Groundwater Solutions

Review of
Santos Narrabri Gas Project
Potential for Adverse
Groundwater Impact

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1.0 Executive Summary

This report summarises outstanding concerns about the assessment of potential groundwater impacts from the development of the Santos Narrabri Gas project that were raised during the Independent Planning Commission Public Hearing by Kevin Hayley of Groundwater Solutions. Groundwater Solutions was retained by the EDO on behalf of the North West Alliance to provide an independent expert review of the numerical groundwater modelling conducted for the Project application Environmental Impact Statement (EIS).

This review identified aspects of the numerical modelling that contradict statements in the EIS and subsequent documentation claiming:

1) The numerical modelling is founded on conservative assumptions.
2) The project has negligible risk of adverse impact to groundwater users.

The primary concerns relate to the uncertainty in model predictions, simplifying assumptions in model development, and the lack of observation data to reject alternative models that predict larger magnitude impacts than those reported in the EIS.

The proposed conditions of consent have been reviewed and, from a modelling perspective, six recommendations are proposed to improve the assessment and management of groundwater impacts of the project.

2.0 Reviewer Qualifications

Kevin Hayley is a consulting geophysicist and groundwater modeler with 16 years of experience constructing and calibrating numerical models of groundwater flow and contaminant transport and utilising 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. Dr. Hayley 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 multiple 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 Australia.

3.0 Introduction

Groundwater Solutions Pty. Ltd. (Groundwater Solutions) was retained by the New South Wales Environmental Defenders Office (NSW EDO) on behalf of the North West Alliance community group to review, and provide expert professional opinion, on the groundwater modelling component of the Santos Narrabri Gas Project (the Project) Environmental Impact Statement (EIS) and response to submissions (RTS) submitted to the New South Wales (NSW) Government by Santos Ltd (Santos).

Groundwater Solutions received documents and provided advice on the following timeline:

- In May 2017, Groundwater Solutions conducted an independent review of the numerical groundwater modelling component of the Project EIS (provided in Appendix A).

- In May 2018, Groundwater Solutions reviewed the RTS documents produced by Santos and, additional numerical modelling conducted by the CSIRO Gas Industry Social and Environmental Research Alliance (GISERA) (provided in Appendix B).
- In July 2020, Groundwater Solutions reviewed the following documents in advance of the Independent Planning Commission (IPC) public hearing:
  - A supplementary RTS document produced by Santos;
  - New South Wales Department of Planning Industries and Environment (DPIE) documents including:
    - Department's assessment report (including the Water Expert Panel (WEP) Report);
    - DPIE – Water Advice on conditions;
    - DPIE – Water Advice on Supplementary RTS;
    - DPIE – Water Final Advice.

After consideration of the additional materials, this report summarizes Groundwater Solutions' professional opinion and technical recommendations on the potential groundwater impacts of the Project.

This review has been conducted in accordance with the guidelines/principles detailed in the '*Expert Witness Code of Conduct'* (Schedule 7, Uniform Civil Procedure Rules, 2005).

4.0 Background

A detailed review of the numerical modelling that the Project groundwater impact assessment conducted in 2017 (Appendix A), found several critical limitations in the methodology used to assess uncertainty in model predictions. The remainder of this section provides some background information on model uncertainty to facilitate understanding of the potential impacts the project could have on groundwater users in the region.

4.1 The Scientific Method

The scientific method is an empirical method of acquiring knowledge that involves formulating a hypothesis and conducting experiment(s) to test the hypothesis. A fundamental tenet of the scientific method is that hypotheses can never be proven correct, only discounted when shown to be inconsistent with experimental evidence (Popper, 1959). When applying the scientific method to numerical modelling of environmental processes, a model is simply considered *one* hypothesis about what we believe the true, but unknown, system is like.

Scientists amass evidence to support hypotheses, but cannot *prove* something is correct. As such, models cannot predict what is going to happen, only what is likely to *not happen* (Doherty, 2015). Therefore, to correctly utilise models, we need to frame our questions to align with model limitations and ask our questions appropriately. For example, instead of asking what is going to happen (which models are ill-equipped to answer) we need to ask what is the *bad thing* we are trying to avoid and, can we discount the occurrence of the *bad thing* based on current evidence and hydrogeological understanding.

4.2 Model Uncertainty

Numerical models can't capture the complexity of natural systems. This is because environmental systems are infinitely complicated, and it is not possible to construct models on the same scale of variation that occurs in reality. Due to data scarcity and the complexity of natural systems, we can never know what the true system is like and we must make inferences (informed guesses) and approximations that are consistent with the limited data we have. Approximations must be made to ensure tractable models, however; approximations always introduce uncertainty. Generally, there are four main types of uncertainty that impact the predictions of groundwater models.

- *Measurement uncertainty* which arises due to measurement errors and instrument inaccuracies.
- *Model parameter uncertainty* which is due to the fact that we can't see what's under the ground because our observation data is limited. Also, model parameters are non-unique which means more than one set will fit the observation data.
- *Model structural uncertainty* which is due to our inability to represent the complexity of natural systems in a model.
- *Future scenario uncertainty* because we don't know the future.

All these sources combine to cause model predictive uncertainty, which is, essentially: *how wrong is our prediction?* Modellers can never get rid of uncertainty in model predictions, only reduce uncertainty due to informed data collection. Nonetheless, model predictions will never be a single number – model predictions are always distributions. Ignoring uncertainty leaves decision-makers blind to risk and the potential of equally plausible bad things occurring. Thus, rigorous quantification of uncertainty when constructing numerical models is critical.

4.3 Bayesian Methods

The extension of the scientific method is to consider the range of plausible models consistent with background information available, collect observations, and revise the range of plausible models to only contain models that are consistent with both background information and the observations. In practice this is done through a statistical technique called Bayesian inference that uses Bayes Equation (Bayes, 1763):

$$P(m|d) \propto P(d|m)P(m) \qquad \textit{Equation 1}$$

- Where: *m* refers to models considered, and *d* refers to observation data;
- $P(m)$ is a probability distribution over the range of plausible models consistent with background information referred to as the *prior*;
- $P(d|m)$ is the likelihood of a given model reproducing the observation data;
- $P(m|d)$ is the probability distribution over the range of plausible models consistent with both background information and observation data, referred to as the *posterior*.

Bayesian techniques allow for the understanding of a modelled system, or state of information, to be quantified and updated by the inclusion of additional observation data – such as the revision of site understanding that occurs between an initial desktop review and a full detailed site investigation. Most modern methods of uncertainty analysis are based on Bayesian methods (Tarantola, 2006). A discussion of this technique applied to groundwater modelling is provided in an explanatory note by the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC) (Middlemis & Peeters, 2018).

5.0 Review of EIS model

This section summarizes the review and discussion of the EIS model aspects that are relevant to the discussion of model uncertainty.

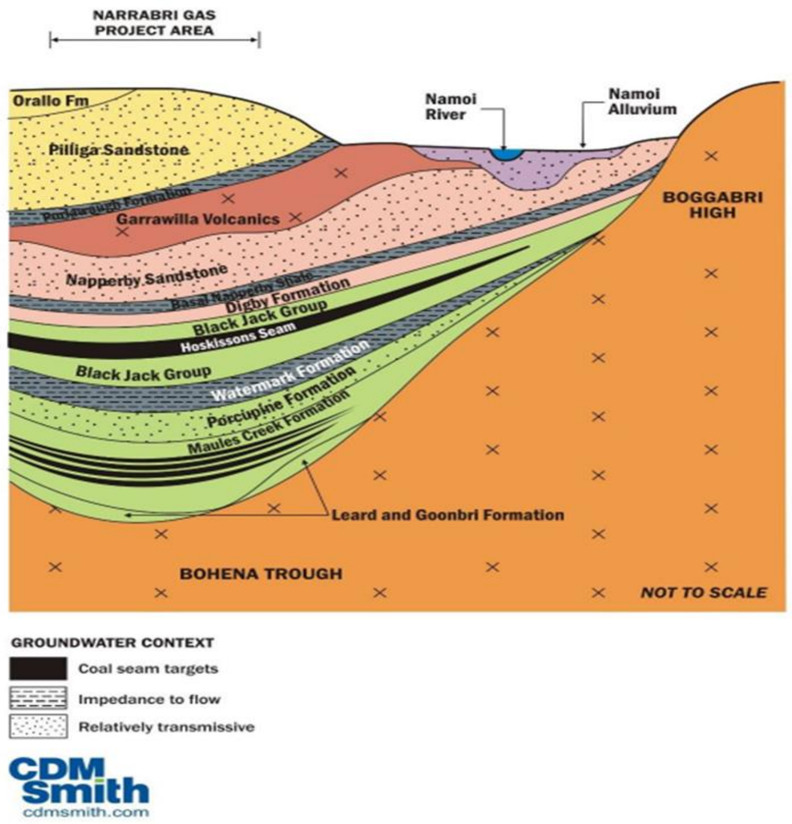
5.1 Conceptual Hydrogeological Model

A conceptual hydrogeological model is described as *"A descriptive representation of a groundwater system that incorporates an interpretation of the geological and hydrological conditions"*(Anderson & Woessner, 1992; Barnett et al., 2012). During development of the conceptual model for the EIS Groundwater Impact Assessment, CDM Smith did a thorough review of available data to describe the groundwater system. As noted in the EIS Groundwater Impact Assessment, *"connections between the target coal seams and alluvial units will control the potential magnitudes and locations of impacts on shallow groundwater sources".* The WEP report also states that *"the nature of the hydraulic connection between the GAB and GOB aquifers is critical in assessing the likely future impact of CSG production."*

The hydrogeological conceptual model for the Project (figure 5.1) is based on a literature review and point observations from outcrops and boreholes. The interpretation developed from this information is of overlapping sedimentary basins with continuous layers of low permeability rock or aquitards. Due to the nature of any geological investigation, there remains considerable uncertainty in the local scale thickness, structure, and orientation of layers that could have large impacts on the connection between target coal seams and near surface aquifers that are used for water supply.

Figure 5.1: Geological Conceptual model (from figure 2-1 in the EIS Groundwater Impact Assessment)

Figure 2-1 Project area schematic showing lithology and WSPs



In particular, the connectivity between target coal seams and overlying aquifers could be very sensitive to:

- local scale variations in thickness or gaps in key low permeability units;
- alternative interpretations on how the Gunnedah-Oxley Basin sub-crops beneath the Namoi Alluvium; and
- the presence of local scale zones of enhanced vertical permeability due to faulting.

As described in Section 4, there are alternative interpretations that are equally plausible due to the uncertainty. The interpretation adopted for the EIS of laterally continuous layers of low permeability with no alteration due to faulting between the target coal seams and water supply aquifers is the interpretation least likely to predict groundwater impacts of project development. This is due to the continuous layers forming a barrier to groundwater flow between target coal seams and near surface aquifers. Almost any alternative plausible conceptual model that considers faults and/or heterogeneity in the layers would form a less of a barrier to groundwater flow.

5.1.1 Faulting

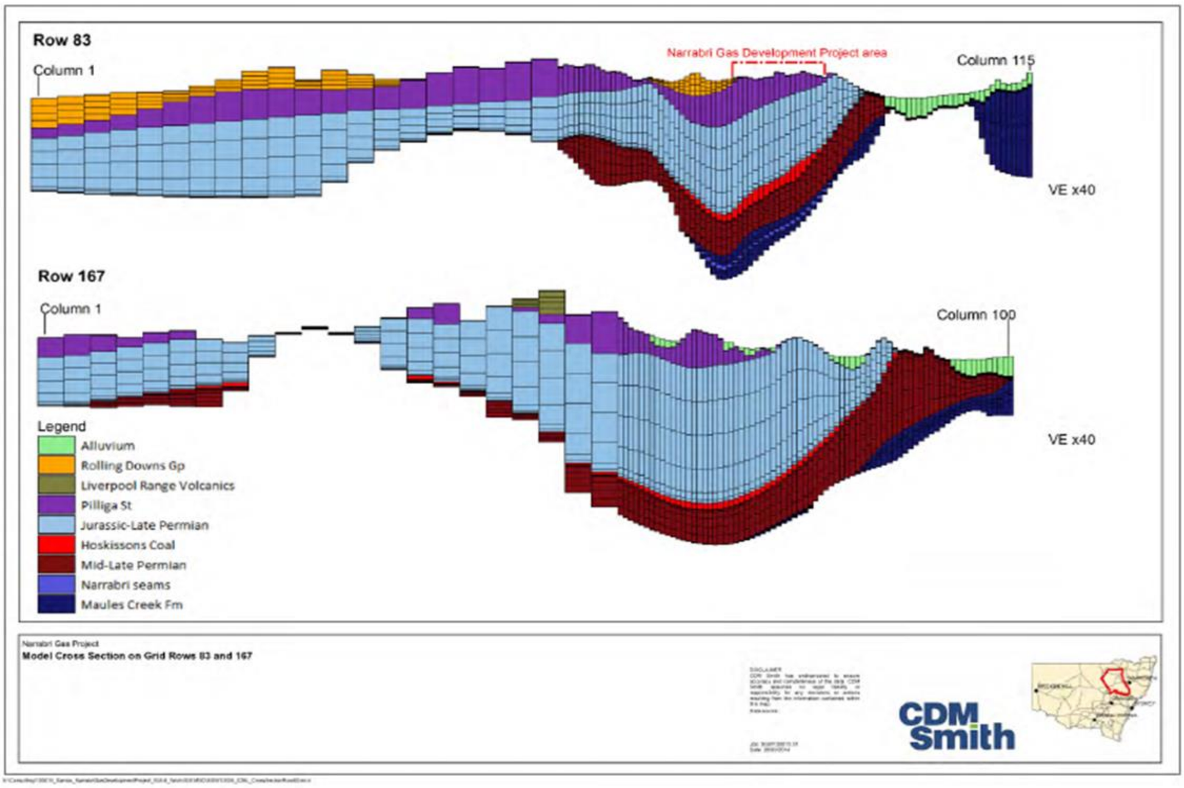
A detailed assessment of the structural geology in the Project region is outside this reviewer's area of expertise. However, the absence of faulting in the conceptual model developed for the EIS was raised as a concern by the WEP, and recent studies from the area (Iverach et al., 2020), suggest that structures, such as faults, may play a larger role in regional groundwater flow than was considered in the Groundwater Impact Assessment.

5.2 Numerical Model

Numerical models are based upon hydrogeological conceptual models (interpretation of the geology). Darcy's Law, that relates pressure gradient and groundwater flux, and the principle of mass conservation are then used to mathematically describe the flow of water through the ground. Groundwater flow between two points over time is described by the 3D transient groundwater flow equation which is a partial differential equation which is too complicated to solve analytically so methods to approximate the solution of the derivations are required. Consequently, the construction of a numerical model divides space and/or time into discrete pieces so that the governing equations of groundwater flow can be solved on a computer and generally requires the simplification or approximation of a conceptual hydrogeological model (Barnett et al., 2012).

In the simplification of the conceptual model for numerical model development, all geologic layers between target coal seams and near surface aquifers were lumped into large zones with uniform properties (figure 5.2). Based on the interpretation of laterally continuous layers of low permeability, the model parameters assigned to the zones between target coal seams and near surface aquifers had vertical hydraulic conductivity values that were at the low end of available estimates. The simplification and model parameter assignment done in the development of the numerical model effectively "lock in" the interpretation of low hydraulic connectivity between target coal seams and near surface aquifers. These aspects of the numerical model place large limitations on all further attempts to consider model predictive uncertainty.

Figure 5.2: Numerical Groundwater Model (from figure 6-11 in the EIS Groundwater Impact Assessment)



Alternative methods of model parameterization that allow for spatial variability within model zones (Doherty et al., 2011) would facilitate the consideration of localized zones of higher vertical permeability discussed in the preceding section and provide a much more robust framework for quantitative uncertainty analysis. These methods have successfully been applied in the assessment of groundwater impacts of Coal Seam Gas (CSG) development in Queensland with a thorough consideration of uncertainty (OGIA, 2019)

5.3 Model Calibration

Model calibration is a process that occurs after model design and construction, by which parameters are adjusted until model predictions fit historical measurements or observations (Barnett et al., 2012). In the context of Bayesian Inference introduced in section 4.3, calibration is the process of reducing the range of plausible models by discarding or altering models that are inconsistent with observations.

It has been shown that for calibration to provide a meaningful reduction in predictive uncertainty, the observation data must be similar in nature to the predictions of interest (Christensen et al., 2006; Watson et al., 2013; White et al., 2014). For the Groundwater Impact Assessment of the project, the predictions of interest are changes in flux, to the Alluvial and GAB aquifers due to project development. Changes in flux are difficult to measure, however, they are proportional to changes in pressure gradient. So, a calibration dataset that would reduce the uncertainty in predictions of groundwater impact would have a pumping stress similar to that of the project development and transient observations of drawdown or pressure changes.

A dataset of pumping and transient water level changes was not available for the calibration of the EIS model and the only data considered were static water table elevations in the alluvium. During calibration to static water level observations, parameters assigned to layers controlling the hydraulic connectivity between target coal seams and near surface aquifers were fixed at initial estimates. A single calibrated model was produced.

The calibration provides no information about the hydraulic connectivity between target coal seams and near surface aquifers, and the uncertainty in predictions is not reduced from initial prior estimates.

6.0 Model Predictions and Uncertainty Analysis

6.1 Santos EIS modelling

The Groundwater Impact Assessment presented in the EIS is based on model simulations using one model with parameters derived from the conceptual model review. The results indicate a nominal predicted impact from the Project on the Great Artesian Basin and Alluvial aquifers used for water supply in the region.

A statistical evaluation of alternative models or alternative parameters was not conducted as part of the Groundwater Impact Assessment with lack of observation data cited as the reason. *"Formal uncertainty analysis based on the identification of plausible combinations of the model parameters that satisfy acceptable calibration criteria has not been attempted due to the lack of suitable calibration data"* (Santos Ltd., 2017). In place of a statistical uncertainty analysis a heuristic predictive sensitivity analysis was conducted by altering model parameters by one order of magnitude and producing seven alternative predictive simulations.

The background literature review conducted as part of the Groundwater Impact Assessment found that *"The existing ranges of values for* K_v *adopted for strata of the GAB and Gunnedah-Oxley Basin vary over almost four orders of magnitude"*(Santos Ltd., 2017) which is a much larger range than considered in the uncertainty analysis. The model simplifications to create large zones of uniform parameter value restrict the consideration of a wider range of potential parameter values, and the evaluation of only 7 alternative models prevents a statistical evaluation of the likelihood of groundwater impacts.

Even with this limited evaluation of uncertainty, the predictions show a large range of impacts. Simulations that included higher vertical hydraulic conductivity and lower storage parameters predicted maximum drawdown in Great Artesian Basin Aquifers used for water supply that was an order of magnitude higher (5.7 m vs. < 0.5 m) than predicted by the parameters used in the rest of the Groundwater Impact Assessment.

6.1.1 Cumulative Effects

There is limited guidance in Australia on the appropriate way to address cumulative effects in numerical modelling applications (*Nelson*, 2016) . As part of the Groundwater Impact Assessment, two simulations were conducted to assess groundwater impact of the Narrabri Coal Mine both in isolation and combined with the Project. The simulations predicted that groundwater impacts of combined project and coal mine were dominated by impacts caused by the coal mine. All other scenarios presented in the Groundwater Impact Assessment, and CSIRO modelling discussed in the next section, considered the project in isolation. This is not a true reflection of the future impact on groundwater users in the region who will be affected by combination of projects.

6.2 CSIRO -GISERA Modelling

In the 2018 RTS document (Santos Ltd., 2018), responses to questions on model predictive uncertainty referred to a study by CSIRO that conducted a statistical uncertainty analysis on simulations of the project (Sreekanth et al., 2017).

The CSIRO study adopted the conceptual model used in the EIS Groundwater Impact Assessment. The model parameterization was similar to the Groundwater Impact Assessment model with the only extension being vertical gradation of parameter values within some of the lumped zones. Five hundred alternative parameter sets that acceptably reproduced the available near surface water level dataset were used to assess uncertainty of groundwater.

Given that the CSIRO study used the same conceptual model as the EIS and centred the range of parameter values considered close to the values adopted by the modelling in the EIS, it is unsurprising that the median predictions from this study are largely consistent with predictions from the EIS. However, the range in predicted impacts to water use aquifers is large, and predictions at the higher end of the range show impact from the Project.

Predictions of changes in flux to the Great Artesian Basin Pilliga sandstone show a maximum change of 2299 ML/yr at the 95th percentile. This prediction is approximately 8 % of the Long-Term Annual Extraction Limit from the Pilliga Sandstone of 29.68 GL/yr. Predictions of changes in flux to the Namoi Alluvium the 95th percentile predictions show a maximum change in flux of 30 ML/yr which is 0.04% of average annual extraction of 75,510 ML/year reported for the Lower Namoi alluvium (Sreekanth et al., 2017).

These results demonstrate that a statistically significant population of the simulations run in this study predict a groundwater impact that, while not catastrophic, would be of concern to current users of this groundwater resource, particularly if superimposed on a larger impact from the Narrabri Coal Mine which was not considered in this modelling and is predicted to have a larger magnitude impact.

The statement of limitations section of the CSIRO study identifies uncertainties in conceptual modelling and the presence of geologic structures not included in this assessment may influence the predictions of flux changes. The authors also identify that the hydraulic properties of layers between the Pilliga sandstone and target coal seams could be represented with approaches that consider spatial variability to better assess the uncertainty in predicted flux. The combination of these limitations and the adoption of the EIS conceptual model, based on interpretations of laterally continuous layers of low permeability, means that the results of this study will underestimate the full uncertainty in predicted impacts. The results of this study are also likely to be biased towards predicting lower groundwater impact from the project relative to a more comprehensive uncertainty analysis that included the potential for localised zones of higher vertical permeability due to heterogeneity or faulting.

7.0 Discussion

In this reviewer's professional opinion, the development of the groundwater model for the EIS Groundwater Impact Assessment is based on reasonable professional judgement and follows guidelines available at the time. The hypothesis proposed by Santos that the project development **will not** have an impact on groundwater users in the region is shown to be consistent with all available observation data and is therefore a valid one. However, the uncertainty analysis conducted for the EIS to assess alternative hypotheses was very limited in scope. The uncertainty analysis did show that predictions of impact are highly sensitive to relatively small variations in parameter values, suggesting a wide range of possible impacts.

Further uncertainty analysis conducted by the CSIRO adopted the same conceptual model as used in the EIS and did not account for the additional uncertainty due to uncertainty in the conceptual model and possibility of localised enhanced permeability from faulting.

The adopted conceptual model for both studies is based on the interpretation of laterally continuous confining layers of low vertical permeability with no localized alterations due to faulting. While this interpretation may be the simplest interpretation of available data it is also one that will lead to the lowest predictions of groundwater impact from the project relative to alternatives that consider faulting and heterogeneity. This fact contradicts statements made in the EIS and other documents that the modelling is founded on conservative assumptions.

For the previously mentioned reasons the CSIRO study likely provides an underestimate of full uncertainty in groundwater impacts due to the project. However, in spite of any limitations, the study demonstrates that a statistically significant population of alternative possible models (5-10 %) predict impacts to groundwater that are likely to be of concern for local groundwater users.

Based on this analysis, an alternative hypothesis that the project **will** have an adverse impact on groundwater users cannot be rejected as inconsistent with any observation data and is therefore also valid. This fact contradicts statements made in the EIS and other documents that the risk of adverse impacts to local groundwater users from project development is negligible.

The only way to reduce the range of possible models and potentially reject the hypothesis that the project will have adverse impacts on groundwater users is through the collection of additional observation data, and analysis.

8.0 Recommendations

The recommended conditions of consent produced by DPIE include many reasonable measures to reduce the uncertainty in groundwater impact from the project. The following recommendations are specific measures not mentioned in the conditions of consent that would improve the quantitative assessment and management of risk to groundwater users should the project proceed.

1) At present no study has fully captured the full uncertainty in the potential groundwater of the project through consideration of the potential for localized zones of higher vertical hydraulic conductivity or permeability. An extension of the CSIRO uncertainty analysis study, or any further modelling work to include a highly parameterized approach that considers lateral variability in layers between the target coal seams and water use aquifers would be a recommended first step in this direction. The modelling used for assessment of CSG impacts in Queensland (OGIA, 2019) provides an example of leading practice in this approach.
2) A dataset that will reduce the uncertainty in the predicted impacts needs to be similar to the prediction. A series of extensive pumping tests with a large network of monitoring wells would provide a calibration dataset to reduce uncertainty. This testing could be conducted soon after the installation of the monitoring network required by the conditions of consent, and ideally designed to test hydraulic connections of known faulted areas in the region. Combined with the updated model parameterization from recommendation 1, calibration constrained uncertainty analysis based on pumping test data would provide a revised analysis of groundwater impact with reduced uncertainty on a much shorter timeframe than the currently recommended three-year interval.
3) Conditions regarding the groundwater model update (B37) focus on the Australian Groundwater Modelling Guidelines (Barnett et al., 2012), class system and do not explicitly mention uncertainty analysis beyond a citation of the IESC explanatory note (Middlemis & Peeters, 2018). An explicit condition requiring quantitative uncertainty analysis at each model update is recommended.
4) Currently groundwater model conditions do not mention any requirements to evaluate cumulative effects from the project and Narrabri coal mine. It is recommended that all further modelling adopt a “null-scenario” that includes the mine and simulates both additional groundwater impact of the project and the mine. The model simulates unconfined flow, so the cumulative impact of both projects is not necessarily equal to the sum of each projects impact simulated in isolation.
5) Conditions regarding compensatory water supply (B30&31) will require a quantitative estimate of impact to water supply from changes in flux to water supply aquifers. These quantitative estimates can only be supplied by modelling as there is no way to measure this flux change. Given the uncertainty in model predictions in discussed in this document a more explicit framework for compensatory water supply that considers model prediction uncertainty is recommended.
6) At the culmination of the phase 1 pilot project there will be a larger dataset available to further reduce the uncertainty in predicted groundwater impact, and better assess project risk to groundwater users. Presently the adaptive management plan is based on observation thresholds that could be triggered well after the cause of adverse impact has already occurred. It is recommended that the adaptive management plan include measures that are based on modelled predictions and the concept of hypothesis rejection discussed in this document. For example this inclueds the hypothesis of unacceptable groundwater impacts still not being able to be rejected after the data collected during phase one is used in a calibration constrained uncertainty analysis of predicted groundwater impacts.

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10.0 Appendix A: Review of Santos Narrabri Gas Project Environmental Impact Statement

Review of
Santos Narrabri Gas Project
Environmental Impact Statement

Kevin Hayley

May, 2017

1 Executive Summary

This report is the result of independent review of the numerical groundwater modelling component of the Narrabri Gas Project (the Project) Environmental Impact Statement (EIS). Construction of the numerical groundwater model is deemed to be based on sound reasoning and consideration of background information, and is consistent with standard industry practice and relevant guidelines. There is a lack of observation data used to calibrate the model parameters with the exception of the net flux to groundwater over the Naomi Alluvium aquifer. As a result, the selected model parameters are based on expert review of background information and as such, have greater uncertainty than model parameters calibrated to observation data. The key model parameters and predictive model stresses influencing predictions of groundwater impact, have a large level of uncertainty, which results in high uncertainty in the model predictions.

The predictive uncertainty analysis presented in the EIS is deemed to be inadequate for two main reasons:

The uncertainty analysis lacks statistical rigour to be able to assess the likelihood of adverse impacts to groundwater receptors.

A conservative predictive simulation is not run or presented. A conservative simulation is one that adopts combinations of model parameter values and representation of development stress that would produce the largest impact on receptors, while maintaining parameter values that are within a plausible range given existing system understanding and observations. This is a worst-case scenario that cannot be discounted on the basis of currently available understanding and observation data.

Recommendations for further work on predictive uncertainty analysis are given in Section 12.

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

Groundwater Solutions Pty. Ltd. was retained by the NSW EDO on behalf of the North West Alliance community group to review, and provide expert professional opinion on the groundwater modelling component of the EIS for the Project submitted to the New South Wales (NSW) Government by Santos Ltd. [*Santos Ltd.*, 2017]

Specifically, Groundwater Solutions was requested to address the following questions:

In your opinion are the groundwater conceptual and numerical models, including design, construction, uncertainty, sensitivity analysis and data inputs, adequate?

In your opinion are the predictive modelling and potential groundwater impacts identified in the EIS appropriate?

Provide any further observations or opinions which you consider to be relevant, including in relation to the potential impacts of the Project on groundwater.

To address these questions, Appendix F of the EIS the Project Groundwater Impact Assessment (GIA) [*Santos Ltd.*, 2017], and Chapter 11 of the EIS were reviewed with respect to the Australian Groundwater Modelling Guidelines [*Barnett et al.*, 2012] and other relevant technical literature.

Results of the review of the groundwater modelling work completed for the Project application are discussed below, and are subdivided into the main components of a groundwater modelling project to allow evaluation of each stage of the modelling process. The questions outlined above form the basis of the discussion section.

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

4 Background

The proposed development of the Project, involves installation of up to 850 gas wells on 425 pads over an area of 950 km^2. Gas extraction wells will target coal seams at 500m to 1,200m below ground surface, and water will be pumped to depressurize the coal seam and allow for gas development. As part of the investigation into potential environmental impacts of the project, a numerical model of groundwater flow was built for Santos by hydrogeological consultants CDM Smith, in order to simulate the impact on near surface water supply aquifers that are connected to sensitive Groundwater Dependent Ecosystems.

The predictions of interest from this model are the propagation of pressure changes from the targeted coal seams in the Gunnedah-Oxley Basin, to shallow water supply aquifers including the Namoi Alluvium and Great Artesian Basin (GAB) Pilliga Sandstone.

5 Model Objectives

The stated objectives of the Project modelling component as outlined in Section 6.1 of the GIA are as follows:

- *Estimate changes in hydraulic head in the target coal seams, and water table elevations in connected hydro-stratigraphic units due to the proposed coal seam gas field development activities;*
- *In areas where drawdown is predicted, estimate the recovery time for hydraulic head to return to pre- coal seam gas development levels;*
- *Identify and quantify the potential groundwater loss or gain in each Water Sharing Plan zone due to intra and inter-formational flows; and*

- *Identify those landholders who may potentially be impacted by coal seam gas activities and quantify the predicted impacts.*

A notable amount of effort has been expended to review available data sources, conceptualize the groundwater system and develop a numerical model of groundwater flow. The model is based on a logical review of available data, reasonable simplifying assumptions, and consistent with best industry practices. The numerical model developed for the Project is deemed fit for the purpose of meeting the stated objectives.

However, in the absence of a calibration dataset that could inform predictions, or a statistically rigorous predictive uncertainty analysis, the model predictions are a qualitative expression of expert opinion consistent with the physics of groundwater flow rather than a quantification of predicted impacts.

Moreover, Pre-coal seam gas development levels in the target seams are unknown due to absence of baseline hydraulic head measurements, and any estimate of change in hydraulic head in that unit will be uncertain as a result of this data paucity.

Therefore, the achievement of modelling objectives is limited by lack of calibration and baseline data, and lack of statistical rigour in uncertainty analysis.

6 Conceptual Model

A conceptual model is a qualitative description and understanding of a groundwater flow system based on current knowledge of geology, climate, observable aspects of the hydrologic system in surface water features and wells, and expert opinion.

In a numerical groundwater modelling study, a conceptual model is used as the basis for a numerical model that can simulate the flow of groundwater through the subsurface. This section is structured to assess the main parts of the conceptual model which include hydro-stratigraphy, parameter selection, data review, and interpretation of likely groundwater flow.

6.1 Hydro-stratigraphy

A critical review of the hydro-stratigraphic conceptual model would require location specific knowledge and experience that is outside this reviewer's area of expertise, and as such, a review of the hydro-stratigraphic conceptual model is outside the scope of this review.

It is noted that only one hydro-stratigraphic conceptual model was created and alternative geometries were not considered. Hydro-stratigraphic conceptual models based on point observations from borehole data have uncertainty due to the interpretation and interpolation that must be performed between observation data locations, even with studies based on a relatively large geological dataset such as this one. Although it requires substantial additional effort, and as a result, is rarely done in practice, the consideration of alternative conceptual models is recommended by the Australian Groundwater Modelling Guidelines [*Barnett et al.*, 2012]. Uncertainty in conceptual models and the resulting numerical model geometry, is not incorporated into commonly used parameter uncertainty methods [*Doherty*, 2015], and as a result can introduce uncertainty and bias into model predictions that are difficult to quantify. Previous studies investigating the topic of conceptual model uncertainty [*Refsgaard et al.*, 2012], suggests that conceptual model uncertainty is a dominant source of predictive uncertainty in modelling projects lacking calibration data such as this one. Different geological interpretations about how the

Gunnedah-Oxley Basin sub-crops beneath the Namoi Alluvium could have a large impact on model predictions.

6.2 Hydraulic Parameters

A key parameter for the predictions of propagating pressure changes due to the depressurisation of the target coal seams, is the vertical hydraulic conductivity (K_v) of stratigraphic layers between the coal seams in the Gunnedah-Oxley Basin and the receptors in the Namoi Alluvium and GAB Pilliga Sandstone. As discussed in the GIA, K_v parameters can assume a large range of values for sedimentary rocks, up to seven orders of magnitude for sandstones, and as stated in the GIA: "*The existing ranges of values for K_v adopted for strata of the GAB and Gunnedah-Oxley Basin vary over almost four orders of magnitude from 1E-6m/d to 4E-3m/d.*" (P 5-10 of the GIA). Based on the geological interpretation of laterally continuous aquitards, CDM Smith, formed an expert opinion that the most likely value of K_v is on the low end of the existing estimates. This opinion is supported by reasonable arguments based on literature review of typical rock property values [*Bear*, 1972; *Freeze and Cherry*, 1979], and observed pressure and salinity changes between deep Gunnedah-Oxley Basin strata and shallow aquifers. However, the application of literature values for a rock type to a numerical model layer representing several hydro-stratigraphic units lumped is subject to uncertainty as discussed further in Section 8.2.

6.3 Data Review

A thorough assessment of publicly available water table data was conducted by CDM Smith to develop a conceptual model of groundwater flow. Deeper pressure measurements from drill stem tests (DST) were discounted based on observations of pressure increasing at a rate greater than hydrostatic pressure with depth. The higher-pressure observations in the DST data were used to support the qualitative interpretation that the deep groundwater system is well confined and resistant to rapid pressure propagation to overlying units including the shallow water supply aquifers. The absence of hydraulic head measurements in the deeper hydro-stratigraphic units from wells installed as part of pilot projects is a limitation of the groundwater flow system assessment. Transient observation of hydraulic head in deeper Gunnedah-Oxley Basin strata above the Bibblewindi 9-Spot Pilot location were reviewed by CDM Smith. The observed hydraulic head changes were interpreted to be not responding to the groundwater extraction during the one year time span of observation, this interpretation was also used to support of the qualitative interpretation of a confined deep groundwater system, which is reasonable for the area near the Pilot location.

6.4 Groundwater Flow System

Based on the geological interpretation and the available hydraulic data, a conceptual model of flow was formed that contains a shallow Alluvial system, the Namoi Alluvium, consisting of sands and gravels interacting with a deeper bedrock system, the GAB and Gunnedah-Oxley Basin, which consists of layered sandstones, mudstones, shales and coal seams. In regions where the permeable bedrock aquifers are in contact with the alluvial sediments, some connectivity and interaction exists between the units.

6.4.1 Faulting

CDM Smith contends that faults in the area do not contribute to groundwater flow based on seismic data leading to the interpretation that faulting is Permian to Triassic (>200 Million years) in age.

This is a reasonable assumption, and a more critical analysis would require detailed knowledge of the regional geology which is outside this reviewer's area of expertise.

6.4.2 Implications

The key implication for the predictions of impacts to the Naomi Alluvium is identified on page 5-40 of the GIA, "*Connections between the target coal seams and alluvial units will control the potential magnitudes and locations of impacts on shallow groundwater sources in the alluvium*."

The above statement also applies to predictions of impacts in the GAB Aquifers. A hydraulic connection between the target coal seams and the GAB Pilliga Sandstone or Namoi Alluvium could occur through heterogeneity (holes) in confining layers, faulting, or the connection at the interface between the Gunnedah-Oxley Basin strata and the Namoi Alluvium. If a hydraulic connection exists, the pressure changes due to coal seam gas development could propagate at a faster rate and higher magnitude, causing a larger degree of impact to the water supply aquifers.

7 Numerical Model Design and Construction

7.1 Model Code

MODFLOW-SURFACT^{TM} was selected as a modelling code for the Project due to its numerical stability when simulating unconfined conditions. The open source MODFLOW USG code [*Panday et al.*, 2013] would also have been a valid alternative. However, MODFLOW-SURFACT^{TM} is deemed to be an appropriate choice.

7.2 Model Discretization and Layers

To make predictions of groundwater impacts, a numerical model requires that a region of interest be broken up into discrete cells or elements, where the partial differential equations governing groundwater flow are solved.

The discretization interval of 1 to 5 km is appropriate for a model of this large regional scale (53,000 km^2). The simplification of the hydro-stratigraphic conceptual model into aquifers and aquitards is reasonable for the predictions of interest, and the vertical discretization of the model layers is appropriate.

7.3 Boundary conditions

Boundary conditions applied at the model lateral extents are derived from consideration of the conceptual model of groundwater flow, they are far enough from the area of simulated stress to avoid influence. The application of a river boundary condition is reasonable, and recharge outside the Namoi Alluvium is estimated based on logical assumptions of climate and geology. The net flux over the Namoi Alluvium is estimated based on an observation dataset of water table elevations discussed in Section 8.

8 Numerical Model Calibration and Sensitivity Analysis

Model calibration is a process of estimating model parameters that cause a model to best reproduce historical observations. Models with a large amount of calibration data that is similar to the predictions being made, and with a calibration time frame larger than the prediction time frame are considered to have a lower degree of extrapolation and a lower degree of predictive uncertainty

[*Barnett et al.*, 2012]. Models with limited calibration data that is similar to predictions being made are considered to have a high degree of extrapolation and higher predictive uncertainty.

8.1 Model Calibration

CDM Smith used an inverse modelling technique to estimate steady net flux into the Namoi Alluvium based on water table elevation observations. This flux is a combination of recharge, evapotranspiration, pumping, and surface water interaction not captured by the river boundary condition. As stated in the GIA, the focus of the calibration procedure was to produce an initial head distribution for the predictive modelling that was consistent with the observed water table elevations and the results of a steady state equilibrium model. All model parameters other than the net flux over the Namoi Alluvium were fixed at initial estimates.

With respect to all model parameters other than the net flux over the Namoi Alluvium, the model is uncalibrated.

No deeper hydraulic head measurements or transient observations from pilot projects were used to constrain model parameters. As a result, the parameterization of the model other than the net flux over the Namoi Alluvium is not constrained by any hydraulic observation data and will have a higher degree of uncertainty.

8.2 Adopted Hydraulic Parameters

The adopted values of hydraulic parameters used for predictive modelling are discussed in Section 6.7 of the GIA, and are based on a reasonable review of existing data, previous studies, geological interpretations and literature values. A key comment on this section concerns selection of the K_v of the aquitard layers, because these layers are the dominant controls on the connectivity between the target coal seams and the receptors in the Namoi Alluvium and GAB aquifers this parameter will control the speed and magnitude of pressure propagation from the target coal seams to the water supply aquifers. CDM Smith argues for the adoption of values that are on the low end of the existing estimates, based on literature values for clay and shale aquitards, and evidence based on pressure and groundwater salinity changes with depth. In the simplification of the hydro-stratigraphic conceptual model into numerical model layers, several distinct hydrogeological units ranging from sandstone, coal, and clay to marine shales were lumped together as an aquitard. This could lead to an underestimation of drawdown propagation to receptors if there is spatial heterogeneity in the presence, thickness and competence of the interpreted low conductivity hydro-stratigraphic units. Adopting aquitard literature values for the bulk rock property of the combined unit on a regional scale may be an underestimate of vertical conductivity. The key point is that the vertical hydraulic conductivity parameters that control the predictions of interest have a relatively high level of uncertainty.

9 Predictive Modelling

Predictive modelling is based on the simulation of historical production of water from Gunnedah-Oxley Basin coal seam gas Pilot Projects in the region and the planned Project development. As with all simulations, a level of uncertainty is associated with the future scenarios as the final actual development of the field is likely to differ from current plans in timing, location, and magnitude of pumping, due to unforeseen events and additional information gained during development.

9.1 Coal seam development simulation

Simulation of groundwater extraction in the target coal seams is conducted by extracting water from the system at a specified rate from grid cells designated as pumping wells. The specified rates are based on results of reservoir modelling simulations that account for the complexities of coal desaturation that cannot be included in a regional groundwater model, due to scale and computational difficulty. Uncertainty in coal porosity in the reservoir simulation extends into the specified rates, and has been accounted for by providing three alternative levels of water extraction: base, high and low, to represent uncertainty in water extraction rates. Additionally, the reservoir modelling will not necessarily account for leakage into the reservoir from surrounding strata which will predominantly be controlled by the permeability of the rock closest to the coal seam.

If the hydraulic conductivity of layers surrounding target coal seams is high, the application of well boundary conditions to represent coal seam desaturation may undervalue the total water extracted from the system due to under estimation of leakage into the coal seams. This will result in under-prediction of impacts at receptors. However, in the absence of a large degree of leakage into the reservoir, application of the specified rates to a groundwater model unable to simulate buffering of pressure changes by coal desaturation, may be conservative with respect to predicting impacts at receptors.

The three alternate levels of water extraction presented (base, high and low), do not account for uncertainty in leakage into the reservoir. Simulation of coal seam depressurization is a complex process that cannot be simulated in a regional groundwater model due to the high computational burden of simulating multiphase flow. The simplification of the processes required to approximate it in a groundwater model, results in subjective decisions with inherent uncertainty. Thus, the range of the three extraction rate values produced by the reservoir modelling may not span the full range of appropriate extraction rates to apply to a groundwater model to capture the uncertainty in simulating coal desaturation.

The variability and uncertainty in possible extraction rates is not included in any of the simulations investigating the effect of the Narrabri Coal Mine adjacent to the Project or parameter uncertainty, so the combined effect of higher than base case extraction and higher K_v layers or cumulative effect of the Narrabri Coal Mine is never presented.

9.2 Cumulative effects

Other projects in the region were reviewed for the potential for significant cumulative impacts. The development of Narrabri Coal Mine Stage 2 Longwall Project was identified as having the potential for cumulative impacts, other regional development projects were not considered because the effects on predictions were anticipated to be negligible.

The development of Narrabri Coal Mine Stage 2 Longwall Project was simulated in two scenarios: mine development in isolation, and mine development combined with the base extraction rate representation of the Project.

The results of the two Narrabri Coal Mine simulations were compared to infer the relative additional impact of the Project which was deemed to be small relative to the impact of the Narrabri Coal Mine. However, cumulative effects of the Narrabri Coal Mine are not considered in any of the other simulations exploring the effect of higher or lower water production for the Project or hydraulic parameter uncertainty.

10 Predictive Uncertainty Analysis

An informal qualitative predictive uncertainty analysis was conducted by CDM Smith to examine the sensitivity of predicted impacts to variations of hydraulic parameters. The K_v of hydro-stratigraphic units between the targeted coal seams and the receptors was varied by one order of magnitude. The K_v controls the rate and magnitude of upward propagation of pressure changes, higher K_v leads to faster and larger pressure propagation.

The specific storage of the conductivity of the hydro-stratigraphic units between the targeted coal seams and the receptors was varied by one order of magnitude. Specific storage controls the amount of water released from compressed storage due to pressure changes. A low storage system will allow larger magnitude pressure changes due to coal seam dewatering to propagate more quickly.

The equivalent parameter for unconfined units is specific yield, which controls how much water comes out of a unit due to decline in the water table. Groundwater extraction from low specific yield systems will cause greater drawdown at the water table than high specific yield systems.

Only one simulation considered combined effects of parameter changes (BCS-5) which used a higher K_v and lower specific storage. All predictive uncertainty simulations used the base level of water extraction and neglected cumulative effects, so, as discussed in section 9.1, the combined effect of higher than base case extraction, higher K_v and lower specific storage is not presented.

11 Discussion

11.1 Conceptual Model, Numerical Model Design and Construction

In this reviewer's professional opinion the groundwater conceptual model, numerical model design and construction are adequate for the stated modelling objectives and meet the standards outlined in the Australian Groundwater Modelling Guidelines [*Barnett et al.*, 2012] and other technical references e.g. [*Anderson and Woessner*, 1992].

11.2 Model Calibration

The calibration data used for the Project are near surface water levels which will provide some information about the regional directions of groundwater flow. However, near surface water levels will provide no constraint on the aspects of the model that control the connectivity between the targeted coal seams and shallow receptors in the Namoi Alluvium and Pilliga Sandstone. The regional direction of groundwater flow is fairly irrelevant with respect to predictions of drawdown and capture [*Leake*, 2011].Therefore, the existing hydraulic head dataset provides no constraint on predictions and the model is effectively uncalibrated.

As discussed in section 5.3.2 of the Australian Groundwater Modelling Guidelines [*Barnett et al.*, 2012], modelling without calibration is of value, and predictive uncertainty analysis can still be undertaken using the initial parameter estimates and uncertainties, although there is a lower degree of confidence in predictions. For data input to provide a meaningful reduction in predictive uncertainty it needs to be similar in nature to the predictions of interest [*Christensen et al.*, 2006; *Watson et al.*, 2013; *White et al.*, 2014]. An example of this type of dataset would be long term depressurization of the target coal seam and transient observation of drawdown in overlying layers. Thus, truly useful data for constraining predictions of impact will not be available until the project has been constructed and operating.

11.3 Uncertainty analysis

A widely adopted philosophy of science is that a theory can never be proven correct only disproven by data [*Popper*, 2005]. The existing model can be thought of as expressing the most likely outcome based on the prior understanding of the model system, however there are an infinite number of alternative models consistent with all observations and background knowledge [*Tarantola*, 2006]. The acceptance of alternative models is a guiding principal of the Australian Groundwater Modelling Guidelines [*Barnett et al.*, 2012]. The combination of this philosophy with Bayes statistical theorem [*Bayes*, 1763] forms the basis of most applied uncertainty analysis methods.

Section 1.5.5 of the Australian Groundwater Modelling Guidelines [*Barnett et al.*, 2012] states:

"The level of effort applied to uncertainty analysis is a decision that is a function of the risk being managed. A limited analysis, such as an heuristic assessment with relative rankings of prediction uncertainty, or through use of the confidence-level classification, as described in section 2.5, may be sufficient where consequences are judged to be lower. More detailed and robust analysis (e.g. those based on statistical theory) is advisable where consequences of decisions informed by model predictions are greater."

Given that the Project involves installation of substantial infrastructure, and groundwater extractions from bedrock units in areas where current extraction levels have reached, or exceeded, sustainable groundwater diversion limits (Section 2.13 of the GIA), the consequences of the decisions made by this model are deemed to be large. Considering, the model predictions are unconstrained by a calibration dataset, quantification of predictive uncertainty is the only quantitative analysis that can be performed.

In the uncertainty analysis conducted by CDM Smith, simulations to assess the sensitivity of model predictions to variations in extraction rate and model parameter values are done independently. The sensitivity simulation BC-S5 varied both vertical hydraulic conductivity and specific storage parameters. However, base case water extraction rates were used which are less than half the total volume of the high case water extraction rates, specific yield was held steady and cumulative effects from the Narrabri Coal Mine were not simulated. A conservative simulation that includes high vertical hydraulic conductivity, low storage, low specific yield, high water extraction rates, and cumulative effects from the Narrabri Coal Mine is not presented as part of this assessment.

The existing heuristic predictive uncertainty analysis is deemed to be inadequate. A discussion of alternative approaches is provided in Section 12.

11.4 Predictive Modelling

The predictive scenarios were based on the representation of coal seam gas development as specified pumping rates derived from reservoir simulations. As discussed in section 6.1 of this report, representation of coal seam gas development in a groundwater model is challenging, requires subjective simplifications and has a high degree of uncertainty. Simulations were run to assess the predicted impact of a base, high and low level of water extraction. It is this reviewer's professional opinion that the range of uncertainty in water extraction rates should be expanded to account for the absence of formation leakage in the reservoir simulation. The extraction rates should also be included as an adjustable parameter in any further uncertainty analysis

11.5 Cumulative Effects

Simulations were conducted to assess cumulative effects of the Narrabri Coal Mine, combined with the Project using the adopted model parameters and the base case extraction rates. There is limited guidance in Australia on the appropriate way to address cumulative effects in application modelling [*Nelson*, 2016]. The cumulative effects simulations demonstrate that the predicted effects in a simulation of the Narrabri Coal Mine and this Project are dominated by the effect of the Mine that is not part of this assessment. Based on this, further simulations and reported results considered the Project in isolation.

A simulation of the Project in isolation is not a true representation of the actual water extraction and subsequent impacts, and the assessment of cumulative effects did not consider the uncertainty in model parameters or water extraction volumes.

A more rigorous assessment of cumulative impacts would require that the simulation of the existing and approved Narrabri Coal Mine be adopted as a 'Null Scenario' as described in [*Barnett et al.*, 2012], all simulations addressing model parameter and extraction rate uncertainty include cumulative effects assessment, and that all discussion of simulated impacts include discussion of the combined cumulative impact as well as the additive component to the impacts from the Project.

12 Recommendations

It is recommended by this reviewer that additional effort be placed on predictive uncertainty analysis.

A formal predictive uncertainty analysis can be undertaken by assessing the uncertainty in each of the initial parameter estimates, and assigning appropriate standard deviations and bounds. Unconstrained Monte Carlo sampling of parameter values followed by predictive simulations, would allow drawdown at selected locations to be quantitatively assessed in a way that could inform a discussion about the likelihood of adverse impacts.

Alternatively, linear methods of uncertainty propagation are applicable to uncalibrated models [*Doherty*, 2015].

The processes of water level data matching used in the Project could be challenging for formal uncertainty analysis. However, this is a result of a technical choice of calibration technique and could potentially be automated with Python scripting [*Bakker*, 2014], and applied to realizations of alternative hydraulic parameter sets.

It is recommended that uncertainty in the extraction rates be included in formal uncertainty analysis.

The aquitard layers in the numerical model are representations of several distinct hydro-stratigraphic units and are likely to have significant heterogeneity laterally and vertically. It is recommended that the uncertainty analysis include spatial variability in the vertical hydraulic conductivity of the aquitard layers either on a model cell by cell basis or through pilot points [*Doherty et al.*, 2011], to capture the possibility of locally distinct zones of higher K_v. Additionally, it is recommended to increase the range of possible vertical hydraulic conductivity values beyond the one order of magnitude range in values assessed in the current analysis and based on the discussion presented in Section 6.2 and 8.2 of this report.

An ideal analysis of predictive uncertainty would consider alternative conceptual models and numerical model geometries, particularly with respect to the connection between the Gunnedah-Oxley Basin and Namoi Alluvium. However, it is recognised that consideration of alternative conceptual models represents a large degree of effort and is not common industry practice. In this case, alternative conceptual models should be considered if they lead to orientations of layers representing permeable sediments in contact with target coal seams, such as the Black Jack Group, that sub crop under the Namoi Alluvium in a way that causes a larger hydraulic connection than the current model but cannot be ruled out by the existing geological dataset. However, the consideration of spatially variable aquitards discussed above will serve as a surrogate for alternative conceptual models.

It is recommended that a conservative simulation be run consisting of high vertical hydraulic conductivity, low specific storage, low specific yield, and high water use case.

Finally, as discussed in Section 11.5, it is recommended that the base model, conservative model, and uncertainty analysis be run on representation of the Narrabri Coal Mine alone and the combined simulation of the Project and the Narrabri Coal Mine, and that all discussion of impacts and uncertainty include both the predicted cumulative impact and the component of that impact caused by the Project obtained by differencing simulation results.

On this basis of this type of uncertainty analysis, an informed risk-based decision about the potential impacts of the Project can be made, by considering a most likely outcome (the current model), a high impact case that is less likely but cannot be discounted on the basis of the current observation dataset, and a histogram of predictions from formal uncertainty analysis that could provide a measure of the likelihood of higher impact results.

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11.0 Appendix B: Review of Santos Narrabri Gas Project Environmental Impact Statement Response to Submissions

Groundwater Solutions

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

Kevin Hayley

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^{TM} 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^{TM} 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' 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).

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