# Appendix J

## Groundwater Assessment peer review reports

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DATE: 14 September 2016

TO: Luke Edminson
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FROM: Dr Noel Merrick

RE: Hume Coal Project - Groundwater Impact Assessment Peer Review

OUR REF: HA2016/8: Peer Review of Hume Coal Groundwater Model

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## Introduction

This report is provided in response to a contract dated 29 October 2015 for conducting a peer review of the Hume Coal EIS groundwater impact assessment with emphasis on the numerical groundwater modelling being conducted by Coffey Geosciences.

The Scope of Services for the peer review is limited to:

- attendance at the Hume Water Strategy Meeting (Technical Groundwater Component) in Sydney;
- preliminary review of draft groundwater modelling documentation;
- preparation of discussion notes and comments based on the draft groundwater modelling documentation;
- attendance at a meeting in Sydney to discuss the draft groundwater modelling documentation, with emphasis on the robustness of work to date and notification of any areas requiring additional work;
- review of final groundwater modelling documentation; and
- preparation of a written peer review report.

The review has been conducted by Dr Noel Merrick in accordance with national groundwater modelling guidelines. It is understood that Dr Frans Kalf is undertaking a broader review of all aspects of the groundwater assessment, in parallel.

## Documentation

At the time of writing, the following documents were available for review:

*A.* Coffey Geotechnics Pty Ltd, 2016, *Hume Coal Project Groundwater Assessment Volume 1: Data Analysis.* Report GEOTLCOV25281AB-ACA for Hume Coal Pty Ltd. 8 August 2016. 70p + 6 Appendices.

*B.* Coffey Geotechnics Pty Ltd, 2016, *Hume Coal Project Groundwater Assessment Volume 2: Numerical Modelling and Impact Assessment.* Report GEOTLCOV25281AB-ACB for Hume Coal Pty Ltd. 8 August 2016. 67p + 8 Appendices.

In each case, two earlier versions of Documents A and B were reviewed, with provision of verbal review comments only.

The reviewer was involved in various stages of the model development process:

- attendance at the Hume Water Strategy Meeting (Technical Groundwater Component) in Sydney on 28 July 2015;
- attendance at the water peer review meeting in St Leonards on 10 March 2016; and
- attendance at the groundwater model peer review meeting in St Leonards on 22 July 2016.

The major sections in Document A are:

Executive Summary
1. Introduction
2. Climate
3. Surface drainage
4. Geology
5. Subsurface hydraulic properties
6. Groundwater levels
7. Groundwater inflows to the Berrima mine void
8. Groundwater character
9. Groundwater use
10. Hydrogeological conceptual model
11. References

The Appendices for Document A are:

A. Baseflow Analysis
B. Specific Capacity Analysis
C. Additional Hydraulic Conductivity Analysis
D. Hydraulic Head Database
E. Hydraulic Head Surfaces
F. Hydraulic Head Data for the Southeastern Basalt Body

The major sections in Document B are:

Executive Summary
1. Introduction
2. Proposed mining
3. Model development
4. Model calibration
5. Predictive simulation
6. Predictive results
7. Impact assessment
8. Parameter sensitivity analysis
9. Conclusions
10. Limitations
11. References

The Appendices for Document B are:

A. Hume Mining Schedule and Mining Heights

B. Hydraulic Head Targets and Calibrated Hydrographs
C. Downdip and Updip Panel Areas
D. Total and Differential Drawdown of the Water Table and at the Base of the Hawkesbury Sandstone at Virtual Piezometers
E. Total Drawdown of the Water Table at 17 and 30 Years Since the Start of Mining
F. Semesterly Accounts for Intercepted Baseflow to Surface Water Sources and Induced Release from Groundwater Storage in Groundwater Sources
G. Private Water Bore Register, Locations, Results, and Drawdown Hydrographs
H. Basalt Model used to Assess Drawdown in Private Bore GW106103

## Review Methodology

There are two accepted guides to the review of groundwater models: the Murray-Darling Basin Commission (MDBC) Groundwater Flow Modelling Guideline[1], issued in 2001, and the newer guidelines issued by the National Water Commission (NWC) in June 2012 (Barnett *et al*., 2012[2]). Both guides also offer techniques for reviewing the non-modelling components of a groundwater study.

The 2012 NWC guide builds on the 2001 MDBC guide, with substantial consistency in model conceptualisation, design, construction and calibration principles, and the performance and review criteria, although there are differences in details. However, there is an expectation of more effort in uncertainty analysis, although the guide is not prescriptive as to which methodology should be adopted.

The groundwater model development has been reviewed according to the 2-page Model Appraisal checklist[3] in MDBC (2001). This checklist has questions on (1) The Report; (2) Data Analysis; (3) Conceptualisation; (4) Model Design; (5) Calibration; (6) Verification; (7) Prediction; (8) Sensitivity Analysis; and (9) Uncertainty Analysis. Non-modelling components of the groundwater impact assessment are addressed by the first three sections of the checklist, which are informed primarily by Document A.

A detailed assessment has been made in terms of the peer review checklist in **Table 2**. Supplementary comments are offered in the following sections. It should be noted that the verbal review comments offered at the various workshops and meetings have been adopted substantially within the final reports submitted for review.

## Report Matters

### Document A

Document A is a substantive report of 70 pages plus a 2-page Executive Summary and six appendices. It is well structured and well written with graphics of reasonably quality. It serves as a standalone report without any undue reliance on other reports or inaccessible data sources.

The purpose of the investigation is stated in the Executive Summary and in Section 1: “to support the development of a regional numerical groundwater flow model” and “to assess impacts on the groundwater system and dependent users from proposed mining”. The first objective is addressed in Document A by development of a competent defensible conceptual model that underpins the development of the numerical model addressed in Document B.

Document A follows a systematic methodology and relies upon innovative data analysis and interpretation.

Editorial suggestions:

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[1] MDBC (2001). Groundwater flow modelling guideline. Murray-Darling Basin Commission. URL: www.mdbc.gov.au/nrm/water_management/groundwater/groundwater_guides

[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.

[3] The NWC guide includes a more detailed checklist with yes/no answers but without the graded assessments of the 2001 checklist, which this reviewer regards as less academic and more informative for readers.

- Figure 3.1: Add creek names on the mine lease; Bong Bong Weir; Berrima Weir; Illawarra Highway.
- Table 3: Define WG and HAW in a footnote.
- Section 4.2: Define “MBA” upon first use.
- Section 4.3: Define “BCSC” and “IEC” upon first use.
- Kh and Kv are nowhere defined.
- Section 5.1: principle (horizontal stress) → principal
- Figure 5.4: Define the sigma terms.
- Section 5.2.1, paragraph 1: The final sentence on solar radiation seems superfluous.
- References: Add Coffey (2007).

### Document B

Document B is a well-structured report of 67 pages and eight appendices, plus a 1-page Executive Summary. The graphics are of good quality. The report is not fully standalone as reliance on Document A is necessary to provide the conceptual underpinning for the numerical model.

The purpose of the investigation is stated in Section 1: “to assess impacts on the groundwater system and dependent users from proposed mining”. The objective is addressed in Document B by reporting on the construction, calibration and application of a numerical groundwater flow model. This model is used to predict environmental impacts due to mining, and to explore a number of drawdown mitigation options, namely:

- backfilling with co-disposed tailings;
- sealing individual mining panels; and
- injection of mine inflow water back into the void.

In the Executive Summary there is a statement that “the maximum total drawdown that is caused by Hume operations is 87%”. As readers might be confused by the difference between total drawdown and differential drawdown, it would be worth adding that groundwater extraction by private users will account for 13% of the drawdown to be experienced by the groundwater system.

Editorial suggestions:

- Section 3.2.4: “not considered a separate groundwater source” → “not considered by DPI Water a separate groundwater source”
- Section 4.3.2: Kh Large scale Kv → Large scale Kv
- Clarify whether 99 bores (page 60) or 117 bores (page 53) have more than 2 m drawdown.

## Data Matters

Data collation, analysis and interpretation are covered in Document A.

This report covers data acquisition through investigations of climate, stream hydrology, drilling, geology, hydrogeology, hydrostratigraphy, aquifer and aquitard characterisation, piezometry, mine inflows, groundwater flow, water salinity and groundwater usage.

A very large groundwater database has been assembled. Water level information has been obtained at 59 sampling points across 24 sites. There are 46 standpipes at 19 sites, 11 vibrating wire piezometers (VWPs) at three sites, and two private water bores, in the groundwater monitoring network.

Extensive aquifer/aquitard characterisation has been achieved through 28 packer tests, 59 core tests at five sites, and two pumping tests. Coupled with other data drawn from the Southern Coalfield, the best available data has been used to characterise the hydraulic conductivity field in three dimensions (prior to model calibration).

In order to minimise the uncertainty in model predictions, the model has been constrained to replication of data types belonging to four disparate groups:

- groundwater level hydrographs;
- baseflow to streams;
- groundwater discharges to existing mines; and
- measured hydraulic conductivities.

The baseflow analysis provides an important upper limit on rainfall recharge rate, often a difficult parameter to quantify.

Adequate consideration is given to the possible effects of faults and intrusions (especially Mt Gingenbullen) on the groundwater regime. A couple of barrier faults were judged to be necessary inclusions in the numerical model.

In Section 6.2, there is an important observation that the drawdown effects due to the Berrima Mine are prevented from substantial migration to the south, but are unimpeded to the north. This shows that cumulative impacts from the two mines are likely to be limited.

Another important observation is noted in Figure 6.1 (and Figure 6.7), where two zones of desaturation are inferred beneath perched water tables in basalt and the Wianamatta Group shales. This effectively protects the upper formations from drawdown effects due to mining, as those effects cannot propagate upwards through unsaturated material. Document A notes that the “majority of private bores in the basalt are located here”. In passing, it is noted that the extent of the desaturation could be due in part to pumping of groundwater for irrigation use.

Although substantial effort has been applied to estimation of groundwater use, the lack of metering on private bores and expected groundwater consumption by unregistered bores will compromise the calibration of a numerical model. To obviate this to some degree, local groundwater level reductions observed on monitoring hydrographs have provided some insight into whether particular bores are pumping close to entitlement allowances. A case in point is illustrated in Section 9.1 where a particular bore was inferred to be pumping 1.5 ML/day in light of observed drawdowns at monitoring bores H32, H35 and H73. Metering of bores is always preferable in order to minimise scientific uncertainty. Figure 9.1 shows that the number of known private water bores is huge.

Some suggested improvements to data analysis are offered here:

- Table 1: Updating the rainfall statistics beyond January 2015.
- Section 3.1: Justification for adoption of 0.0125 as the specific yield; this can probably be referenced to Tammetta and Hewitt (2004).
- Figure 4.2: Addition of groundwater flow directions for the benefit of general readership.
- Section 4.3.1: Explanation for the term “access gallery” for an intrusion.
- Section 5.1: What is the consequence for not correcting laboratory core measurements for overburden pressure?
- Section 5.3, Section 10.2: To honour the natural variability in measured hydraulic conductivities, the summary statements for Kh and Kv/Kh should note that the stated values have an uncertainty of about half an order of magnitude either way.
- Table 4, Section 8.1: Updating the EC and sulphate statistics beyond May 2014.

Document B relies on the data acquisition and data analysis reported in Document A. However, some additional data sources are introduced in Document B:

- Heights of desaturation above Berrima Mine.
- Reassessment of private bore pumping volumes.

## Model Matters

### Model Construction

The construction of the groundwater flow model is developed in Section 3 of Document B. The model extent is indicated clearly in Drawing 1, being about 32 km (east-west) and about 38 km (north-south). The cell sizes range from 50 m to 200 m, giving good spatial resolution where required. In all there are 15 layers in the model; six of these are applied to the Hawkesbury Sandstone in order to honour the known vertical head gradient across that formation, and two thin layers are allocated to the expected caving zone above the Wongawilli coal seam. Two layers beneath the coal seam permit potential propagation of drawdown effects beyond the outcrop limits of the coal seam.

MODFLOW-SURFACT is the software of choice, and this is appropriate and commonly used for groundwater models of mines. The use of the older version 3 precludes specification of time-varying properties, but for this particular model that option is not necessary.

No spatial variability is applied to the properties of a particular layer (apart from thickness). This is a common approach in groundwater models of mines. An assumption has been made that the occurrence of alluvium is so minor that it has not warranted separate specification. Its exclusion is unlikely to be significant, especially as the alluvium is not designated by DPI Water as a separate water source.

The boundary conditions are adequately justified. These are generally no-flow at distant borders, fixed head at Wingecarribee Reservoir, reference heads at streams (RIV and DRN), escarpment (DRN) and mines (DRN). All are appropriate. The river leakance value of 0.01 day$^{-1}$ is considered high, but this is a conservative assumption that is likely to give an overestimation of mining induced losses from streams.

Specifically excluded from the model are:

- Robertson Basalt.
- Mt Gingenbullen intrusion.
- Cement Works Fault.
- Irrigation recharge.
- Alluvial zones.

However, an adequate defence is put forward for each omission, and this practice is supported by the Principle of Parsimony advocated in modelling guidelines.

Given the avoidance of land subsidence by the chosen mining method for the proposed mine, the height of drainage above caved workings is limited to two thin dedicated caving layers. This is appropriate.

The effect of background pumping by private groundwater users is accommodated in the model. As noted earlier, the lack of metering makes the estimation of pumped volumes and pumping patterns difficult. The estimation process is done as well as could be expected.

An additional local model was developed separately for the basalt outcrop, given that this was represented in the regional model only as a source of vertical recharge to the underlying regional water table. The purpose of the model was to check the likely drawdown at one private bore (GW106103), the only bore in basalt predicted to be drawn down by more than 2 m. The model extent is shown in Figure 1 of Appendix H, being about 6 km (east-west) and about 4 km (north-south). The cell size is uniformly 100 m, and there are two layers in the model. Calibration was limited to the steady-state responses at 25 private bores.

## Transient Calibration

The flow model has been calibrated in transient mode from January 2011 to December 2014, and verified through to mid-2015. Monthly stress periods define the temporal resolution of the model, as is normally practised in groundwater models for mines during the calibration phase. There is a model “warm-up” phase from 1926 to the end of 2010, but the temporal resolution during this time is not clear.

As the aim of model calibration is to replicate observed responses, it is important that only reliable data be used. For this model, a thorough quality analysis has been done in order to excise unreliable data.

Several lines of evidence are provided in support of calibration in the form of a scatter plot at the end of the verification period (Figure 4.2), performance statistics at the end of the verification period, cross-section head contours (Figure 4.3), water table contours (Figure 4.4), consistency with field hydraulic conductivities (Figure 4.5), agreement with measured mine inflows (Figure 4.6), consistency with the conceptual flow budget magnitudes (Table 4) and individual hydrograph matches. No residual plots are shown; they would be useful in showing which areas of the model are well calibrated and which are poorly calibrated.

Normally, a scatter plot and performance statistics would be given for the entire calibration period, rather than at one date only. Based on the hydrographic comparisons, the transient flow calibration is considered reasonable in terms of groundwater heads as the observed trends are reproduced and absolute levels and vertical gradients are similar to those observed, though not perfect. The performance statistics at the verification end date are close to the limit of what is acceptable, being about 12 %RMS, 17 mRMS and 3.1 m residual mean. The performance statistics for the full calibration period are not disclosed. The performance is downgraded by the inclusion of several VWP records which are always difficult to replicate in complex mining groundwater models.

The scatter plot in Figure 4.2 shows symmetry about the diagonal line of best fit, indicating no undue bias to overestimation or underestimation of groundwater levels. Possible sources of error are offered in Section 5.3 of Document B.

Calibration to Berrima mine inflow is very good, and simulated baseflows are consistent with inferred rates. Spatial and vertical head patterns are also consistent with expectations.

The flow budget components in Table 4 of Document B compare favourably with pre-modelling estimates in Table 6 of Document A. Evapotranspiration is about three times what was expected, and private pumping is about 50% higher. The mass balance discrepancy of about 4% is higher than normal (1-2%). This indicates that the model must have had some difficulty with numerical convergence.

The calibrated hydraulic conductivity distributions in Figure 4.5 are well supported by field measurements at various scales.

## Model Class

The NWC 2012 guide has the concept of "model confidence level", which is defined using a number of criteria that relate to data availability, calibration, prediction scenarios and key indicators. Document B assigns a class of 2-3, weighted about 70% to Class 3 and 30% to Class 2. That is sufficient and appropriate. This recognises correctly that, in practice, a model is likely to straddle two or more classes. The full decision table in Table 2-1 of the guidelines, or the simplified list in **Table 1** (supplied here), could be completed with ticks or highlights to indicate elements of the model that are Class 1, 2 or 3. The row with the most ticks can be argued to be the applicable class.

**Table 1. Model Confidence Class Characteristics**

| CLASS | DATA | CALIBRATION | PREDICTION | INDICATORS |
|---|---|---|---|---|
| 1 | Not much.<br>Sparse.<br>No metered usage.<br>Remote climate data. | Not possible.<br>Large error statistic.<br>Inadequate data spread.<br>Targets incompatible with model purpose. | Timeframe >> calibration<br>Long stress periods.<br>Transient prediction but steady-state calibration.<br>Bad verification. | Timeframe > 10x<br>Stresses > 5x<br>Mass balance > 1% (or single 5%)<br>Properties <> field.<br>Bad discretisation.<br>No review. |
| 2 | Some.<br>Poor coverage.<br>Some usage info.<br>Baseflow estimates. | Partial performance.<br>Long-term trends wrong.<br>Short time record.<br>Weak seasonal replication.<br>No use of targets compatible with model purpose. | Timeframe > calibration.<br>Long stress periods.<br>New stresses not in calibration.<br>Poor verification. | Timeframe = 3-10x<br>Stresses = 2-5x<br>Mass balance < 1%<br>Some properties <> field measurements.<br>Some key coarse discretisation.<br>Review by hydrogeo. |
| 3 | Lots.<br>Good aquifer geometry.<br>Good usage info.<br>Local climate info.<br>K measurements.<br>Hi-res DEM. | Good performance stats.<br>Long-term trends replicated.<br>Seasonal fluctuations OK.<br>Present day data targets.<br>Head and flux targets. | Timeframe ~ calibration.<br>Similar stress periods.<br>Similar stresses to those in calibration.<br>Steady-state prediction consistent with steady-state calibration.<br>Good verification. | Timeframe < 3x<br>Stresses < 2x<br>Mass balance < 0.5%<br>Properties ~ field measurements.<br>Some key coarse discretisation.<br>Review by modeller. |

## Scenario Analysis [Document B]

Table 8 in Document B provides a definition of the two prediction scenarios that differ according to the presence or absence of Hume mining. The base case includes co-disposed tailings emplacement filling 36% of the mined void. Variants of the base case examined other mitigation options, although their results are not reported.

Annual stress periods define the temporal resolution of the model, as is normally practised in groundwater models for mines during the prediction phase. The prediction period is 19 years, followed by 81 years of recovery for the adopted base case and null scenario.

Document B notes that there were many trial runs with various mitigation options to determine the required level of abstraction from Hume bores for mine water management.

Flow budgets (averaged over 19 years) are provided in Tables 10 and 11 for the base case and the null scenario, respectively.

Differential water table drawdown impacts are examined spatially (Figures 6.6 and 6.7) and temporally at representative sites (Figure 6.4). In accordance with the Aquifer Interference Policy (AIP), the extent of impact is displayed for drawdowns of 2 m or more.

The prediction scenarios are designed properly and the analysis of results is competent. The findings are focused on the minimal harm considerations of the AIP and the licensing requirements of water sharing plans. The primary AIP consideration is drawdown, which is assessed in terms of differential drawdown (relevant to the AIP) and total drawdown (relevant to practical considerations as to whether or when a particular private bore might go dry). The latter consideration goes beyond what is required by the AIP. There is no specific analysis of the water quality AIP minimal harm considerations for shift in beneficial use of groundwater and increase in stream salinity. The latter case is not applicable as no increased baseflow to streams would occur.

The potential drawdown impact zone is well defined. A total of 117 bores is likely to be affected beyond the AIP threshold, with only one of those bores situated in basalt (GW106103)[4]. Each potentially affected bore is listed in Table 1 of Appendix G and shown on Map 1 of the same appendix. The predicted temporal drawdown at each bore is illustrated in 24 charts.

For licensing purposes, complex disaggregation of model results was required for 16 designated water sources, 14 of which register some predicted take. The maximum groundwater take is 5.2 ML/day while the maximum surface water take (in the form of intercepted baseflow) is 0.9 ML/day (for Medway Rivulet) which is about one-third of the estimated average natural baseflow. The median maximum from the separate water sources is 0.04 ML/day. The takes are also reported temporally in 6-monthly steps.

## Sensitivity Analysis [Document B]

Table 8 in Document B provides a definition of the three sensitivity prediction scenarios that assess the importance of key uncertain model parameters: A: caving height; B: vertical hydraulic conductivity; and C: mine drain conductance. The respective increases in mine inflow are about 4%, 28% and 0%. Only the vertical hydraulic conductivity is significant. As noted in Document B, this parameter is as well constrained as is possible through the calibration process.

There is no comment on whether the perturbations applied in the sensitivity analysis have compromised calibration performance. The sensitivity results are meaningful only if the model remains adequately calibrated.

Also, there is no examination of model outputs other than mine inflow. Does the sensitivity analysis result in any significant changes in the estimated drawdown and baseflow impacts?

There is no separate report section on uncertainty analysis. Explicitly, uncertainty in mine inflow is assessed through the sensitivity analysis. Implicitly, it is argued in Document B that uncertainty in model predictions is low because all model parameters are constrained through a multi-objective calibration process that honours heads

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[4] However, the separate basalt model predicts less than 2 m drawdown at this bore.

and flows simultaneously.

## Conclusion

The purpose of the reported groundwater investigation is an assessment of potential environmental impacts due to the Hume Coal mining method and mine plan, in the context of the minimal harm considerations of the Aquifer Interference Policy and the licensing requirements of water sharing plans. The modelling component of the investigation is also expected to comply with national guidelines for groundwater modelling.

The reviewer finds that the modelling study is fully compliant with guidelines, and often goes beyond state of the art techniques.

The reviewer also finds that there is a very thorough assessment of the complex licensing requirements in terms of 16 relevant water sources.

With respect to the requirements of the Aquifer Interference Policy, the drawdown minimal harm consideration is explored fully. The assessment of whether or when a particular private bore might go dry goes beyond what is required by the Aquifer Interference Policy. However, there is no specific analysis of the water quality minimal harm considerations for shift in beneficial use of groundwater and increase in stream salinity. The latter case is not applicable as no increased baseflow to streams would occur.

Accordingly, overall, the reviewer considers that the model is *fit-for-purpose*.

Table 2. MODEL APPRAISAL: **Hume Coal Model**

| Q. | QUESTION | Not Applicable or Unknown | Score 0 | Score 1 | Score 3 | Score 5 | Score | Max. Score (0, 3, 5) | COMMENT |
|---|---|---|---|---|---|---|---|---|---|
| **1.0** | THE REPORT | | | | | | | | |
| 1.1 | Is there a clear statement of project objectives in the modelling report? | | Missing | Deficient | Adequate | [✓ Very Good] | | | For both documents. |
| 1.2 | Is the level of model complexity clear or acknowledged? | | Missing | No | [✓ Yes] | | | | 70% Class 3 & 30% Class 2 confidence classification. What is achieved could be substantiated by ticking checklist attributes for all classes, as models will bridge several classes. |
| 1.3 | Is a water or mass balance reported? | | Missing | Deficient | Adequate | [✓ Very Good] | | | Doc B: Tables 4, 10, 11. |
| 1.4 | Has the modelling study satisfied project objectives? | | Missing | Deficient | Adequate | [✓ Very Good] | | | AIP and WSP requirements are met. Drawdown mitigation options are explored. |
| 1.5 | Are the model results of any practical use? | | | No | Maybe | [✓ Yes] | | | Adequately calibrated to multiple observation datasets. Reliability is thereby enhanced. |
| new | Is the model “fit-for-purpose”? | | | No | Maybe | [✓ Yes] | | | Purpose is assessment of potential environmental impacts due to mining method and mine plan. Fitness is defended in Section 4.3.5. |
| **2.0** | DATA ANALYSIS | | | | | | | | *Document A.* |
| 2.1 | Has hydrogeology data been collected and analysed? | | Missing | Deficient | Adequate | [✓ Very Good] | | | Large groundwater database: 59 sampling points at 24 sites. Extensive aquifer/aquitard characterisation by packer tests (28), core tests (59) and pumping tests (2). Good coverage of hydrostratigraphy and water quality. |
| 2.2 | Are groundwater contours or flow directions presented? | | Missing | Deficient | [✓ Adequate] | Very Good | | | Flow directions should be added to Figure 6.3: Wianamatta Group and Upper Hawkesbury Sandstone head surfaces. Similar maps in Appendix E for Lower Hawkesbury Sandstone and Wongawilli Seam. |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2.3 | Have all potential recharge data been collected and analysed? (rainfall, streamflow, irrigation, floods, etc.) | | Missing | Deficient | Adequate | [✓ Very Good] | | | Rainfall recharge is well constrained by baseflow analysis. Groundwater and creek water levels are examined to infer gaining/losing status. |
| 2.4 | Have all potential discharge data been collected and analysed? (abstraction, evapotranspiration, drainage, springflow, etc.) | | Missing | Deficient | Adequate | [✓ Very Good] | | | Substantial private abstraction – difficult to estimate. |
| 2.5 | Have the recharge and discharge datasets been analysed for their groundwater response? | | Missing | Deficient | [✓ Adequate] | Very Good | | | Limited illustration of cause-and-effect analysis (e.g. Figure 3.3 and commentary in Section 6.1). Hydrographs in Appendix D are not compared with rainfall residual mass. Vertical head gradients are considered (e.g. minor in Figure 6.6). |
| 2.6 | Are groundwater hydrographs used for calibration? | | | No | Maybe | [✓ Yes] | | | Extensive monitoring network. |
| 2.7 | Have consistent data units and standard geometrical datums been used? | | | No | [✓ Yes] | | | | |
| **3.0** | CONCEPTUALISATION | | | | | | | | *Document A.* |
| 3.1 | Is the conceptual model consistent with project objectives and the required model complexity? | | Unknown | No | Maybe | [✓ Yes] | | | Thorough development of conceptualisation. |
| 3.2 | Is there a clear description of the conceptual model? | | Missing | Deficient | Adequate | [✓ Very Good] | | | Most of Document A. Summarised in Section 10. |
| 3.3 | Is there a graphical representation of the modeller's conceptualisation? | | Missing | Deficient | Adequate | [✓ Very Good] | | | Figure 10.3. |
| 3.4 | Is the conceptual model unnecessarily simple or unnecessarily complex? | | | Yes | [✓ No] | | | | Some unnecessary features are justifiably excised. |
| **4.0** | MODEL DESIGN | | | | | | | | *Document B.* |
| 4.1 | Is the spatial extent of the model appropriate? | | | No | Maybe | [✓ Yes] | | | Dimensions 38 km x 32 km. Area 752 km$^2$. 379 columns x 425 rows x 15 layers. Cell sizes 50m to 200m. 6 layers in Hawkesbury Sandstone. Separate layers for caving.<br>Local model: 6 km x 4 km. Area 15 km$^2$. 100 columns x 40 rows x 2 layers. Cell size 100m. |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 4.2 | Are the applied boundary conditions plausible and unrestrictive? | | Missing | Deficient | [✓ Adequate] | Very Good | | | Generally no-flow at distant borders, fixed head at Wingecarribee Reservoir, reference heads at streams (RIV and DRN), escarpment (DRN) and mines (DRN). All appropriate. RIV leakance of 0.01 /day is high, hence likely to overestimate mining induced losses from streams (conservative assumption).<br>Not included: Irrigation recharge; Cement Works Fault; Robertson Basalt; Mt Gingenbullen intrusion. |
| 4.3 | Is the software appropriate for the objectives of the study? | | | No | Maybe | [✓ Yes] | | | MODFLOW SURFACT v3. There is a later v4 that allows time-varying properties; however, not necessary for this mine model. |
| **5.0** | CALIBRATION | | | | | | | | *Document B.* 2011-2014: 4 years. Also 1926-2010 model warmup. |
| 5.1 | Is there sufficient evidence provided for model calibration? | | Missing | Deficient | Adequate | [✓ Very Good] | | | Several lines of evidence: scattergram; performance statistics for verification; hydrographs plots; spatial pattern; section head pattern; mine inflow; baseflows; K values.<br>Did not use PEST.<br>No indication of spatial distribution of residuals.<br>No scattergram for full calibration period. |
| 5.2 | Is the model sufficiently calibrated against spatial observations? | | Missing | Deficient | [✓ Adequate] | Very Good | | | Spatial head pattern in Figure 4.4 is as expected. Section head pattern in Figure 4.3 is reasonable. Vertical head gradients on hydrographs – some good, some poor. |
| 5.3 | Is the model sufficiently calibrated against temporal observations? | | Missing | Deficient | [✓ Adequate] | [✓ Very Good] | | | Mine inflow very good.<br>Hydrographs for all bores are presented for comparison. Reasonable groundwater level matches and trends – simulated responses are quiescent. Some vertical gradients are reproduced. |
| 5.4 | Are calibrated parameter distributions and ranges plausible? | | Missing | No | Maybe | [✓ Yes] | | | Figure 4.5 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 5.5 | Does the calibration statistic satisfy agreed performance criteria? | | Missing | Deficient | [✓ Adequate] | Very Good | | | 3.1m residual mean; 17mRMS; 12 %RMS. |
| 5.6 | Are there good reasons for not meeting agreed performance criteria? | | Missing | Deficient | [✓ Adequate] | Very Good | | | Reasons given in Section 4.3.1 for VWP groundwater levels. |
| **6.0** | VERIFICATION | | | | | | | | *Document B.* Jan-Aug. 2015: 8 months. |
| 6.1 | Is there sufficient evidence provided for model verification? | | Missing | Deficient | [✓ Adequate] | Very Good | | | Several lines of evidence: scattergram; performance statistics; hydrographs plots; spatial pattern; section head pattern; mine inflow; baseflows. No comparison offered with calibration performance.<br>Short period of time (6-8 months). |
| 6.2 | Does the reserved dataset include stresses consistent with the prediction scenarios? | | Unknown | No | Maybe | [✓ Yes] | | | Short period of time (6-8 months). |
| 6.3 | Are there good reasons for an unsatisfactory verification? | | Missing | Deficient | [✓ Adequate] | Very Good | | | Reasons given in Section 4.3.1 for VWP groundwater levels. |
| **7.0** | PREDICTION | | | | | | | | *Document B.* |
| 7.1 | Have multiple scenarios been run for climate variability? | | Missing | Deficient | [✓ Adequate] | Very Good | | | Average climate only. |
| 7.2 | Have multiple scenarios been run for operational /management alternatives? | | Missing | Deficient | Adequate | [✓ Very Good] | | | Mitigation options. But only the base case is reported. |
| 7.3 | Is the time horizon for prediction comparable with the length of the calibration / verification period? | | Missing | [✓ No] | Maybe | Yes | | | 19 years' prediction. 5 years combined calibration and verification. |
| 7.4 | Are the model predictions plausible? | | | No | Maybe | [✓ Yes] | | | Thorough investigation. |
| 8.0 | SENSITIVITY ANALYSIS | | | | | | | | *Document B.* |
| 8.1 | Is the sensitivity analysis sufficiently intensive for key parameters? | | Missing | Deficient | [✓ Adequate] | Very Good | | | A: caving height; B: vertical hydraulic conductivity; and C: mine drain conductance. |
| 8.2 | Are sensitivity results used to qualify the reliability of model calibration? | | [✓ Missing] | Deficient | Adequate | Very Good | | | Not reported. |
| 8.3 | Are sensitivity results used to qualify the accuracy of model prediction? | N/A | Missing | Deficient | [✓ Adequate] | Very Good | | | Only for mine inflow: 0-28% increase. Not reported for changes in drawdown and baseflow impacts. |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **9.0** | UNCERTAINTY ANALYSIS | | | | | | | | *Document B.* |
| 9.1 | If required by the project brief, is uncertainty quantified in any way? | | Missing | No | [✓ Maybe] | Yes | | | Based on sensitivity analysis for three model parameter perturbations.<br>Not a formal uncertainty analysis.<br>Only reported for mine inflow: 0-28% increase. Not reported for changes in drawdown and baseflow impacts. |

**KALF AND ASSOCIATES Pty Ltd**
**Hydrogeological, Numerical Modelling Specialists**

# KA Peer Review of Coffey Groundwater Modelling Assessment of the Hume Coal Project

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**B.Sc. M.App.Sc PhD**
**12 September 2016**

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## Background and Summary of Key Issues

This report is the Kalf and Associates Pty Ltd (KA) final peer review commissioned by Hume Coal Pty Ltd (Hume) for the Coffeys Geotechnics Pty Ltd (Coffey) hydrogeological and groundwater modelling assessment. This KA review of the Coffey reports (Volume 1 Data Analysis and Volume 2 numerical modelling) follows on from KA requested clarifications and comments about the earlier draft versions of those reports. For the modelling review herein the available Modelling Guideline documents (NWC 2012, MDBC 2001) content have been taken into consideration in this assessment. A modelling appraisal checklist is provided herein as an attached Appendix.

POSCO Australia proposes to develop and operate an underground mine that would extract coal from the Wongawilli Coal seam in the Permian Illawarra Coal Measures. Mining proposed is known as the Pine Feather (PF) method. This method uses non-caving first workings in order to restrict any subsidence of overlying strata. Longwall mining panels are therefore not to be employed and hence there would not be any development of goaf caving. The PF mining would involve construction of parallel but separated relatively small dimension tunnels (‘plunges’) extending either side of a ‘panel’ comprised of gate roads (Figure 1.1 Coffey 2016 Vol 1). The plunges would remain open post-mining with deformation extending to less than 3m into the overlying roof according to the Coffey report (Section 1.1 Coffey 2016 Vol 1). Further more detailed discussion on this deformation is provided in the same Coffey (2016) report in Section 10.5.

Mining is proposed for a period of 19 years followed by closure and rehabilitation over a two year period. During operations coal washery tailings are to be placed in the main mined out voids with subsequent sealing of ‘panel’ gate roads using bulkheads. Excess mine water will also be stored in the sub-surface workings.

The mining zone is situated within the Hawkesbury River Basin with Triassic Narrabeen and Hawkesbury Sandstone overlying the Coal Measures together with an isolated younger basalt area south of the Hume mining zone. Alluvial development is limited along the upstream reach of the Wingecarribee River, the main drainage within the region but is not a significant issue with regard to mining influence.

Modelling included using data from the Berrima mine that was active from 1926 to 2011 for setting up the starting hydraulic head distribution followed by transient calibration from 1 January 2011 to 31 December 2014.

The modelling results indicate that total drawdown within the sedimentary strata would affect 117 private bores with 99 private bores having a drawdown (i.e. ‘differential drawdown’) predicted greater than 2m or more due to only the Hume mining after 17 years of operation (Figure 6.6 Coffey 2016 Vol 2). Table 16 (Vol 2) indicates bores that may require replacement during mining as a consequence of drawdown influence.

No direct leakage from the Wingecarribee River flow due to the Hume Project is predicted although there would be some interception of about 0.85 ML/day of its baseflow at year 13. Interception of Medway Rivulet baseflow is predicted to be about 0.93 ML/day (Table 14 Coffey 2016 Vol 2).

The modelling results indicate shallow watertable drawdown greater than 2m that may influence ecosystems. This influence, if any, is still to be determined by ecologistists.

Groundwater quality in the mine site area varies depending on lithology of the strata although the overall salinity is low and within the 'fresh' category. Hawkesbury Sandstone has the best quality with an average EC of 296 microSeimens, whilst the Wongawilli Coal seam has an average EC of 392 microSeimens.

Inflow rate to the mine steadily increases to a maximum in year 15 to about 6.3ML/day and then decreases more rapidly to less than 1.5 ML/day in year 22 (Figure 6.1 Coffey 2016 Vol 2). Inflow includes predominately intercepted groundwater storage in the sedimentary strata and some very minor baseflow volume. Total volume of intercepted water comprising almost all sedimentary strata groundwater is predicted to be about 33 GL during the active mine operation.

## Peer Review Assessment

### *Previous Studies and Reviews*

The surrounding region of the proposed Hume Coal Mine has had previous mining operations since the 1800s all of which have now been abandoned. These mines include the Berrima Mine (1926 to 2013); Loch Catherine Mine (1924 to 1958) beneath the Berrima Colliery Stockpile; Southern Colliery 5km from Hume site and several other smaller operational adits.

Parsons-Brinckerhoff (2015) prepared a fieldwork and monitoring report for Hume Coal Pty Ltd while Pritchard et al. (2004) provide a review of the status of groundwater resources in the Southern Highlands, NSW. Additional references on studies conducted in the region are provided in Coffey (2016 Vol1 and 2).

### *Hydrogeological and Modelling Description*

Coffey (2016 Vol 1 and 2) have provided a detailed and informative exposition of the hydrogeology and modelling assessment of the impact of sub-surface mining at the proposed Hume Coal Project. The reports cover a wide range of topics that are included within the main headings as follows. ***Volume 1:*** *Executive Summary; Climate; Surface drainage; Geology; Subsurface hydraulic properties; Groundwater levels; Groundwater inflows to Berrima void; Groundwater character; Groundwater use; Hydrogeological conceptual model; References.* ***Volume 2:*** *Executive Summary; Proposed mining; Model development; Model Calibration; Predictive simulation; Predictive results; Flow budget; Drawdown; Impact assessment; Parameter sensitivity analysis; Conclusions; Limitations and References.*

### *Model Conceptualisation and Simulation Methods*

Model pre-mine interpolated water table for the Hume Mine Project region by Coffey is shown in Figure 4.4 (Vol 1); pre-mine hydraulic heads in Sandstone and coal seam (Figure 6.3 and in Appendix E); hydraulic head section (Figure 6.1 Vol 1) and interpolated heads for the basalt flow unit cross-section in Figure 6.7 (Vol 1). No post-mine conceptual figure is provided.

A total of 13 active model layers (Coffey 2016 Vol 2, Table 2) were used for the Hume numerical model. They include layer 1 representing the Wianamatta Group (where present); layers 2 to 7 subdividing the Hawkesbury Sandstone into variable thickness layers; layer 8 comprising the Narrabeen Group interburden; layers 9 to 12 representing the Wongawilli Seam and Illawarra Coal Measures and basal layer 13 representing the Shoalhaven Group. This layer subdivision is considered to be suitable and provides sufficient vertical resolution of model hydraulic head calculation.

Coffey has used the well-known MODFLOW-SURFACT (MS) code for the Hume numerical model. No plan view of the cell mesh is provided because of unsuitable cell mesh print resolution according to Coffey. However, model area and the area of the proposed Hume workings within it are presented in Drawing 1 ‘Regional Locality Plan’ (Volume 2) at the end of that report. The cell mesh is comprised of 379 columns and 425 rows with dimensions 50m x 50m over the Hume mine site expanding to 50m x 100m and 200m x 200m elsewhere. A representative cell mesh layering cross section is presented in Figure 3.1 (Coffey 2016 Vol 2).

The boundaries chosen for the model area are considered suitable. They included no-flow boundary along topographic divides; discharge zones along drainage channels; constant head of the Wingecarribee Reservoir and discharge zones at escarpments modelled as ‘drain’ cells. Remaining boundaries are at a sufficient distance not to interfere or influence drawdowns within or immediately surrounding the Hume proposed mining zone.

Depictions of the various ephemeral and perennial stream channels have been modelled using the MS ‘River’ package with the ability of the model to set stage such that the Wingecarribee River acts either as a gaining or losing stream. This package was also used for simulating Medway Dam heads. Remaining ephemeral channels were set using the ‘drain’ package. This approach is suitable for the modelled area.

The model applies recharge as a constant percentage of incident rainfall. Evapotranspiration rate was applied at a constant 3mm/day (1095.5 mm/year) with a 1.5m extinction depth. This extinction depth is quite shallow but its limited affect would be countered to a large extent by the relatively high potential ET rate applied.

Transient simulation over a long period (1926 to 2011) was used to set up initial historical heads followed by transient production simulation and a verification period. Initial hydraulic parameters were based on measured values of the mining site and elsewhere (Coffey 2016 Vol 1, Figures 5.1, 5.2).

### *Model Calibration and Prediction*

The calibration simulations were conducted in two stages. The first stage included a transient simulation over the period of Berrima mining from 1926 to 2011 to provide a model area starting head distribution in lieu of the conventional ‘Steady State’ simulation. This was followed by a second stage during the end of mining period at Berrima from 1 January 2011 to 31 December 2014. Verification was conducted for a short period from 1 January 2015 to mid-2015. The approach used for calibration is considered by KA to be suitable for the hydrogeological conditions and mining activity in the area.

Calibration transient targets included hydrographs of one to three years duration at 49 points in the subsurface at 23 locations. In addition the DeBeaujeu bore (Figure D1 Appendix D Volume 1) was used for monitoring the Berrima mining influence. There is agreement that the groundwater level response hydrograph (Appendix D) of this bore is predominately due to mining influence but also with minor influence of recharge.

The hydrograph of Culpepper Production (C Prod) bore that is situated to the east of the DeBeaujeu bore indicates short intermittent to more intense intermittent pumping signatures that has also been influenced by Berrima mining and to a minor extent due to lower rainfall period during 2012.

Calibrated hydraulic conductivity and storage parameters used in the model are provided in the Table 3 (Coffey 2016 Vol 2). A comparison of calibrated and *"observed",* that is hydraulic testing or core values, is provided in Figure 4.5 (Vol 2). All values of hydraulic conductivity and storage appear plausible.

The values for vertical hydraulic conductivity of model layers 4 and 5 that represent part of the subdivided Hawkesbury Sandstone are lower than in adjacent layers. Coffey contend these somewhat lower values are justified based on the calibration outcomes. Coffey has advised that if layers 4 and 5 had been given similar vertical hydraulic conductivity as adjacent layers the modelled base flows would have been too low and observed mine inflows too high. Also under these conductivity conditions shallow drawdown would have been too large and deeper drawdowns too small.

Calibration fit statistic for the modelled and observed hydraulic heads is about 12% SRMS (scaled root mean square) which just exceeds the 10% recommended by MDBC (2001) (Coffey 2016 Figure 4.2 Vol 2). But given the unknown precise mining activity over time at previous active mines this is acceptable.

A comparison made between measured and modelled head distribution section (Figure 4.3 Vol 2) on first inspection is considered to be only fair; however, it is noted that the sections are not equivalent but are offset from each other and the interpreted head distribution is based on relatively sparse manually interpolated data whilst the model heads are calculated at every cell mesh location yielding a much higher head resolution in the modelled section. Comparison between measured and simulated hydrographs is considered reasonable to quite good (Appendix B).

Model verification is considered by KA to be preliminary over the relatively short time period available from 1 January 2015 up to July 2015. Hence additional verification will require ongoing monitoring for a longer time period.

### *Sensitivity and Uncertainty*

Several sensitivity runs were conducted that included changing the relaxation deformation height of the plunges; an increase in vertical hydraulic conductivity of model layers by a factor 3. As noted above, the implications independently of increasing model layers 4 and 5 vertical hydraulic conductivity was also assessed. In addition, sensitivity included a change in Hume mine drain conductance that yielded only a minor change in inflow. While there is no formal uncertainty analysis Coffey have outlined the sources of uncertainty in the hydraulic head targets and have confidence that the calibration and in particular the vertical hydraulic conductivity values *"have a high level of reliability"* and therefore reduce uncertainty in model outputs (Vol 2, Executive Summary and Section 8 – Coffey 2016).

### *Groundwater Monitoring and Mitigation*

There is currently an extensive groundwater level and quality monitoring network operated by Hume (Volume 1 Executive Summary) and in addition, rainfall, and streamflow monitoring at four gauges is also conducted. It is understood this monitoring would continue prior to and during the mining project. The monitoring data, including where possible private bore water levels, would be adequate to validate the modelling predictions.

Mitigation measures (Section 5.3.1 Vol 2 Coffey 2016) would form an integral part of the mining project and include bulkhead sealing and tailings backfilling. In addition, injection of excess mine water back into the voids through the bulkheads is proposed.

It is understood that the fate of any injected water and any expression of tailings liquor will be assessed in a separate document by another consultant and KA understands that assessment be conducted using a suitable solute-transport numerical simulation code. Those outcomes are not part of the review presented herein nor was it included in the brief provided by Hume for inclusion in this review.

Although not specifically discussed in either report volumes there is a need to indicate what action Hume would take for those 99 private bores (Table 2, Vol 2 Appendix G, Coffey 2016) that will be affected due to Hume mine differential drawdown greater than the ‘minimal harm’ of 2m and how the projected 16 replacement bores (Table 16, Vol 2) would be assessed, constructed and tested.

### *Conclusions and Considerations*

This peer review has assessed the adequacy of the hydrogeological data and the numerical model for predicting the drawdown influences of the proposed Hume coal mining project. The hydrogeological description, conceptualisation, model design, simulations have been conducted in a professional manner and the exposition of these activities in the two Coffey reports are described in detail. No major flaws in the hydrogeological information or the modelling have been detected in the reports Volumes 1 and 2.

Because of the influence of Hume mining is likely to affect a large number of bores, frequent monitoring of the groundwater system would need to be continued prior to and during mining operation operations and for some years post mining. Monitoring bore data should be reviewed and compared with modelling results every 2 years.

## References

***Coffey Geotechnics Pty Ltd (Coffey 2016)*** *Hume Coal Project Groundwater Assessment*. Reports *Volume 1 and 2 prepared for Hume Coal Pty Ltd. August.*

***National Water Commission (NWC) 2012*** *Australian Groundwater Modelling Guidelines. Report prepared by Barnett, B., et al. Waterlines Report Series No 82, June.*

***Murray Darling Basin Commission (MDBC) 2001.*** *Groundwater Flow Modelling Guideline. Report prepared by Middlemis, H., Merrick, N., and Ross, J., Jan.*

***Parsons-Brinckerhoff (2015)*** *Water Fieldwork and Monitoring Report. Draft Report2200539A-RES-REP-7812 RevA prepared for Hume Coal Pty Ltd. Nov*

***Pritchard et al. (2004)****A review of the status of the groundwater resources in the Southern Highlands, NSW. NSW Department of Infrastructure, Planning and Natural Resources. May.*

# APPENDIX

## MODEL APPRAISAL

| | ISSUES | Not applicable or Unknown | | | | | COMMENTS |
|---|---|---|---|---|---|---|---|
| **1.0** | **THE REPORT** | | | | | | |
| 1.1 | Is there a clear statement of project objectives in the modelling report? | | Missing | Deficient | Adequate | [✓ Very good] | |
| 1.2 | Is the level of model complexity clear or acknowledged? | | Missing | No | [✓ Yes] | | |
| 1.3 | Is a water or mass balance reported? | | Missing | Deficient | Adequate | [✓ Very good] | |
| 1.4 | Has the modelling study satisfied project objectives? | | Missing | Deficient | Adequate | [✓ Very good] | |
| 1.5 | Are the model results of any practical use? | | | No | Maybe | [✓ Yes] | |
| **2.0** | **DATA ANALYSIS** | | | | | | |
| 2.1 | Has hydrogeology data been collected and analysed? | | Missing | Deficient | Adequate | [✓ Very good] | |
| 2.2 | Are groundwater contours or flow directions presented? | | Missing | Deficient | Adequate | [✓ Very good] | |
| 2.3 | Has all relevant potential recharge data been collected and analysed? | | Missing | Deficient | Adequate | [✓ Very good] | |
| 2.4 | Has all relevant potential discharge data been collected and analysed? | | Missing | Deficient | Adequate | [✓ Very good] | |
| 2.5 | Have the recharge and discharge datasets been analysed for their groundwater response? | | Missing | Deficient | Adequate | [✓ Very good] | |
| 2.6 | Are groundwater hydrographs used for calibration? | | | No | Maybe | [✓ Yes] | |
| 2.7 | Have consistent data and standard elevation units been used? | | | No | [✓ Yes] | | |
| **3.0** | **CONCEPTUALISATION** | | | | | | |
| 3.1 | Is the conceptual model consistent with project objectives and the required model complexity? | | Unknown | No | Maybe | [✓ Yes] | |
| 3.2 | Is there a clear description of the conceptual model? | | Missing | Deficient | [✓ Adequate] | Very good | |
| 3.3 | Is there a graphical representation of the modeller's conceptualisation? | | Missing | Deficient | [✓ Adequate] | Very good | |
| 3.4 | Is the conceptual model unnecessarily simple or unnecessarily complex? | | | Yes | [✓ No] | | |
| **4.0** | **MODEL DESIGN** | | | | | | |
| 4.1 | Is the spatial extent of the model appropriate? | | | No | Maybe | [✓ Yes] | |
| 4.2 | Are the applied boundary conditions plausible and unrestrictive? | | Missing | Deficient | Adequate | [✓ Very good] | |
| 4.3 | Is the software appropriate for the objectives of the study? | | | No | Maybe | [✓ Yes] | |
| **5.0** | **CALIBRATION** | | | | | | |
| 5.1 | Is there sufficient evidence provided for model calibration? | | Missing | Deficient | Adequate | [✓ Very good] | |
| 5.2 | Is the model sufficiently calibrated against spatial observations? | | Missing | Deficient | Adequate | [✓ Very good] | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 5.3 | Is the model sufficiently calibrated against temporal observations? | | Missing | Deficient | Adequate | [✓ Very good] | |
| 5.4 | Are calibrated parameter distributions and ranges plausible? | | Missing | No | Maybe | [✓ Yes] | |
| 5.5 | Does the calibration statistic satisfy agreed performance criteria? | | Missing | Deficient | [✓ Adequate] | Very good | |
| 5.6 | Are there good reasons for not meeting agreed performance criteria? | 🟩 | Missing | Deficient | Adequate | Very good | Performance criteria have been met |
| **6.0** | **VERIFICATION** | | | | | | |
| 6.1 | Is there sufficient evidence provided for model verification? | | Missing | Deficient | [✓ Only just Adequate] | Very good | Preliminary but much longer period would be desirable with ongoing monitoring. |
| 6.2 | Does the reserved dataset include stresses consistent with the prediction scenarios? | 🟩 | Unknown | No | Maybe | Yes | |
| 6.3 | Are there good reasons for an unsatisfactory verification? | 🟩 | Missing | Deficient | Adequate | Very good | |
| **7.0** | **PREDICTION** | | | | | | |
| 7.1 | Have multiple scenarios been run for climate variability? | | [✓ No] | Deficient | Adequate | Very good | |
| 7.2 | Have multiple scenarios been run for operational management alternatives? | | [✓ No] | Deficient | Adequate | Very good | |
| 7.3 | Is the time period for prediction comparable with the duration of the calibration period? | | Missing | [✓ Greater than] | Similar to | Less than | |
| 7.4 | Are the model predictions plausible? | | | No | Maybe | [✓ Yes] | |
| **8.0** | **SENSITIVITY ANALYSIS** | | | | | | |
| 8.1 | Is the sensitivity analysis sufficiently intensive for key parameters/ | | Missing | Deficient | [✓ Adequate] | Very good | |
| 8.2 | Are sensitivity results used to qualify the reliability of model calibration? | | Missing | Deficient | Adequate | [✓ Yes] | |
| 8.3 | Are sensitivity results used to qualify the accuracy of model prediction? | | Missing | Deficient | [✓ Adequate] | Very good | |
| **9.0** | **UNCERTAINTY ANALYSIS** | | | | | | |
| 9.1 | If required by the project brief, is uncertainty quantified in any way? | | Missing | No | [✓ Adequate] | Yes | |
| 9.2 | **Is the model 'fit-for-purpose'?** | | | No | | [✓ Yes] | |