CARMICHAEL COAL PROJECT
GROUNDWATER FLOW MODEL
INDEPENDENT REVIEW
(RE: APPROVAL CONDITIONS 22 & 23)

Prepared for	**Adani Mining Pty Ltd**	28 November 2014

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1. Overview

This report summarises the outcomes of an independent peer review by Hugh Middlemis of the Carmichael Coal Project numerical groundwater flow model developed by GHD for Adani Mining, consistent with the requirements of the Commonwealth approval Conditions 22 and 23 (EPBC 2010/5736).

Condition 22 requires the approval holder (Adani) to undertake an independent peer review of the adequacy of the groundwater flow model to characterise groundwater impacts, with consideration of the parameters used into the groundwater flow model, the required additional modelling information and the model re-runs outlined in Condition 23. The peer review must be undertaken by a suitably qualified independent expert, approved by the Minister in writing.

For the record, the reviewer (Hugh Middlemis) meets these requirements: he is an independent groundwater modelling specialist with more than 25 years' experience in this field. He is principal author of the MDBA groundwater modelling guidelines (Middlemis et al, 2001) and was awarded a Churchill Fellowship in 2004 to benchmark groundwater modelling against international best practice.

Condition 23 requires the approval holder (Adani) to re-run the model, with the model revisions and re-runs to incorporate the following parameters in the scenarios and address additional information requirements:

- (a) Re-define the current General Head Boundary (GHB) arrangement, as agreed by the Department in writing including the following:
    - (i) remove the GHB from its current location in all layers to the western edge of the model domain
    - (ii) review and justify the GHB conductance values used in the model to reflect the differences between aquifers and aquitards and also between aquifers (e.g. Clematis and Colinlea Sandstones), and modify if required;
    - (iii) GHB cell elevations to be re-set using data as agreed by the Department in writing
    - (iv) report on the impacts on groundwater levels and net flows between the model domain for the revised GHB boundaries and compare with previous modelling results.
- (b) Review and justify the recharge parameters for the Clematis Sandstone to represent the flux into the recharge beds of the Great Artesian Basin, and modify if required;
- (c) Document outflow mechanisms used in the model for the Doongmabulla Springs Complex and individual model layers, using maps to show the spatial distribution of model discharges
- (d) Document and incorporate known licensed groundwater extractions within the model domain
- (e) Document and justify any other changes made as part of the model re-runs that are not outlined above
- (f) As per the IESC information guidelines provide an assessment of the quality of, and risks and uncertainty inherent in, the data used in the background data and modelling, particularly with respect to predicted potential scenarios
- (g) Provide adequate data (spatially and geographically representative) to justify the conceptualisation of topographically driven flow from south to north (and west to east) in both shallow and deep aquifers.

The review was conducted by Hugh Middlemis in accordance with the principles of the Australian Groundwater Modelling Guidelines issued by the National Water Commission (NWC) in June 2012 (Barnett et al., 2012), as well as the Murray Darling Basin Commission Groundwater Flow Modelling Guideline (Middlemis et al, 2001), which was the foundation for the 2012 guidelines. The 2012 guideline suggests a compliance checklist suitable for high-level appraisals, which can also be used to summarise the outcomes of a review. The completed summary checklist is presented at Table 1, and justifications for the opinions indicated are summarised in the comments field, with key elements explored/detailed further in later sections.

The review process did not identify any material weaknesses in the model design, boundary conditions, parameter values or calibration performance. The exploration of model uncertainty in conceptual and parameter value terms is commendable and the results indicate low sensitivity/uncertainty. It is my professional opinion that the model revisions have been undertaken competently, consistent with condition 23, and the revised model design and performance is consistent with guidelines and suitable as is for impact assessment purposes, with future model refinements dependent on monitoring to obtain data for validation.

Table 1 – Groundwater Model Compliance Checklist: 10-point essential summary

Question	Yes/No	Comments re Carmichael Coal project groundwater model
1. Are the model objectives and model confidence level classification clearly stated?	Yes	Not crystal clear in 2012 & 2013 GHD reports. Nov 2014 report provides a clear statement of class 2 confidence level. Summary of objectives: • the investigations aim to describe the existing environmental values of groundwater resources using pre-existing published data and information collected from site specific field investigations; • the potential impacts of the proposed development on groundwater resources will be assessed, mitigation/management options identified, along with ongoing groundwater monitoring requirements, through development and application of a medium complexity (class 2) groundwater flow model. Further detailed discussion on this topic is given in Section 4 below.
2. Are the objectives satisfied?	Yes	The model design and results satisfy the objectives and are described adequately in the reports. The 2014 model revisions invoke an alternative model conceptualisation, with much greater outflow towards the GAB (west). This essentially forms a best practice method to address model uncertainty. The predicted impacts are only marginally different from the EIS & SEIS work that achieved conditional approval, and combined with the comprehensive parameter sensitivity analysis that has been undertaken, indicate overall low model uncertainty.
3. Is the conceptual model consistent with objectives and confidence level classification?	Yes	The conceptualisation is described in basic terms in the 2012/13 reports, consistent with the study objectives; the 2014 report is much improved in detailing the conceptual model and confidence level. The 2014 model revision results show low sensitivity to whichever conceptualisation is applied, indicating low uncertainty and confirming the class 2 model confidence.
4. Is the conceptual model based on all available data, presented clearly and reviewed by an appropriate reviewer?	Yes	A multi-disciplinary team from GHD has been involved in the hydrogeological data analysis and review, in consultation with DNRM hydrogeologists on key elements (mostly hydrogeological structure & parameter values). Additional data was obtained to inform the 2014 western boundary revisions, and the model layer structure, properties and boundary conditions have been reviewed (with inputs from DNRM staff). Good presentation of conceptual model in 2014 report (e.g. Figure 2 herein).
5. Does the model design conform to best practice?	Yes	The model design, software, extent, layers, cell size, boundaries and parameters described in detail in various reports are consistent with best practice. In fact, the investigation of an alternative conceptualisation to address the condition 23 model revisions is not common practice and should be considered a leading practice method of addressing the key area of conceptual model uncertainty.
6. Is the model calibration satisfactory?	Yes	Steady state calibration performance is good in statistical and spatial pattern terms, consistent with guidelines. Transient calibration has not been undertaken, which is a model weakness that has been addressed via comprehensive sensitivity and uncertainty analysis. The calibration performance measures for the model as a whole were not materially affected by the revised western boundary condition, although the three bores in the southern Clematis outcrop area showed much worse matches to measurements. To improve the match would require increased recharge in this key area, and/or aquifer parameter changes, plus contemporaneous groundwater monitoring data for model validation, which is recommended for future investigation.
7. Are the calibrated parameter values and estimated fluxes plausible?	Yes	An appropriate level of complexity in parameter distributions has been applied to achieve overall good calibration performance. The parameter values and fluxes are plausible and consistent with site-specific testing and literature values, and have been reviewed by DNRM hydrogeologists. Head-dependent flow boundary (“GHB”) conductance (“C”) values were changed from the uniform 1000m^2/day value adopted in EIS/SEIS models to a spatially variable value based on calibrated parameters in each layer. This resulted in many orders of magnitude changes to C values, and yet model results indicated very little sensitivity (e.g. 5% change to water balance terms). Calibration considers measured data on groundwater levels, as well as fluxes including bore extractions (low volumes) and measured stream flow (baseflow) volumes (high volumes). Recharge rate sensitivity testing is appropriate.
8. Do the model predictions conform to best practice?	Yes	The model has been interrogated to give outputs relevant to the assessment of the objectives (impacts). The graphical presentations are generally very well executed.
9. Is the uncertainty associated with the predictions reported?	Yes	A substantial effort has been applied to analyse parameter sensitivity and evaluate the uncertainty of model predictions, and the presentation of the results is commendable in its execution. It is worth re-stating that the alternative concept approach applied to address the condition 23 revisions (invoking maximum western outflow to the GAB) is an effective best practice method to address structural model uncertainty. The predicted impacts are only marginally different from the EIS & SEIS work that achieved conditional approval, and thus indicate low uncertainty.
10. Is the model fit for purpose?	Yes	My professional opinion is that the model has been developed/revised competently and appropriately for the stated project/study objectives, consistent with condition 23.

2. Review Approach and Key Information Sources

The review was conducted in accordance with the principles of the Australian Groundwater Modelling Guidelines issued by the National Water Commission (NWC) in June 2012 (Barnett et al., 2012), as well as the Murray Darling Basin Commission Groundwater Flow Modelling Guideline (Middlemis et al, 2001), which was the foundation for the 2012 guidelines.

Appendix A presents a detailed compliance assessment using the 2012 guideline model review checklists, and Table 1 above presents a summary of those investigations (i.e. application of Table 9-1 from the 2012 guidelines). The review report sections below explore some key issues in detail.

The review was undertaken in a progressive manner from August to November 2014, with regular telephone meetings and email correspondence with the GHD modelling team and Adani staff regarding model refinements and results. Telephone and email discussions were also held with:

- Peter Baker (Principal Science Advisor, Office of Water Science, Commonwealth Department of the Environment (DotE)
- Ashley Bleakley and Adrian McKay, project officers with the Queensland Department of Natural Resources and Mines (DNRM).

Face-to-face review meetings were held in Brisbane over 5-6 November 2014 with GHD, Adani and DNRM staff. A brief audit investigation was undertaken of the model data files at GHD's Brisbane office on 5 November 2014, with James Dowdeswell (GHD) navigating through various data files on the model setup, inputs and results to answer questions raised by the reviewer.

A range of previous reports and related documents were provided by Adani in August for consideration by the reviewer (see references list herein). Interim technical information on the model revision, setup and results were provided by GHD throughout the review period, and was eventually compiled into the technical report by GHD to formally address Condition 23:

- GHD (2014). Carmichael Coal Project, Response to Federal Approval Conditions, Groundwater Flow Model, Prepared for Adani Mining Pty Ltd, November 2014.

A detailed review was completed, but it was not possible to evaluate comprehensively the entire range of hydrogeological data nor every element of the gigabytes of model data files. While this review does not consider or address all uncertainties and risks, it aims to investigate any weaknesses relating to the model design and implementation, based on application of the review protocols in modelling guidelines.

3. Impact Assessment Modelling Approach

The following points summarise the model design, calibration, sensitivity testing and prediction approach undertaken, which this review finds provides a sound basis for impact assessment:

3.1. **conceptual model** summarised in Figure 1 (after GHD, 2014) – see next page

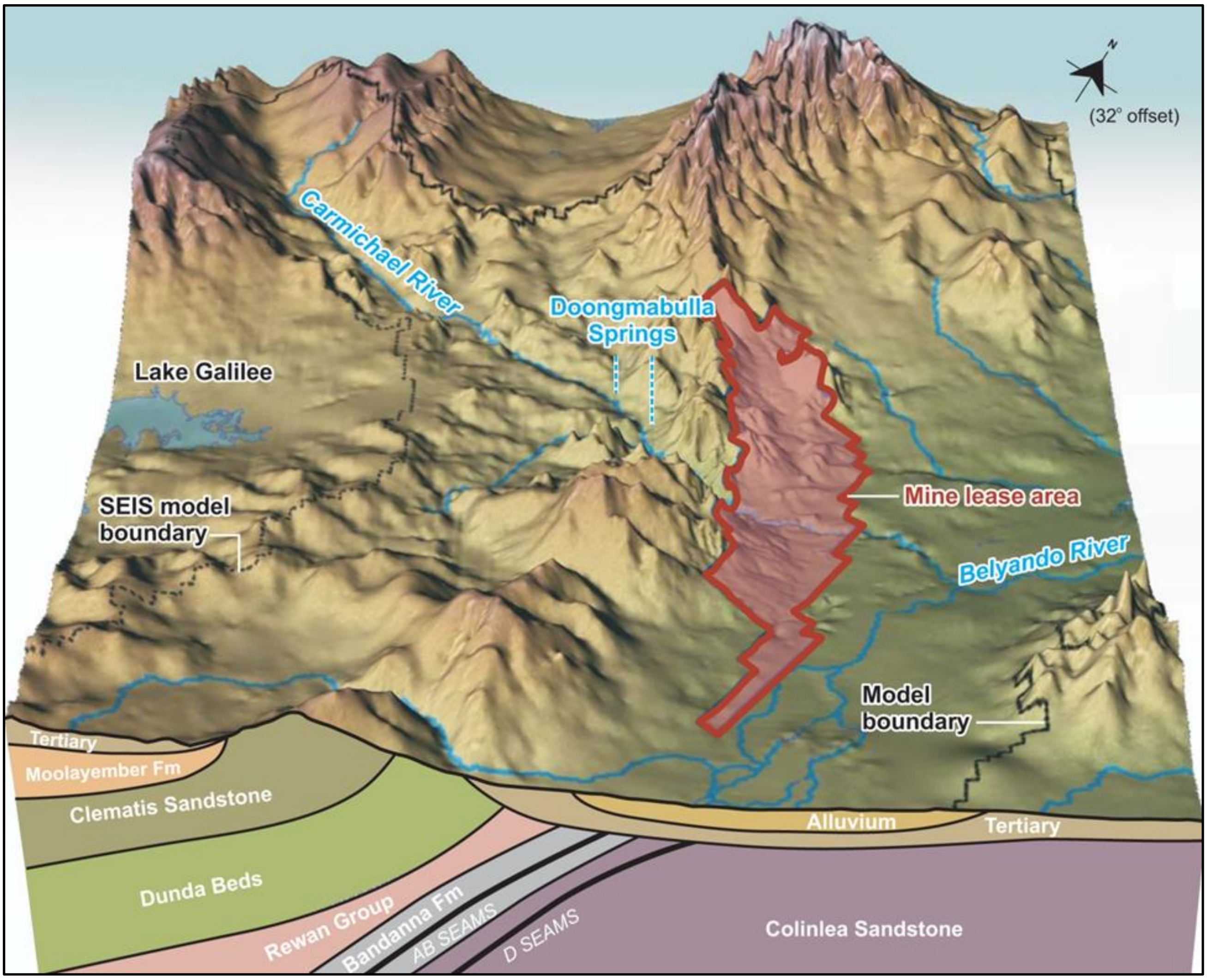
3.2. **93 x 108 km model extent** with maximum cell size of 1000 m provides adequate regional extent (boundaries remote from mine area, allows for interconnection with GAB); minimum cell size of 50 m provides adequate detail internally where needed (e.g. mine area, Carmichael River and springs);

3.3. **12-layer regional model** with model layer elevations based on geological structure/mapping, validated against drill logs, notably including QPED (deep oil/gas well) data in Lake Galilee area;

3.4. **Rewan Group** (key aquitard) represented with two layers (6 & 7) to help resolve failure zone parameters above underground mine areas, and also to help resolve hydraulic effects of thick aquitard; a wide range of parameter values were applied to sensitivity testing, which helps address questions re faulting/fracturing in the Rewan; DNRM recommend (and I concur) need for split of basal layer 12 into two layers in future model updates, as discussed further in section 5 below;

3.5. **modelling software is Modflow-Surfact** (industry-leading and suitable); model comprises more than 4 million cells, of which more than 3 million are active (flow) cells; this is more than 3 times larger than what the industry regards as a large model of 1 million cells; long run times result for transient simulations but not in itself unmanageable;

Figure 1 - Carmichael Coal conceptual groundwater model (after GHD, 2014)



3.6. **long term monitoring bore data** shows generally low temporal variability (except close to river) justifying use of averages for model calibration targets; some data points are historical (e.g. from when the bore was drilled); current access and other constraints can limit the ability to obtain new measurements; ongoing monitoring plans appear to be designed to obtain contemporary data to validate historical measurements and thus the model (in due course);

3.7. **steady state calibration to pre-mining conditions** and long term average groundwater level data establishes a sound baseline for impact assessment; calibration performance is consistent with guidelines, related scatter plots and water balance criteria are acceptable; calibration considers groundwater heads as well as stream-spring-aquifer interaction volumes;

3.8. **transient prediction simulations of mine dewatering** use parameter variations to account for the failure zone above underground mining areas; these are applied in a conservative way, including the SEIS model refinement of splitting the Rewan Group into two layers to improve parameter resolution for these effects; the model stress period arrangement indicates annual increments for the first five years, which is acceptable; however, subsequent stress periods are 5-yearly to 2049, then 10-yearly to 2059, which is possibly a little coarse but not unreasonable; future modelling programs should review and/or refine this arrangement

3.9. **steady state post-mining prediction runs** conservatively over-estimate the long term project impacts compared to steady state pre-mining (“null scenario” in terms of the 2012 guideline);

3.10. **lack of transient calibration is a model weakness** that is addressed via comprehensive sensitivity analysis; for example, variations to GHB conductance values (orders of magnitude) confirms low sensitivity/uncertainty; transient prediction runs essentially provide detailed information on the development of dewatering impacts during the mining period, while the comparison of steady state pre-mining and post-mining impacts provide a conservative long term impact assessment;

3.11. **condition 23 model revisions involved major changes to the western boundary** to investigate the effect of maximising outflows to the GAB; this is an alternative conceptualisation method that addresses model uncertainty; results show little sensitivity in terms of calibration performance and predicted impacts; **the revised 2014 model confirms that there is topographically-driven flow from south to north (towards the Carmichael River and the springs) whether or not there are significant flow components towards the west** (towards the GAB); future model work programs are recommended to investigate refinements of the recharge to improve the match to southern Clematis water levels and to investigate the flow system in the Lake Galilee area; this is discussed further in various sections below

3.12. **post-closure model scenarios** included evaporation from residual open pit void lakes; the steady state prediction (conservative over-estimate) of long term post-closure impacts indicated up to 0.13 m drawdown at Doongmabulla Springs and up to 1 ML/d reduced baseflow to the Carmichael River; further data from operational mining and regional monitoring will allow the review and further refinement of the parameters applied to these simulations (e.g. evaporation rate assumptions and sensitivities, waste infill configurations).

4. Model Conceptualisation and Complexity

4.1 Model Review Issues and Guideline Criteria

Condition 23 required the approval holder (Adani) to undertake model revisions and re-runs, notably regarding the western boundary condition, and also the "conceptualisation of topographically driven flow from south to north (and west to east)", along with review and justification of a range of parameters and recharge values. Condition 22 required Adani to undertake an independent peer review to consider "the parameters used in the groundwater flow model, the required additional modelling information and the model re-runs outlined in Condition 23".

Appendix A presents the detailed review findings from the application of the 2012 model guidelines criteria assessment ("review checklist"). Section 4 (below) provides some detailed commentary on key issues identified during application of the review criteria, notably around conceptualisation, complexity and model design issues. Section 5 (later) provides review commentary on model parameters, sensitivities and uncertainties, as well as on the recharge values.

The conceptualisation of the Carmichael model is acceptable. While there are some issues of model design and/or performance that are worthy of discussion (explored in sub-sections below), they are not material to the model performance as a sound impact assessment prediction tool:

- western boundary condition and outflow to the Great Artesian Basin (GAB)
- topographically-driven flow components from south to north
- inactive cells in layers 4 and above, in central zone west of mine and east of Clematis outcrop
- the guideline issue of model complexity and confidence level classification.

4.2 Western Boundary Conditions and Topographically Driven Flow from South to North

The EIS & SEIS models (GHD 2012, 2103) were set up with the western boundary roughly aligned with the nominal groundwater divide (and topographic divide) between the Carmichael River/Doongmabulla Springs in the central model area and Lake Galilee to the west (the dashed line shown on Figure 1). The western model boundary is designed as a head-dependent flow ("GHB") boundary with cells that would nominally allow for inflow or outflow and a relatively high conductance parameter of 1000 m^2/day that should not constrain boundary flows. However, contour plots of groundwater levels presented in the EIS/SEIS reports are clearly orthogonal to the western boundary in the central-southern area (apart from some minor/local areas indicating outflow). Hence, this western boundary was effectively working as a no flow boundary in the central and southern parts, with clearly limited potential to represent credible volumes of outflow to the Great Artesian Basin (GAB), as accepted wisdom believes is occurring. This is presumed to have initiated commentary to that effect in certain advice statements (e.g. OWS, 2014), and eventually to condition 23.

In the north-west corner, inflow is apparent from the central topographically high areas (see also Figure 1), which then largely short-circuits to outflow to the north-western boundary. It is not completely clear whether this is an accurate reflection of the flow system in this local area (data is sparse), but these conditions do not have a major effect on the gradients or levels in the main central-western part of the model. As implemented, they largely represent a local to semi-regional scale flow system that has little bearing on the main flow system under consideration and the predicted impacts (which do not extend far beyond the mine lease areas in the northern half of the model, but do extend further in the central-south areas). It is interesting to note that the opportunity was taken during the recent model revisions (to meet condition 23) to remove some GHB cells in this north-western corner, which had little effect on model performance. Further consideration of boundary conditions in this north-west corner is not warranted in this review.

Condition 23(a)(i) required the relocation of the western GHB to the western edge of the model domain (from the previous EIS/SEIS model alignment with the topographic divide east of Lake Galilee – see dashed line in Figure 1), along with review and revision of the GHB conductance parameter and cell elevations. This essentially forms an alternative conceptualisation approach that substantially helps to address uncertainty (i.e. consistent with best practice: Barnett et al, 2012; section 3.4).

The model revision involved testing alternative model designs to maximise western outflow towards the GAB, which is a major change from the mainly easterly flow model conceptualisation adopted for the ESI/SEIS. The model revisions were designed and implemented in a competent manner as summarised in the review comments below, and with written Departmental approval consistent with condition 23(a).

Condition 23(a)(ii) required review of GHB conductance values applied to the revised model boundaries. The conductance values are now orders of magnitude lower in the revised model, calculated based on the hydraulic conductance values in each respective layer (whereas a uniform (and not unreasonable) value of 1000 m^2/day was applied to the EIS/SEIS models). The result is that the range of conductance values applied have now been varied through several orders of magnitude, and yet the effect on the model water balance is about 5%, indicating very low sensitivity (whichever level is applied to the western boundary).

Condition 23(a)(iii) required consultation with the Department to establish GHB levels. The minimum level assigned to the western GHB cells for the Clematis Sandstone (layer 4) ranged from about 272 mAHD (for the option 1 (“275m”) setup) to about 247 mAHD (for the option 2 (“250m”) setup) – see Table 6 and Figures 12-24 in GHD, 2014. The option 1 setup is more representative of the measurements of generally shallow water tables in the Lake Galilee area on the (new) western boundary. The option 2 setup is more representative of maximum western outflow towards the GAB. Together, these options explore a wide range of potential uncertainty in the groundwater flow system in this western area.

Condition 23(a)(iv) required commentary on the results from the revised model, which is provided in GHD (2014). The option 1 setup resulted in about 13 ML/d outflow from the Clematis Sandstone, increasing to about 23 ML/d for the option 2 setup (see Table 10 in GHD, 2014). The total boundary outflow volumes of about 77 ML/d for the revised models are not quite double the total outflows of about 41 ML/d in the SEIS model, confirming the major change invoked by the re-conceptualisation of the western boundary.

The model revisions did not result in significant variation to the overall model calibration performance measures, which remain acceptable and consistent with guidelines. However, the revised modelled levels were much lower than the measurements at the three key bores in the southern Clematis outcrop area (RN69443 [drilled 1986], RN16897 [drilled 1966] and RN90261 [drilled 1992]; contemporaneous groundwater levels are not available for these bores due to access issues). The calibrated groundwater level contour plans (and these key bore locations) are shown in Figures 31 and 32 of GHD, 2014.

To improve the model matches at these three key Clematis bores would require increased boundary inflows from the south (i.e. consistent with the Galilee Basin groundwater flow system summarised in Bleakley, 2013; and Hydrosimulations, 2014), and/or increased rates of modelled Clematis recharge (i.e. as suggested by condition 23(b)), and/or aquifer parameter changes. Given the otherwise acceptable model performance for the purpose of impact and uncertainty assessment, it is suggested that this is a task that should be undertaken during future investigations, using the latest groundwater monitoring data for model validation.

Despite the poor match to the three southern Clematis bore levels, there was an essentially unchanged good match at the HD02 monitoring bore further north (drilled in 2012 by Adani, and sited adjacent to the most easterly spring in the Doongmabulla complex). This helps confirm that the model conceptualisation and performance in this Carmichael River and spring complex area is not sensitive to the major western boundary condition changes (i.e. helps address condition 23(c) on spring features).

The major changes to the western boundary condition for the revised model (and the lack of changes to recharge needed to compensate) was the main reason that the revised modelled levels are low in the southern Clematis area. However, there is still a significant component/gradient of flow from south to north (towards the Carmichael River and the Doongmabulla spring complex) and a good match at the spring complex monitoring bore HD02. There is also a significant component of flow to the west in the revised model, and yet the model calibration performance as a whole is consistent with guidelines. Most importantly, the model revisions clearly establish boundary conditions and parameters that do not limit the potential for credible volumes of discharge to the GAB (consistent with the available information on groundwater levels in the Lake Galilee area) and/or with the river and spring complexes, which soundly addresses the spirit of condition 23 as well as the specifics.

The revised model predictions of GAB flow capture amount to what I regard as relatively small volumes of around 50 ML/year, which is offset by a factor of more than 10 times in terms of the Adani commitment for GAB bore capping of 766 ML. The method of estimating GAB flow capture applied to the revised model (zone budget water balance analysis – see Section 3.3 of GHD, 2014) is best practice and is more appropriate than that applied to the EIS/SEIS models (which relied upon flow contributions to the mine via leakage through the Rewan Group and are thus a not a direct estimate of GAB flow capture and over-estimate the capture volumes).

The hydrological capture results in terms of river baseflow and spring drawdown are only marginally different from those predicted by the EIS/SEIS models, and the drawdown extent and magnitude is also not significantly different. GHD (2014) Figures 34-45 and 53-60, and Table 16 present detailed results on the variations in river interaction volumes (addressing conditions 23(a)(iv) and 23(c) in detail), as well as boundary flows (see Figures 34-45 showing outflows/inflows per layer, and Table 15 of GHD 2014).

A very wide range of sensitivity and uncertainty analyses have been undertaken and evaluated by GHD in a best practice sensitivity-uncertainty approach, including consideration of boundary condition parameters, Rewan parameters and recharge rates (see Section 5).

The revised model results confirm that the calibration and prediction performance is largely not sensitive to boundary conditions that maximise (deep) outflows to the GAB, or (shallow) outflow to the Lake Galilee area. This approach effectively addresses hydrogeological and data uncertainties in this western area and in relation to potential impacts on GAB flows in the context of a class 2 impact assessment model. The various alternative conceptualisations of the Carmichael model confirm that there is groundwater flow from south to north whether or not there are significant flow components towards the west and the GAB, and provide evidence of variations in flows/pressures with depth (in terms of measurements and revised model results).

Ongoing investigations and monitoring in this area are required to provide data for future validation of the model in terms of layer elevations and properties for aquifers/aquitards (including geochemistry and isotopes), groundwater levels and quality and surface-groundwater interactions (notably river and spring flows/levels and geochemistry). It is expected that much of this data will be provided by the Groundwater Management and Monitoring Plan (GMMP), and the Rewan Formation Connectivity Research Plan, as well as from other initiatives in progress by others, notably the Bioregional Assessment.

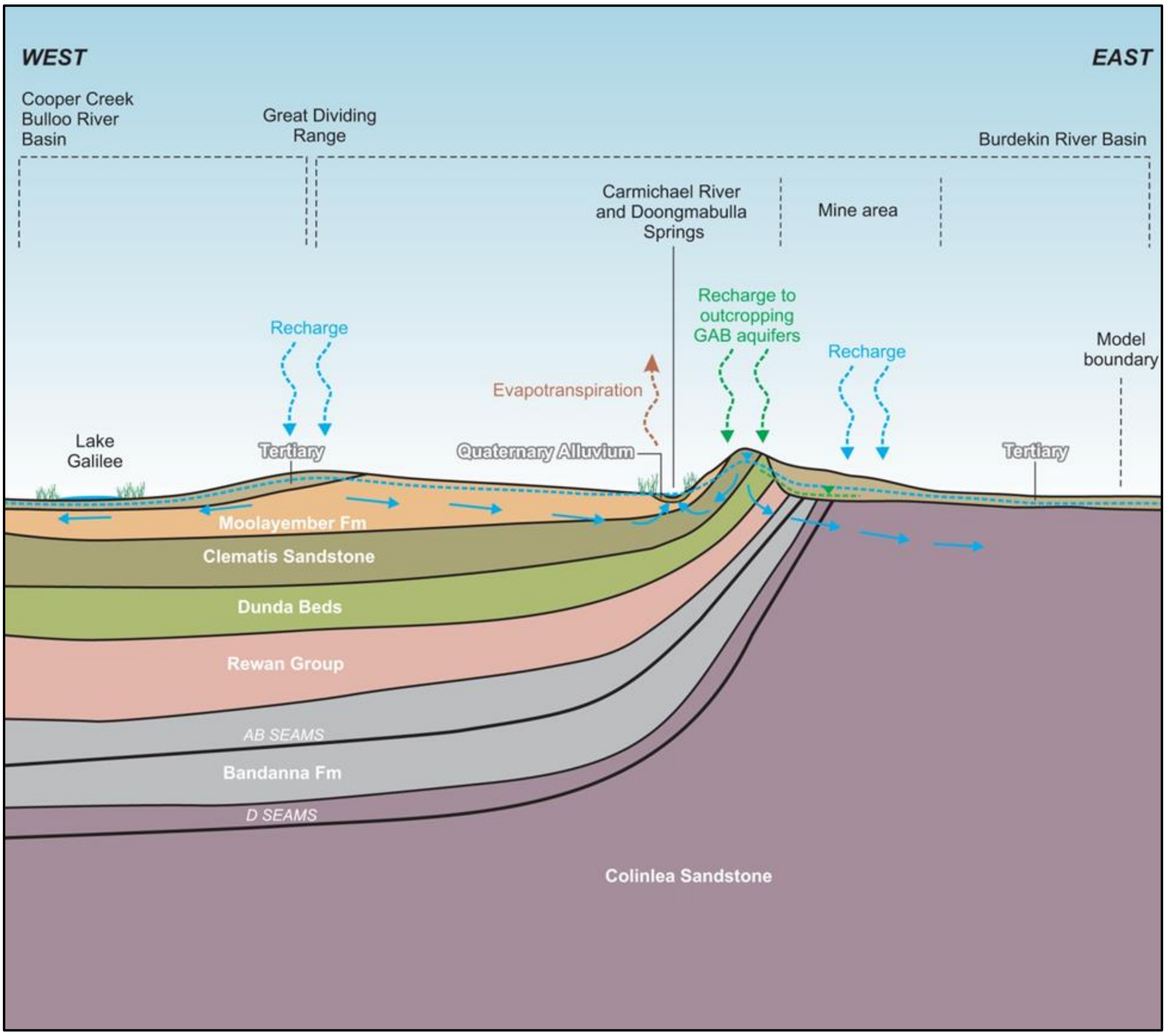
4.3 Inactive Cells East of Clematis Outcrop

During the review and the brief audit of model data files, the area of inactive (“no-flow”) cells immediately east of the Clematis outcrop (and west of the mine) was investigated. These appear as grey shading in Figures 31 and 32 of the revised model report (GHD, 2014) and occur in layer 4 (Clematis) and above. All these cells are in topographically high areas with deep water tables (see Figure 1 and also Figure 2), and also in areas where the Clematis is known from drilling/mapping to not exist (see also Figure 3 of GHD, 2014 for delineation of Clematis outcrop areas). However, the inactive cells have not been designed with the “dummy layer/parameter” treatment as was applied (appropriately) to the eastern extensions of layers 3-7 to represent the Tertiary units that overly the Colinlea Sandstone.

The specification of inactive model cells in this central area appears on the face of it to be a potentially restrictive boundary condition, and the reason for their presence has not been explained cogently by GHD. However, detailed review of model results identified that that these inactive cells are surrounded by unsaturated cells in these shallow layers. This means that, even if they were specified as active cells, they would likely also be unsaturated under pre-mining conditions.

While I find that this is an example of inelegant model design, it is unlikely to have a material effect on model performance in this case (due to the surrounding unsaturated cell distribution). A better design would be to set them as active cells and allow the Surfact software to determine whether they would be unsaturated, as is the case for the cells immediately surrounding them. It is recommended that the model sensitivity to this boundary condition be tested in the next model update by applying the "dummy layer/parameter" treatment to the currently inactive cells in layers 4 and above in this central area.

Figure 2 – Carmichael conceptual model west-east section (after GHD, 2014)



4.4 Discussion on Guideline Issues of Model Complexity

The overall modelling approach applied is reasonable for the mining project impact assessment purpose, despite some issues in relation to definitive compliance with some groundwater modelling guideline requirements (Barnett et al, 2012), notably on the "target model confidence classification" (or model complexity), the steady state calibration and subsequent transient model prediction approach, and the scale of pumping ("stress") volumes.

There is no specific statement in the model reports (GHD, 2012, 2013) on the "model confidence level classification" consistent with the groundwater modelling guidelines (Barnett et al, 2012, section 2.5). However, the project and model objectives context can be clearly understood with those reports referencing the 'significant project' (SDPWO Act) and 'controlled action' (EPBC Act) classifications. There is a clear statement on the hydrogeological study purpose to use a combination of data analysis and modelling to address the groundwater-related Terms of Reference for the Project EIS issued by the Coordinator-General (notably Section 3.4 Water Resources), and specifically to:

- describe the existing environmental values of groundwater resources using pre-existing published data and information collected from site specific field investigations
- assess the potential impacts of the proposed development on groundwater resources
- identify mitigation and management options and ongoing groundwater monitoring requirements.

This indicates that the impact assessment and mitigation measures, along with related environmental management plans, would be developed utilising results from a numerical model. This would require a model confidence level 2 classification in terms of the 2012 guideline (or medium complexity in terms of the 2001 guideline; Middlemis et al, 2001), as would typically be expected for a project of this type. While I feel it was unwise to not present succinct statements on model complexity in the previous model reports (GHD 2012, 2013), the omission is a minor report documentation issue rather than a fundamental model performance issue. The issue has been addressed in the latest report (GHD, 2014) that documents the model revisions to comply with Condition 23. It contains a clear statement on the confidence level as class 2, which is appropriate.

The following consideration of certain specifics may be helpful in addressing potential misunderstandings arising from a simple interpretation of certain guideline issues relating to the model confidence level classification. The issues in question are the steady state calibration and subsequent transient prediction approach, and the low levels of pumping stress applying to the calibration compared to the high levels for the prediction simulations. These attributes are blandly suggested by the 2012 guidelines as nominally indicating low confidence, while providing little other practical guidance and several paradoxical comments. However, this review finds that a class 2 (medium) confidence level is justified in this case, noting that:

- The Carmichael model is calibrated in steady state only, to current bore extraction stresses (0.2 ML/day, or 73 ML/year total, for 6 irrigation bores and 19 stock & domestic bores). River-aquifer interaction stresses are also considered, with measured data sourced from two stream gauging stations established on the Carmichael River in 2011. This short term data record quantifies the baseflow contributions from the aquifer to the Carmichael River, including discharges via Doongmabulla Springs, of around 4 ML/day. These gauging stations also indicate around 0.5 ML/d measured losses from the river to the aquifer for a certain reach downstream of the spring zone. The model is benchmarked to these volumes.
- The transient model prediction runs include the current bore extractions and predict mine inflow volumes generally in the range of 5 to 15 ML/day (with short term peaks up to 25 ML/day), as well as stream depletion impacts due to the mine in the order of 1 ML/day. Clearly, the scale of the river-spring-aquifer interaction stresses are similar for the calibration and prediction simulations, rendering the model wholly consistent with the guidelines in this key area of surface-groundwater interactions.
- The predicted mine inflow volume of up 25 ML/day is clearly orders of magnitude higher than current extractions, but that is typically the case when assessing impacts relating to mining projects. In simple terms, it would take mining project scale stresses to generate the data needed to calibrate a model for the purpose of predicting a mining project in a manner that is wholly consistent with the 2012 guideline suggestions. However, this apparent paradox can be addressed by undertaking sensitivity and uncertainty analyses to evaluate the risks. Indeed, this review finds that the sensitivity and uncertainty analyses have been very well executed for the Carmichael project on a wide range of parameters, including aquifer storage parameter uncertainties via transient predictions, consistent with guidelines.
- It should also be noted that steady state simulations are an acknowledged method of quantifying the worst case long term drawdown impacts (e.g. due to extractions), mainly because the aquifer storage parameter is not invoked and long term average hydrological conditions are assumed. Hence the approach of comparing pre-mining and post-mining steady state model results (as applied in this case) is a very conservative method of evaluating the long term project impacts, one that is consistent with the guidelines (Barnett et al, sections 4 & 6.2). Transient model runs are simply required to provide detail around the development with time of groundwater drawdown and related impacts due to mine dewatering (e.g. project time scale river-spring-aquifer interactions).

In summary, despite the previous (2012-13) poor report documentation on model complexity issues (and despite the less than lucid guidance on model confidence issues in Barnett et al, 2012), this review finds that the Carmichael model should be classified as confidence class 2 in terms of the 2012 guideline (or medium complexity in terms of the 2001 guideline). Model uncertainties have been adequately addressed (as discussed at various points herein), notably including the 2014 revisions to address condition 23, which invoked a best practice alternative conceptualisation approach that confirmed the previous impact predictions, and the south to north topographically driven flow whether or not there is a significant western component of flow to the GAB.

5. Model Parameter Issues

5.1 Clematis and Colinlea Aquifer Parameters

Condition 23(a)(ii) requires consideration of the Clematis Sandstone aquifer parameters in relation to the Colinlea Sandstone. A review of the model data files confirmed that the parameter values presented in the model reports are indeed what is specified in the model, with distinct differences between the values for Clematis (Kh = 1.55 m/d) and Colinlea (Kh = 10^{-5} to 10^{-2} m/d; the Colinlea Kh is spatially variable to achieve a uniform effective transmissivity of 0.015 m^2/d).

These Colinlea Sandstone parameter values are considered to be within a physically realistic range based on consultation with DNRM on 6 Nov 2014. The DNRM also suggested the need to split the existing layer 12 (D-seam underburden and Colinlea Sandstone basement) into two layers, so that the late Permian units below the D-seam can be separated from the underlying early Permian basement. This model refinement would be required in the future to help investigate aquifer connectivity with Mellaluka Springs, where significant drawdowns have been predicted, in conjunction with the data that will be acquired from the three monitoring boreholes recently drilled in this area.

The EIS/SEIS models and the revised model do not assume a ‘singular hydraulic conductivity value’ as suggested by the DotE (letter to Adani dated 3 Nov 2014 approving the western boundary GHB treatment). However, if the DotE actually meant to refer to a singular GHB conductance value, then while it is correct that the EIS/SEIS model adopted a uniform (singular) GHB conductance value of 1000 m^2/d, the revised model now calculates the conductance based on aquifer parameters and cell size. This results in a spatially variable GHB conductance value, with significant differences between the Clematis and Colinlea Sandstones (see Table 5 of GHD, 2014). The model performance is not sensitive to these substantial parameter changes.

As part of this investigation, an unexplained variation in the Kh values was identified in layer 4 in the eastern half of the model. Layers 3 to 7 on the eastern half of the model represent Tertiary units, with a Kh value of 10^{-2} m/d generally, apart from Layer 4 which is 10^{-4} m/d. This was justified by GHD as the outcome of a PEST parameter optimisation run and arguably could be viewed as representing heterogeneity (although this was not applied by design). While this affects the eastern boundary GHB conductance, the flow out across the eastern GHB is similar for layer 4 as for layers 5-7, while layer 3 shows somewhat higher flows (see Figures 34-45 of GHD 2014). This is considered to be not material to model performance (indeed it reflects the identified lack of model sensitivity to GHB conductance values described elsewhere). However, this is another indicator of inelegant model design and/or implementation of parameters that warrants refinement in the future to either ensure consistent parameter values across all layers that represent specific units (or to objectively justify the parameter values applied).

5.2 Rewan Group Parameters

IESC advice (Dec 2013) outlined some concerns about the value of the parameters applied to the Rewan Group as being arguably at the low end of reasonable range. I note that the DNRM (undated) file note on the Rewan hydraulic conductivity (Kh) confirms the adequacy of the values adopted for the model, and that they are supported by the eight site-specific hydraulic tests:

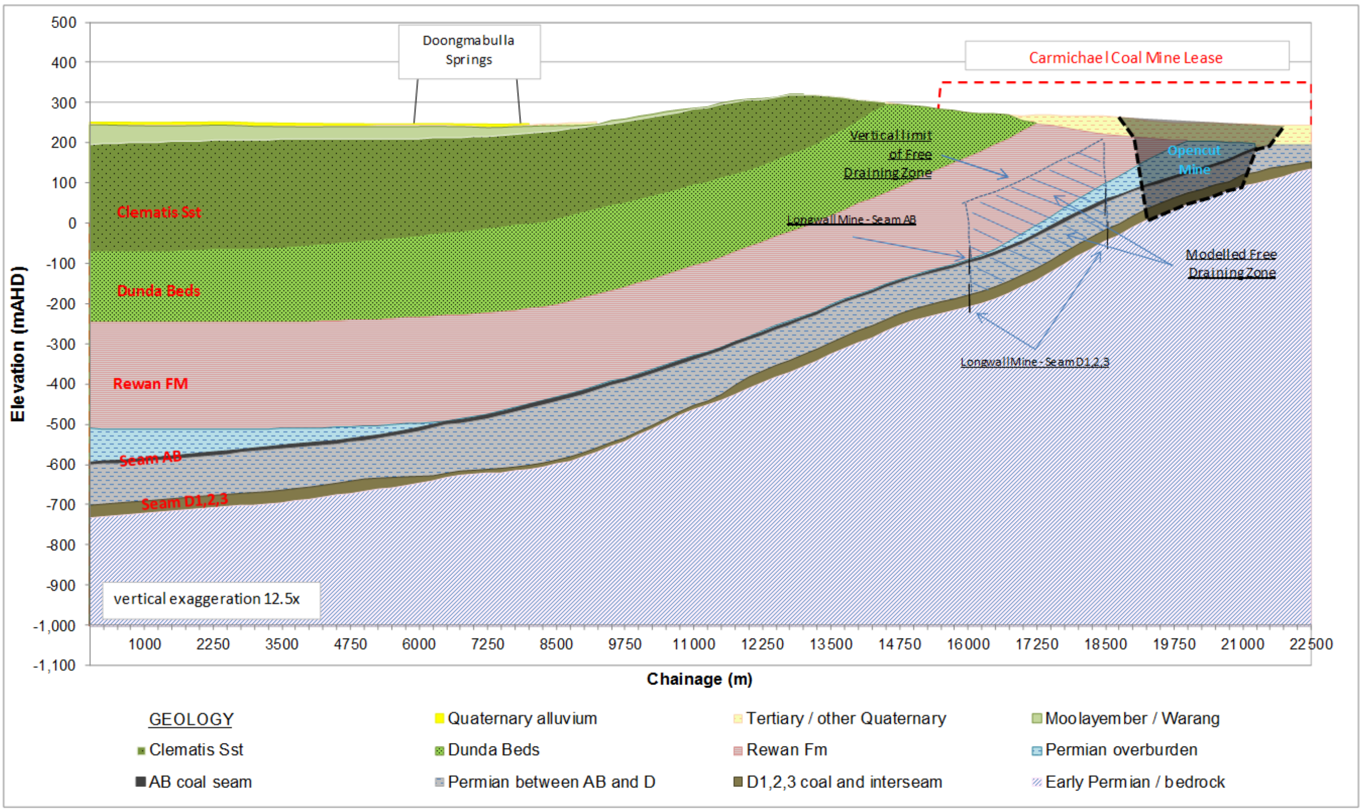
- 3 slug tests were carried out on bores on intervals 56-82 metres deep where the strata was described as unconsolidated, sandy or gravelly clay; results indicated Kh of 2.9×10^{-1} to 2.3×10^{-2} m/d.
- 5 packer tests were carried out on intervals 106-277 metres deep in consolidated material generally described as siltstone, sandstone or mudstone; results indicated Kh range of 3.7×10^{-4} to 9.5×10^{-5} m/d, with an average Kh of 2.3×10^{-4} m/d.

As I am not an expert in Rewan Group properties, I defer to DNRM views, which considered that the packer tests carried out on deeper parts of the Rewan are more representative of the Rewan horizons between the Permian units and the Clematis Sandstone. DNRM also pointed out that the model applied a calibrated Kh value of 7.4×10^{-5} m/d, which is lower than the lowest test figure obtained, and they asked the proponent to carry out further work prior to the SEIS release, which was completed and reported to their satisfaction.

I note that the sensitivity testing undertaken involved increasing the Rewan Group Kh value by an order of magnitude (to 7.4×10^{-4} m/d; see SEIS Appendix K1, Table 26), which is about 3 times higher than the average value from the deep tests. I also note the substantial discussion on Rewan character, parameters and sensitivity testing presented in the SEIS Appendix K6, which also presents much improved discussion and plots on all the sensitivity testing and results, consistent with 2012 guideline recommendations.

Additional parameter changes were made to the vertical hydraulic conductivity (Kv) values to represent a 150 metre thick free-draining fractured zone above the underground (SEIS, section 5.6.3; see also Figure 3 below, after GHD, 2014).

Figure 3 – Geological section, mine areas and free-draining fractured zone



A factor of 50 was applied to the lower zone Kv and a factor of 10 was applied to the upper zone Kv. The zone extends through the overburden (layer 8) and up into the Rewan (layer 7). I note that the model reports cite research by Guo et al (2007) as the basis for fractured zone parameter assumptions. Guo et al (2007) was also used as the basis for research by Tammetta (2013) that is cited in Ditton and Merrick (2014) and has recently been shown to comprise conservatively high parameter values (i.e. it could be argued that the fractured zone assumptions that have been applied also include an allowance for non-mining fracturing of the Rewan). The runs carried out with and without this free draining fractured zone indicate that drainage through the Rewan increased by less than 4% (due to the free draining fractured zone), indicating low uncertainty on the potential effect of Rewan faulting/fracturing.

I am advised that Adani has recently undertaken drilling of two fully cored holes through the Rewan Group (presumably as part of its Rewan Connectivity Research Plan). I am advised that there are plans to undertake a range of tests (e.g. on-site packer testing and laboratory permeability testing) to investigate various aquitard properties. The cored holes once completed will be installed with vibrating wire piezometers as part of the ongoing investigation and monitoring programs, consistent with best practice and the approval conditions. I recommend further tests be undertaken (chemical and isotope testing of pore water samples from the preserved core) to provide formation-scale aquitard parameters for input to the model.

5.3 Recharge Rates

The ESI/SEIS reports describe a suitably wide range of recharge estimates, including a literature review of previous studies, chloride mass balance, PERFECT modelling, and benchmarking against recharge inferred from stream baseflow in Belyando River catchment. This is reprised in the latest report on the revised model (see section 2.10 of GHD, 2014).

The EIS, SEIS and revised versions of the model all apply diffuse recharge at annual average rates of 0.1 to 1.1 mm/year based on optimised PEST model calibration performance. Sensitivity runs were undertaken consistent with best practice by applying factors of up to 10 on recharge rates (i.e. maximum recharge rates to the Clematis of up to 11 mm/year were considered). The parameter range considered is documented in the SEIS report (GHD, 2013), section 5.8, and the results indicated low sensitivity.

While a question remains about the potential for episodic recharge, the low range in measured groundwater level responses in most areas (e.g. apart from in close proximity to rivers and low permeability units) would tend to suggest that episodic recharge may not be a key process in this area. However, GHD (2013, 2014) cites Kellet et al (2003) as indicating that preferred pathway flow (or bypass recharge) processes can occur during heavy rainfall periods (i.e. episodic events) at rates estimated in the order of 0.5 to 28 mm/year. Further sensitivity runs were completed for the SEIS addendum report, testing recharge rates at up to 33 mm/year (documented in SEIS Appendix K6, Section 3.6.2 and Table 8; GHD, 2013) with results indicating low uncertainty in relation to these annual average recharge assumptions (based on a factor of 30 applied to the calibrated rates). Future investigations should consider applying appropriate episodic recharge volumes to short periods, perhaps using data from the very wet periods of 2010-11 and 2011-12 (rather than annual averages) to validate the model.

The revised model western boundary indicates the need for additional inflow across the southern boundary and/or higher recharge to southern Clematis crop, and/or aquifer parameter changes, to improve the model match to measurements in the southern Clematis and western Lake Galilee areas (the model performance is otherwise consistent with guidelines). Contemporaneous and recent groundwater monitoring data on the three southern Clematis bores as a minimum (RN69443, RN16897 and RN90261) is also required for this future model validation process.

6. Summary and Additional Information Recommendations

The review process did not identify any material weaknesses in the model design, boundary conditions, parameter values or calibration performance. The exploration of conceptual and parameter model uncertainty is commendable and the results indicate low sensitivity/uncertainty. It is my professional opinion that the model revisions have been completed competently, consistent with condition 23, and the revised model design and performance is sound. The model is suitable as is for impact assessment purposes, with future model refinements dependent on monitoring to obtain data for validation.

While no immediate action is needed to address model performance issues, future information and model update requirements include:

- split existing layer 12 into two layers, so that the late Permian units below the D-seam can be separated from the underlying early Permian basement, and investigate aquifer connectivity with Mellaluka Springs, using data from the three monitoring boreholes recently drilled in this area
- investigate need for and model sensitivity to the inactive cells immediately east of Clematis outcrop
- investigate recharge inputs including southern boundary inflows, higher recharge to southern Clematis crop, and/or aquifer parameter changes, to improve the model match to measurements in southern model area and also the western (Lake Galilee) area; use recent groundwater monitoring data for this model validation process, and also investigate episodic recharge processes
- chemical and isotope testing of pore water samples from the preserved core of the Rewan to provide formation-scale aquitard parameters for input to the model
- investigate other model design and parameter refinements:
  - Lake Galilee discharge features
  - eastern outflow boundary conductance parameter consistency across all aquifers
  - model sensitivity to refined stress periods (e.g. test periods to not more than 1-2 years)
  - evaporation rate assumptions and sensitivities for post-closure pit void lake runs.

7. References

Appendix A lists the documents provided for consideration during the review.

Barnett, B., Townley, L.R., Post, V., Evans, R.E., Hunt, R.J., Peeters, L., Richardson, S., Werner, A.D., Knapton, A. and Boronkay, A. (2012). Australian Groundwater Modelling Guidelines. Waterlines report 82, National Water Commission, Canberra. URL: http://archive.nwc.gov.au/library/waterlines/82.

Ditton, S. and Merrick, N. (2014). A New Subsurface Fracture Height Prediction Model for Longwall Mines in the NSW Coalfields. Geological Society of Australia, 2014 Australian Earth Sciences Convention (AESC), Sustainable Australia. Abstract No. 03EGE-03 of the 22nd Australian Geological Convention, Newcastle, New South Wales. July 7-10, 2014. Page 136.

Middlemis, H., Merrick, N., Ross, J., and Rozlapa, K. (2001). Groundwater Flow Modelling Guideline. Prepared for Murray–Darling Basin Commission by Aquaterra, January 2001. URL: www.mdba.gov.au/sites/default/files/archived/mdbc-GW-reports/2175_GW_flow_modelling_guideline.pdf

Carmichael Coal Mine Groundwater Flow Model Independent Review

Hugh Middlemis, November 21, 2014

Project Reviewed:	**Carmichael Coal Mine** (Galilee Basin, Queensland)
Independent Review:	Reviewer: **Hugh Middlemis**. Review period: **26 August to 21 November, 2014**.
EIS report	GHD, 2012, Carmichael Coal Mine and Rail Project. Mine Technical Report. Hydrogeology Report 25215-D-RP-0026, revision 2. Prepared for Adani Mining Pty Ltd, 15 November 2012.
Supplementary EIS reports	• GHD, 2013, Carmichael Coal Mine and Rail Project SEIS: Report for Mine Hydrogeology Report. Prepared for Adani Mining Pty Ltd, 13 November 2013 • GHD, 2013, Carmichael Coal Mine and Rail Project SEIS: Mine Hydrogeology Report Addendum. Prepared for Adani Mining Pty Ltd, 24 October 2013 • GHD, 2013, Carmichael Coal Project Groundwater Model Peer Review Final Comments. Letter to Hamish Manzi, Adani Mining Pty Ltd from Keith Phillipson, 18 October 2013. • GHD, 2014, Carmichael Coal Project Response to IESC Advice. Letter to Hamish Manzi, Adani Mining Pty Ltd from Keith Phillipson, 7 February 2014, 19pp and 8 attachments, totalling 147pp. • GHD, 2014, Carmichael Coal Project, Response to Hydrogeology Clarifications requested by DotE. Letter to Hamish Manzi, Adani Mining Pty Ltd from Keith Phillipson, GHD reference 41/26422-61231, 6 May 2014, 9pp.
Previous Independent Review reports, Coordinator-General's report and IESC/OWS reports	• URS, 2013, Adani Carmichael Coal Project Numerical Model Peer Review. Prepared for Adani Mining Pty Ltd, 14 October 2013 • IESC, 2013, Advice to decision maker on coal mining project - Proposed Action: Carmichael Coal Mine and Rail Project, Queensland (EPBC 2010/5736) - New Development. Final Advice, 12 December 2013 • Bleakley, A., 2013, Groundwater Flow Direction Carmichael Project Area. 17 December 2013, 9pp, updated 3 March 2014 (Appendix 3 to Coordinator-General's report, pp.489-496). • Bleakley, A. and McKay, A., undated, Rewan Formation (response to IESC Advice re Carmichael Mine), 1p. • Bleakley, A. and McKay, A., 2014, Carmichael Mine Response to IESC Advice. 2 January 2014, 6pp. • DSDIP, 2014, Carmichael Coal Mine and Rail project: Coordinator-General's evaluation report on the environmental impact statement. Record number D14/58255, May 2014, 608pp. • Hydrosimulations, 2014, CPD-1-2014: A review of the Carmichael Coal Mine and Rail Project Water Hydrogeology Report. Prepared for QLD Dept of State Development, Infrastructure and Planning, 31 March 2014, 7pp. (Appendix 4 to Coordinator-General's report, pp.497-504). • Office of Water Science, 2014, Review of hydrogeological information – Carmichael Coal project. Prepared by Peter Baker, Principal Science Advisor, OWS, Dept of the Environment (C'wlth), 21 May 2014, 18pp.
Groundwater Flow Model Update report and related information	• GHD, 2014, Carmichael Coal Project Proposed Groundwater Boundary Revisions. Memorandum prepared by Keith Phillipson, 10 October 2014 (19pp) and updated 27 October 2014 by James Dowdeswell (28pp), GHD reference: Job 41/28057. • Office of Water Science, 2014, OWS Advice Note 13 October 2014– Carmichael Coal Mine and Rail Infrastructure Project, Queensland (EPBC 2010/5736) – Condition 23 (Groundwater model re-run). Prepared by Peter Baker and Natasha Amerasinghe, 14 October, 2014, 2pp. • Dept of the Environment, 2014, Response - 2010-5736 post-approval review comments on Carmichael proposed groundwater boundary revisions. Prepared by Kelly Strike, Compliance & Enforcement Branch, 16 October 2014. • Dept of the Environment, 2014, Carmichael Coal Mine and Rail Infrastructure Project (EPBC 2010/5736) – Approval of the Redefined General Head Boundary and Cell Elevations for inclusion in the Groundwater Flow Model. Prepared by Mr S.Gaddes, 3 November 2014. • GHD, 2014, Carmichael Coal Project, Response to Federal Approval Conditions, Groundwater Flow Model, Prepared for Adani Mining Pty Ltd, 24 November 2014.

Australian Groundwater Modelling Guidelines (Barnett et al, 2012) formed the basis for the review, notably the guideline checklists (Tables 9-1 & 9-2).

> Barnett, B., Townley, L.R., Post, V., Evans, R.E., Hunt, R.J., Peeters, L., Richardson, S., Werner, A.D., Knapton, A. and Boronkay, A. (2012). ***Australian Groundwater Modelling Guidelines***. Waterlines report 82, National Water Commission, Canberra. URL: http://archive.nwc.gov.au/library/waterlines/82.

Table 1: Compliance Checklist: 10-point essential model aspects list summarising overall compliance

Essential Compliance Question	***Yes/No***
1. Are the model objectives and model confidence level classification clearly stated?	Yes*
2. Are the objectives satisfied?	Yes
3. Is the conceptual model consistent with objectives and confidence level classification?	Yes
4. Is the conceptual model based on all available data, presented clearly and reviewed by an appropriate reviewer?	Yes
5. Does the model design conform to best practice?	Yes
6. Is the model calibration satisfactory?	Yes
7. Are the calibrated parameter values and estimated fluxes plausible?	Yes
8. Do the model predictions conform to best practice?	Yes
9. Is the uncertainty associated with the predictions reported?	Yes
10. Is the model fit for purpose?	Yes

While there is no specific statement in the model reports (GHD, 2012, 2013) on the “model confidence level classification”, the project and model objectives context is clearly understood with the documented reference to the ‘significant project’ (SDPWO Act) and ‘controlled action’ (EPBC Act) classifications.
Further, there is a clear statement on the hydrogeological study purpose to use a combination of data analysis and modelling ‘to address groundwater related parts of Section 3.4 (Water Resources) of the terms of reference for the Project EIS, and specifically to:

- describe the existing environmental values of local groundwater resources using pre-existing published data and information collected from site specific field investigations
- assess the potential impacts of the proposed development on local groundwater resources
- identify mitigation and management options and ongoing groundwater monitoring requirements’.

This implies that the impact assessment and mitigation options, along with related environmental management plans, would be informed by the numerical model, which would require a model confidence level 2 classification in terms of the 2012 guideline, as would typically be expected for a project of this type. While the model reports do not go to the trouble of providing such a statement, this is considered to be a minor report documentation issue rather than a fundamental model performance issue. The issue has been addressed in the latest report (GHD, 2014) documenting the model revision to comply with Condition 23, with a clear statement on the confidence level as class 2.

Table 2: Review criteria on detailed compliance issues

	Review questions	***Y/N***	***Comment*** *(focus on EIS & SEIS)*
1.	**Planning**		
1.1	Are the project objectives stated?	Y	EIS s1.2 (see also footnote to Table 1)
1.2	Are the model objectives stated?	Y	EIS s1.2 & Table 1-1 (see also footnote to Table 1). Further details on model objectives are also provided in other parts of the model report, for example, EIS s5.4.1 Choice of Modelling Code (GHD 2012), and s.5.6.1 Model Predictions.
1.3	Is it clear how the model will contribute to meeting the project objectives?	Y	Yes - see also footnote to Table 1 & item 1.2
1.4	Is a groundwater model the best option to address the project and model objectives?	Y	
1.5	Is the target model confidence-level classification stated and justified?	N	Yes* (see also footnote to Table 1)
1.6	Are the planned limitations and exclusions of the model stated?	N	Not stated specifically, but study and model extent are identified (e.g. s2. of EIS) along with discussion on simplifications required for the study purpose

2.	**Conceptualisation**		
2.1	**Has a literature review been completed, including examination of prior investigations?**	Y	EIS s2.2. Subsequently further investigations have been undertaken, as outlined in table of documentation (p.B-1)
2.2	**Is the aquifer system adequately described?**	Y	See also item 3.5.1 re western bdy
2.2.1	Hydrostratigraphy including aquifer type (porous, fractured rock)	Y	Notably: EIS s2, s4; SEIS s4
2.2.2	Lateral extent, boundaries and significant internal features such as faults and regional folds	Y	Notably: EIS s2, s4; SEIS s4
2.2.3	Aquifer geometry including layer elevations and thicknesses	Y	Notably: EIS s2, s4; SEIS s4, table 4-1, appendix H
2.2.4	Confined or unconfined flow and the variation of these conditions in space and time?	Y	Notably: EIS s4; SEIS s4, table 4-1
2.3	**Have data on groundwater stresses been collected and analysed?**	Y	Existing groundwater usage data accounted for, but is relatively small scale compared to mine dewatering, so measurements of mine dewatering needed to validate the model in future. Climatic stresses have also been considered, and these are on a scale relevant to the development. Carmichael River flow data (two gauges established in 2011) has been used, and is another key data need for future model validation.
2.3.1	Recharge from rainfall, irrigation, floods, lakes	Y	EIS s5.3.2; SEIS s4.3.5, s4.8, table 11
2.3.2	River or lake stage heights	Y	EIS s4.7; SEIS s4.7. Carmichael River stream gauge stations 333301 & 333302. Stream-aquifer interaction data was analysed using topography, stream bed levels and groundwater levels (EIS Table 5)
2.3.3	Groundwater usage (pumping, returns etc)	Y	DNRM licensed bore data identified (20 bores) and included in model (EIS s5.4.2, app.B; SEIS s5.4.2, table 20, App.A)
2.3.4	Evapotranspiration	Y	BoM data considered, concluding that ET exceeds rainfall by 1350 mm/yr on average. EVT max in model set at 5.9 mm/d (long term average from BoM stn 36010), with 1m extinction depth (SEIS s5.4.2).
2.3.5	Other?	NA	
2.4	**Have groundwater level observations been collected and analysed?**	Y	EIS s2, s4.3; SEIS s2, s4.3,
2.4.1	Selection of representative bore hydrographs	Y	SEIS Appendix C
2.4.2	Comparison of hydrographs	Y	
2.4.3	Effect of stresses on hydrographs	Y	Generally low (0.1-0.2m, even post daily rainfall >50mm), except for bores in/near alluvium, where Δ can be 2-3m, presumably due to river stage and/or flood inundation.
2.4.4	Water table maps/piezometric surfaces?	Y	EIS fig 4-7 to 4-12; SEIS fig 12-19.
2.4.5	If relevant, are density and barometric effects taken into account for interpretation of groundwater head & flow data?	NR	
2.5	**Have flow observations been collected and analysed?**	Y	
2.5.1	Baseflow in rivers	Y	Baseflow cannot be measured directly, so stream flow was collected & analysed. EIS s4.7; SEIS s4.7. Carmichael River stream gauge stations 333301 & 333302.
2.5.2	Discharge in springs	maybe	EIS s8; SEIS s8. Unclear whether spring flow data is available (other than via stream flow gauging).
2.5.3	Location of diffuse discharge areas?	Y	EIS s4.8, SEIS s4.9. Carmichael River riparian zone, Doongmabulla Springs, Mellaluka Springs.

2.6	**Is the measurement error or data uncertainty reported?**	maybe	
2.6.1	Measurement error for directly measured quantities (e.g. piezometric level, concentration, flows)	N	Limited discussion in report regarding measurement error, but good treatment of model error.
2.6.2	Spatial variability/heterogeneity of parameters	Y	Various comments throughout reports
2.6.3	Interpolation algorithm(s) and uncertainty of gridded data?	N	
2.7	**Have consistent data units and geometric datum been used?**	Y	mAHD and GDA94, also metres and days typically used for hydrogeology terms
2.8	**Is there a clear description of the conceptual model?**	maybe	No succinct graphical presentation that identifies geological structure, aquifer character and key water balance elements. Adequately described (in a distributed way) and judged to be sound, so issue is one of poor presentation, not poor model capability.
2.8.1	Is there a graphical representation of the conceptual model?	N	No graphical presentation in 2012-13 reports. EIS arguably deficient (figures 5-2, 5-3, table 5-1). Improved by SEIS (figure 28, table 12), especially Appendix K6 (figure 9 & 10). 2014 report is clear and detailed.
2.8.2	Is the conceptual model based on all available, relevant data?	Y	Improved descriptions of conceptualisation with SEIS and related reports (e.g. appendix K6, K8). 2014 report is much improved.
2.9	**Is the conceptual model consistent with the model objectives and target model confidence level classification?**	Y	Model revisions to western boundary to meet approval Conditions 22 & 23 have largely addressed known conceptual uncertainties.
2.9.1	Are the relevant processes identified?	Y	Most key processes were considered for EIS (2012) & SEIS (2013) model platform. The potential for greater westerly groundwater flow to GAB has also now been addressed with model revisions to address Condition 23. There remains scope for future modelling programs to explore/review/revise the following key model elements (even though the EIS & SEIS &/or Condition 23 work was commendable in evaluating uncertainties in relation to these elements): • sensitivity to recharge estimates, notably inflow across southern boundary • validation of surface-groundwater interaction processes using monitoring data from stream & spring flows and geochemistry/isotopes (GAB springs research plan) • findings from investigation of Rewan Group characteristics (Rewan connectivity research plan).
2.9.2	Is justification provided for omission or simplification of processes?	Y	Arguably justified, especially as results from major model revisions for Condition 23 show little change to predicted impacts generally, including at Carmichael River and spring complexes. Importantly, the revised model predicted impacts of GAB flow capture amounts to relatively small volume of around 50 ML/year (which is covered by a factor of about 10 times in terms of Adani commitment for GAB bore capping of 766 ML). Other issues worthy of further investigation in due course are indicated in point 2.9.1.
2.10	Have alternative conceptual models been investigated?	Y	Key alternative parameterisations were tested for sensitivity & uncertainty during EIS & SEIS. Alternative model conceptualisations re western boundary have been tested (Aug-Nov 2014) during revisions to meet approval Condition 23.

3.	**Design and construction**		
3.1	**Is the design consistent with the conceptual model?**	Y	Model extent about 90km square (SEIS s5.4.2), 12 layers, 50m cells size minimum, river & spring features, licensed extraction 150ML/yr.
3.2	**Is the choice of numerical method and software appropriate?**	Y	SEIS s5.4.1. 3D model, variably saturated Modflow-Surfact with Vistas interface plus some data files generated with spreadsheets, and some Dos-prompt command-line program launching. Vertical flow processes accounted for by thick Rewan aquitard (2 layers) and separate layers for coal seams and interburden. PEST utilised for early calibration.
3.2.1	Are the numerical and discretisation methods appropriate?	Y	Automated time stepping applied to ensure numerical stability.
3.2.2	Is the software reputable?	Y	Industry-leading
3.2.3	Is the software included in the archive or are references to the software provided?	NA	
3.3	**Are the spatial domain and discretisation appropriate?**	Y	Recommended extra basement layer in next model update.
3.3.1	1D/2D/3D?	Y	3D
3.3.2	Lateral extent?	Y	90x90km, boundaries well distant from mining area
3.3.3	Layer geometry?	Y	12 layers with adequate resolution for basic impact assessment purposes (SEIS s5.2). Future model campaigns should split the current layer 12 basement into two layers, consistent with DNRM recommendation. New layer 14 would be Early Permian basement, and layer 13 would be sub-D-seam Late Permian underburden. This would permit refined parameterisation to investigate aquifer connectivity with Mellaluka Springs, where significant drawdowns have been predicted.
3.3.4	Is the horizontal discretisation appropriate for the objectives, problem setting, conceptual model and target confidence level classification?	Y	
3.3.5	Is the vertical discretisation appropriate? Are aquitards divided in multiple layers to model time lags of propagation of responses in the vertical direction?	Y	Thick Rewan aquitard represented by 2 layers. See also 3.3.3.
3.4	**Are the temporal domain and discretisation appropriate?**	Y	Mostly yes, with qualifiers outlined below.
3.4.1	Steady state or transient?	Y	Steady state pre-mine calibration (SEIS s5.5). Transient mine predictions (SEIS s5.6). Not ideal, but common practice on greenfields mining projects where data is arguably not amenable to transient simulations. Adequate for purposes of impact assessment where sensitivity/uncertainty assessment runs completed to consider effect of unconfined aquifer storage parameter values (factors of 2 & 1.5 are suitable and were applied in this case).
3.4.2	Stress periods?	Y	Annual for first 5 years, then 5-yearly to 2049, then 10-yearly to 2059. Consistent with mine plan stress info, but arguably a little “lumpy” post-2020. Recommend refined temporal discretisation in next model update.
3.4.3	Time steps?	Y	ATO package (automated to ensure stability)
3.5	**Are the boundary conditions plausible and sufficiently unrestrictive?**	Y	Two issues identified: • **western boundary condition** effectively addressed by condition 23 alternative conceptualisation investigation • **inactive cells east of Clematis outcrop** in centre of model - considered by this reviewer as very likely not material to model performance Some discussion below, with more detailed discussions in review report main text.

3.5.1	Is the implementation of boundary conditions consistent with the conceptual model?	Y	**Western Boundary:** • EIS & SEIS models set up with western bdy roughly aligned with groundwater divide (and topographic divide), and with GHB cells that would nominally allow for inflow or outflow (consistent with that conceptualisation). However, contours of groundwater levels are clearly orthogonal to bdy, so it was effectively no flow (across central and southern bdy, but not in north-west where inflow-outflow short-circuits are apparent). Alternative conceptualisations were considered subsequently to address uncertainty (see next bullet). • 2014 model set up with western bdy moved to western model domain (through centre of Lake Galilee), consistent with condition 23(a) of approval. This is basically an alternative conceptualisation approach (i.e. consistent with best practice methods to explore uncertainty). The results were used in a sensitivity-uncertainty approach to evaluate whether (or confirm that) calibration and/or prediction is affected by maximising (deep) outflows to the GAB and/or (shallow) outflow to Lake Galilee area (i.e. this approach effectively addresses hydrogeological and data uncertainties in this western area).
3.5.2	Are the boundary conditions chosen to have a minimal impact on key model outcomes? How is this ascertained?	Y	**Inactive Cells in centre of model:** Inactive cells east of Clematis outcrop appear to be restrictive, but model runs show that the inactive cells are surrounded by unsaturated cells (i.e. if they were specified as active cells, they would likely also have become unsaturated (due to steeper gradients on layer base levels (result of strata dip) compared to the flatter hydraulic gradients applying in this area) and thus would play no effective part in the model solution). This reviewer considers the use of inactive cells in this area to be inelegant model design in principle, but in this case the approach is likely to have no material effect on model performance. However, it is recommended that the inactive cells in this central area be set as active in the next model update (with "dummy layer/parameter" treatment as applied to the eastern extensions of layers 3 to 7 to represent Tertiary units), and sensitivity testing be done to demonstrate whether the current setup has a material effect (expect answer is "no").
3.5.3	Is the calculation of diffuse recharge consistent with model objectives and confidence level?	Y	SEIS s5.3.2. Diffuse recharge rates at annual average rates (around 1-5 mm/yr) consistent with documented studies and accepted wisdom. Achieves adequate model calibration performance and tested for sensitivity (rates up to 33 mm/yr). Question remains about episodic recharge potential, and need for additional inflow across southern boundary and/or higher recharge to southern Clematis crop, as discussed in review report main text. Recommend investigation of these recharge processes in next model update.
3.5.4	Are lateral boundaries time-invariant?	Y	
3.6	**Are the initial conditions appropriate?**	Y	
3.6.1	Are the initial heads based on interpolation or on groundwater modelling?	Y	Modelling
3.6.2	Is the effect of initial conditions on key model outcomes assessed?	NA	Iterative model runs applied, with feedback of final conditions to inform initial conditions during refinement (good practice).

3.6.3	How is the initial concentration of solutes obtained (when relevant)?	NA	
3.7	**Is the numerical solution of the model adequate?**	Y	
3.7.2	Solution method/solver	Y	PCG5
3.7.2	Convergence criteria	Y	Order of mm; low water balance error term in SEIS model (not so for early EIS model runs).
3.7.3	Numerical precision	Y	
4.	**Calibration and sensitivity**		
4.1	**Are all available types of observations used for calibration?**	Y	
4.1.1	Groundwater head data	Y	All available groundwater level data has been used. Levels from 3 key Clematis bores south of Carmichael River (69443, 16897 & 90261) use historical data and not dipped recently due to access constraints. Recommend measurement as key data need (to reduce uncertainty) prior to next model update.
4.1.2	Flux observations	Y	Licensed irrigation extractions (20 bores) are included at 30% of licensed volume as meter data is not available (SEIS s5.4.2). Stock & Domestic bores included at 2ML/year. Total modelled extractions (non-mine) amount to less than 0.2 ML/d, so even if 100% of licensed irrigation volumes were included, it would still not amount to a significant volume. Impacts at each of the existing bores are identified in the model reports. The model treatment effectively/practically addresses Condition 23(d) to 'incorporate known licensed groundwater extractions'. Stream flow in Carmichael River at two stations installed in 2011 (limited data) used to identify loss of about 460 kL/d (between gauges) with good match to model of 620 kL/d (SEIS s5.5.3).
4.1.3	Other: environmental tracers, gradients, age, temperature, concentrations etc.	Y	SEIS s4.8 describes a range of recharge methods considered including previous studies, chloride mass balance, benchmarking against recharge inferred from stream baseflow in Belyando River catchment. Recommend further investigation of recharge in next model update.
4.2	**Does the calibration methodology conform to best practice?**	Y	
4.2.1	Parameterisation	Y	• Parameters applied to fracture zone overlying underground mine areas based on subsidence study and consistent with accepted practice (and involves higher values (more permeable) than latest research (Ditton and Merrick, 2014), with implementation refined through SEIS model with Rewan split into 2 layers. • Issues identified by IESC advice (Dec 2013) re parameters applied to Rewan as being arguably at low end of reasonable range, but DNRM (undated) filenote on Rewan properties confirms adequacy, supported by site-specific hydraulic testing. • EIS & SEIS model version assumed uniform 1000m^2/d conductance (C) for all GHB cells (e.g. SEIS table 13). Subsequent model updates to address condition 23 applied spatially variable GHB conductance based on the layer Kh value (giving a median C of 1.9m^2/d, roughly 3 orders of magnitude lower than SEIS value). Sensitivity testing showed that GHB flows varied by less than 5%, indicating low sensitivity whether western bdy level is set at 275 mAHD or 250 mAHD.

			- Kh in eastern half of model for the Tertiary stack of layers 3-7 is 10^{-2}m/d except for Layer 4 which is 10^{-4}m/d. Justified by GHD as due to PEST result and arguably representing heterogeneity (although this was not applied by design). Affects conductance values for eastern bdy GHB cell (layer 4 C value is order of 10^{-2}m^2/d, which is 100 times lower than for layers 3,5,6&7). Thus flow out via layer 4 would also be significantly lower, which means most flow would occur via the other layers. This is considered to be not material to model performance, as evidenced via groundwater level contour consistency across layers (i.e. little head difference between layers) and lack of model sensitivity to conductance value – see point above. However, this is another indicator of inelegant model design and/or implementation of parameters that warrants refinement in the future. - Clematis KH (1.55m/d) value quite distinct from Colinlea (10^{-4} to 10^{-2} m/d), and within physically realistic range (consultation by reviewer with DNRM on 6 Nov 2014 confirmed acceptability, even with 12 layer structure). Kh differences also carry through into GHB conductance values. The model treatment does not assume a 'singular hydraulic conductivity value' as suggested by the DotE (letter to Adani from dated 3 Nov 2014 approving western bdy GHB treatment).
4.2.2	Objective function	Y	
4.2.3	Identifiability of parameters	Y	
4.2.4	Which methodology is used for model calibration?	Y	PEST and traditional methods of successive approximation
4.3	**Is a sensitivity of key model outcomes assessed against?**	Y	SEIS s5.8, with more info presented in SEIS Appendix K6, including further sensitivity runs (s3.6)
4.3.1	Parameters	Y	SEIS s5.8 - comprehensive treatment
4.3.2	Boundary conditions	Y	EIS & SEIS (s5.8) ran detailed sensitivity analysis on bdy condition parameters. 2014 model was set up with western bdy moved to western model domain (through centre of Lake Galilee), consistent with condition 23(a) of approval. This is basically an alternative conceptualisation approach (i.e. consistent with best practice methods to explore uncertainty). The results were used in a sensitivity-uncertainty approach (including varying the conductance value through at least 3 orders of magnitude) to confirm that the calibration and prediction performance are largely not sensitive to bdy conditions that maximise (deep) outflows to the GAB, or (shallow) outflow to Lake Galilee area. This approach effectively addresses hydrogeological and data uncertainties in this western area and in relation to potential impacts on GAB flows.
4.3.3	Initial conditions	Y	Steady state pre-mining assumed for EIS/SEIS - results were not tested for sensitivity. The condition 23 alternative conceptualisation investigation, however, did result in quite different steady state heads, which were used as the initial condition for predictions of mine impacts, and the results showed that the model performance is not sensitive to initial conditions.
4.3.4	Stresses	Y	SEIS s5.8 - comprehensive treatment, including recharge increase to 33mm/yr

4.4	**Have the calibration results been adequately reported?**	Y	SEIS s5.5.3 is commendable
4.4.1	Are there graphs showing modelled and observed hydrographs at an appropriate scale?	N	Poor temporal data available
4.4.2	Is it clear whether observed or assumed vertical head gradients have been replicated by the model?	Y	SEIS s4.3 – measured gradients typically in order of 2-4m. However, modelled vertical gradients amount to mostly less than 1m, apart from 4 out of the 20 bores for which data is available (SEIS appendix K6, tables 2-4). Further model improvements would require local scale variations in parameters which may be difficult to justify (other than by achieving a calibration match). Further investigation of vertical head gradients is recommended during future work programs, especially once additional data is obtained in relation to the influence of the Rewan aquitard.
4.4.3	Are calibration statistics reported and illustrated in a reasonable manner?	Y	
4.5	**Are multiple methods of plotting calibration results used to highlight goodness of fit robustly? Is the model sufficiently calibrated?**	Y	SEIS s5.5.3 is commendable
4.5.1	Spatially	Y	
4.5.2	Temporally	N	No time series plots are presented of modelled and measured groundwater levels.
4.6	**Are the calibrated parameters plausible?**	Y	SEIS table 14
4.7	**Are the water volumes and fluxes in the water balance realistic?**	Y	SEIS table 17, figure 33
4.8	**Has the model been verified?**	Y	SEIS s5.5.4 identifies post-calibration data on groundwater levels to verify the model
5.	**Prediction**		
5.1	**Are the model predictions designed in a manner that meets the model objectives?**	Y	SEIS Table 15. Includes parameter variations for effects of fracturing above longwall panels, which also effectively addresses questions about fracturing in the Rewan Group (see also SEIS Appendix K6, figure 16).
5.2	**Is predictive uncertainty acknowledged and addressed?**	Y	For example, SEIS s5.8 and figures 41-44. See also SEIS Appendix K6 figures 12-17 and s3.6
5.3	**Are the assumed climatic stresses appropriate?**	Y	Long term average assumed, with sensitivity runs considering a range of recharge values of 0.004 to 33 mm/yr (SEIS Appendix K6 Table 8)
5.4	**Is a null scenario defined?**	Y	Pre-mining steady state
5.5	**Are the scenarios defined in accordance with the model objectives and confidence level classification?**	Y	Appropriate for model complexity and impact assessment purpose
5.5.1	Are the pumping stresses similar in magnitude to those of the calibrated model? If not, is there reference to the associated reduction in model confidence?	N	No specific statements about model confidence level (see also footnote at Table 1 above), but adequate commentary is provided re sensitivity analysis results.
5.5.2	Are well losses accounted for when estimating maximum pumping rates per well?	N	Drain features used, which is appropriate
5.5.3	Is the temporal scale of the predictions commensurate with the calibrated model? If not, is there reference to the associated reduction in model confidence?	N/Y	Calibrated model is steady state, whereas operational predictions are transient, but a post-mining steady state run is also evaluated, so overall treatment is adequate.
5.5.4	Are the assumed stresses and timescale appropriate for the stated objectives?	Y	
5.6	**Do the prediction results meet the stated objectives?**	Y	With excellent consideration of sensitivity and uncertainty (notably SEIS s5.8 and SEIS Appendix K6 s3.6)
5.7	**Are the components of the predicted mass balance realistic?**	Y	
5.7.1	Are the pumping rates assigned in the input files equal to the modelled pumping rates?	Y	Checks during model run-time by reviewer on 5 Nov 2014 confirmed reported values.

5.7.2	Does predicted seepage to or from a river exceed measured or expected river flow?	N	Good benchmarking of modelled leakage against stream gauge data (albeit short term)
5.7.3	Are there any anomalous boundary fluxes due to superposition of head dependent sinks (e.g. evapotranspiration) on head-dependent boundary cells (Type 1 or 3 boundary conditions)?	N	See also discussion of eastern BC effects above in item 4.2.1.
5.7.4	Is diffuse recharge from rainfall smaller than rainfall?	Y	
5.7.5	Are model storage changes dominated by anomalous head increases in isolated cells that receive recharge?	N	None are apparent
5.8	**Has particle tracking been considered as an alternative to solute transport modelling?**	NA	
6.	**Uncertainty**		
6.1	**Is some qualitative or quantitative measure of uncertainty associated with the prediction reported together with the prediction?**	Y	For example, SEIS s5.8 and figures 41-44. See also SEIS Appendix K6 figures 12-17 and s3.6
6.2	**Is the model with minimum prediction-error variance chosen for each prediction?**	Y	Effectively yes. SEIS s5.8 presents good info on the comprehensive sensitivity/uncertainty assessments, and figures 41-43 identify that the model shows Type 1/2 sensitivity responses (impact of parameter sensitivity on predictions is insignificant).
6.3	**Are the sources of uncertainty discussed?**	Y	
6.3.1	Measurement of uncertainty of observations and parameters	Y	Various places throughout the reports (e.g. re Carmichael River gauged stream flows and lack of direct measurements on springs flows, and lack of metered volumes on existing extractions, also Rewan Group parameters).
6.3.2	Structural or model uncertainty	Y	Discussed to a certain extent in the EIS & SEIS reports. The model variations to address Condition 23 have largely addressed the other identified structural uncertainty regarding outflows to the GAB.
6.4	**Is the approach to estimation of uncertainty described and appropriate?**	Y	SEIS s5.8 and SEIS Appendix K6 s3.6.
6.5	**Are there useful depictions of uncertainty?**	Y	For example, SEIS s5.8 and figures 41-44. See also SEIS Appendix K6 figures 12-17
7.	**Solute transport**	NA	
8.	**Surface water–groundwater interaction**		
8.1	**Is the conceptualisation of surface water–groundwater interaction in accordance with the model objectives?**	Y	EIS table 4-2, s4.7, s4.8; SEIS s4.7, s4.8. Carmichael River stream gauge data used (stns 333301 & 333302). Stream-aquifer interaction data was analysed using topography, stream bed levels and groundwater levels (EIS Table 5). Water chemistry also analysed.
8.2	**Is the implementation of surface water–groundwater interaction appropriate?**	Y	Appropriate features were used for streams including EVT along riparian zones, with benchmarking to measured data, and sensitivity testing of parameter values. Lake Galilee does not have discharge or recharge feature associated with it (other than the GHB boundary applied for the Condition 23 model variations), and future model updates should investigate a suitable conceptual design and implementation (e.g. using information that will become available from the Bioregional Assessment investigations in progress).
8.3	**Is the groundwater model coupled with a surface water model?**	N	
8.3.1	Is the adopted approach appropriate?	NA	
8.3.2	Have appropriate time steps and stress periods been adopted?	NA	
8.3.3	Are the interface fluxes consistent between the groundwater and surface water models?	Y	Good benchmarking to (short term) stream gauging on Carmichael River, and consideration of rainfall-runoff model results to benchmark recharge assumptions.