Groundwater Solutions

Review of Santos Narrabri Gas Project Environmental Impact Statement

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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™ 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™ 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.

13 References

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