



Groundwater Solutions

Review of
Santos Narrabri Gas Project
Environmental Impact Statement
Response to Submissions

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May, 2018

1 Executive Summary

This report is the result of an independent review of the numerical groundwater modelling component of the Narrabri Gas Project (the Project) Environmental Impact Statement (EIS) Response to Submissions (RTS) (Santos Ltd., 2018).

The RTS was reviewed to determine whether the additional material provided addresses the concerns raised in the original EIS review (Hayley, 2017).

This report summarises the additional technical information provided in the relevant sections of the RTS and a discussion of the key issues raised in the previous EIS review with respect to the RTS.

Overall the additional material provided in the RTS fails to address the concerns raised in the initial model review. The RTS discusses further modelling work completed by CSIRO Gas Industry Social and Environmental Research Alliance (GISERA) (Sreekanth et al., 2017). This work substantially improves upon the modelling methodology described in the original EIS and, partly, addresses concerns highlighted in the EIS review. However, the GISERA documentation lacks specific explanations of the number of model parameters, the model parameter ranges and methods of model parameter assignment. Furthermore, the GISERA work does not consider uncertainty in the conceptual model of regional hydrogeology, and so underestimates the actual model predictive uncertainty.

Several concerns regarding the groundwater modelling predictive uncertainty analysis identified in Hayley (2017) were also mentioned in submissions presented by the Commonwealth Government Independent Expert Scientific Committee (IESC) on Coal Seam Gas and the NSW Department of Primary Industries.

2 Reviewer Qualifications

Kevin Hayley is a consulting geophysicist and groundwater modeler with 13 years of experience in the construction and calibration of numerical models of groundwater flow and contaminant transport, and in using geophysical methods for environmental monitoring and mineral exploration. He received his Ph.D. from the University of Calgary in 2010 where he conducted research into monitoring salt-impacted soil using time-lapse geophysics. He has strengths in numerical methods, inverse problems and uncertainty analysis. He has authored more than 20 peer reviewed journal and conference papers on topics ranging from geophysical inversion methods to computational hydrogeology with cloud computing. He has conducted several groundwater modelling projects with large transient datasets involving calibration and uncertainty analysis for environmental impact assessments of oil sands extraction in Alberta Canada, mine planning, and large infrastructure projects in Victoria Australia. He holds accreditation as a professional Geophysicist and Geoscientist with governing bodies in the Canadian provinces of Alberta and British Columbia.

3 Introduction

In 2017, Groundwater Solutions Pty. Ltd. was retained by EDO NSW on behalf of the North West Alliance to review and provide expert professional opinion on the groundwater modelling component of the Project EIS (Santos Ltd., 2017) submitted to the New South Wales (NSW) Government by Santos Ltd (the Proponent). This review was completed in May 2017 and used as a component of the North West Alliance's submission commenting on the Project EIS (Hayley, 2017).

In April 2018, the RTS was made publicly available and Groundwater Solutions Pty. Ltd. was again retained by EDO NSW to provide expert opinion.

The sections of the RTS reviewed for groundwater impacts and groundwater modelling details were:

Part A

- Executive Summary
- The Project
- Response to IESC
- Response to DPI Water
- Response to EPA
- Response to Gilgandra Shire Council
- Response to non-agency submissions

Part B

- Appendix B Project Commitments
- Appendix D Water Baseline Report

Part D

- Appendix L Errata

Specifically, Groundwater Solutions was requested to consider whether the additional material provided addressed the issues raised in the initial EIS review in 2017.

Results of the RTS review are discussed below. A summary of the additional material is provided with the reviewed sections of the RTS and a discussion of the RTS with respect to issues raised in the initial EIS document review.

This review has been conducted in accordance with the *'Expert witness code of conduct'* (Schedule 7, Uniform Civil Procedure Rules 2005).

4 Summary of New Material Provided in Response to Submissions

There were approximately 23,000 submissions received in response to the Project EIS and the RTS attempted to address comments and concerns. The RTS provided detailed responses to specific comments from Government agencies, the IESC and DPI Water. The response to non-agency submissions was done as a group statement attempting to address specific issues raised by multiple submissions. It is not possible to determine whether this reviewer's previous comments were specifically addressed in this part of the RTS as the response to non-agency submissions did not reference individual submissions.

The RTS largely addresses submission comments by discussing relevant aspects of the existing EIS. However, some additional information is provided with the RTS as follows:

- An updated and revised baseline water report (located in Appendix D of the RTS) is the largest piece of new material provided. Groundwater data from the original EIS baseline water report have been updated with more recent measurements and some additional information is provided. Data errors identified by the submission comments have been corrected. A review and summary of the baseline water report is presented in section 6 of this report.

- To address comments about simulated vertical flux between the Great Artesian Basin (GAB) and Namoi Alluvium, a review of the regional groundwater flux estimates in the Project area from previous studies was provided in Section 6.11.3 of the RTS.
- In response to questions about the groundwater model predictive uncertainty analysis, the RTS references further groundwater modelling work done by the CSIRO Gas Industry Social and Environmental Research Alliance (GISERA) (Sreekanth et al., 2017). For completeness, the GISERA report has also been reviewed in this report.
- Numerous minor edits and clarifications are provided in the RTS identifying errors in the EIS, such as monitoring bores listed in the wrong geologic unit.

5 Key Issues Raised in Review of EIS

The review of the original EIS (Hayley, 2017) identified some key parts of the groundwater modelling done in support of the EIS that were deemed to be insufficient. Primarily, these included aspects of the groundwater model calibration and predictive uncertainty analysis which are described in the following sections and used to discuss the adequacy of the RTS.

5.1 Model Calibration

The EIS review (Hayley, 2017) highlighted the fact that the recharge to the Namoi Alluvium was the only parameter adjusted to fit observed water table observations as part of a model calibration. The vertical hydraulic conductivity of aquitards is the dominant parameter controlling propagation of pressure from the target coal seams up to receptors on the surface. Due to the absence of any data to constrain this parameter it was not adjusted to fit observation data as part of model calibration. Consequently, the EIS model is uncalibrated in terms of vertical hydraulic conductivity. Similarly, the GISERA modelling did not include calibration due to lack of data capable of providing information on hydraulic parameters.

As discussed in section 5.3.2 of the Australian Groundwater Modelling Guidelines (Barnett et al., 2012), modelling lacking calibration is still of value, and predictive uncertainty analysis can still be undertaken using the initial parameter estimates and uncertainties. However, there is a lower degree of confidence in predictions obtained using this method.

5.1.1 Calibration Data

In the baseline water report (RTS – Appendix D), the primary sources of potential calibration data are the static hydraulic head estimates. These estimates could be used to inform steady state simulations of background groundwater flow. However, this data is unlikely to reduce the uncertainty of estimated groundwater flow regime changes due to Project development (Leake, 2011). The EIS review (Hayley, 2017) concluded that it was appropriate for the EIS modelling to proceed without model calibration.

Several submissions, and the RTS itself, raised the issue that some potentially valuable calibration data has been overlooked. The IESC submission recommended that the model could be improved by consideration of data from coal mines, particularly Narrabri North underground mine. The Proponent's response discusses the difficulty in representing mine dewatering effects in a regional model and the fact that the dewatering in Narrabri North occurs in the upper coal seam where only 5% of extraction is planned. As a result, the Proponent claimed coal mine data would not improve predictions within the Early Permian coal, where the largest extraction is planned.

The model developed for the EIS uses the MODFLOW-SURFACT™ code on a regional scale, which meant that it was difficult to achieve localised refinement, and the inclusion of local scale features and data. This code selection is a technical choice to achieve model simplicity and stability. Alternatives such as MODFLOW USG (used in the GISERA study), MODFLOW 6, and FEFLOW all offer the potential for localized grid or mesh refinement and accommodate the representation of mines or local scale pumping wells in a regional model. The Proponent's statements that the Narrabri North mine would not inform predictions within the Early Permian coal are likely correct. However, pressure changes within the target coal seam are not a key prediction of interest with respect to the environmental impact of the Project. If the Narrabri North mine dewatering data is accompanied by appropriate groundwater monitoring, then the dataset may be useful for constraining the hydraulic parameters of the geologic strata between the target coal seams and the key environmental receptors in the GAB aquifers (alluvium and surface). This would reduce predictive uncertainty.

In response to statements by IESC, DPI Water, and non-agency submissions regarding uncertainty in the simulated extraction volumes, the Proponent discusses pilot data available from *"thirty -seven appraisal wells from seven coal seam gas pilots in Early Permian targets,"* upon which the simulated extraction volumes were based. The submission from DPI water questions why the model was not calibrated on pilot extraction volume, and pressure observation data.

The Proponent responded that extraction rates from the pilot project were used to inform simulated extraction rates and, could not be used as calibration observations as these were used as model inputs. This is a result of the technical choices made representing the coal seam depressurization process in the model. If a drain boundary condition was used with an adjustable conductance parameter, as was done with the GISERA modelling, then the extraction volumes during the pilot project could be used as observation data to aid constraint of model predictive uncertainty, while still allowing extraction volume uncertainty to be included in the predictive uncertainty analysis. A further discussion of extraction volumes is included in section 5.2.1 below.

The Proponent also responded that coal seam depressurization observations due to pilot well pumping were not used for calibration because the model was regional scale. As with the coal mine data discussed above, this limitation is a result of the technical choice to adopt the structured grid MODFLOW-SURFACT™ code. Modelling codes that allow for unstructured grids and localized refinement can enable the inclusion of local scale pumping tests and observation well data in the calibration of a regional scale model.

5.1.2 Model update and recalibration planning

It was noted in the EIS review (Hayley, 2017), that a dataset for model calibration that will reduce prediction uncertainty will be available after the Project has begun operation if an appropriate monitoring network is established.

The groundwater monitoring plan included in the EIS (Appendix G3) stipulates the groundwater model is to be revised, updated and calibrated based on new data if water level triggers are hit in the monitoring network. The triggers were set based on simulations conducted with the current model.

The review from the IESC recommended that the monitoring plan explicitly include provisions for model recalibration regardless of whether trigger levels are reached. The Proponent responded to this recommendation by discussing the trigger-based plan for model recalibration.

The submission from NSW DPI Water also recommended that the monitoring plan mandate development of a calibrated groundwater model: *“A groundwater monitoring plan that will enable the development of a calibrated model is recommended as a condition of consent as is the requirement for a calibrated model to be developed. Santos in its EIS has committed only to the calibration of the model if necessary.”* Again, the response from the Proponent was to discuss the existing trigger-based plan for model calibration.

The review from NSW EPA did not discuss model calibration but recommended that geology data be recorded during well field development and used to update and refine the groundwater model. The response from the Proponent was to discuss the existing plan to refine the model if triggers are hit in monitoring wells.

In the Proponent’s response to non-agency submissions it was acknowledged that issues relating to the model calibration were raised, however the only response was to highlight the CSIRO review describing the model as *“fit for purpose”*.

The groundwater monitoring targets proposed in the existing groundwater monitoring plan are the result of model simulations, and the water level target effectiveness and correlation to negative future impacts will be highly uncertain due to the high degree of model predictive uncertainty. Therefore, relying on the existing groundwater monitoring plan targets to dictate model updates, calibration and a reassessment of Project groundwater impacts risks missing opportunities to understand and mitigate negative groundwater impacts earlier in the Project development. In this reviewer’s opinion, consistent with the submissions from the IESC and NSW DPI Water, the monitoring plan should be updated to include a fixed schedule of model updates, recalibration with appropriate uncertainty analysis, and re-evaluation of Project environmental risk.

5.2 Uncertainty analysis

The EIS modelling review (Hayley, 2017) found that the qualitative uncertainty analysis conducted for the groundwater model described in the EIS was inadequate to quantitatively assess the risk of adverse groundwater impacts. A quantitative and statistically rigorous assessment of Project risk represents the application of the best available science, is more consistent with the Australian groundwater modelling guidelines, and has been applied for other coal seam gas groundwater modelling projects in Australia (Sreekanth & Moore, 2015). These concerns were also repeated by the submissions of the IESC and NSW DPI Water. In the RTS the Proponent highlights the external review by CSIRO that was done for the EIS claiming that the sensitivity analysis conducted as part of the EIS modelling was a sufficient alternative for a formal uncertainty analysis. A primary limitation of the EIS sensitivity analysis identified in (Hayley, 2017) was that the predictive impacts on receptors of higher vertical hydraulic conductivity, high water use scenario, and cumulative impacts from the Narrabri coal mine were assessed in isolation from one another with no simulation considering the combined effects presented. Thus, the qualitative uncertainty analysis conducted by the Proponent fails to present a conservative estimate of predicted groundwater impacts which considers the combined effects of factors that may lead to larger magnitude impacts.

The GISERA modelling study was used to support some claims in the RTS, however only the mean value of predictions from the GISERA study are discussed in the RTS rather than the predictive uncertainty range.

Specific aspects of the model uncertainty analysis are discussed below.

5.2.1 Uncertainty in Extraction Rates

The EIS modelling sensitivity analysis used three extraction rates based on data from pilot well development and on reservoir modelling considering different values for coal porosity. The extraction rates considered included a low extraction scenario of 35GL, a base scenario of 37.5GL and a high extraction scenario of 87.1GL of extraction over 25 years. The EIS provides no evidence that any consideration of different rates of leakage into the reservoir from surrounding strata was taken into account.

The EIS review (Hayley, 2017), and submissions from the IESC and NSW DPI Water, raise questions as to whether these three scenarios adequately represent the uncertainty in extraction volumes necessary to develop the gas resource. There are two possible ways to represent water extraction for gas development in a groundwater model. The first is to use an applied extraction rate that is estimated based on reservoir modelling and data as was done for the EIS modelling. The second is to simulate the decrease in pressure required to extract the gas as a drain boundary condition as was done with the GISERA modelling. A conductance parameter on the drain boundary condition acts as a surrogate for the unsaturated flow happening near the wells that is not represented in a groundwater model.

The Proponent stated in the RTS that the requested licence volume is 37.5 GL, and therefore there is no uncertainty in the volumes applied. In terms of representing the potential environmental impact of developing the gas resource rather than just extracting the licenced volume, it is this reviewer's professional opinion that the method of representing the extraction as a drain boundary condition is superior and better suited for uncertainty analysis.

The GISERA work (Sreekanth et al., 2017) does not document the range of conductance values applied to the wells, or if the conductance parameter was applied to each well as a single parameter or individual parameters. As such, it is difficult to judge whether this modelling work is a rigorous exploration of extraction rate uncertainty. As discussed in section 5.1.1 above, calibration to historical production rates at pilot wells would provide some information on a reasonable range for conductance parameters. The GISERA study did consider alternative values for vertical conductivity and so would have included some consideration of alternative scenarios of leakage into the reservoir. However, the vertical hydraulic conductivity parameters used are poorly documented, so it is difficult to assess the rigour of the assessment. Similarly, the method of applying the vertical hydraulic conductivity parameter is undocumented. Therefore, it is assumed that it was a constant value over the whole geologic unit represented in the model. As discussed in section 5.2.2 above, it is this reviewer's opinion that this approach would fail to capture the uncertainty due to spatially variable thickness and competence of the confining aquitards.

The distribution of cumulative extraction volumes obtained from the GISERA study are shown in figure 7 of (Sreekanth et al., 2017). The low, base and high case extraction volumes used in the EIS modelling are consistent with the distribution shown in the GISERA report. As such, whilst there is currently no evidence that the rates used in the EIS modelling are unrealistic, the uncertainty in extraction volumes is better represented with the approach taken by the GISERA modelling.

5.2.2 Conceptual Model Uncertainty

The EIS modelling review raised concerns that uncertainty in the conceptual model was not included in assessments using alternative conceptual models. This subject was also raised by IESC, NSW DPI Water, and non-agency submissions, and included comments on the representation of faulting in the area.



In the RTS, the Proponent responded by stating that the conceptual model is based on several previous studies of the region and was also used in the GISERA work, and, therefore, the conceptual model is not in dispute.

The GISERA study “concluded that more up-to-date knowledge of the Surat Basin formations and alluvium was available from other studies” (Sreekanth et al., 2017), used the same conceptual model as the EIS for the Gunnedah Basin, and updated information from other studies for the Surat Basin and alluvium. It was identified as a limitation of the GISERA modelling that “The conceptual model used for building the numerical groundwater model development is underpinned by the existing geologic and hydrogeologic data and current state of knowledge about the Gunnedah and Surat Basin formations. Collection of more hydrogeologic datasets including environmental tracers can improve the conceptual understanding of the groundwater connectivity and recharge and help better constrain the prediction uncertainty.” (Sreekanth et al., 2017). (Sreekanth et al., 2017) also noted that “Geologic structures including faults have not been included in the regional groundwater model used in this analysis. Further studies are required to quantify the effect of the presence of faults on the flux changes induced by CSG development.”

The fact that the same conceptual model has been used for multiple studies is a reflection of the fact that there is no data available for updates, and that insufficient time and effort has been applied between studies to explore alternatives, rather than confirmation that the conceptual model is correct. Even in areas with detailed geological data available, an infinite number of alternative conceptual model geometries could be proposed that would be consistent with all available data and geological understanding. Alternative models with variable aquitard thickness, continuity and the potential for faulting induced pathways away from locations of direct observation, would produce highly variable model predictions. At the current time there is no dataset available that is sufficient to say that these alternative models are not possible. Consideration of alternative conceptual models is recommended by the Australian groundwater modelling guidelines (Barnett et al., 2012) and many recent groundwater modelling publications e.g. (Ferre, 2017).

Producing multiple numerical groundwater models based on alternative conceptual models is time consuming and expensive. As discussed in the EIS review (Hayley, 2017), an alternative approach is to use spatially variable model parameterization that can allow for important model parameters to the prediction of interest, such as vertical hydraulic conductivity, to take on localized high or low values, representing gaps or faults in the confining strata. This issue was also identified as a limitation by (Sreekanth et al., 2017), who also suggested spatially variable or highly parameterized approaches to representing the hydraulic properties of the intraburden layers.

5.2.3 Parameter Uncertainty and predictive uncertainty analysis

The EIS review (Hayley, 2017) commented that the qualitative sensitivity analysis done as part of the EIS modelling lacked statistical rigour, and that it failed to consider a worst-case scenario presenting the maximum impacts that the current data and system understanding cannot disprove.

These comments were also mentioned in the IESC and NSW DPI Water submissions. The Proponent’s response in the RTS pointed to the CSIRO independent review, and the GISERA modelling. The recommendation to explore a worst-case scenario included in the EIS review (Hayley, 2017), and the IESC’s recommendation to explore parameter combinations that could lead to drawdown values exceeding 2m, were not addressed in the RTS.



The GISERA modelling does represent a substantial improvement in model predictive uncertainty analysis. However, the report is poorly documented in terms of describing how parameters were applied to the model, and the parameter value ranges used for the uncertainty analysis. The parameterization method of the vertical hydraulic conductivity parameters that will dominantly control the propagation of pressure from the coal seams to receptors is not documented. As such, it is assumed that it was applied as a uniform value. As discussed in section 5.2.2 above, a spatially variable parameterization of vertical hydraulic conductivity that could consider the effects of localized gaps and preferential pathways in the confining layers would be a more rigorous method in the absence of considering alternative conceptual models. The GISERA documentation does mention the representation of five mines in the local area for assessment of cumulative effects, though the details of that representation are not provided. This is a substantial improvement from the EIS modelling where cumulative effects of one mine development were included in the base simulation only, and not included in simulations of higher water use and higher vertical hydraulic conductivity.

Methods of considering spatially variable parameter fields are well established and available through free software (Doherty, 2015). Similarly, the exploration of maximum or minimum prediction values representing the limits of a prediction that are consistent with available data and system understanding through Pareto front methods are well established, and available through free software (Doherty, 2015)

In response to non-agency submissions, the Proponent claims that due to lack of data, heterogeneity in hydraulic properties cannot be included in the model. However, this logic does not apply to an uncertainty analysis where alternative spatially variable parameter sets could be considered in the predictive uncertainty analysis.

6 Review of Updated Baseline Water Report

An updated baseline water report is provided as part of the RTS.

The executive summary of the baseline water report (Appendix D of RTS) states that there are now 52 monitoring locations for hydraulic head (up from 50) and 41 monitoring locations for groundwater quality. The surface water monitoring program is unchanged.

Section 4 of the report only presents data from 50 head monitoring bores. Data for 19 Santos monitoring bores and four DPI Water monitoring bores have been updated to include data up to mid-2017.

Some tables and plots have been updated to address errors in geologic unit assignment of bores in the original EIS.

The plots of monitoring data have been updated to include recent data, however no data quality assessment and processing has been done. As such, the plots are dominated by spurious data likely recorded during removal and replacement of data logging equipment for download. Also, data shifts are likely due to changes in monitoring equipment level.

With respect to the groundwater model, and the potential for a calibration dataset, there is no additional information. Some of the observed vertical hydraulic head gradients between the target coal seams and overlying aquifers could be useful for constraining vertical hydraulic conductivity.

However due to historical groundwater use in the GAB aquifers it is unlikely that the recorded groundwater levels are representative of a system at equilibrium.

7 Discussion and Conclusions

The review of the EIS groundwater modelling (Hayley, 2017) identified two key shortcomings: the lack of a statistically rigorous uncertainty analysis; and, the lack of a worst case simulation that produced a maximum prediction while still maintaining consistency with observation data and reasonable parameter values. There is very little in the RTS that addresses these issues except for references to the GISERA modelling work. The GISERA modelling work represents a substantial improvement to the original EIS modelling. However, the work is poorly documented with respect to parameter values, parameter bounds, the application of parameters to the model, and the number of adjustable parameters considered in the uncertainty analysis. The GISERA modelling did not consider alternative conceptual models. Therefore, the predictive uncertainty arising from assumptions, simplifications and lack of data in the conceptual model development, termed “*structural uncertainty*” (Anderson et al., 2015; Hunt & Welter, 2010), was not considered. Consequently, the GISERA work is likely to understate the true uncertainty based upon current understanding of the groundwater system and the observation dataset. As discussed in section 5.2.2 above, an extension of the GISERA modelling methodology to include spatially variable vertical hydraulic conductivity could be an alternative to considering alternative conceptual models, which would involve little additional effort. This is also discussed in the GISERA report.

For those reasons, whilst the GISERA modelling study is the most rigorous assessment of the likely Project impacts to groundwater currently available, it needs be updated to meet the current state of best ground water modelling science. In this regard, I consider that a reasonable consideration of the Project impacts would include the median values from the GISERA study as a most likely (median) value, and the 95th percentile values as predictions that cannot be excluded given the current data (although impacts higher than the 95th percentile may be deemed to be unlikely).

For example, the most likely median prediction of flux change to the Pilliga Sandstone aquifer has a peak rate of 84 ML/y which is 0.3% of the long term annual Average Extraction Limit (LTA) of 29,690ML/y. The 95th percentile prediction (which impacts are unlikely to exceed) is 2,299ML/y, which represents 7.7% of the LTA (Sreekanth et al., 2017). However, as stated above, the GISERA study is likely to underestimate predictive uncertainty. Therefore, I consider that in order to provide more confidence in an upper bound of predicted impacts, further work which uses the 95th percentile prediction from the GISERA study, and which considers alternative conceptual models or spatially variable intraburden hydraulic properties, is required.

In my opinion, a more rigorous assessment of the environmental impacts of the Project, consistent with the current state of best groundwater modelling science, would include the adoption of an updated GISERA model. The updated GISERA model should include spatially variable vertical hydraulic conductivity. In addition, discussion of updated GISERA model predictions should include a most likely (median) value, and a value that is at the upper edge of likely model predictions (using either a maximized worst case prediction or the 95th percentile).

8 References



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