand side y-axis, corresponds to values of all the pilot points across all the realisations. The spatial variability (1) is a measure of heterogeneity, while (2) is the representation of uncertainty in results. The variation in results (model outcomes) is driven by (2), not by (1). It is not clear from the report what the range of parameter values is to which the ensemble of model results corresponds. It is therefore not possible to evaluate if the range of model outcomes is acceptable or realistic.

Recommendation: Improve report transparency by including justification of parameter ranges and distributions, how history matching targets are derived, and clear communication of spatial variability within a single realisation and within an ensemble of realisations.

2.1.2 Long wall mining

This section reviews '*Q2: Is the methodology used to model the impacts of long wall mining under the SEIS B scenario adequate and appropriate, particularly with respect to prediction of impacts to the Doongmabulla Springs Complex?'*

The methodology used to represent long wall mining does not limit the ability of the model to predict impacts on the Doongmabulla Springs Complex.

Yes. The representation of the SEIS B scenario for enhanced hydraulic conductivity is appropriately implemented within the model. The ability of the model to make predictions to Doongmabulla Springs Complex is **not limited** by the way the long wall mining is implemented.

There are two alternate scenarios simulated for the collapse of the roof following long wall mining:

- SEIS A uses same assumptions as GHD model
- SEIS B uses recommendations from RP5.4 (Rewan hydraulic properties report, 2021)

The difference in the two scenarios considered is the height of fracture propagation above the goaf and the enhancement of the hydraulic conductivity. In the SEIS A scenario the fracture propagation height is 150 m with an enhanced hydraulic conductivity of x50 for the first 75 m and x10 for the top 75 m. The SEIS B scenario used a fracture propagation height of 230 m and a ramp function for the enhanced hydraulic conductivity of 5 m/d above the caved zone to background calibrated value at 230 m above the caved zone. The background hydraulic conductivity of the Rewan Formation is typically 10^{-6} to 10^{-5} m/d. The SEIS B scenario has a greater height of fracturing and a greater enhancement of the hydraulic conductivity.

The fracture propagation height reaches the surface in ~45% of long wall panels from the calculations in the Rewan hydraulic properties report (2021), these calculations are for each long wall panel individually whereas only the average of 230 m has been applied in the model to every long wall panel. The conclusion from the Rewan hydraulic properties report (2021) is that the weathered Tertiary sediments near the surface have a high enough clay content that any surface cracks will be short lived and self-seal. This self-sealing of the cracks will prevent any enhanced pathway for surface water or rainfall to recharge the groundwater above the background estimates of recharge. Consequently, no enhanced recharge has been simulated in the model after long wall mining.

Drawdown estimated at Doongmabulla Springs Complex is less than 0.1 m for SEIS A scenario (figure 5.5 on p 108 of the groundwater model report [3]) and greater than 0.2 m for SEIS B scenario (figure 5.6 on p 109 of [3]). This drawdown of greater than 0.2 m is not discussed in the report.

2.1.3 Pilot points

This section reviews '*Q3: Has the use of pilot points resulted in a more accurate representation of parameters instead of using one parameter value per layer?*

Level of concern: 1

Future groundwater modelling should address the following recommendations:

- only use pilot points for hydraulic properties where the HSU is present
- clearly document pilot point parameterisation, and discuss spatial parameter patterns in relation to the hydrogeological conceptualisation
- justify rationale for spatial correlation between parameters used for predictive model ensembles.

Level of concern: 1

No. The pilot point parameterisation used in this project leads to an underestimate of the range of predicted impacts as spatial correlation between pilot point parameters is not implemented in sampling for the predictive ensemble. There is no discussion of how the spatial patterns inferred for the hydraulic properties of the hydrostratigraphic units relate to the available hydrogeological or geological information. This reduces confidence that the pilot points provide an accurate representation of reality.

Pilot points are a parameterisation approach that allow spatial heterogeneity in parameter fields to be inferred from observations. As there are usually many more pilot points than observations, there are too many degrees of freedom for this kind of parameter inference. Optimisation using pilot points resolves this issue by introducing regularisation terms. A spatial correlation is imposed on the parameter field and the objective function for optimisation is penalised for deviations from this spatial correlation. Imposing spatial correlation is essential as it (1) ensures the optimisation is numerically tractable and (2) safeguards against overfitting to individual observations. Overfitting with pilot points often creates 'bulls-eye' features in a parameter field, where the area in close vicinity of a pilot point has a much higher or much lower value than its surroundings. While this can be a good thing, isolating the effect of outlying observations, it often leads to unrealistic parameter fields that are not representative for the actual heterogeneity of the hydraulic property.

A parameterisation with piecewise constant zone of parameter values can potentially result in a worse fit with observed values, but, when sampled from an appropriate distribution, is more conservative when estimating the range of predicted drawdown. This approach appears to have been used in the initial stages of model development (p 70 in [3]) but is not clearly documented. The groundwater model report [3], states on p 73: *'Parameters were not assumed to be spatially dependent (correlated)'*. This assumption is unlikely to be consistent with available geological information, as the sediments would exhibit spatial correlation, at least at the scale of the closest spaced pilot points. The pilot point parameterisation scheme implemented in PESTPP-IES generally results in parameter fields that display spatial continuity as the algorithm will only deviate from the initial value if it results in a locally better fit to the observation targets. Weak or no imposed spatial correlation often gives rise to bulls-eye features such as is apparent in figures 4.3 on p 75, 4.6 on p 78, 4.10 on p 82 and 4.11 on p 83 in [3]. As discussed in section 2.1.1, the independent sampling of parameters without accounting for spatial correlation leads to underestimation of the range of predicted impacts.

The groundwater model report [3] does not provide a map with the location of the pilot points in relation to the observation locations. The groundwater model report [3] only provides maps of final parameter values for a selected set of hydraulic properties (Figure 4.3, 4.6, 4.10 and 4.11). It does not provide maps of the final parameter fields for the other hydraulic properties parameterised with pilot points. They are only reported in Appendix B of [3] as histograms. This is not sufficient as it does not allow to evaluate spatial variability. The locations of pilot points and their corresponding parameter values for all realisations were provided in the dataset provided in response to the request for additional information.

Inspection of pilot point locations and parameter values indicates that the same locations for pilot points are used for every hydrostratigraphic unit (HSU) and every hydraulic property. Many of the HSU's, such as the alluvium, Clematis or Rewan formation, have a limited spatial extent in the model domain. Despite that, there are pilot points assigning hydraulic properties to these HSUs in locations where the HSUs are not present. This leads to many pilot point parameters that have no or should have no effect on the groundwater model. Although PESTPP-IES can handle insensitive parameters and there is no computational cost for adding insensitive parameters, it is not good modelling practice to have many insensitive parameters. This only complicates the analysis of results. Maps of the base parameter combination for all properties and HSUs indicate that property values for some HSUs differ from the initial value in areas where the HSU is not present.

Cross-referencing the spatial parameter fields with the location of bores with observations used for history matching (Figure 4.1 on p.72 [3]), indicates areas of the model for which parameter values are at or close to the minimum or maximum of the range, where there are no observation locations to drive that variability. The discussion of the spatial variability in inferred parameter fields in the groundwater model report [3] does not include any interpretation of what geological features the inferred spatial variability may correspond to. As an example, the spatial distribution of modelled horizontal hydraulic conductivity for the Clematis Sandstone shown in Figure 4.3 (p.75 of [3]) indicates that the highest values of Kh are in the north west of the model area. This would indicate hydraulic conductivity increases with depth, where hydraulic conductivity is generally expected to decrease with depth.

Recommendation: For each hydrostratigraphic unit, only use pilot points for hydraulic properties where the HSU is present. Omit pilot points at locations where the HSU is not present.

Recommendation: Improve documentation and reporting on pilot point parameterisation (location, initial value, final value, spatial variability). Discuss spatial patterns emerging from parameter inference in relation to the geology and hydrogeology of the region.

Recommendation: Specify or maintain spatial correlation between parameters when sampling for a predictive ensemble. Note that ensembles generated by PESTPP-IES by default maintain this spatial correlation.

2.1.4 Grid cell size

This section reviews '*Q4: Is the model cell size of 500 m in the mining areas appropriate especially with respect to identifying long-term impacts from residual voids post mining?*'

The model cell size of 500 m used in the mining areas allows accurate representation of the mining activity to identify long term impacts from residual voids post mining.

Yes. The 500 m model cell size in the mining areas allows accurate representation of the mining activity to identify long term impacts, especially as finer discretisation, up to 20 m, is used locally around spring complexes and rivers.

Level of concern: 3

However, grid cell size in riparian areas requires careful consideration of model parameters for depth to groundwater, ET rates and extinction depths in each cell (see Section 2.1.5).

2.1.5 Initial heads

This section reviews '*Q5: Do the initial heads determined in the history matching process adequately represent the observed groundwater heads and groundwater system? In particular:*

- *Does the model represent the pre-mining groundwater lows observed north of the Carmichael River in the Bandanna Formation, Colinlea Sandstone and Joe Joe formation? Does the model incorporate findings from the conceptualisation?*
- *Do the initial heads and simulated groundwater levels in the Carmichael River alluvium adequately represent that aquifer and if not, how might this affect the understanding of surface water-groundwater interaction? Has the use of dry bores north of the river affected the process?*'

Level of concern: 1

The review identified issues related to overestimated modelled groundwater levels and how the river boundary condition and the lateral constant head boundary conditions are represented in the numerical model that could significantly underestimate impact predictions. Future groundwater modelling should address the following recommendations:

- Rectify errors in the modelled groundwater levels and surface water – groundwater ineractions near the Carmichael River to improve confidence in the ability of the model to predict 0.2 m drawdown at the Doongmabulla Spring Complex

- Verify that lateral boundary conditions are consistent with the groundwater system characterisation and do not significantly underestimate impact predictions
- Identify, document, and revise model to address the reasons why the model overpredicts groundwater levels and surface water – groundwater fluxes near the Carmichael River.

Level of concern: 2

- Identify, document, and test model sensitivity to river boundary conditions and modelled groundwater levels in the riparian zone
- Identify, document, and justify whether spring flux estimates are sensitive to changes to modelled groundwater levels and river boundary conditions in the riparian zone
- Identify, document, and justify whether any dry bores in the alluvium north of the Carmichael River were used for model calibration and whether this affects modelled groundwater levels or fluxes.

Level of concern: 1

More than half of the modelled initial heads are above observed groundwater levels in the history-matching hydrographs (Appendix C on p 157-190 of the groundwater model report [3]).

Pre-mining groundwater lows observed north of the Carmichael River

The groundwater model report [3] does not provide contour maps for simulated groundwater level in the Bandanna Formation, Colinlea Sandstone or Joe Joe formation. Instead, the review used the history-matching hydrographs in Appendix C of [3] for bores in the Bandanna Formation (C008P2, C006P1) and Colinlea Sandstone (C006P3R) located in the observed groundwater lows north of the Carmichael River. Simulated groundwater levels are 9 to 11 m above observed levels in all 3 bores, indicating that pre-mining groundwater lows are not adequately represented in the model.

The spatial variability of base case parameter values for horizontal hydraulic conductivity in the AB coal seam of the Bandanna Formation (Figure 4.1 on p 82) and in the D seam of the Colinlea Sandstone (Figure 4.11 on p 83) does not show zones of increased conductivity north of the Carmichael River. The Upper Rewan Formation (Figure 4.6 on p 78) has higher vertical conductivity zone north of Carmichael River, but this pattern is not apparent in the vertical conductivity of the Lower Rewan Formation (Figure 4.7 on p 79).

Recommendation: Rectify errors in the modelled groundwater levels (9 to 11 m above observed groundwater levels) to improve confidence in the ability of the model to predict 0.2 m drawdown at the Doongmabulla Spring Complex.

An additional issue that affects the initial heads simulated in the entire model, not just the area north of Carmichael River, is the specified head lateral boundary in all HSUs, where the HSU is present at the edge of the model domain. The location of the western boundary is determined based on the surface water divide. However, the available regional potentiometric surfaces for the various HSUs show that the surface water boundary does not coincide with a groundwater divide and is therefore not suited as a boundary condition location.

For example, the modelled steady-state groundwater level contours for the AB coal seam (Figure 4.15 on p 89) are very steep gradients near this boundary. The drawdown contours for the AB coal seam under the Open-cut (Figure 5.9 on p 112), SEIS-A (Figure 5.10 on p 111) and SEIS-B (Figure 5.11 on p 112) modelled scenarios show a clear effect of the western boundary condition. In contrast, the maximum groundwater drawdown contours for the Clematis Sandstone do not reach the western boundary under the Open-cut (Figure 5.4 on p 106) or SEIS-A (Figure 5.5 on p 107) modelled scenarios. Steeper drawdown gradients are evident in the Clematis Sandstone near the western boundary under the SEIS-B scenario (Figure 5.5 on p 107). When the groundwater head is fixed at the boundary, no drawdown can be simulated at the boundary. The intersection of a fixed head boundary within the cone of depression could significantly underestimate groundwater drawdown.

Recommendation: Specify lateral boundary conditions based on groundwater system characterisation. Verify that lateral boundary conditions do not significantly underestimate impact predictions.

Groundwater levels in the Carmichael River alluvium

Table 5 summarises modelled and observed groundwater levels in the alluvium, which are systematically overestimated. In the first two bores downstream of the Doongmabulla Spring Complex (HD03B and C027P1), predicted groundwater levels are above the land surface. At the next bore downstream (C029P1), predicted groundwater levels are above the riverbed. In the 3 remaining alluvial bores further downstream (C19001SP, C14027SP and C14028SP), predicted groundwater levels are 8 to 12 m above observed values. Systematic over prediction of groundwater levels in the alluvium relative to observations could significantly underestimate impact predictions in the alluvium and in the vicinity of the Doongmabulla Spring Complex.

Recommendation: Rectify errors in the modelled groundwater levels (5-10 m above observed groundwater levels) to improve confidence in the ability of the model to predict 0.2 m drawdown in the vicinity of the Doongmabulla Spring Complex.

Table 5 Comparison of steady state modelled and observed groundwater levels in the alluvial bores

DSC = Doongmabulla Springs Complex; mAHD = elevation in metres with respect to the Australian Height Datum; GWL = groundwater level; d/s downstream

Bore	Location	Land surface level (mAHD)	River bed level, (GHD, 2013)	Observed GWL Nov 22 (mAHD)	Steady state modelled GWL (mAHD)	Notes
HD03B	Carmichael R d/s DSC	230.16		226.08	233	modelled GWL above ground
C027P1	Carmichael R in mine lease 1	227.615	224	222.07	228	modelled GWL above ground
C029P1	Carmichael R in mine lease 2	226.048	220	214.39	222	modelled GWL above riverbed
C19001SP	Carmichael R in mine lease 3	227.93		215.17	223	modelled GWL 8 m too high
C14027SP	Carmichael R d/s mine N	218.126		203.67	216	modelled GWL 12 m too high
C14028SP	Carmichael R d/s mine S	219.629		205.63	218	modelled GWL 12 m too high

Overestimated modelled groundwater levels in the Carmichael River alluvium cause the river to be simulated as a gaining stream rather than a losing stream (Table 5). In contrast, streams within the model domain are conceptualised as ephemeral streams that only flow during the wet season in response to rainfall when they contribute to groundwater recharge in the Carmichael River alluvium. For example, field observations of stream levels in the Carmichael River at Moray West, CAR04 and CAR02 (p 142-145 of the Hydrogeological Conceptual Model report [2]) are above their nearest respective bores HD03B, C027P1 and C19001SP, confirming losing conditions. The first two monitoring sites show that the groundwater level responds rapidly to surface water level changes indicating recharge occurs, the most downstream site (C19001SP) does not respond as rapidly suggesting there is an impediment to recharge from the stream in this location.

The initial heads are determined from a steady-state model run in which the major streams (Belyando and Carmichael rivers, Cattle and Dylingo creeks) are simulated using a specified head boundary condition in the RIV package. The river boundary condition in the groundwater model is consistent with the hydrogeological conceptual model. However, this effectively makes the streams an infinite source of water to the groundwater system for the steady-state stress period, which could overestimate modelled groundwater levels near the major streams.

During the history matching process, the modelled streams contain water for 3 months of the year during the wet season when they recharge the aquifer if groundwater levels are below the stream stage. During the other 9 months, the streams act as drains, receive groundwater if groundwater levels are above the bed of the stream.

Overestimated modelled groundwater levels near the Carmichael River mean it is modelled as a gaining rather than a losing stream. This is not an adequate representation of the surface water – groundwater interactions along the Carmichael River, meaning that the model is not capable of accurate prediction of groundwater drawdown impacts on the groundwater-dependent ecosystems along the Carmichael River. This also means that groundwater drawdown in the vicinity of the Doongmabulla Spring Complex is likely to be significantly underestimated.

Recommendation: Rectify errors in the modelled groundwater levels and surface water – groundwater interactions near the Carmichael River to improve confidence in the ability of the model to predict 0.2 m drawdown in the vicinity of the Doongmabulla Spring Complex.

Surface water-groundwater processes in the model, for both the river and spring features, are adequately represented in the model. However, the errors in the modelled groundwater levels and surface water – groundwater fluxes near the Carmichael River indicate that either too much water enters, or not enough water leaves the alluvium.

Model estimates of water entering the alluvium are overestimated in 2 ways related to:

1. leakage from the stream (water entering the alluvium) by assuming there is no clogging layer in the stream bed, making the streams an infinite source of water to the alluvium during the wet season
2. stock and domestic water use from Joshua Spring, which is not represented in the model.

The major outflow of water from the alluvium should be via evapotranspiration (ET). However, the model likely underestimates ET due to limitations in the parameterisation and calibration of the ET boundary conditions. The EVT package (p 60 of the groundwater model report [3]) has a maximum ET rate of 4.4 mm/d near surface water features when the groundwater is at (or above) the land surface, which decreases linearly to 0 mm/d at a groundwater depth of 6 m. The modelled extinction depth of 6 m is shallow in comparison to riparian vegetation thresholds of groundwater depth, which can exceed 20 m (Kath et al., 2014). Vegetation water use may be limited from this depth but over a large area is a substantial volume.

This is also affected by the scale of the grid cells, which are 150 m along the streams and increase rapidly away from the streams. The EVT package uses the average grid cell elevation to determine the depth to groundwater and modelled ET rate. Trees tend to grow low in the landscape but within a grid cell there could be many metres of topographic differences that is not accounted for in the model. Depth to groundwater at C14027SP and C14028SP is about 14 m (Table 5) and estimated ET rate using the CMRSET analysis is greater than on the surrounding floodplain, indicating vegetation groundwater use from about 14 m depth occurs in this area (p 123-129 in the hydrogeological conceptual model report). This suggests that the extinction depth for vegetation water use should be at least 15 m and allowing for sub-grid topographic differences an extinction depth of 20 m could be justified.

Recommendation: Identify, document, and address the reasons why the model parameterisation and calibration of the river and evapotranspiration boundary conditions incorrectly predicts elevated groundwater levels and surface water – groundwater fluxes near the Carmichael River.

Level of concern: 2

The river boundary condition also affects the modelled maximum groundwater drawdown contours in the Clematis Sandstone under the Open Cut only (Figure 5.4 on p 106), SEIS A (Figure 5.5 on p 107) and SEIS B (Figure 5.6 on p 108) in the groundwater model report [3]. At river cells, maximum drawdown is simulated to be zero in these 3 scenarios, which causes the 0.1 m drawdown contours to be largely parallel to the

Carmichael River. The model uses the RIV and EVT packages in the riparian zone that are highly non-linear head dependent threshold processes. If the groundwater levels in the model are incorrect, then the fluxes calculated using these packages will also be incorrect.

Incorrectly specified boundary conditions can directly affect predictions. During history-matching, especially with automated approaches such as PESTPP-IES, model parameters will compensate for these incorrectly specified boundary conditions, leading to biased parameter estimates. This in turn leads to biased predictions of impact, where impact predictions are sensitive to these parameters. Due to the complexity of the model parameterisation, it is not possible to identify if parameters have been biased and if these affect predictions in this review.

Recommendation: Identify, document, and test sensitivity of model predictions to river boundary condition and modelled groundwater levels in the riparian zone.

The river boundary condition requires 2 parameters, the stage height of the stream as the specified head and the conductance of the riverbed. The specified heads are listed in Table 3.3 of the groundwater modelling report (p 56) as depth values for the steady-state, wet and dry seasons. In the steady state stress period, the streams are conceptualised as always leaking to groundwater. In the transient part of the model, the wet season lasts for 3 months, where the streams leak to the groundwater, and the other 9 months of the year there is no water in the stream and so there is no leakage to groundwater. The method to calculate the steady-state depths is not described but is less than half that of the wet season depth for the Carmichael River, and Cattle and Dyllingo creeks, and is more than half the wet season depth for the Belyando River. There is no justification given as to why the steady-state head is not a quarter of the wet season value as this boundary condition is close to a linear relationship, but it is unlikely to significantly affect model predictions.

Recommendation: Identify, document, and test sensitivity of model predictions to river boundary condition and modelled groundwater levels in the riparian zone, including the method used calculate the steady-state stream depths.

The description of the conductance term in the report does not match the value used in the model. The conductance equation (p 54 of the groundwater model report [3]) uses the area of the cell that contains the river boundary condition whereas it should be the area of the streambed within the cell. The value used of 1500 m^2 is equivalent to 150 m length of stream within the model cell multiplied by 10 m width. The Carmichael River has a channel width of around 10 m (p 138 of the Hydrogeological Conceptual Model report [2]). It appears the value used for the area is correct but the description in the report is incorrect.

The hydraulic properties of the riverbed sediments are reportedly unknown (p 54 of the groundwater model report [3]), with river boundary conductance allowed to vary during the history-matching period. The hydraulic conductivity used for the bed sediments of 1 m/d is above that measured in the alluvium (between 0.023 and 0.12 m/d; Table 9 in GHD, 2013). This effectively means that the stream bed provides no resistance to stream leakage and that the aquifer below is the constraint on recharge in the model. There is no information given on the bed material of the streams. The reported observations from HD03B and C027P1 show good connection. However, observations from C19001SP, the most downstream site, suggest there is an impediment to stream leakage in this area.

Recommendation: Identify, document, and test sensitivity of model predictions to river boundary condition and modelled groundwater levels in the riparian zone, including the method used to represent the clogging layer present in the stream bed. Without representing this clogging layer in the model, stream leakage to the alluvium will be overestimated.

The Doongmabulla Spring Complex is conceptualised in the model as being sourced from the Clematis Sandstone at depth and then discharging into the alluvium at the surface (p 56 of the groundwater model report [3]). Field observations show that the spring discharge sustains pools in Cattle Creek and Carmichael

River through the dry season, although there are also pools and salt scalds upstream of the springs on Cattle Creek indicating that the pools may be maintained by surface water and that groundwater discharge may be more widespread than just the springs (p 158 of the Hydrogeological Conceptual Model report [2]).

The flow rates from the springs have been estimated from existing relationships on wetland area and some gauging at Joshua Spring (Table 10.2 on p128 of the Hydrogeological Conceptual Model report [2]). Most of the flow from Joshua Spring is diverted into a dam for stock and domestic use. The model does not account for the water diverted from Joshua Spring meaning that recharge to the alluvium is overestimated.

The implementation of the springs in the groundwater model is consistent with the hydrogeological conceptualisation for the Doongmabulla Spring Complex. Recharge to the alluvium from spring discharge is a minor water balance component so these overestimates are of low concern.

Recommendation: Identify, document, and justify whether modelled and observed spring flux estimates are sensitive to modelled groundwater levels and river boundary conditions in the riparian zone.

Effect of dry bores north of the river on surface water-groundwater interaction

It is unclear if the dry bores in the alluvium north of the Carmichael River have been used in the model calibration. These bores, apart from C19024SP and C19025SP, are not in the Carmichael River catchment and the alluvium here is not in hydraulic connection with the Carmichael River alluvium. If the calibration using pilot points is conducted adequately, then even if these bores are included in the calibration, it should not impact upon the Carmichael River alluvium. While not often done, the dry bores can be used as a constraint in the history matching, i.e. as an upper limit. The simulated groundwater head should not be higher than the screened interval of the bore.

Recommendation: Identify, document, and justify whether any dry bores in the alluvium north of the Carmichael River were used for model calibration and whether this affects modelled groundwater levels or fluxes.

2.1.6 Head change targets

This section reviews '*Q6: Has the use of many more head change targets than absolute heads in the history matching process resulted in poorer matches between simulated initial heads and observed heads?*'

Level of concern: 2

Future groundwater modelling should address the following recommendations:

- Document and justify methods used to calculate head change and flux targets.
- Use local scale modelling to improve estimates of initial hydraulic properties for the regional model.

Level of concern: 2

The PESTPP-IES optimisation adjusts the weights of the different groups of observations (initial heads, drawdown, flux) to have approximately equal importance. The weights for the initial head targets are multiplied by $\sqrt{2}$ to double their relative contribution to the objective function. It is therefore unlikely that the head change targets dominate the optimisation.

The groundwater model report provides limited information on how the 239 hydraulic head targets relate to the 130 hydrographs with measured groundwater levels provided in Appendix C of [3]. Similarly, there is no information provided on how the 11,202 head change targets are calculated. During the meeting on 3 March 2023 with EMM Consulting, the modelling team clarified that the head change targets are changes in time, as the difference with the first value observed at the well, after transforming the timeseries to monthly time series. Discrepancies between manually measured and logger data were not resolved for this calculation. It is therefore possible that there are multiple head targets at the same location.

There is mention of two flux targets on p 70 of the groundwater model report [3], but not which flux targets. It can be assumed that the flux targets correspond to those reported in Table 4.3 in section 4.2.6 (p 96 of [3]) for Joshua Spring and 'Other Doongmabulla springs'. It is unclear whether methods used to calculate head and flux targets lead to parameter values that would under- or over-estimate impact predictions.

Recommendation: Document and justify methods used to calculate head change and flux targets in future groundwater modelling reports.

Local scale modelling of the observed mine dewatering rates in response to groundwater pumping would increase confidence in the estimated hydraulic properties of the HSUs in the vicinity of the mine dewatering bores. Local scale modelling, such as analytical pumping test equations, is numerically more tractable than using the regional groundwater model, requires substantially less run time, and is less affected by model boundary conditions.

Recommendation: Use local scale modelling of mine dewatering to improve estimates of initial hydraulic properties for the regional model to improve confidence in impact predictions.

2.1.7 Omission of landholder water use in model

This section reviews '*Q7: Has the modelling approach which does not include landholder water use from bores, in particular the Joe Joe to the south of the lease, resulted in predicted mining impacts in this area that match the head change targets?*'

Level of concern: 2

This is hard to judge based on what is reported in the groundwater model report [3]. Future groundwater modelling should either include estimated water use by landholders or demonstrate through sensitivity analysis that omission of landholder water use causes impacts to be overestimated.

Level of concern: 2

The omission of landholder groundwater extraction from the model will lead to biased estimates of hydraulic properties during history matching. To match the historical observed groundwater levels, which are a result of groundwater dynamics that include pumping from landholder bores, the model will compensate for the missing extraction volumes by changing modelled hydraulic properties. Due to model complexity, it is not possible to predict whether the inclusion of landholder water use during model calibration will increase or decrease modelled hydraulic properties. Therefore, it is not possible to know if predictions made with a model calibrated in this way, will increase or decrease predicted impacts.

The hydrogeological conceptual modelling report states '*There is no available metered landholder groundwater use, and this remains an unknown mechanism with potential to further emphasise declining groundwater level trends*' (p 63 of the Hydrogeological Conceptual Model report [2]). The updated SEIS groundwater flow model report (Figure 25 of GHD, 2015) however reports modelled bore abstraction rates for stock and irrigation water use that range from 0.14 to 120.6 m^3/day. It is not clear why this approach to estimating landholder water use is not adopted.

Recommendation: Include estimated water use by landholders in the model or demonstrate through sensitivity analysis that omission of landholder water use causes impacts to be overestimated.

2.1.8 Confidence in predicted impacts to the Doongmabulla Spring Complex

This section reviews '*Q8: Does the modelling of the open cut mining only scenario (including parameters used and methodology of the uncertainty analysis) provide an appropriate level of confidence in the predicted impacts to DSC?*'

Level of concern: 1

No, the model parameters and uncertainty analysis do not provide an appropriate level of confidence to support regulatory decision making related to impacts at the Doongmabulla Spring Complex. The review finds that the groundwater model is not fit-for-purpose, as it is not suitable for a robust uncertainty analysis and confidence in the range of predicted impacts needed to support regulatory decision making is low. Key issues are related to overestimated modelled groundwater levels and how the river boundary condition and the lateral constant head boundary conditions are represented in the numerical model that could significantly underestimate impact predictions.

Additional detail and recommendations related to the uncertainty analysis are outlined in Section 2.1.1 and to the model parameters and boundary conditions in Section 2.1.5.

2.1.9 What matters must be addressed before optimisation of mining activities?

This section reviews '*Q9: What matters must be addressed to the model methodology prior to undertaking an Optimisation model of mining activities to ensure no greater than 0.2 m drawdown at DSC?*'

Level of concern: 1

Before optimising the mining plan, the following groundwater modelling workflow is recommended to address issues identified with the model methodology in this review (relevant sections in brackets):

1. Clearly define the quantity of interest (QoI) (Section 2.1.1)

2. Clearly define the observation targets used to constrain the model (sections 2.1.1 and 2.1.6)

3. Ensure model parameters are consistent with the conceptualisation (sections 2.1.1 and 2.1.7)

4. Stress-test the model to test model convergence and effect of boundary conditions (Section 2.1.1)

5. Generate initial ensemble of realisations for observation targets and QoIs (sections 2.1.1 and 2.1.3)

6. Perform a sensitivity analysis for observation targets and QoIs (sections 2.1.1, 2.1.3 and 2.1.5)

7. Constrain the initial ensemble with the observations (sections 2.1.1 and 2.1.5).

Level of concern:1

Modifications to the model methodology are needed before undertaking an Optimisation model of mining activities to ensure no greater than 0.2m drawdown at the Doongmabulla Spring Complex. Changes to the model methodology should use the following workflow to address issues identified in this review:

1. Clearly define the quantity of interest (QoI): a 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. This project likely will have multiple QoIs, i.e. maximum drawdown under the open-cut scenario at spring locations but can also include QoIs formulated around a change in flux.

2. Clearly define the observation targets used to constrain the model, such as initial heads, drawdown, and fluxes.
3. Parameterise the numerical model with parameter bounds informed by information in the Hydrogeological Conceptual Model report [2]
4. Stress-test the model:
    a. evaluate a limited number of extreme parameter combinations to test convergence of the model for both the historical and predictive scenarios.
    b. evaluate a limited number of scenarios to test the effect of boundary conditions on QoIs and observation targets. These can include changing the prescribed constant head value at the western boundary or including a nominal extraction rate for landholder pumping in the Joe Joe formation.
5. Generate an initial ensemble of model realisations and corresponding simulated values for observation targets and QoIs, by sampling the prior parameter distributions, with the prior parameters informed by the Hydrogeological Conceptual Model report [2] and accounting for spatial correlation between parameters.
6. Perform a sensitivity analysis using the results of the initial ensemble to identify which parameters are important to reproduce the observation targets and the parameters important to the QoIs.
7. Constrain the initial ensemble with the observations. Several approaches can be used, ranging from the rejection algorithm used in the groundwater model report [3] to PESTPP-IES.

Optimise the mining plan using the updated groundwater model, subject to constraints formulated as exceedance probabilities of drawdown thresholds at key locations or other targets relevant to achieving environmental objectives.

2.2 Groundwater Management and Monitoring Program

This section addresses questions from DES related to the GMMP Review report [1], which ‘is *to meet the requirement of EA Condition E6 to provide a final GMMP review.*’ (p 5 of [1]). The original GMMP report (Adani Mining, 2021) was developed to ‘*address both the Commonwealth and Queensland State environmental approval conditions, inclusive of proposed groundwater quality triggers (chemistry) and groundwater level thresholds.’* (p 16 of Adani Mining, 2021).

This review has identified major issues related to confidence in the method used to detect and manage impacts on groundwater levels and how groundwater level observations are represented in the numerical groundwater model.

2.2.1 Groundwater level thresholds

This section addresses ‘*Q10: Does CSIRO/GA support the use of GW thresholds based on the open cut only model scenario?*’.

Level of concern: 1

The next GMMP update should review the relative benefits of using groundwater level thresholds or predictive models supported by a multiple-lines-of-evidence approach to detect and manage impacts on groundwater levels for the Carmichael Coal Mine.

In addition, future updates should follow the precautionary principle and consider the distribution and duration of the baseline monitoring data, consequence of approach used to detect and manage impacts on groundwater levels, and the timeframe and uncertainty of modelled drawdown.

Level of concern: 1

Detection of whether measured groundwater drawdown exceeds modelled predictions is challenging and highly uncertain (OGIA, 2021). Impacts on groundwater levels can be managed using groundwater level thresholds or predictive numerical models. Predictive models, when supported by a robust uncertainty analysis and other lines of evidence, can provide greater certainty for adaptive management that explicitly accounts for conceptual, climatic and parameter uncertainty.

The GMMP report (Adani Mining, 2021) sets out the method used to calculate groundwater level thresholds agreed for the Carmichael Coal Mine. Groundwater level thresholds (mAHD) ($h_{threshold}$) use the average baseline groundwater level (mAHD) ($h_{average\ baseline}$), a proportion of the maximum predicted groundwater drawdown ($A\ (d_{max\ predicted})$) and a proportion of the range of natural fluctuations in groundwater levels over the baseline period ($B\ (h_{max\ baseline}$ - $h_{min\ baseline})$) (Section 3.2.3 on p 18-19 of the GMMP Review report [1]):

$$h_{threshold} = h_{average\ baseline} - \left(A(d_{\max predicted}) + B(h_{\max baseline} - h_{\min baseline})\right)$$

The GMMP report (p 256 of Adani Mining Pty Ltd, 2021) describes 5 methods to calculate groundwater level thresholds based on a proportion of the maximum predicted groundwater drawdown and of the range of natural fluctuations in groundwater levels over the baseline period:

1. Unconfined aquifers: 50% of maximum predicted drawdown + 50% of natural fluctuations
2. Confined aquifers: 75% of maximum predicted drawdown + 50% of natural fluctuations
3. Predicted drawdown >10 m: 90% of maximum predicted drawdown + 50% of natural fluctuations
4. Predicted drawdown < natural fluctuation: 100% predicted drawdown + 50% natural fluctuations
5. Bore C025P1 is dry for more than 6 months.

In contrast, the Underground Water Impact Report 2021 for the Surat Cumulative Management Area (OGIA, 2021) takes a regional approach to modelling and managing cumulative impacts from coal seam gas development based on regularly updated numerical modelling and uncertainty analysis. OGIA (2021) note that '*In most instances, impacts on groundwater levels that may have occurred from resource development cannot be measured directly. This is because monitoring data (groundwater level and chemistry) is influenced by a range of resource-related and non-resource-related activities. Further analysis is therefore required to separate out resource-related impacts from other influences.*'

Cumulative impacts under the Water Act 2000 (Qld) consider timeframes ranging from short-term impacts over 3 years from when the model is reported to long-term or maximum impacts that occur at any time in the future (OGIA, 2021). OGIA (2021) use a multiple-lines-of-evidence for the analysis of monitoring data for impacts, including:

- statistical and visual correlation of observed trends with a range of factors such as estimated rainfall recharge, estimated groundwater use and associated water extraction
- analysis of hydraulic gradients, hydrochemistry, and isotopes of strontium (^{87}Sr and ^{86}Sr)
- spatial trend analysis of potentiometric maps (groundwater level maps) and hydrographs

- analysis of trends and stressors for key water balance factors – groundwater use, associated water extraction (coal mines and P&G production) and climate – in combination with conceptualisation of key connectivity features and impact pathways.

Recommendation: Review the relative benefits of using groundwater level thresholds or predictive models to detect and manage impacts on groundwater levels for the Carmichael Coal Mine in the next GMMP update. This review should also consider the benefits of following the multiple-lines-of-evidence approach used by OGIA (2021) for the analysis of monitoring data for impacts.

The groundwater level threshold method used for the Carmichael Coal Mine assumes that '*groundwater levels can vary by half the natural fluctuation before mining operations are considered to influence the groundwater level*' (footnote 19 on p 256 of Adani Mining Pty Ltd, 2021). Predicted drawdown is less than the natural fluctuation for all unconfined monitoring bores.

Groundwater level thresholds (m) relative to the average baseline groundwater level (mAHD) are calculated using 3 of the 5 methods (Table A.1 on p 49-55 in Appendix A of the GMMP Review report [1]):

- 100% of maximum predicted drawdown plus 50% of natural fluctuation over baseline period
- 90% of maximum predicted drawdown plus 50% of natural fluctuation over baseline period
- 75% of maximum predicted drawdown plus 50% of natural fluctuation over baseline period.

The groundwater level thresholds therefore depend on the quality and duration of baseline monitoring data and the modelled maximum predicted drawdown for each monitoring location. The updated groundwater level thresholds are based on the maximum drawdown predictions from model Scenario 1 (open-cut mining only) (Table A.1 on p 49-55 in Appendix A of the GMMP Review report [1]).

Groundwater level thresholds assume baseline groundwater level fluctuations are normally distributed, subtracting 50% of natural fluctuations in groundwater levels (the median value) from the average groundwater levels measured during the baseline period. However, groundwater levels in monitoring bores over the baseline period are not normally distributed. Figure 3 shows the method systematically under- or over- estimates natural fluctuations, where negative values indicate the average is less than the median (50% NF) using monitoring bores in the alluvium and Joe Joe Group as an example.

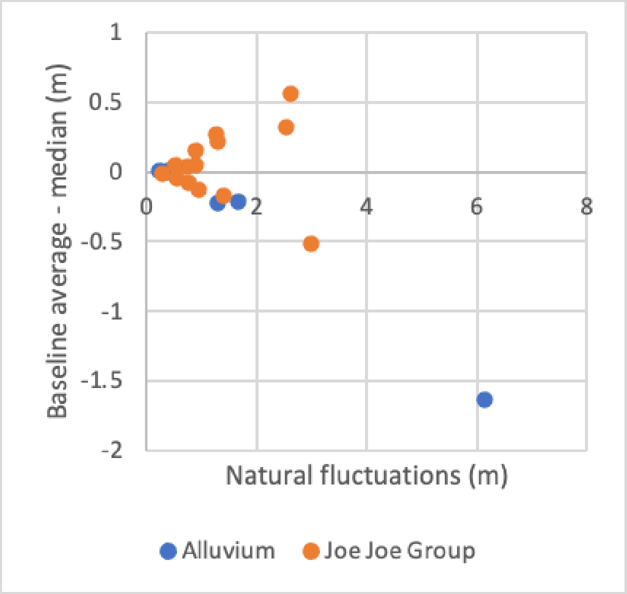

Figure 3 Comparison of difference between average and median values (m) and natural fluctuations (m) and over the baseline period for monitoring bores in the alluvium and Joe Joe Group

The rules used to calculate the groundwater level thresholds appear to be consistent with those documented in the GMMP (Table 45 on p 258 of Adani Mining Pty Ltd, 2021). Table A.1 contains errors in reported values for bore C14028SP in the alluvium (p 49 in Appendix A of the GMMP Review report [1]). Only alluvium and Joe Joe Group values were reviewed for this report.

There is concern about whether the choice of rules used to calculate the groundwater level thresholds follows the precautionary principle – '*if the impacts of a decision are not fully understood, then we should err on the side of caution, to avoid serious and irreversible consequences. Lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation' (Samuel, 2020).* For example:

- alluvium bores include an additional 50% of the maximum predicted drawdown value because the 'predicted drawdown < natural fluctuations' rule is used instead of the 'unconfined aquifers' rule
- Joe Joe Group bores include an additional 15% of the maximum predicted drawdown value because 'predicted drawdown > 10 m' rule is used instead of the 'confined aquifers' rule.

Other concerns are related to monitoring and modelling timeframes:

- duration of the baseline monitoring period is very short (2 years) with respect to climate patterns and climate change, as noted in previous reviews (Appendix F of the GMMP Review report [1]). To use an extended baseline period may also potentially assume climatic stationarity. A moving average for the minimum and maximum values in natural fluctuations may be a more robust approximation but is then determined by the moving average window length. Further consideration is warranted to establish a viable precautionary approach.
- groundwater level thresholds only use maximum predicted drawdown, which does not give any way of comparing to modelled timeframes for drawdown at each location. Table 45 (on p 258 of Adani Mining Pty Ltd, 2021) includes timeframe for maximum predicted drawdown and baseline monitoring period, as well as comments about each bore
- low confidence in the range of predicted impacts, as well as the timeframe of these impacts, has reduces confidence in the groundwater level triggers calculated using the maximum drawdown predictions from model Scenario 1 (open-cut mining only).

Recommendation: Future updates should follow the precautionary principle and consider the:

- distribution and duration of the baseline monitoring data
- consequence of method used to calculate threshold values
- timeframe and uncertainty of modelled drawdown values used to calculate threshold values.

2.2.2 Large drawdown predicted in Joe Joe formation in the Mellaluka springs area

This section reviews '*Q11: The GMMP Review report, Appendix A now includes predicted drawdowns in Joe Joe formation bores in the Mellaluka Springs area of between 60 and 80 m for the open cut only scenario. This is an increase from previous predicted drawdowns (under the 2013 SEIS model) which were less than 1 m for these same bores. Are these increases realistic? Have they been influenced by the lack of landholder water use being included in the model in this area?'*

Level of concern: 2

Improve transparency of reporting for future groundwater modelling by demonstrating that the range and spatial variability of modelled hydraulic properties is consistent with the observations and the conceptual understanding of the groundwater system.

The summary of the conceptual hydrogeological model for the Joe Joe Group in Table 2.1 on p 18 of the GMMP Review [1] report includes:

- local groundwater flow in the area: '*Joe Joe Group: Groundwater flow converges on C14003SP and C14004SP and is influenced by the local faulting/highly permeable zone. Flow affected locally by discharge to the Mellaluka Spring Complex (MSC) and pumping from landholder bores.*'
- recharge: '*recharged only though vertical leakage from other units*
- geological basement: '*Early Permian Joe Joe Group is considered the geological basement in this region*' and '*Model layer 15 is base of the model is set 100 m below the top of Joe Joe Group, to allow for regional groundwater flow below the base of the mine'*
- aquifer properties: *Kh* is $2x10^{-4}$ – $4.1x10^{-1}$ m/d.
- model layer 15: top of model layer ranges from -220 mAHD in west to 220 mAHD in east. Modelled constant head boundary ranges from 200 mAHD in east to 300 mAHD in north. Contours near Mellaluka Spring are 220 to 240 mAHD.

Large drawdowns predicted in model layer 15 for the Joe Joe Group are consistent with high K and low S values. Table 4.5 on p 98 of the groundwater model report [3] notes the following changes to modelled hydraulic properties for the updated model in model layer 15: hydraulic conductivity is 3-4 orders of magnitude higher, specific storage is similar and specific yield is 2 orders of magnitude lower.

As discussed in section 2.1.7, it is unclear if these parameter values are realistic or biased because they appear to compensate for boundary conditions, in this case, the absence of landholder pumping in addition to the constant head boundaries used to represent the Joe Joe Group in model layer 15.

Recommendation: Improve transparency of reporting for future groundwater modelling by demonstrating that the range and spatial variability of modelled hydraulic properties is consistent with the observations and the conceptual understanding of the groundwater system.

2.2.3 Initial heads in Tertiary and Weathered zone

This section reviews '*Q12: Are the initial heads in the Tertiary sediments and Weathered zone representative of the observed groundwater system in these units? Has the use of dry bores in the Weathered zone affected the process?*'

Level of concern: 1

The review identified issues related to overestimated modelled groundwater levels and how the Tertiary and Weathered zone are represented in the numerical model that could significantly underestimate impact predictions. Future groundwater modelling should address the following recommendations:

- Rectify errors in the modelled groundwater levels and modelled extents for the Tertiary and Weathered zone to improve confidence in the ability of the model to predict 0.2 m drawdown at the Doongmabulla Spring Complex
- Clearly document the terminology and methodology used to describe hydrostratigraphic units.

Level of concern: 1

The areas of large modelled maximum drawdown in the Clematis Sandstone coincide with areas where (1) the Clematis Sandstone is mapped within the mine lease or (2) where the Tertiary aquifer that overlies the Clematis is mapped within the mine lease. This is consistent with the conceptualisation that drawdown from the open-cut mine operations propagates laterally through the Tertiary aquifer into the Clematis Sandstone. As this represents a direct pathway to impact, the mapped extent of the Tertiary aquifer directly affects impact predictions.

The groundwater model report [3] does not include modelled contour maps for groundwater levels in the Alluvium, Tertiary or Weathered zones. The hydrographs in Appendix C of [3] indicate that simulated values in Tertiary and Weathered zone bores are systematically higher than the observed values, often by more than 10 m. The overestimated groundwater levels, indicate that groundwater levels in the Tertiary and Weathered zone are not adequately represented in the model.

Recommendation: Rectify errors in the modelled groundwater levels (5-10 m above observed groundwater levels) to improve confidence in the ability of the model to predict 0.2 m drawdown in the vicinity of the Doongmabulla Spring Complex.

There appears to have been a transition in terminology from Tertiary (in the earlier reports) to Weathering and Weathered Zone (layer 2 in the current model) for formations overlying the mine area and the eastern part of the model domain. This has created further confusion as the model includes another layer representing the Tertiary formations: 'Tertiary and non-alluvial quaternary sediments' (layer 3). Updates to the groundwater model include '*incorporation of the weathered zone*' (p 2 of the groundwater model report [3]) based on recommendations compiled by GHD (2013). The weathered zone is represented as an aquitard (Table 3.1 on p 30 of [3]) and '*shows a distinct thickening towards the scarp and is likely to impede vertical recharge from rainfall, where it exists*' (Table 2.1 on p17 of [3]).

The fault mapping and modelling report (2021) mapped clear distinctions between the Tertiary and Weathering Zone across the mine site and in the east of the model domain (illustrated by the red and purple formations in Figure 4). However in the model these formations have been combined into one layer 'Weathering Zone – layer 2'. It does not appear that a rationale for this approach has been provided. Average annual modelled recharge rate for the weathered zone is 0.002 mm/year (Section 3.5.3 on p 58 of the groundwater model report [3]). Hydraulic properties for model layers are reported in Appendix B on p 150-156 of [3] for:

- weathering zone:
  - *Kh* values are normally distributed between about 10^{-5} and 10^{-2} m/d
  - *Kv* values have a bimodal distribution between about 10^{-6} and 10^{-2} m/d
  - *Ss* values are fairly evenly distributed between 10^{-7} and 10^{-5} 1/m
- Tertiary sediments:
  - *Kh* values have a positively skewed distribution between about 10^{-3} and 10^{0} m/d
  - *Kv* values have a normal distribution between about 10^{-4} and 10^{-1} m/d
  - *Ss* values have a negatively skewed distribution between 10^{-6} and 10^{-5} 1/m

None of the 12 Tertiary (or Tertiary/Joe Joe Group) monitoring bores Table A.1 on p 49-55 or Table E.2 on p 131 of the GMMP Review report [1] and shown on Figure 29 on p 343 of the GMMP report (Adani Mining Pty Ltd, 2021) and Figure 3.1 on p 15 of [1]) are within the modelled extent of the Tertiary sediments (Figure 3.5 – Top of Tertiary and non-alluvia, Quaternary sediments (layer 3) on p 34 of the groundwater model report [3]). Instead, they are within the extent of the Weathering zone (Figure 3.4 – Top of weathering zone (layer 2) on p 33 of [3]). This coincides with the purple area mapped as Tertiary sediments in Figure 4 on the eastern side of the model.

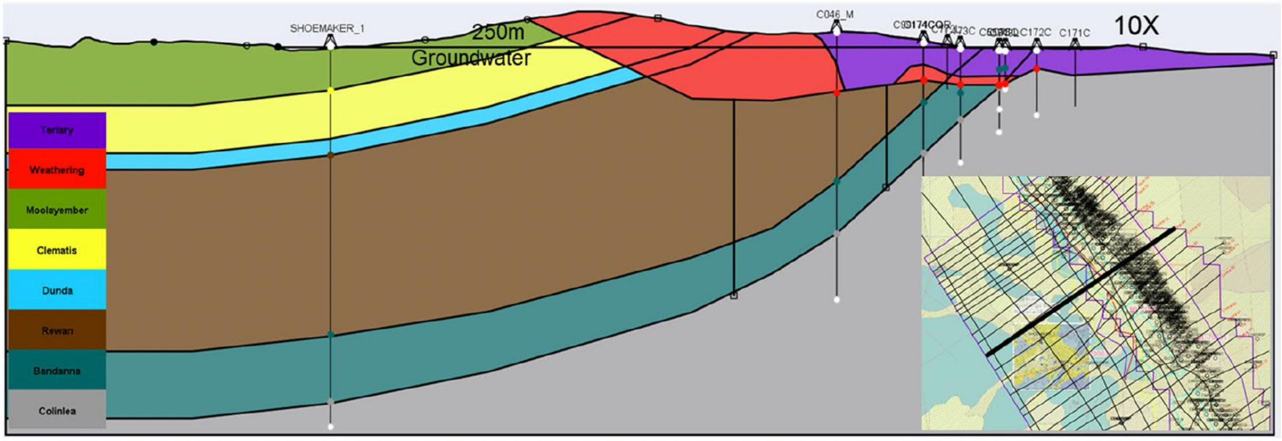

Figure 5.1 Southwest-northeast cross-section through Project Area (from Murray 2021)

Figure 4 Southwest-northeast cross-section through Project Area (Figure 5.1 on p 47 of the Hydrogeological Conceptual Model report [2])

The modelled pre-mining heads are only shown in hydrographs, not in a contour map. The top of model layer 2 'Weathering zone' ranges from 180 mAHD in the east to 310 mAHD in the north (Figure 3.4 on p 33 of the groundwater model report [3]). The top of layer 3 'Tertiary and non-alluvial Quaternary sediments' is 230 m AHD, except for small area in the mine lease area (Figure 3.5 on p 34 of [3]). The modelled regional boundary conditions in surficial layers map (Figure 3.18 on p 49 of [3]) shows that the constant head boundary conditions range from 190 mAHD in the east to 290 mAHD in the west.

Recommendation: Identify, document, and justify the terminology used to describe the 'Tertiary' and 'Weathering Zone' hydrostratigraphic units and the methods used to map the Cenozoic stratigraphic units.

2.2.4 Bravus proposed additional monitoring bores and locations

This section reviews *'Q13: Do you support the Bravus proposed additional monitoring bores and locations? Do you support DES recommendations for additional bores? Any additional bores?'*

Level of concern: 2

The 8 additional monitoring bores are needed to address identified knowledge gaps in the extent and magnitude of impacts and to inform future groundwater model updates. In addition, monitoring bores in the Joe Joe Group would improve understanding of groundwater flows to the east and to the south of the mine site, as well as potential impacts on the Mellaluka springs.

Level of concern: 2

The additional monitoring bores proposed by both Bravus and DES, in the Bandana Formation and Colinlea Sandstone, appear appropriate (Section 4 on p 45 of the GMMP Review report [1]). The additional monitoring bores are designed to address specific identified gaps in the groundwater monitoring network to improve understanding of the extent and magnitude of mining and dewatering impacts and improve the hydrogeological conceptualisation and characterisation needed for future groundwater model updates. This includes 8 additional monitoring bores in the:

- Colinlea Sandstone: 1 bore between C19026SP and C011P3; 1 bore between C19026SP and C19031VWP and adjacent to existing Clematis Sandstone bore C14012SP/C14013SP; 3 bores on the western boundary of the mining lease

- Bandanna Formation: 1 bore between C008P2 and C19018SP and adjacent to existing Clematis Sandstone bore C14012SP/C14013SP; 2 bores on the western boundary of the mining lease.

Recommendation: Drill the 8 new monitoring bores in the Colinlea Sandstone and Bandanna Formation. Additionally, it is recommended that up to three new monitoring bores targeting the Joe Joe Group are drilled on the eastern edge of the mine site, beyond the mine site in the east of the model domain. These additional bores will provide evidence to inform the conceptualisation of the regional groundwater flows to the east of the mine site and will likely assist in model development by providing data to characterise the groundwater condition in this area of the model.

Monitoring for potential impacts to Mellaluka Springs

Bravus proposes waiting until drawdowns are observed at the bores targeting the Colinlea Sandstone on the southern boundary of the mine site (C19004SP and 19003SP) before installing additional monitoring bores between the mine site and Mellaluka Springs. We support the proposal to add monitoring bores between the mining lease and Mellaluka Springs, to allow for the detection of dewatering impacts near Mellaluka Springs.

Recommendation: It is recommended that the additional monitoring bores be drilled when drawdowns are observed at any of C847SP, C848SP, C9849SPR. These existing bores are located north of the C19004SP and 19003SP. Drilling the new, southern, bores at this time will provide sufficient time to record a baseline dataset before mine related drawdowns will be expected to be recorded.

2.2.5 Faster than predicted groundwater drawdown

This section reviews '*Q14: What action should be taken if the actual monitored rates of groundwater drawdown are faster than predicted?*' and makes the following recommendations to be addressed in the next GMMP update:

Level of concern: 1

- address concerns related to how impacts on groundwater levels are detected and managed in 1) the GMMP report, 2) the hydrogeological conceptual model, and 3) groundwater model report
- document and justify the rationale for approach(es) used to evaluate faster than predicted groundwater drawdown given the high degree of numerical uncertainty for predicted impacts.

Level of concern: 2

- improve report transparency by enabling simultaneous, side-by-side comparison of groundwater level monitoring, trigger thresholds and modelled drawdown predictions.

Detection of whether measured groundwater drawdown exceeds modelled predictions is challenging and highly uncertain (OGIA, 2021) – see discussion and recommendations in Section 2.2.1. Protection of groundwater-dependent ecosystems requires confidence in the conceptual understanding of the groundwater flow system, as well as the measurement and modelling of groundwater levels.

The groundwater model is used to '*predict the extent and magnitude of groundwater drawdown induced by mining activities*' and '*Drawdown was calculated at every output time by subtracting the modelled hydraulic heads at each model cell for the given scenario from a null case (no mining) scenario'* for the history-matching, mine operation and closure periods (Section 5.3 on p 104 of the groundwater model report [3]).

Groundwater level monitoring is currently reported to DES using bi-monthly exceedance reports following the methodology in Section 5.3 the GMMP report (p 233 – 276 of Adani Mining, 2021). Section 3.2.3 of the GMMP Review report [1] have identified reported exceedances related to:

- replacement bores having naturally different water level elevations
- altered cable lengths (and thus historical water level elevations) in artesian bores
- natural water level declines due to prolonged below average rainfall conditions
- nearby landholder water use
- depressurisation and slow recovery following sampling and/or bore renovations.

Level of concern: 1

This review has identified serious concerns about how the numerical model significantly underestimates the range of impact predictions (Section 2.1), as well as limitations for the method used to determine groundwater level trigger thresholds (Section 2.2.1) that limit confidence in being able to determine whether '*actual monitored rates of groundwater drawdown are faster than predicted*'.

Recommendation: Address concerns related to how impacts on groundwater levels are detected and managed in 1) the GMMP report, 2) the hydrogeological conceptual model, and 3) groundwater model report identified by this review.

Recommendation: Document and justify the rationale for approach(es) used to evaluate faster than predicted groundwater drawdown following the precautionary principle given the degree of numerical simulation uncertainty. As there is a lack of scientific certainty further consideration of conditions at each location, and the rate, duration, and magnitude of the observed deviations from the predicted result. This would additionally inform management measures and actions to safeguard from irreversible environmental damage.

Level of concern: 2

Only maximum predicted drawdown is used to calculate groundwater level thresholds (Section 2.2.1). This means actual groundwater level monitoring cannot easily be compared to the trajectory of modelled drawdown at a location.

Further, comparison of groundwater level trigger thresholds (Appendix A of the GMMP Review Report [1]), baseline groundwater level monitoring (Appendix B of [1]), history matching hydrographs (Appendix C of the groundwater model report [3]), and modelled drawdown predictions (open-cut mining only) (Appendix D of [3]) requires simultaneous review of multiple appendices from 2 different reports on plots that use different time scales and groundwater levels or drawdowns. Locating monitoring bores requires close inspection of Figure 29 on p 343 of the GMMP report (Adani Mining Pty Ltd, 2021) and Figure 3.1 on p 15 of [1].

Recommendation: Improve report transparency by enabling simultaneous, side-by-side comparison of a) groundwater level trigger thresholds, baseline groundwater level monitoring and history matching hydrographs with b) modelled drawdown predictions using plots with comparable time scales and groundwater levels/drawdowns.

2.2.6 Water quality trigger exceedances

This section reviews '*Q15: In order to address ongoing and upward trending water quality trigger exceedances – what do you recommend as an appropriate action?*'

The next GMMP update should continue to report groundwater quality monitoring and to update water quality triggers using the expanding baseline dataset. Further analysis and re-evaluation of the existing hydrochemistry environmental tracer database for the Carmichael Coal Mine is warranted.

Level of concern: 3

Groundwater quality analysis is compared to the bore-specific and hydrostratigraphic unit-specific trigger values (Section 3.2.2 on p 17-18 of the GMMP Review report [1]), with exceedances reported if they occur in two consecutive monitoring events for each water quality parameter and monitoring location. Exceedances occurred in 47 of the 69 monitoring bores (78 exceedances across 14 parameters) in most hydrogeological units sampled in June 2022. Groundwater quality trigger levels have not yet been determined for 16 bores due to a lack of baseline data.

Investigations found reported exceedances were related to:

- Natural fluctuations or water level variations
- Slow stabilisation following bore installation/bore renovations.
- Geochemical processes, including iron oxidation through introduction of dissolved oxygen
- Changing rainfall pattern, from below average to average with high intensity events.

Recommendation: On-going monitoring and updating of water quality triggers with the expanding baseline dataset.

This is consistent with management recommendations from Fensham et. al., (2017) for the Doongmabulla Galilee Group Springs to '*serve as a baseline to assess potential future impacts of mining on the groundwater quality of the springs*'.

Recommendation: Further analysis of groundwater chemistry fingerprints for each of aquifer system is warranted in conjunction with a re-evaluation of the existing hydrochemistry environmental tracer database for the Carmichael Coal Mine using a team of independent scientists with relevant expertise in the interpretation of water quality data to test alternative hydrogeological conceptual models (Section 2.4.1).

2.2.7 Vibrating wire piezometers

This section reviews '*Q16: Please provide advice on the suitability and reliability of the use of VWP monitors.*' Adherence to installation methodology, operating practices, testing, and monitoring as specified by the manufacturer is needed to ensure reliable operation of VWPs.

Level of concern: 3

Vibrating Wire Piezometer (VWP) sensors are installed and used for many geotechnical and groundwater applications. VWPs have gained increasing popularity in the geotechnical instrumentation industry due to features including long-term durability, high-accuracy, low hydrostatic lag time, long-distance data telemetry and ease of interoperability and automation.

Likely error sources related to reliability or anomalous VWP data can include but are not limited to:

- Installation procedures and instrument calibration
- Water infiltration into signal cables causing short circuits
- Electromagnetic interference from any adjacent high voltage cables
- Poor cable connection in the terminal box or the readout unit
- Inconsistent handling of the readout unit
- Lack of grounding or lightning protection measures

- Grouting quality and consistency.

When used in controlled environments (i.e. within dam structures), VWPs can be maintenance free once embedded in the structures. There is generally no need to re-calibrate them with instrument zero-drift being a minor/non-existent issue. Many manufacturers provide instructions or processes to assess the condition of the instrument in situ.

The existing ISO standard (ISO 18674-4:2020) for piezometers may provide useful guidance for the consistent application of such instrumentation. Likewise, the USACE Engineering and Design: Instrumentation of embankment dams and levees guideline (USACE 2020) has additional content on the use of VWPs.

Robust data acceptance practices are still required to ensure data veracity for use. It is noted the bores listed as installed with VWPs are self-identified as having a generally low or medium hydrography trend reliability in the Hydrogeological Conceptual Model report [2], for the Rewan Formation (Table 8.5, p 64 of the groundwater model report [3]), the Bandanna Formation (Table 8.6, p 67 of [3]), and the Colinlea Sandstone (Table 8.7, p 71 of [3]). In optimum conditions, with robust installation methodology, standardised operating practices, as well as regular testing and monitoring according to manufacturer specifications, VWPs may be reliable sensors.

Recommendation: Follow installation methodology, operating practices, testing and monitoring as specified by the manufacturer to ensure reliable operation of VWPs.

2.3 Rewan Formation Connectivity Research Plan

This section addresses the question from DES related to the additional geological work undertaken as part of the Rewan Formation Connectivity Research Plan reported in the Southern Highlands Structural Geology (2022) and summarised in the Hydrogeological Conceptual Model report [2].

This review has identified major issues related to how the updated hydrogeological conceptual model is represented in the numerical groundwater model.

2.3.1 Additional geological work in the Clematis Sandstone and Dundas Beds

This section reviews '*Q17: What additional geological work with respect to the extent of the Clematis Sandstone and Dundas Beds is required to improve the confidence in the modelling outputs for the optimisation model?'*

Level of concern: 1

Future groundwater modelling should address the following recommendations:

- use updated structural geological model and hydrogeological conceptual model
- use updated groundwater model layer extents and model parameters
- clearly document rationale, methods and data sources used to update the geological modelling.

Level of concern: 2

Continue to improve the hydrogeological conceptual model using site specific data to better constrain AEM inversions.

Level of concern: 1

Regional scale mapping across a range of scales is used to develop the structural geological model underpinning the groundwater model. Consistent 1:100 k mapping coverage is now available for all of Queensland, including the Carmichael Coal Mine area. The Bioregional Assessment and structural surfaces in the 'Integrating Bioregional Assessment model' report by Southern Highlands Structural Geology (2022) (Figure 5) pre-date this new dataset.

Recommendation: Update the structural geological model and hydrogeological conceptual model underpinning the groundwater model using the updated, consistent 1:100k surface mapping coverage, except where on-ground mapping gives higher confidence in the hydrogeological characteristisation.

Depending on which regional surface geological model is used (1:250k, 1:100k), the boundary between the Clematis-Dunda beds can shift by approximately 2 km in the vicinity of Doongmabulla Springs and Surprise Creek. For example, the largest values of predicted maximum drawdown for the open-cut only scenario in the Clematis Sandstone occurs where this layer is mapped within the mine lease area to the south of the Carmichael River (Figure 3.7 on p 26 of the groundwater model report [3]). Any change in the mapped extent of the Clematis Sandstone in this area will directly affect predicted drawdown in the Clematis Sandstone.

Accurate geological boundaries increase confidence in geological modelling, and in turn the groundwater model. Factors to consider include the shape and extent of some of the geological outliers, such as those to the south of the Carmichael River, as well as groundwater recharge patterns in different geological units.

Recommendation: Identify, document, and update groundwater model layer extents and model parameters using updated 1:100 k geological mapping for Queensland.

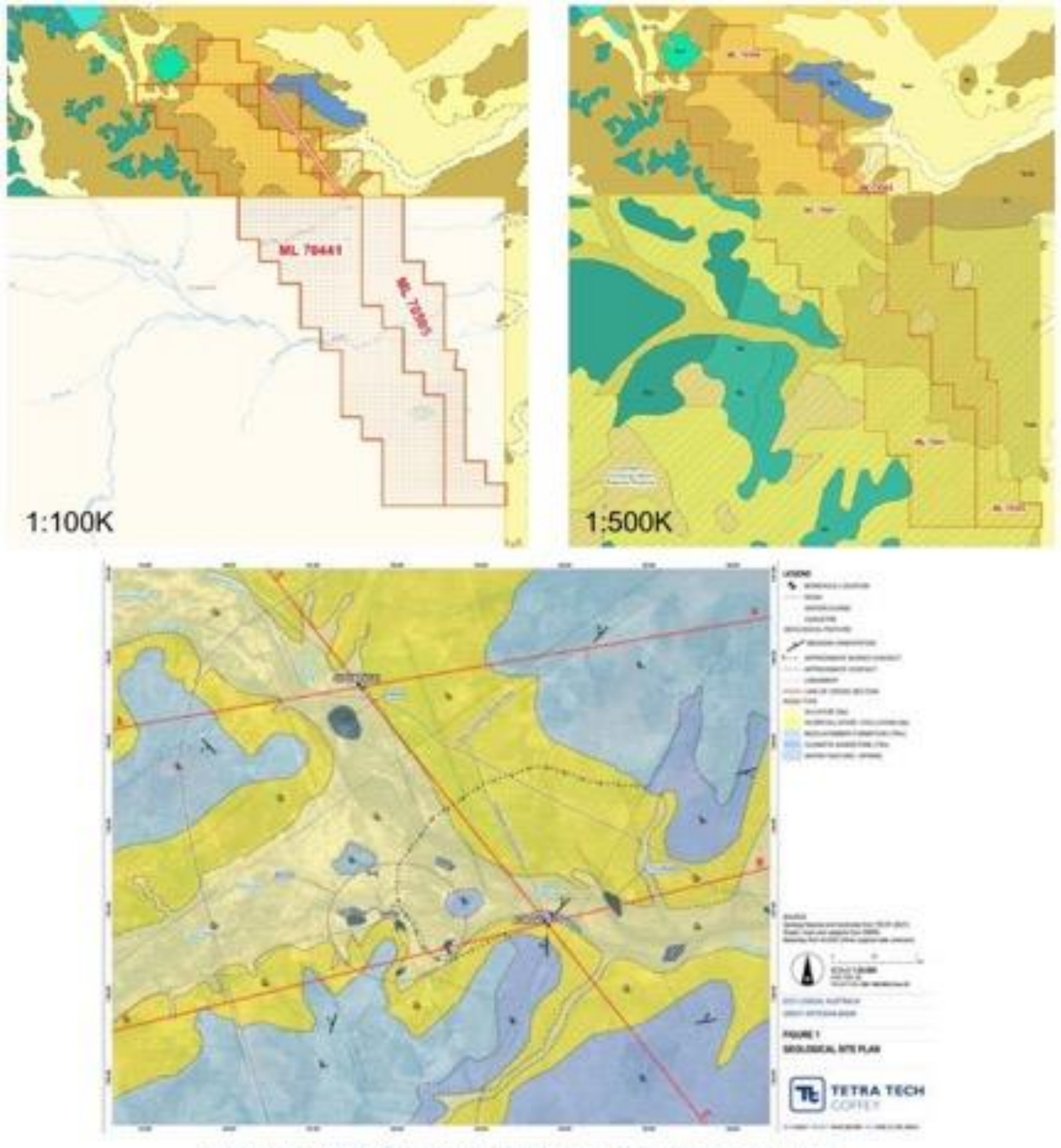

Figure 5 Regional scale mapping from the Integrating BA model report (p 4, Southern Highlands Structural Geology, 2022) showing range of mapping scales used to develop the structural geological model

Modelled outcrop extents represented in the updated groundwater model (Figure 3.25 on p 59 of the groundwater model report [3]) have changed significantly from the SEIS Hydrogeology report (Figure 30 on p 95 of GHD, 2013) for the alluvium, Tertiary/Weathering Zone and Moolayember Formation. The Hydrogeological Conceptual Model report [2] cites the fault mapping and modelling report (2021) as the source of the new geological model. However, the maximum extent shown in Figure 35 on p 52 of the fault mapping and modelling report (2021) is inconsistent with the modelled extent of these layers. The changes in the geological model outside this extent are not explained in the conceptualisation report and it is unclear what work has informed these changes.

The groundwater model report [3] refers to the integrating Bioregional Assessments (BA) model report (Southern Highlands Structural Geology, 2022), which revises the geological model within a smaller extent than the groundwater model extent. Additionally, the Integrating BA model (Southern Highlands Structural Geology, 2022) attempts to correlate a regional scale geological model (The Bioregional Assessment model) constructed to gain a broad understanding of conditions across the entire Galilee Basin, with a local scale model constructed for the Carmichael Coal Mine.

Additional sources of information to improve the subsurface geological modelling within the broader groundwater model extent include stratigraphic picks interpreted by Hansen and Uroda (2018) for the Galilee and Eromanga basins from geophysical logs, are fit for purpose as part of any future updates to the geological model. For example, these new interpretations suggest that the Dunda beds extends across much of the groundwater model area, west of the Carmichael Coal Mine lease area. The stratigraphic picks of Hansen and Uroda (2018) are included as part of publicly available data compilation by Vizy and Rollet (2022).

Recommendation: Identify, document, and justify the rationale, methods and data sources used to update the geological modelling and how it is represented in the groundwater flow model.

Level of concern: 2

Interpretation of Airborne Electromagnetic Method (AEM) Surveys was included in the revision of the geological model (including in the Hydrogeological Conceptual Model report [2], Fault leakage potential (2021) and Fault mapping and modelling (2021) reports). The outputs of Geoscience Australia's AEM dataset and inversions (Ray et. al., (2021)) can be further refined and further constrained with site specific data. It may be beneficial to revisit the AEM data set to constrain and re-invert existing AEM section models using data from site specific downhole conductance logs. This would aid and improve confidence in AEM interpretation.

Recommendation: Continue to improve the hydrogeological conceptual model using site specific data to better constrain AEM inversions.

2.4 Great Artesian Basin Springs Research Plan

This section addresses questions from DES related to the additional geological work undertaken as part of the Great Artesian Basin Springs Research Plan reported in the GAB Springs Geochemistry (2021) and summarised in the Hydrogeological Conceptual Model report [2].

This review has identified major issues related to the field and laboratory analytical methods, and the evaluation and interpretation of the hydrochemistry and environmental tracer database used to update the hydrogeological conceptual model.

2.4.1 Isotopic sampling and analysis

This section reviews '*Q18: Has sufficient isotopic work been undertaken to advance our understanding of the source aquifer?*' and makes the following recommendations to be addressed in the next Hydrogeological Conceptual Model report update:

Level of concern: 1

- Identify, document, and justify field and laboratory analytical methods
- Use a carefully selected team of independent scientists with relevant expertise to re-evaluate the existing hydrochemistry and environmental tracer database and interpretation methods
- Consider the evolution in the signature of a particular tracer along an inferred flow path
- Consider the role of evapotranspiration and geochemical cycling in the signature of tracers
- Consider whether multiple groundwater sources could be present in the signature of tracers
- Consider the effects of temporal variations in vertical hydraulic gradients in the system.

Level of concern: 1

Isotopic sampling for the Carmichael Coal Mine has generally fulfilled the spirit of the recommendations of the last review (CSIRO and GA, 2019). However, serious limitations in the analysis, presentation, and interpretation of the isotopic data remain. These limitations highlight the inherent challenges of using hydrochemistry and environmental tracer techniques in this environment.

The GAB Springs Geochemistry (2021) report provides only a cursory overview of analytical methods, which makes it very difficult to interpret the tritium data without understanding what the detection limit is and whether it changed between sampling campaigns.

Recommendation: Identify, document, and justify field and laboratory analytical methods

However, a more in-depth analysis of the existing environmental tracer database for the Carmichael Coal Mine and Doongmabulla Springs Complex is warranted. Any re-evaluation needs to be supported by additional documentation – including field sampling techniques, laboratory detection limits, data for individual springs – and confirmation that the existing isotopic data is fit-for purpose.

The data re-evaluation should consider specific questions or hypotheses about this hydrogeological system and how to test these questions using environmental tracers and other techniques. Other environmental tracer measurements, in particular noble gases, chlorine-36 and methane should also be considered. The available data suggest a mixture of water sources at the springs and in surrounding groundwater – including groundwater sources beyond the age-range dateable using carbon-14. Sampling for helium-4, chlorine-36 and for krypton-81 can be used to better characterise the origin of the older groundwater source(s). However, owing to the cost and the limited laboratory capacity for these measurements, it would be prudent to thoroughly reassess the existing database in conjunction with other sources of information before undertaking additional environmental tracer sampling campaigns at this site.

Any re-evaluation of the existing hydrochemistry and environmental tracer database requires a multi-disciplinary team of experts. This includes expert knowledge of water quality, hydrology, hydrogeology, hydrochemistry, environmental tracers, ecohydrology, numerical modelling, integrated risk assessment and other relevant geoscientific fields. The requisite expertise is available in several Commonwealth agencies (CSIRO, GA and ANSTO), universities, and in the private sector.

Recommendation: Re-evaluate the existing hydrochemistry and environmental tracer database for the Carmichael Coal Mine using a carefully selected multi-disciplinary team of experts to test and explore alternative hydrogeological conceptual models.

Based on the available information, the Doongmabulla Springs Complex appears representative of springs and other baseflow ecosystems that develop near recharge beds of the Great Artesian Basin (Herczeg 2008). In this environment, baseflow is provided either in the form of 'rejected recharge' where recharge beds are unconfined or by artesian leakage through thin or weakened cover (Herczeg 2008). However, these spring systems are complex and alternative hydrogeological conceptualisations have also been proposed (see Flook et al. 2020 and Raiber et al. 2022a, for example). Among the factors to consider in a conceptualisation of the springs associated with the GAB are that:

- several aquifers can potentially contribute to spring flow
- individual aquifers can contribute via local and longer flow paths
- geological structural controls on groundwater flow may be present (faults, etc.)
- various sources of groundwater can mix near the springs.

As such, the approach used to infer the source waters to the Doongmabulla Springs Complex from tracers has a few limitations. The underlying experimental design used so far is to sample groundwater from different potential aquifers and see which one has a signature most consistent with the one found in the springs. However, there can be a significant evolution in the signature of a particular tracer along a flow path spanning from intake beds to discharge zones in regional systems (Herczeg 2008; Raiber et al. 2022a,b; Suckow et al. 2020). Thus, using the 'average' signature for a given tracer across an aquifer is less useful in this context because the springs will tend to only 'see' the tracer composition as it is at the end of a flow path.

Recommendation: Consider the evolution in the signature of a particular tracer along inferred flow paths spanning from intake beds to discharge zones when re-evaluating the existing environmental tracer database.

Extensive evapotranspiration and geochemical cycling in regional groundwater discharge zones can substantially modify environmental tracer signatures near the springs relative to source aquifers (Duvert et al. 2015; Lamontagne et al. 2022). For example, under the Australian climate, shallow groundwater in regional discharge zones is often more saline than regional groundwater. This becomes an issue when, for example, salinity is used to quantify the contribution of different aquifers to a spring. If the effect of evapoconcentration of shallow groundwater is not considered, the contribution from more saline sources will tend to be overestimated.

Recommendation: Consider whether evapotranspiration and geochemical cycling has substantially modified the signatures when re-evaluating the existing environmental tracer database.

End-member mixing analyses must include tracers that are well-suited to track deeper groundwater contributions to springs because deeper sources tend to be smaller inputs relative to shallower aquifers. A frequent scenario for springs and river baseflow ecosystems across Australia is that they are a mixture from different groundwater sources, but the deeper sources represent a smaller fraction of the overall groundwater input (Banks et al. 2019; Gardner et al. 2011; Lamontagne et al. 2022). This need not always be the case but perhaps should be considered as the 'null' hypothesis when investigating new springs, rather than assuming that the springs could be fed via a single source. Assuming that multiple sources could be present ensures that the appropriate set of tracers is used, especially for deeper, typically older sources.

Groundwater from a particular aquifer can also be a mixture from several sources (Lamontagne et al. 2015; Moya et al. 2016). One of the reasons for characterising hydrochemistry and environmental tracers along whole flow paths is to help understand where aquifers themselves can become mixtures from several groundwater sources. Alluvial aquifers in particular frequently show a contribution from various sources (Duvert et al. 2015).

Recommendation: Consider whether multiple groundwater sources, including deeper sources, could be present in the signatures when re-evaluating the existing environmental tracer database.

A last consideration for the interpretation of environmental tracers in modern hydrogeological systems – especially in confined aquifers – is that the current vertical head gradients near springs and rivers may not always be representative of the recent past conditions (Herczeg 2008; Lamontagne et al. 2015). Pumping withdrawals since European settlement has locally reversed the vertical hydraulic gradients in many hydrogeological systems, including in the GAB. Thus, it is possible to find evidence of very old groundwater in aquifers where no obvious old groundwater sources should be present under current hydraulic gradients. This issue is especially important in the context of the Doongmabulla Springs Complex, where the current hydraulic head in Permian-age formations appears inconsistent with upward discharge.

Recommendation: Re-interpretation of the environmental tracer database for the Carmichael Coal Mine and Doongmabulla Springs Complex should consider both the potential for a significant evolution of the hydrochemistry and environmental tracers along potential flow paths and the effects of temporal variations in vertical hydraulic gradients in the system.

Level of concern: 2

The following are additional observations at a more technical level for GAB Springs Geochemistry (2021):

1. '*Recharge*': The report frequently uses the term 'recharge' but the term is never properly defined. The meaning of 'recharge' here seems to be *recharge from recent rain events* as opposed to other input pathways to an aquifer (interaquifer transfers, bank or flood recharge for an alluvium, etc.). It is important to clearly define or re-define this term if used in a different context because it influences the interpretation of environmental tracer data and the development of a hydrogeological conceptual framework for the springs.
2. *Sampling and Analytical methodology (p.10)*: The protocols for collecting surface and groundwater for hydrochemistry and environmental tracer measurements are not provided. This brings a significant uncertainty to the interpretation of more reactive chemical species used in the report because many are highly sensitive to sampling conditions. For example, Fe and Mn concentration in an aquifer can significantly change if the redox environment around or within a borehole is compromised (typically, via the introduction of atmospheric oxygen in an otherwise oxygen-free aquifer). Likewise, the dissolved concentration of many metal species can change between sampling and analysis if basic precautions are not taken (such as immediate filtration and acidification of the samples following collection in the field). In the context of the Carmichael Coal Mine, where a reduced (that is, oxygen-free) geochemical environment in most aquifers should be anticipated, it is largely pointless to use redox-sensitive chemical species as environmental tracers unless appropriate and rigorously applied sampling protocols are followed. This may have been the case but cannot be evaluated here owing to the lack of information. Likewise, as discussed for tritium in the previous section, it is also necessary to provide the detection limit and precision of the measurements, especially if different laboratories are used between sampling campaigns.
3. *High EC in rainfall (p*.11): The report states that some high electrical conductance (EC) values found in Queensland rainfall were caused by 'storms' during this period. However, these EC values correspond to 1/5 seawater and are clearly an error, most likely caused by unit conversion in the database used. As EC is unfortunately recorded with different units across Australia, this is not an uncommon source of confusion.
4. *Evaluation of major ion chemistry (p.11)*: The interpretation of major ion chemistry was made by comparing plots of EC relative to individual analytes of interest (Ca, Na, Cl, etc). This is an unusual way to interpret major ion data and probably not a very useful one – a linear relationship between EC and most major ions is expected in a context like the Carmichael Coal Mine, where groundwater and surface water salinity can vary by more than ten-fold across the study area. A range of alternative graphical techniques is available to summarise major ion data, such as Piper plots and many others, and tools for building these are now commonly available as freeware. Moreover, the use of tools like Piper plots would enable to look at 'processes' such as the evolution of the groundwater chemistry during transport in a complex hydrogeological system. This is essential when the hydrogeological environment is conducive to changes in the hydrochemistry along flow paths. These processes must be understood before a 'signature' is allocated to the groundwater of a particular aquifer for the purpose of quantifying its contribution to a spring. Overall, the major ion chemistry at the springs is more like the Clematis Sandstone but a mixed signature between several aquifers sources also seems possible.
5. *Minor elements (p*. 15): The justification for using minor elements to identify groundwater sources to the springs is confusing. That they are inherently at low concentrations does not make them more sensitive tracers. Many of the minor elements listed either more or less reflect the ambient salinity (like boron) or the localised redox environment (like manganese). There is probably more value in the use of minor elements to understand changes in the redox conditions in the context of the Carmichael Coal Mine area, where strong redox gradients are possible in different parts of the system, especially at the interface between aquifers and/or aquitards.

6. *Missing figures (p.19)*: Captions for a Figure 3.2 and Figure 3.12 are provided but not the figures themselves
7. *Stable isotopes of water (p.19)*: One of the most versatile environmental tracers is the isotopic composition of the water molecule and a significant database has been assembled for the Carmichael Coal Mine. However, the presentation and interpretation for this tracer has been split in two sections in the report (Figures 3.12 and 3.32), which is unnecessary. In addition, the figures themselves are difficult to interpret. For example, the 'red triangles' are meant to represent springs but we know at least one of these symbols is for groundwater from a bore, not surface water from a spring. Whilst departure of groundwater samples from the meteoric water line is not uncommon, whether there is enough information here to justify a 'Permian line' (and why) is unclear. Frustratingly, individual springs are not identified. Nevertheless, the stable isotopes of water provide potential insights into this system and are worth exploring in more detail. Notably, individual springs appear to have distinct isotopic compositions, suggesting that may be fed by different flow paths within the Clematis Sandstone or receive different contributions from the Clematis Sandstone and other aquifers. This is worth exploring further.
8. *^{14}C of dissolved inorganic carbon (^{14}C-DIC)*: Carbon-14 is an age-dating tracer for groundwater of intermediate transport timescales (thousands to tens of thousands of years). It is also one of the most difficult tracers to interpret owing to aquifer-rock interactions potentially modifying the ^{14}C-DIC content along a flow path (usually by lowering the ^{14}C values through generation of ^{14}C-free DIC, or 'dead' C). Various schemes have been used to correct for 'dead' C inputs by using the δ^{13}C signature of DIC, which is similarly influenced by aquifer-rock interactions (Kalin 2000). Notwithstanding the lack of correction for 'dead' C inputs here, the main feature of the ^{14}C data is that it is relatively low (<10 pMC) in most groundwater samples regardless of the aquifer sampled and intermediate (10 – 60 pMC) in most spring samples (noting here again the uncertainty in Figure 3.33 about what are the spring samples exactly). The large variability in ^{14}C-DIC within Clematis Sandstone either reflects relatively long transport timescales along the groundwater flow paths or that groundwater in this aquifer represents various mixtures of relatively old and young groundwater sources. However, considering the geological environment (coal-bearing formations, etc) the possibility remains of a strong 'dead' C input, which would need to be carefully considered in the interpretation of the ^{14}C data.
9. *Tritium (pp. 21 & 36)*. Tritium is an age-dating tracer for groundwater of short transport timescales (years to decades). Tritium is one of the most robust environmental tracers because it is part of the water molecule and easy to sample in the field. However, a drawback of tritium under current conditions is that the tritium input to the atmosphere from nuclear weapon testing post-WWII has now largely decayed (the half-life for tritium being 12.3 years). In the Southern Hemisphere, tritium in rainfall is now near natural levels, which are low (1-2 TU; Tadros et al. 2014) relative to existing analytical capabilities. Thus, this part of the report was difficult to review because there is the possibility that the marked differences in the lowest tritium values reported for the 2018 and 2021 campaigns are due to the samples having been sent to different laboratories. That one laboratory would have a higher or lower detection limit is not an issue. However, not knowing what the detection limit is for a particular sample and the precision of the measurement when getting close to this detection limit prevents a rigorous interpretation of the data at present. Thus, the classification of samples in the report into 'young', 'intermediate' and 'older' groups is tenuous. It also does not consider that groundwater and especially spring water are often mixtures of different water sources of different ages. There is potentially very useful information in the tritium data from the Carmichael Coal Mine and this clearly requires a re-evaluation.
10. *Strontium isotopes (p.37)*: As per previous studies in the area, the isotopic composition of strontium in the springs is most like Clematis Sandstone groundwater. However, the overall fit is poor and many springs have no matching signatures from any of the groundwater sources

investigated. This suggests that we are potentially missing one source of water contributing to the springs and that this source (or sources) has a distinct isotopic composition. There is scope for further comparison with groundwater strontium measurements made in the same geological formations (Moya et al. 2016). Alternatively, whilst the $^{87}Sr/^{86}Sr$ is usually considered 'conservative' this may not always be the case in environments where there is extensive cycling of carbonates (with Sr behaving in a similar fashion to calcium during geochemical cycling). Thus, as for many other tracers presented in the report, it would be worthwhile to look more closely at the evolution of the isotopic signature of strontium along inferred flow paths rather than try to derive an 'average' value for a given source.

2.4.2 Satisfactory completion of additional recommended works

> This section reviews '*Q19: Have all the additional works as recommended by CSIRO/GA in 2019 been addressed (whether completed or not) to your satisfaction in particular to support the identification of the source(s) aquifer(s)?'*

CSIRO and GA, in consideration of the information supplied and cognisant of the available time to Bravus since approval, acknowledges that effort was undertaken to address our prior recommendations. These efforts are recognised as a satisfactory beginning since approval. However, it is recommended that efforts are continued to address the recommendations made in 2019.

Were the additional works recommended to support the identification of the source aquifer(s) of the Doongmabulla Springs Complex in CSIRO and GA (2019) completed to a satisfactory standard?

a) hydrogeochemical analysis of water samples for comparison within and across relevant aquifers (Clematis Sandstone, Dunda Beds and Rewan Formation), including isotope and ageing tracers

No. The GAB Springs Geochemistry (2021) report provides only a cursory overview of analytical methods, which also hinders a proper evaluation of some of the environmental tracer data.

b) comprehensive review of groundwater level and quality data from relevant aquifers, including data from new proposed nested bores in the vicinity of DSC

Yes. Efforts have been made to assess the groundwater levels and water quality data from relevant aquifers as part of the modelling review. Continued refinement and development is warranted.

c) undertake hydrochemistry interpretation from surface and spring water samples to improve understanding of the hydrogeology. The hydrogeochemical analyses include but are not limited to: Noble gases – for example helium to identify if any deeper groundwater contributes to the springs (identification of source aquifers); radioactive noble gases - to identify source aquifers of recent (decades) to intermediate (centuries) age; and strontium isotopes - to identify the source rock of a particular groundwater system.

Partly. Efforts made to assess and interpret hydrochemistry data. However, additional analysis and interpretation is required by suitably qualified multi-disciplinary team of experts.

d) detailed geological mapping including cores from bores drilled in the vicinity of DSC and facies modelling to better inform hydraulic connectivity within and across all aquifers

Yes. New facies modelling data has been incorporated in the Rewan lithofacies interpretation (2021) report. Continued refinement and development is warranted.

e) incorporate the airborne electro-magnetic modelling recently completed by Geoscience Australia (Ray et. al., 2021)

Yes. AEM data acquired by GA included in Fault mapping and modelling (2021) report.

f) *revise the conceptual understanding of the source aquifer(s) for DSC and groundwater system based on additional information to update future groundwater modelling*

Partly. Conceptual understanding updated and documented in hydrogeological conceptual model report [2] but is inconsistently used and documented in the groundwater model report [3]. Additional analysis and interpretation is required to update the conceptual understanding of the source aquifer(s) and the groundwater systems.

g) *implement measures identified in Lake Eyre Basin Springs Assessment project by the Queensland Herbarium relevant to the DSC (Fensham et al., 2017)*

Yes. Efforts made to assess and contribute to the management recommendations for hydrochemistry.

h) *optimise the spatial distribution of monitoring bores, including nested or co-located bores intersecting different aquifer units, to enable improved future analysis of water level and hydrochemistry data.*

Yes. Efforts made to optimise the distribution of monitoring bores. Continued efforts must be maintained to better understand the groundwater system and potential impacts.

i) *acquire drill cores to better understand the intact hydrostratigraphy being drilled through to inform the conceptual model. Tests could be conducted on the core samples to assess and quantify hydraulic properties being implemented in the numerical model*

Yes. An assessment of hydraulic conductivities using core tests included in Rewan hydraulic properties (2021) report. Ongoing testing will further inform and refined the hydrogeological conceptual model.

j) *incorporate mine geotechnical information regarding geological stress regime changes and the potential changes to hydraulic properties as development progresses and material is removed.*

Yes. Efforts made to further understand the geological stress regime and its implications to hydraulic properties included in the Fault leakage potential (2021) report. Continued assessment is required as mine development progresses.

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