Appendix F

Revised Groundwater Modelling

Hume Coal Project

Revised Groundwater Modelling for Response to Submissions

FOR

Hume Coal Pty Ltd

BY

NPM Technical Pty Limited
trading as
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Role	Persons
Authors	Adam Skorulis and Dr Damian Merrick
Contributors	Braiya White, Joel Vernon
Internal Reviewer	Dr Noel Merrick

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1 INTRODUCTION

The Hume Coal Project (Hume Coal Pty Limited) submitted its Development Application and accompanying Environmental Impact Statement (EIS), including a detailed groundwater assessment to the NSW Department of Planning (DP&E) in March 2017. Following public exhibition (July 2017), Hume Coal received submissions from government agencies and the community. In response to these submissions, HydroSimulations was engaged initially by Hume Coal to undertake a detailed model audit and verification, following on from Dr Noel Merrick's [1] role as a peer reviewer of the EIS modelling. Consequent to the audit, HydroSimulations was engaged to update, revise and undertake sensitivity analysis on the groundwater model developed by Coffey Geoscience (2016b) for the EIS (EIS model) (included as Appendix E and F). These updates, revisions and sensitivity analyses have been undertaken in response to submissions from the NSW Government and interest groups to respond directly to those issues raised in submissions.

The following report presents the method and results of the additional groundwater modelling and sensitivity analysis undertaken by HydroSimulations. This report should not be considered as a replacement of the EIS Model report but as an adjunct to it.

1.1 SCOPE OF WORK

The agreed scope of work reflects those issues raised during submissions and have been categorised into the following six distinct stages, expanded below;

A. Response to the independent peer reviewer report, agency reviews and interest group submissions
B. Model tests
C. Model revision
D. Scenario analysis
E. Uncertainty analysis
F. Sensitivity analysis

This report provides a detailed response to the issues raised during submissions and presents the results of the additional groundwater modelling and associated tasks conducted for scope items B – F in response to those submissions.

1.1.1 A – RESPONSE TO SUBMISSIONS

The first action in scope A was to review and respond to those issues and comments described in the report prepared by HydroGeoLogic Pty Ltd through Hugh Middlemis, '*Hume Coal Project EIS Independent Expert Review Groundwater Modelling'* Report dated 6 December 2017. Hugh Middlemis was commissioned as an expert reviewer to assess the EIS groundwater model report by the DP&E. These issues and comments are discussed below in **Section** 3.

The second step involved a review of submissions authored by UNSW (23 June 2017) and Pells Consulting (22 June 2017), followed by consultation on the requested additional modelling to be undertaken with DI Water and DP&E on 25 August 2017, and Hugh Middlemis and DP&E on 9 October 2017. This enabled the scope of revised modelling to be finalised and undertaken.

[1] Dr Noel Merrick is a Director of HydroSimulations

This report forms part of the overarching 'Response to Submissions' report (RTS) and will serve as an appendix report to support the overall RTS, specifically addressing the detailed work requested by some of the submissions received from DI Water, WaterNSW, Dr Steven Pells (Pells Consulting), Doug Anderson (UNSW) and various interest groups, during exhibition. A detailed response to each of their issues and the response following the additional groundwater modelling can be seen in **Section** 3. In particular, responses to the comments raised in the HydroGeoLogic review are presented in **Appendix A**.

1.1.2 B – MODEL TESTS

Scope item B consists of the revisions made by HydroSimulations to the EIS groundwater model (Coffey, 2016b) presented in the EIS in March 2017.The revisions made to the EIS groundwater model included a re-run of the model using a later version of MODFLOW-SURFACT with better solver settings that reduced the high mass balance errors in the EIS model. Additionally, calibration statistics were re-calculated for the entire observed dataset, rather than a subset, without the inclusion of less reliable vibrating wire piezometer (VWP) data.

The model layer thicknesses used in the EIS model were examined to assess the thicknesses used for the different layers across the model domain, particularly the thickness of material modelled between the base of the Hawkesbury Sandstone and the working section of the Wongawilli Seam. This was conducted to determine whether submissions made on this subject were justified, or whether the EIS reporting was not sufficiently clear on how this was represented in the EIS groundwater model.

A trial conversion to MODFLOW-USG was later completed, as suggested by Andrew Druzynski of *DI Water*. This conversion further reduced the mass balance errors and runtimes and MODFLOW-USG was retained as the software utilised for the model update, revision and sensitivity analysis detailed in this report.

1.1.3 C – MODEL REVISIONS

Scope item C of this report details the revisions made to the EIS groundwater model; these are documented within **Section 1.1.3**.

The focus of these revisions was to incorporate features in the model that were not available within the software used for the EIS groundwater model (MODFLOW SURFACT – V3).

With the conversion of software to MODFLOW-USG, the approach to simulate the proposed mining of the Hume Coal Project was revised. Within the EIS groundwater model, drain cells remained active after the completion and sealing of a mine panel. This was used as an accounting method to determine the time required for a void to fill with water. The Time Varying Materials (TVM) package available in MODFLOW-USG was utilised within the revised model to more accurately simulate the properties of the workings and available void volume following coal extraction. This allowed for the drain cells used to simulate active pumping from workings to be switched off following the cessation of pumping within each panel. The TVM package was not available in the software used for the EIS groundwater model (Coffey, 2016b).

The pseudo-soil function was also activated as part of the model revisions and allowed for a more realistic simulation of recovery within the groundwater system following cessation of the Hume Coal Project.

Unnecessary features within the model were removed to conserve memory and improve run-time. This included the removal of extra rows south of the active model domain, as well as inactive layers below the base of the model. Stress period lengths were progressively increased from 6 months out to 5 years following the cessation of active Hume Coal Project mining. This reduced the number of stress periods from 202 to 54.

1.1.4 D – CLIMATE SCENARIO ANALYSIS

While defensible, the EIS model predictions were based on average climate into the future. This is a standard and proper approach for predictive modelling to ascertain mining effects exclusive of potential climate effects.

However, as requested by DI Water, Scope Item D presents results from a climate scenario analysis conducted on the prediction model. This analysis utilised the 108 climate sequences adopted by WSP, the consultancy responsible for the surface water assessment in the EIS submitted in March 2017.

As the running of 108 separate climate scenarios would be slow and inefficient using conventional modelling techniques, customised programming was completed that allowed for automatic generation of model input files, with the simulations conducted in parallel within the cloud using AlgoCompute software by HydroAlgorithmics Pty Ltd. A more detailed explanation of the cloud computing utilised to complete this scope item can be found in **Section 1.1.4**

Outputs from the climate scenario analysis are:

- Mine inflow
- Baseflow reduction for simulated streams
- Number of bores impacted by 2m or greater drawdown
- 2m drawdown extent

These are presented as percentage differences between 5th and 95th percentile aggregate outputs from all scenarios.

Further model runs were completed that used the 'wettest' and 'driest' climate scenarios, based on maximum and minimum average daily rainfall. These are compared against outputs based on the average climate values utilised in the EIS groundwater model (Coffey, 2016b).

1.1.5 E – UNCERTAINTY ANALYSIS

At the time of publication (March 2017), the EIS groundwater model was completed in line with groundwater model guidelines and SEARs prescribed by government agencies. However, over the past year State and Commonwealth expectations, and the recent release of the draft IESC Explanatory Note for Uncertainty Analysis in Groundwater Modelling, have resulted in uncertainty analysis being required for most mining project proposals.

Uncertainty analysis as conducted for scope item E is not often undertaken in the groundwater modelling industry. This is due to the time requirements and subsequent high cost implications associated with computing a sufficient number of *monte carlo* simulations for different realisations of model properties. That is, for an uncertainty analysis to be robust, enough simulations should be completed to ensure the analysis sufficiently explores the full range of uncertainty within each examined model property. Efficient uncertainty analysis for complex models has only become possible recently, with the release of software enabling cloud computing such as AlgoCompute software by HydroAlgorithmics Pty Ltd, and PEST Cloud software by S.S. Papadopulos & Associates, Inc. and Watermark Numerical Computing. However, increased timeframes and cost are still pertinent considerations for uncertainty analysis of this level. Cloud based uncertainty analysis allows multiple processors to be used simultaneously on third-party hardware via the cloud. Using this method, 500 hours of processor time can be run in around 2 hours, with the bulk of the work effort now being involved in model set-up and post-processing the results.

Specialist programming was required to automatically generate the model input files for the necessary number of realisations of the model, which were then utilised in the sequential batch running of the steady-state, calibration, null and prediction models for each realisation. Sets of runs for multiple realisations occurred in parallel using cloud computing to enable up to 256 computers to process the vast amounts of data simultaneously.

The uncertainty analysis was conducted on vertical and horizontal hydraulic conductivity, based on distributions of hydraulic conductivity with depth for observations within the Hume Coal Project area and the greater Southern Coalfield.

Outputs from the uncertainty analysis include:

- Mine inflow
- Bore drawdown
- Baseflow interception for four streams

Post-processing of the uncertainty analysis results provided the following:

- Water table drawdown - at 50th percentile.
- 2m water table drawdown contours - at 33rd, 50th, and 67th percentiles.
- A risk map - showing the cell-by-cell confidence that water table drawdown would be less than 2m.

1.1.6 F – SENSITIVITY ANALYSIS

Submissions received during exhibition included comments that the sensitivity analysis conducted on the EIS groundwater model (Coffey, 2016b) were not extensive enough.

Further sensitivity analysis was conducted on these aspects of the groundwater model:

- Magnitudes of formation specific storages and specific yields
- Simulation with/without pseudo-soil
- Drain conductance – adjusted to be higher by 1 order of magnitude
- Vertical basalt barrier - effect of its presence/absence
- Evapotranspiration rate and extinction depth.

To address those issues raised in the submissions, the following model outputs focused on in the sensitivity analysis include:

- Calibration %RMS
- Mine inflows
- 2m water table drawdown extent
- Number of bores impacted by 2m or greater drawdown
- Baseflow interception at simulated streams.

2 HISTORY OF GROUNDWATER MODELLING FOR THE HUME COAL PROJECT

Groundwater modelling has been used to assess the impacts of the Hume Coal Project on the regional groundwater systems of the Southern Highlands region of NSW. The original modelling completed for the EIS has been revised and updated in a number of stages, in light of access to more advanced modelling software, and in response to submissions on the EIS. This section of the report aims to clearly step through and identify how various models have been used to assess uncertainty surrounding the impacts predicted for the proposed Hume Coal Project.

2.1 COFFEY GEOTECHNICS EIS GROUNDWATER MODELLING

The groundwater assessment for the Hume Coal Project EIS undertaken by Coffey Geotechnics was submitted in two volumes: Volume 1: Data Analysis (Coffey 2016a) and Volume 2: Numerical Modelling and Impact Assessment. A large groundwater database was collated for the Hume Coal Project to support the development of a regional numerical groundwater flow model. The collation of the groundwater data and subsequent analysis allowed development of a hydrogeological conceptual model based on the large number of observations in the database. The database contained observations for the following groundwater system parameters:

- Long-term rainfall observations providing a long-term annual average for the mine lease of 957 mm.
- Baseflow estimates from streamflow observations providing an estimated baseflow to drainage channels within the mine lease of about 1.5% to 2% of annual rainfall.
- Hydraulic conductivity measurements from packer tests and pumping tests as well as estimates derived from specific capacity data in government records. These indicate that hydraulic conductivity and storativity decrease with depth and that hydraulic conductivity in the Hume area has greater magnitudes than elsewhere in the Southern Coalfield (being located on a lip of the Sydney Basin).
- Groundwater level and quality monitoring data reveal a hydraulic head field that is elevated along the western Hawkesbury Sandstone outcrop and at Wingecarribee Reservoir to the southeast, and that decreases to the south and northeast.
- Discharge observations from Berrima workings, providing calibration targets for deep groundwater discharges.

The observations within the database reduce the uncertainty surrounding appropriate parameters to use within a groundwater model. The objective of model calibration for the EIS was to simultaneously replicate the following observation datasets:

- Hydraulic conductivity
- Hydraulic heads
- Shallow groundwater discharge (baseflow to streams)
- Deep groundwater discharge (discharge/ inflow to mine voids)

Calibration of the numerical groundwater model to this data set provided a basis for the predictive simulation of Hume Coal Project Mining operations. The groundwater model developed by Coffey Geotechnics and reported on in Coffey (2016b) is referred to in this report as the **EIS model**.

2.2 HYDROSIMULATIONS' REVISED GROUNDWATER MODELLING FOR RESPONSE TO SUBMISSIONS

Several model versions were progressively developed by HydroSimulations during the model revision process. This allowed for ongoing assessments of whether revisions to the EIS model were appropriate and maintained a good calibration to observed data. The progressive model versions also allowed assessment of whether the revisions sufficiently addressed questions raised of the EIS model in submissions. A flow chart of the model versions used by HydroSimulations is shown in **Figure 1**.

The models are named:

1. Preliminary Modified EIS Model – MODFLOW SURFACT V4
2. Preliminary Modified EIS Model – MODFLOW USG
3. Preliminary Mean K Model
4. Modified EIS Model
5. Mean K Model

2.2.1 PRELIMINARY MODIFIED EIS MODEL – MODFLOW SURFACT V4

The EIS model was built and run using the Visual MODFLOW graphic user interface (GUI). A GUI serves as a front end to MODFLOW code and allows for visualisation of the model domain and the parameters within. HydroSimulations' preferred GUI is Groundwater Vistas. The main differences between the two programs are the physical appearance of the program, menu design, and some minor changes to naming conventions of model input files; both Groundwater Vistas and Visual MODFLOW provide access to the same versions of MODFLOW.

Preliminary revisions to the EIS model involved the conversion of the model from the Visual MODFLOW format into a format useable in Groundwater Vistas. Initially, MODFLOW SURFACT V4 software was used to evaluate model revisions in order to remain consistent with the software used in the EIS. MODFLOW SURFACT V4 software is almost the same as MODFLOW SURFACT V3 used in the EIS, but has additional features available, such as the Time Varying Material Property (TMP) module, allowing for simulation using realistic properties for the void following coal extraction.

2.2.2 PRELIMINARY MODIFIED EIS MODEL – MODFLOW USG

This version of the model was run following the conversion of the EIS model from MODFLOW-SURFACT V4 software to MODFLOW USG. The pseudo-soil function was enabled within this model, the simulation of mining was conducted using the TVM function, and the height of relaxation was corrected to intercept layers up to 2m above the roof of the Wongawilli Seam. No changes were made to the hydraulic or storage properties in this model.

2.2.3 PRELIMINARY MEAN K MODEL

This version of the model provided a 'proof of concept' in relation to the adoption of a depth dependent, spatially variable hydraulic conductivity field, as would be simulated in the uncertainty analysis. This model allowed for testing to be done on the various forms of scripting needed to check calibration on-the-fly, and to only keep and process necessary model outputs from the many runs required to satisfactorily complete the Monte Carlo process.

This model served the basis for a preliminary set of uncertainty analysis runs and helped inform the most efficient process for conducting the final uncertainty analysis. The number of runs required to achieve sufficient convergence of the Monte Carlo process was also tested using this model.

As the hydraulic conductivity field may vary greatly between any uncertainty analysis run and the EIS model, it is possible that the initial heads used in the EIS model might not be appropriate for an hydraulic conductivity field produced using the Monte Carlo process. Accordingly, the uncertainty analysis runs use a ‘warm up’ steady state model simulation using the randomised hydraulic conductivity field to produce an initial head field for the subsequent calibration model simulation.

The calibrated initial conditions from the Preliminary Mean K Model were also used in uncertainty simulations where convergence of a steady-state warm up run was not possible.

2.2.4 MODIFIED EIS MODEL

In response to submissions, further data and sensitivity analyses were conducted on the storage properties used in the EIS model. Following the analysis, the specific storage values and specific yield values in the model were increased to values closer to values from literature and to Hume area field test values.

These changes had minimal impact on the model calibration and were adopted for ongoing climate scenario analysis, in particular the simulations of the wettest and driest scenarios.

2.2.5 MEAN K MODEL

Following the revision of storage parameters, the depth dependent hydraulic conductivity field used in the Preliminary Mean K Model was merged with the Modified EIS Model to provide a baseline model for the final uncertainty analysis. As for the Preliminary Mean K Model, the Mean K Model establishes appropriate initial conditions in order to avoid a potentially non-convergent realisation.

The Mean K Model was also used to conduct a sensitivity analysis on the number of pilot points used within each model layer to provide a pattern of spatial heterogeneity. There are greater memory and computing requirements associated with a greater number of pilot points, but better spatial resolution is more able to account for local variations in geological structure and groundwater head variations. The sensitivity analysis was used to determine the number of pilot points that were most appropriate to use based on a balance between the quality of model outputs and the memory and time requirements associated with higher resolution.

3 A – RESPONSE TO HYDROGEOLOGIC INDEPENDENT EXPERT REVIEW

Hugh Middlemis of HydroGeoLogic Pty Ltd was commissioned by the NSW Department of Planning and Environment to conduct an independent expert review of groundwater and related modelling elements of the EIS submitted for the Hume Coal Project. The review was issued on 6 December 2017 by HydroGeoLogic of which Mr Middlemis is the Principal Groundwater Engineer and Director (HydroGeoLogic, 2017).

The key driver for the review was the extent and magnitude of the predicted drawdown as presented in the EIS. Using the EIS Model, simulated drawdown ranged from 2 to 80 m at 93 private bores at 71 properties in and around the project site. The review aimed to identify whether the assessments and conclusions reached by the EIS groundwater model were supported by evidence presented within the EIS, and whether additional information, monitoring, assessment or modelling were adequate to ensure the groundwater impact assessment was appropriately robust. The review also provides commentary on submissions made by Pells Consulting (Stephen Pells), UNSW (Doug Anderson) and Hydroilex (John Lee) in response to the EIS.

HydroSimulations was engaged by Hume Coal to conduct additional investigations and groundwater modelling in response to issues and feedback on the EIS groundwater model as identified in the HydroGeoLogic (2017) review.

A summary of the key matters raised in relation to the EIS groundwater model and the responses by HydroSimulations are presented in the following sections.

A summary table was prepared as part of HydroGeoLogic's report to directly address the key matters raised by the reviewer. A finalised copy of the table and subsequent responses by HydroSimulations can be found attached in the Review Summary Table (**Appendix A).** It is understood that there are no key matters that remain unsatisfactorily addressed. Mr Middlemis concluded:

> *"In summary, it is my professional opinion that the Hume Coal model is fundamentally consistent with best practice in design and execution, although the EIS documentation is deficient (not sufficiently clear on some details; …). It is fit for mining project impact prediction purposes. Certain model performance improvements are warranted, along with uncertainty analyses and updated reporting (it is understood that these are in progress…)."*

3.1.1 WATER BALANCE

The HydroGeoLogic (2017) review makes comment relating to a lack of clarity within the EIS report documentation relating to key areas of modelling. The review suggested this lack of clarity may lead to potential misinterpretations of the model setup and performance.

HydroGeoLogic (2017) states that the approximate 5% discrepancy within the water balance tables has the potential to be misinterpreted as being indicative of a poor model solution, and outside the 1% discrepancy limit at any stress period as defined in the Australian Groundwater Modelling Guidelines (the guidelines) (Barnett *et al*., 2012). The review finds this not to be the case and states the water balance data presented are consistent with aquifer storage depletion due to mine dewatering. The review also provides a contrary opinion to comments made in submissions by the NSW Department of Primary Industries (DPI, 2017) and UNSW (2017), stating that the reported discrepancy is not indicative of flaws in the EIS groundwater model, and that downgrading the model to a Class 1 confidence level based on the discrepancy in the water balance tables is invalid.

In response, the HydroSimulations' rerun of the EIS model using MODFLOW SURFACT V4 with more sophisticated solver software achieved a mass balance error of less than 0.2%. This finding indicates a robust model solution and is under the 1% limit set by national groundwater modelling guidelines. Further detail on the EIS model rerun using SURFACT V4 software can be found in **Section 4.1**.

3.1.2 CALIBRATION

HydroGeoLogic (2017) also refutes the claims of the UNSW (2017) and DPI (2017) submissions, that suggested the EIS model was of Class 1 model confidence due to an SRMS statistic of 11.9%. The reviewer agrees that an SRMS of greater than 10% is a Class 1 model indicator but finds very few other characteristics within the EIS groundwater model to be assessed as a Class 1 model. The reviewer finds the Class 1 classification given to the model within submissions to be a misrepresentation of the model guidelines commentary and assesses the model to be of a Class 2 confidence.

Following model revisions and the upgrade to MODFLOW USG, the model SRMS was reduced to 10.76%, and about 30% of the uncertainty realisations achieved less than 10 %RMS. These model revisions and results are further specified in **Section 4, Section 5** and **Section 7**.

3.1.3 MODELLING OF THE INTERBURDEN

The reviewer (HydroGeoLogic, 2017) made comment on how the EIS model reported implementation of the interburden between the Hawkesbury Sandstone and the working section of the Wongawilli Seam, stating that it was unclear. Issues relating to the interburden were also raised by Pells Consulting (2017) and UNSW (2017).

An internal review of the EIS groundwater model by HydroSimulations found that the interburden thickness (or absence) is correctly represented in the EIS groundwater model and did not need to change as part of the model revisions.

The HydroGeoLogic (2017) review also found that parameters applied to the interburden are representative of the aquifer tests for coal measures in the area, and stated that low permeability parameters had not been applied to the interburden within the model. This is supported by the hydraulic properties provided in the EIS at Table 3 in Coffey (2016b), which show no contrast in hydraulic properties between layer 7 (base of HBSS) and the underlying layer 8 (interburden).

Further detail on the interburden thickness and hydraulic parameters is provided in **Section 4.2**.

3.1.4 REPRESENTATION OF THE HEIGHT OF RELAXATION

Reviewers of the EIS model also identified apparent inconsistencies within the EIS report (Coffey 2016b) in relation to the implementation of the relaxation zone simulated above the Hume Coal Project mine footprint. Figure 5.2 of the groundwater modelling report (Coffey 2016b) indicates the relaxation zone above the Hume Coal mine area extends into the lower Hawkesbury Sandstone.

The internal review by HydroSimulations found that drain cells had been used to simulate the 2m high relaxation zone in Layer 10 only, however in some areas Layer 10 does not include 2m of thickness. This was identified following the investigation of layer thickness by HydroSimulations, across the model domain. Subsequent model revisions made by HydroSimulations have corrected the model to extend the relaxation zone to 2m above the mine workings, independent of model layering. This means there are now zones of enhanced hydraulic conductivity directly connecting the mine workings (layer 11) and the lower Hawkesbury Sandstone (layer 7) in places.

More detail of the model revisions made to the relaxation zone by HydroSimulations can be found in **Section 5.**

3.1.5 DRAIN CELL CONDUCTANCE FOR MINING

The HydroGeoLogic review of the EIS groundwater model reports the history match calibration of drain conductance to mine inflow and groundwater level data at Berrima as a good example of a best practice method. The adjustments made to the drain conductance parameter at the Hume Coal Project based on differing cell size at Hume compared to Berrima were deemed appropriate by the reviewer.

The HydroGeoLogic review also makes comment in relation to submissions by Pells Consulting (2017) and UNSW (2017) that contend the conductance value used in the EIS model is incorrectly calculated and very low. The review found to be incorrect the claim that the conductance value adopted in the EIS is equivalent to having mine workings "sealed or surrounded by a thick layer of compacted clay". The review finds the methods described by Pells Consulting to be inapplicable in this circumstance and inferior to the best practice history match calibration methods applied to the EIS groundwater model. It also appears contradictory to earlier published work (Pells and Pells, 2012) related to unsaturated flow into mine workings which found that:

> "*Desaturation lowers the hydraulic conductivity at this location, forming, in effect, a new layer retarding vertical discharge. The column below the new retarding layer, starved of flow from above, but still capable to transferring flow downward, will begin to desaturate further. A positive feedback loop is thus formed, as further desaturation leads to further reductions in hydraulic conductivity, and so on… Inflow into a longwall mine, for example, may be reduced significantly due to the nature of any such desaturation.*

The implementation of the effect described by Pells and Pells (2012), among other influences, into a groundwater model is undertaken by varying the drain cell conductance and ensuring model calibration.

HydroSimulations did not alter the drain conductance value within model revisions. However, sensitivity analysis on drain conductance was conducted using values an order of magnitude (10x) higher than used in the EIS model. The results of the sensitivity analysis can be found in **Section 8.2**.

3.1.6 HAWKESBURY SANDSTONE HYDRAULIC CONDUCTIVITY PARAMETERS

The HydroGeoLogic (2017) review finds the modelled hydraulic conductivity values applied to the Hawkesbury Sandstone as reasonable. As conceptualised, the hydraulic conductivity values applied to model layers representing the Hawkesbury Sandstone decrease with depth, and also lie near the middle of the range of observed values indicated by various forms of aquifer testing. The sensitivity analysis conducted in the EIS on vertical hydraulic conductivity (Kv) of the Hawkesbury Sandstone was found to be adequate, but the review recommended the undertaking of uncertainty analysis on horizontal hydraulic conductivity (Kh) of the Hawkesbury Sandstone.

HydroSimulations has conducted a Monte Carlo uncertainty analysis on vertical and horizontal hydraulic conductivity, based on the distributions of hydraulic conductivity with depth from aquifer testing within the Hume Coal Project area and the greater Southern Coalfield. Statistical analysis of model convergence for key outputs was conducted on the uncertainty analysis to ensure a sufficient number of runs were simulated, and the results are reliable. The uncertainty analysis on hydraulic conductivity is reported in **Section 7**.

3.1.7 RAINFALL RECHARGE AND EVAPOTRANSPIRATION RATES

It was noted in the review, that despite well-constrained calibration to groundwater levels and shallow and deep fluxes (stream baseflows and Berrima mine inflow), rainfall recharge rates appeared relatively low. The review identified scope for further sensitivity to be conducted on an alternative model with higher recharge.

HydroSimulations conducted cloud-based climate scenario analysis using 108 sequences of historical rainfall data from 1889 to 2014. The aggregate statistical outputs from this scenario analysis are representative of the model's response to the wettest and driest periods experienced in this 108 years and help assess the uncertainty associated with mine inflow and baseflow impacts. The climate scenario analysis is presented in **Section 6**. The model demonstrates that mine-related impacts on the groundwater system are largely insensitive to climate.

Ongoing uncertainty in relation to the evapotranspiration value used in the EIS model was also discussed in the review. The value used was found to be unconstrained by specific measurements or estimates which warrants additional sensitivity testing on the maximum ET rate and extinction depth.

HydroSimulations has conducted sensitivity analysis on the evapotranspiration rate and extinction depth applied to the model. The results of the analysis are presented in **Section 8.4**.

3.1.8 STORAGE VALUES

The HydroGeoLogic (2017) review is in agreement with comments by Pells Consulting (2017) concerning specific storage (Ss) and notes that the specific storage (Ss) values used within the EIS model are very low. However, as the confined storativity parameter (a product of Ss and the layer thickness) is utilised by MODFLOW, the Hydrogeologic (2017) review found the values to be valid and acceptable.

Pells Consulting (2017) was critical of the specific storage values adopted in the Hume Coal model, on the basis of being "mathematically impossible" when the component parts of an unreferenced formula are considered (their equation (1)). The three "mathematically impossible" values are 5E-7, 7E-7 and 1E-6 m^{-1}. However, the alternative Pells Consulting groundwater models use similar values: e.g. 5.05E-7, 5.52E-7, 7.16E-7, 1.52E-6 m^{-1}, etc.

During model revisions, HydroSimulations has increased the specific storage values in the model to align more closely with the values gained from site specific pumping tests as presented in the Groundwater Assessment Data Analysis (Coffey 2016a). The updated specific storage values used by HydroSimulations are further detailed in **Section 5.1**.

3.1.9 BULKHEAD FAILURE

While no specific considerations were made concerning the failure of bulkheads in the EIS, the HydroGeoLogic (2017) review is of the opinion that the method used to simulate mining in the EIS provides an assessment of the drawdown impacts associated with bulkhead failure (by the mining drains being kept active in the EIS model for some years after coal has been extracted).

No further considerations relating to bulkhead failure have been made in the HydroSimulations model revisions. The text below is sourced from Chapter 13 of the overarching Response to Submissions document.

"The catastrophic failure of bulkheads constructed as monolithic plugs is not considered to be a credible scenario due to the inherent nature of their design. A monolithic plug consists of a long plug of cement or grout or another engineered material that fully occupies the host mine heading. These remain in place through two primary mechanisms – self-weight, and interface shear strength between the sides, roof and floor of the mine heading and the plug. A tertiary mechanism is also proposed for the plugs to be constructed for Hume Coal – a slight taper (or wedge-shape) opening in the direction of the sealed off part of the mine. This means that the pressure on the plug will act to jam it more tightly into the tapered sides of the heading.

The bulkheads will be sited, designed, constructed and monitored generally in accordance with international standards, and will be designed to high factors of safety (nominally 4x). As a rule of thumb, this results in the length of the plugs being approximately 1/10 of the maximum possible head – so for example, a plug designed for 100m of head would be about 10m long, and should withstand 400m of head (given the 4x safety factor).

The construction of the bulkheads will include assessment of the surrounding strata and may include pre-treatment of the surrounding strata with a curtain of microfine grout or similar material to reduce the potential for leakage through the rock around each bulkhead. This pre-treatment will be employed on an needs-basis following an assessment of each installation site, and would typically involve drilling a ring of grout holes around the perimeter of each roadway, followed by grouting with microfine cement which is designed to penetrate any cracks or small fissures present in the rock.

The bulkheads will be constructed from a low-shrinkage material, and may also be interface-grouted following construction to ensure no gaps exist between the plug and the rock.

The majority of the panels in the mine are oriented so that the mine workings slope away downhill from the main headings, further mitigating the risk of bulkhead failure, and meaning that the majority of the water contained in each panel will remain contained in the panel even if the bulkheads were to be temporarily depressurised.

Bulkhead sites will be included in the mine's inspection system and monitored according to a trigger and response plan (TARP). The trigger levels and the responses set out in the TARP will be determined by a risk assessment.

If unacceptably high levels of leakage become apparent – as set under the TARP - the panel may be temporarily depressurised and remedial grouting can be employed.

Over the long term (post-mining) the bulkheads will become redundant when the mine workings fill completely with water, and the pressure on either side of the seals equalises."

3.2 MODEL CONFIDENCE

The Hydrogeologic (2017) review provided an assessment of the model class based on how characteristics of the EIS model aligned with confidence class characteristics defined in the Australian Groundwater Modelling Guideline. The review found the EIS model to be of dominantly Class 2 weighting.

HydroSimulations assessed separately the model confidence class for the Preliminary Modified EIS Model (MODFLOW SURFACT V4), and concluded that minor modifications to the EIS Model had achieved a model of Class 2/3 confidence, as summarised in Table 1.

Table 1 **Model confidence level assessment and classification (for the Preliminary Modified EIS Model)**

CLASS	DATA	CALIBRATION [5 yrs]	PREDICTION [19 yrs]	INDICATORS
1 [COUNT 4]	Not much. Sparse. ★ No metered usage. Remote climate data.	Not possible. ★ Large error statistic. (with VWP) Inadequate data spread. Targets incompatible with model purpose.	Timeframe >> calibration Long stress periods. Transient prediction but steady-state calibration. Bad verification.	★ Timeframe > 10x (recovery) ★ Stresses > 5x Mass balance > 1% (or single 5%) (original model) Properties <> field. Bad discretisation. No review.
2 [COUNT 9]	Some. Poor coverage. Some usage info. ★ Baseflow estimates.	★ Partial performance. Long-term trends wrong. ★ Short time record. ★ Weak seasonal replication. No use of targets compatible with model purpose.	★ Timeframe > calibration. Long stress periods. ★ New stresses not in calibration. Poor verification.	★ Timeframe = 3-10x (end mining) Stresses = 2-5x Mass balance < 1% ★ Some properties <> field measurements. Some key coarse discretisation. ★ Review by hydrogeo.
3 [COUNT 12]	★ Lots. ★ Good aquifer geometry. Good usage info. ★ Local climate info. ★ K measurements. Hi-res DEM.	Good performance stats. ★ Long-term trends replicated. Seasonal fluctuations OK. ★ Present day data targets. ★ Head and flux targets.	Timeframe ~ calibration. ★ Similar stress periods. Similar stresses to those in calibration. Steady-state prediction consistent with steady-state calibration. ★ Good verification.	Timeframe < 3x Stresses < 2x (revised model) ★ Mass balance < 0.5% ★ Properties ~ field measurements. Some key coarse discretisation. ★ Review by modeller.

4 B – MODEL TESTS

The EIS groundwater model (Coffey, 2016), which used MODFLOW SURFACT V3 software, was audited and then rerun by HydroSimulations using a later version of MODFLOW SURFACT (SURFACT V4) in which better solver settings were applied in an effort to reduce the mass balance errors presented in the EIS report.

The model layer thicknesses used in the EIS model were also examined, particularly to assess the thickness of material modelled between the base of the Hawkesbury Sandstone and the working section of the Wongawilli Seam. This was conducted to determine whether submissions made on this subject were justified, or whether the EIS reporting was not sufficiently clear on how this was represented in the EIS Model.

4.1 MODEL RE-RUN IN MODFLOW SURFACT V4

The EIS groundwater model (Coffey, 2016b) model received feedback in submissions relating to a mass balance error of greater than the maximum recommended 1%. These metrics and statistics have been updated for the HydroSimulations re-run of the EIS model using SURFACT V4 and updated solver settings.

4.1.1 MASS BALANCE ERROR

Re-running the EIS model with updated solver settings in SURFACT V4 yielded much lower mass balance error than reported in the EIS groundwater model. **Table 2** shows a direct comparison between the reported mass balance percentages for the EIS model and the model re-run conducted by HydroSimulations.

The mass balance discrepancy is below 1% for a Class 2 model and below 0.5% for a Class 3 model.

Table 2 Comparison of cumulative mass balance error between the EIS model and the HydroSimulations re-run

Cumulative Percent Discrepancy		
Model Run	**EIS model (Coffey, 2016)**	**HydroSimulations Re-Run**
Calibration	-3.8	-0.15
Prediction	-27.6	-0.15

4.1.2 FLOW BUDGETS (SURFACT MODEL)

The global water balances for the Preliminary Modified EIS Model (using MODFLOW SURFACT V4) are shown in **Table 3**, averaged over the calibration period of 4.7 years, and in **Table 4**, averaged over the prediction period of 19 years.

For each simulation period, rainfall recharge accounts for about 75% of groundwater system inputs, the balance being provided by river leakage (about 20%) and Wingecarribee Reservoir leakage (about 5%). About half of the groundwater losses are to “drains”, meaning creeks, mine(s) and the escarpment. Evapotranspiration consumes about 20%, baseflow to rivers is about 13% and pumping from private bores is about 15% of groundwater use.

Table 3 Simulated Average Water Balance During the Calibration Period

Component	Groundwater Inflow (Recharge) (ML/day)	Groundwater Outflow (Discharge) (ML/day)
Rainfall Recharge	37.8	-
Evapotranspiration	-	13.7
Rivers	10.4	8.0
Drains	-	30.9
Constant Head	2.3	-
Wells	-	10.0
TOTAL	**50.6**	**62.6**
Storage	**12.0 LOSS**	
Discrepancy (%)	**0.15**	

Notes:

"Rivers" = Wingecarribee River and Medway Dam
"Drains" = Creeks, Berrima Mine, Escarpment
"Constant Head" = Wingecarribee Reservoir
"Wells" = Landholder Bores

Table 4 Simulated Average Water Balance During the Prediction Period

Component	Groundwater Inflow (Recharge) (ML/day)	Groundwater Outflow (Discharge) (ML/day)
Rainfall Recharge	34.8	-
Evapotranspiration	-	10.1
Rivers	9.9	6.7
Drains	-	26.2
Constant Head	2.4	-
Wells	-	7.6
TOTAL	**47.2**	**50.7**
Storage	**3.5 LOSS**	
Discrepancy (%)	**0.15**	

Notes:

"Rivers" = Wingecarribee River and Medway Dam
"Drains" = Creeks, Berrima Mine, Escarpment, Hume Coal Project
"Constant Head" = Wingecarribee Reservoir

"Wells" = Landholder Bores

4.1.3 KEY CALIBRATION STATISTICS

The re-run of the EIS model in the updated MODFLOW SURFACT v4 software showed minimal improvements in the key calibration statistics of the Root Mean Square (RMS) magnitude and the Scaled Root Mean Square (SRMS) percentage.

The calibration model was then converted from MODFLOW SURFACT V4 software to MODFLOW USG, initially with no other changes and subsequently with specific storage values increased to more closely match field investigations (further detailed in **Section 5.1**).

Revised calibration statistics have been obtained on all available time-series calibration data as opposed to the 'last available observed water levels' presented for the EIS model (Coffey, 2016b).

Table 5 shows a comparison between the reported calibration statistics from the EIS model and the re-run conducted by HydroSimulations with the Preliminary Modified EIS Model (MODFLOW USG).

Table 5 Comparison of key calibration statistics between the EIS model and the Preliminary Modified EIS Model USG conversion

Key statistic	EIS Model (Coffey, 2016b)	HydroSimulations USG conversion
Number of Data Points	**49**	**2502**
Residual Mean (m)	3.1	3.7
Absolute Residual Mean (m)	12.14	12.19
Root Mean Square (m)	**17.06**	**15.41 m**
Scaled Root Mean Square (%)	**11.9**	**10.76%**

Figure 2 shows a scattergram of modelled and observed hydraulic heads for the entire calibration period. Poor performance is recognised at bore B62U on the western edge of Berrima Mine workings. While this bore is screened in Hawkesbury Sandstone, observations suggest that the water table could be perched.

Data from two monitoring bores (B63WW and H35B) have been weighted out of the computation of the calibration statistics, as shown by the light green symbols in **Figure 2**. B63WW is a vibrating wire piezometer outlier adjacent to Berrima Mine workings at the level of the Wongawilli Seam. H35B is identified as being located within the perched Wianamatta Group. As discussed within the EIS, zones of unsaturated Hawkesbury Sandstone underlie the areas of the Wianamatta Group where it is present. This indicates low vertical connectivity between the units and shows perched groundwater systems may be present within the Wianamatta Group.

In the model, there is no specific characterisation of hydraulic properties simulating the conditions required to cause perching within the Wianamatta Group. As such, a poor match between modelled and observed heads for a sensor indicating perched groundwater conditions, such as H35B, is expected and observed in both the EIS groundwater model and the HydroSimulations re-run.

Pressure head profiles presented within Volume 1: Data Analysis (Coffey, 2016a) indicate that perching is occurring at the base of the Wianamatta group. Specific capacity test data also presented in Coffey (2016a) show hydraulic conductivity estimates of approximately 1 m/day, the same value as used in the model for the uppermost layer, indicating the approach to modelling the Wianamatta Group, in absence of more extensive data, is appropriate.

4.1.4 FLOW BUDGETS (USG MODEL)

The global water balances for the Preliminary Modified EIS Model (using MODFLOW USG) are shown in **Table 6**, averaged over the calibration period of 4.7 years, and in **Table 7**, averaged over the prediction period of 19 years.

Much lower mass balance discrepancies are achieved with USG software: 0.01% for the calibration period, and 0.00% for the prediction period.

For each simulation period, rainfall recharge accounts for about 72% of groundwater system inputs, the balance being provided by river leakage (about 23%) and Wingecarribee Reservoir leakage (about 5%). About half of the groundwater losses are to “drains”, meaning creeks, mine(s) and the escarpment. Evapotranspiration consumes about 25%, baseflow to rivers is about 10% and pumping from private bores is about 17% of groundwater use.

Table 6 Simulated Average Water Balance During the Calibration Period

Component	Groundwater Inflow (Recharge) (ML/day)	Groundwater Outflow (Discharge) (ML/day)
Rainfall Recharge	37.8	-
Evapotranspiration	-	20.1
Rivers	11.7	7.6
Drains	-	33.4
Constant Head	2.4	-
Wells	-	13.8
TOTAL	**51.9**	**74.9**
Storage	**22.9 LOSS**	
Discrepancy (%)	**0.01**	

Notes:

“Rivers” = Wingecarribee River and Medway Dam
“Drains” = Creeks, Berrima Mine, Escarpment
“Constant Head” = Wingecarribee Reservoir
“Wells” = Landholder Bores

Table 7 Simulated Average Water Balance During the Prediction Period

Component	Groundwater Inflow (Recharge) (ML/day)	Groundwater Outflow (Discharge) (ML/day)
Rainfall Recharge	34.9	-
Evapotranspiration	-	13.2
Rivers	11.6	5.6
Drains	-	27.1
Constant Head	2.5	-
Wells	-	9.4
TOTAL	**49.0**	**55.4**
Storage	**6.4 LOSS**	
Discrepancy (%)	**0.00**	

Notes:

“Rivers” = Wingecarribee River and Medway Dam
“Drains” = Creeks, Berrima Mine, Escarpment, Hume Coal Project
“Constant Head” = Wingecarribee Reservoir
“Wells” = Landholder Bores

4.2 MODEL LAYER THICKNESS EXAMINATION

In submissions received on the EIS Model, questions arose relating to whether the EIS Model had implemented a non-realistic, uniform layer thickness to represent the interburden between the base of the Hawkesbury Sandstone and the proposed working section of the Wongawilli Seam.

HydroSimulations conducted an examination of the model geometry which showed that the interburden between the bottom of the Hawkesbury Sandstone and the top of the working section of the Wongawilli Seam is spatially variable, and closely matches the interpolated interburden thickness figure shown in the EIS groundwater report (Coffey 2016a, Figure 4.3).

Figure 3 shows the modelled thickness in metres of the interburden surrounding the proposed Hume Coal Project area; it is comprised of the cell-by-cell sum of the thickness from the top of model layer 8 to the base of model layer 10. It should be noted that a model layer built using the software available when building the EIS model (MODFLOW SURFACT V3) required fully extensive layers of non-zero thickness. In the model, the area outside the Hume Coal Project Area has an interburden thickness of approximately 1m which is comprised of:

- a minimum thickness of 0.4 m applied to Layer 8 (Interburden) in areas where interburden is identified as absent, with hydraulic parameters equivalent to those used to represent the mined section of the Wongawilli Seam; and

- a minimum thickness of 0.29 m applied to both underlying layers 9 and 10 (Wongawilli Seam above mined section), with hydraulic parameters equivalent to those used to represent the mined section of the Wongawilli Seam

Therefore, a total combined minimum thickness of 0.98 m is applied to layers 8 to 10 between the roof of the mined section of the Wongawilli seam and the base of the Hawkesbury Sandstone.

This is conceptually correct and aligns with the geological interpretation for the area. The EIS Model, therefore, presents a correct representation of the conceptual model; however, this aspect had not been fully explained or reported in the EIS report.

5 C – MODEL REVISION

The following section details those changes made by HydroSimulations to the EIS model to improve performance and to more accurately simulate the progression of mining. These model revisions enabled the updated version of the EIS model to be utilised in the cloud computing runs for scenario analysis and uncertainty analysis as has been conducted for scope items D and E. The model outputs following these changes are then presented with discussion examining any variations observed between the EIS Model and the revised HydroSimulations Model (hereafter referenced as the **Modified EIS Model**).

Numerous revisions have been made by HydroSimulations to the EIS groundwater model, undertaken for the following reasons:

- availability of newer, more sophisticated versions of software;
- identification of techniques for improving prediction accuracy and reducing run time;
- feedback and comments responding to concerns raised by NSW government agencies; and
- feedback and comments responding to concerns raised by external reviewers.

The proposed amendments and changes were communicated to the DP&E through their independent reviewer, Hugh Middlemis, via both draft and final responses to his report titled *Hume Coal Project EIS Independent Expert Review Groundwater modelling* and during a face-to-face meeting between Hugh Middlemis and Dr Noel Merrick at DP&E's premises in Sydney on 9 October 2017.

Equally important are aspects of the EIS model that have not been modified. These unaltered features include:

- lateral model extent;
- model geometry (especially layer thicknesses);
- top layer elevations;
- model parameterisation for hydraulic conductivity properties[2]; while explored within the uncertainty analysis, no recalibration was deemed necessary of the EIS model parameter values;
- model boundary conditions;
- rainfall recharge rates; and
- model initial conditions.

Changes to these model features were considered during the model audit/review (by Dr Merrick) but were deemed unnecessary by HydroSimulations. Any major change in conceptualisation and implementation of the EIS Model (Coffey, 2016a, 2016b) would have involved a near re-build and recalibration of the model, which was not deemed necessary by the peer reviewer Middlemis or as a result of the Hydrosimulations model review. The model review by HydroSimulations concluded that the EIS model is fundamentally sound, as did the review by Middlemis (HydroGeoLogic, 2017).

[2] While not changed in the Modified EIS model, they are altered in the uncertainty analysis base case

Alterations in the approach to modelling made by HydroSimulations, in comparison to the EIS groundwater model, are documented in **Table 8**.

New model features and physical changes made to the model in order to implement the changes in approach are listed in **Table 9.**

With respect to the fourth dot point above, it should be noted that substantial changes were made to the hydraulic conductivity fields for the uncertainty analysis (see **Section 7**). In essence, uniform layer properties were converted to spatially varying properties for the uncertainty analysis.

Table 8 Alterations in approach to modelling

Feature	Alteration	Reason	Outcome
Software interface	From Visual MODFLOW to Groundwater Vistas	MODFLOW GUI (Graphical User Interface) used by HydroSimulations	N/A
Software engine	From MODFLOW-SURFACT v3 to v4	Time-varying material properties (TMP)	Allows changing of property values from coal to void
Solver settings	Tighter convergence (1m --> 0.1m); more inner iterations; automatic time step selection	Poor mass balance (>5%)	Good mass balance (<1%) - Modelled groundwater fluxes more reliable with tighter mass balance
Software engine	From MODFLOW-SURFACT v4 to MODFLOW-USG	Pseudo-soil option not successful with v4. Time-varying material properties (TVM). Allows cloud computing	Better convergence; mass balance <0.1%; solved banded water table drawdown display
Calibration reporting	Inclusion of all data; exclusion of outlier VWP data and perched water table data	Reviewer comment ; notionally “unacceptable” >10 %RMS	<10 %RMS not achieved but values lower than reported for EIS model. - More confidence in representation of groundwater system with lower %RMS
Calibration reporting	Display of spatial residuals	Reviewer feedback	Indicates that residuals are better close to the mine footprint
Stress period (SP) length	From 180 to 182.625 days	1.4% error in timing (e.g. 100 days error after 20 years). (Note: annualised values were adjusted in the EIS to account for the stress period length)	Stress period timing at end of model is accurate
Recovery simulation SP lengths	From uniform 6 months to 1, 5, 10 years out to 100 years	Efficiency - runtime and memory demand	202 --> 54 SP (72% reduction); faster runtime.
Mine drain (DRN) duration	Cessation immediately after mining rather than at the point of complete void refill	Considered to have been a workaround for the lack of a TMP facility in SURFACT v3.	Allows TVM facility to simulate a more realistic recovery post-mining
Updip mining	Mine DRN cells not applied. *[Note that DRN cells were applied in the EIS model but they reported a "to void" volume.]*	Realism. No need to dewater completed mine workings where the water can pool downgradient.	Reduction in "to sump" dewatering requirements. - Shorter duration of complete drainage will allow more realistic simulation of recovery.

Table 9 New model features present in the Modified-EIS model

Feature	Alteration	Reason	Outcome
Time varying materials (K)	Coal void: Kx = 5m/day (x1000) Kz = 1 m/day (x1000) 2m Relaxation zone: Kx x10; Kz x100	Realism. EIS model used host properties (Kx = 0.005; Kz = 0.001 m/day)	Automatic void refill times, rather than manual assumption
Inactive model cells	Removal of two bottom layers; truncation of southern rows and eastern columns	Efficiency - runtime and memory demand	Reduced runtime
Time varying materials (Sy) 1 SUPERSEDED	Coal void: Sy = 0.24	EIS model used host property (Sy = 0.003). Effective Sy scaled down from 1 to allow for partial coal extraction and partial waste infill	Broader 2m drawdown extent. Slower recovery of groundwater levels.
Time varying materials (Sy) 2	Spatially varying Sy to mimic variable coal yield and reject emplacement.	Realism.	Marginal reduction of far-field impacts.
Time varying materials (Ss)	No change.	EIS host value is appropriate (5 x 10^{-7}/m increased globally to 2 x 10^{-6}/m but not time-variant)	Considered insensitive.
"To void" accounting	ZONEBUDGET accounting rather than DRN	Accounts for void inflow and outflow without dewatering	Matches void space when aggregated. Really an unnecessary model function other than showing the temporal profile.
Bulkheads	Activated at completion of each panel by restoring host properties	Realism	Marginal reduction in far-field impacts.
Roadways	Edit model cells to ensure lateral continuity of void cells between mains and side panels	MODFLOW weakness - cannot simulate diagonal flow, only orthogonal flow between model cells	Better conceptually. Greater difference observed between bulkhead and no bulkhead runs.
TVM timing	Mains: active 1 SP after activation of DRN, active contemporaneously with DRN. DRN cells:1 SP after DRNs are deactivated. Updip non-DRN cells: 1 SP after mining is estimated to reach the mains.	Realism. Ease numerical shock.	Realistic depressurisation.

Feature	Alteration	Reason	Outcome
Time Varying Materials (K)	Coal void: Kx = 20m/day (x4000) Kz = 4 m/day (x4000)	Realism. Attempt for model pressure head recovery to reflect what would be expected in open-void scenario.	Increased model run time by 50%
Specific storage (Ss)	Raised x3 (layers 1-5); x4 (layers 6-13)	Reviewer feedback. to better align modelled Ss values with data sourced from Data Analysis	More realistic; marginal calibration benefit by 0.02 %RMS;
Specific Yield	Raised x3 across all model layers	Reviewer feedback, to better align modelled Sy values with data sourced from Data Analysis	More realistic; marginal calibration disbenefit by 0.24%
Relaxation Zone	2m relaxation zone above HCP extended above Layer10 where layer thickness was <2m	The previous model only extended the relaxation zone in to L10 regardless of the layer thickness	More realistic implementation of the relaxation zone. Possibility of increased connectivity between mine workings and lower HBSS
*Greyed model features were later superseded			

5.1 UPDATED SPECIFIC STORAGE VALUES

The specific storage of an aquifer is the amount of water a unit mass or unit volume of aquifer releases, per unit change in hydraulic head, while remaining fully saturated.

A detailed analysis of the specific storage values adopted in the EIS Model was undertaken during the model review due to feedback within submissions on the EIS. Some submissions asserted that the EIS model (Coffey 2016b) utilised specific storage values that were inconsistent with pumping test data indicated within the Data Analysis report (Coffey 2016a) and outside the bounds of what was physically possible for the aquifer material present in the area of the Hume Coal Project.

Although the specific storage values in the EIS model are supported by literature review, they have been increased in the Modified EIS model for better consistency with derived pumping test values. Lower model layers (Layers 6 to 13) underwent a multiplication of the original specific storage values by a factor of 4 while Hawkesbury Sandstone layers and above (Layers 1 – 5) were increased by a factor of 3. **Table 10** compares EIS model values with values indicated in the Data Analysis and the updated values adopted by HydroSimulations in the Modified EIS Model. The values adopted within the model revision are much closer to the average optimised value provided by the pumping tests.

Increasing the specific storage values made no practical difference to the SRMS statistic or the RMS statistic within the revised calibration model (**Table 11**). However, the updated values are more closely aligned to field measurements and are therefore retained in the Modified EIS model.

Table 10 Comparison of modelled Specific Storage [m^{-1}] values with field and literature values presented in Coffey (2016a)

Model Layer	Lithology	Specific Storage (EIS Model, 2016b)	Pump Test – Average Optimised Specific Storage[1]	Specific Storage Indicated in Literature	Modified-EIS Model Specific Storage
1	Wianamatta Group	1×10^{-6}			3×10^{-6}
2	Hawkesbury Sandstone	1×10^{-6}		1×10^{-6} (Hawkesbury Sandstone in Blue Mountains)[2] 1.5×10^{-6} (Hawkesbury Sandstone to 300m depth)[2]	3×10^{-6}
3		7×10^{-7}			2.1×10^{-6}
4		7×10^{-7}			2.1×10^{-6}
5		7×10^{-7}			2.1×10^{-6}
6		5×10^{-7}			2×10^{-6}
7		5×10^{-7}			2×10^{-6}
8	Interburden (Narrabeen Group, WWR Ply and Farmborough Claystone)	5×10^{-7}	3×10^{-6}		2×10^{-6}
9	Wongawilli Seam – above working section	5×10^{-7}			2×10^{-6}
10		5×10^{-7}			2×10^{-6}
11	Wongawilli Seam – working section	5×10^{-7}			2×10^{-6}
12	Illawarra Coal Measures	5×10^{-7}			2×10^{-6}
13	Shoalhaven Group	5×10^{-7}			2×10^{-6}

1.Model layer coverage based on screened lithology of bores used in pumping tests for the calculation of optimised average specific storage. Tammetta (pers. comm.) interpreted a range of (2 to 5) x 10^{-6} m^{-1}.

2.Values indicated for Hawkesbury Sandstone from published estimates in the Blue Mountains (Kelly et al. 2005) and in western Sydney (Tammetta and Hawkes 2009).

Table 11 Effect of increasing specific storage values on key calibration statistics

Model Run	Preliminary Modified EIS model run in SURFACT V4	Preliminary Modified EIS model run in SURFACT V4 with increased specific storage
SRMS %	10.76%	10.74%
RMS (m)	15.41 m	15.38 m

5.2 UPDATED SPECIFIC YIELD VALUES

The specific yield of a rock mass (also known as drainable porosity), is a ratio indicating the volumetric fraction of the bulk rock mass volume that a given rock mass will yield when the water is allowed to drain out under gravity.

The specific yield values adopted in the EIS model (Coffey, 2016b) were questioned within submissions for being lower than reported within the Data Analysis. **Table 12** shows a comparison between the specific yield values adopted in the groundwater model, and those inferred from both the literature and the pumping test data presented in the Data Analysis (Coffey 2016a).

During the model audit and update, a sensitivity run was conducted that used specific yield values in all model layers 3 times (3x) greater than the values from the EIS model. A multiplier of 3x represents approximately a half-order of magnitude, standard practice for Sy (as a full order of magnitude increase can give non-physical values). The resulting range in values from 0.9% to 3.0% gives better consistency with the pumping test estimate (about 1.5%) (see **Table 12**). This step was undertaken following review of submissions and more detailed consideration of the available data in the area. The changes resulted in improvements to the SRMS statistic in the calibration model of 0.25%, and as shown in **Table 13**, increased the specific yields adopted within the Modified EIS model to values which are now, on average, much closer to the values reported within the EIS Data Analysis (Coffey 2016a).

Table 12 Comparison of modelled specific yield values with field and literature values presented in Coffey (2016a)

Model Layer	Lithology	Modelled Specific Yield (EIS Model - Coffey, 2016b)	Pumping Test – Average Optimised Specific Yield	Specific Yield Indicated in Literature	Modified-EIS Model - HydroSimulations Modelled Specific Yield
1	Wianamatta Group	0.01		0.012 (Laminated Shale)[2] – 0.013 (Devonian Siltstone)[2]	0.03
2	Hawkesbury Sandstone	0.01	0.015[1]	0.01-0.02 (Sydney and surrounds Hawkesbury Sandstone)[3]	0.03
3		0.008			0.024
4		0.008			0.024
5		0.005			0.015
6		0.005			0.015
7		0.003			0.009
8	Interburden (Narrabeen Group, WWR Ply and Farmborough Claystone)	0.003		0.005 – 0.007 (Western Coalfield)[4] 0.004-0.008 (Hunter Coalfield)[4]	0.009
9	Wongawilli Seam – above working section	0.003			0.009
10		0.003			0.009
11	Wongawilli Seam – working section	0.003			0.009
12	Illawarra Coal Measures	0.003			0.009
13	Shoalhaven Group	0.003			0.009

1.Model layer coverage based on screened lithology of bores used in pumping tests for the calculation of optimised average specific yield.

2.Values indicated for Wianamatta Group from published estimates for Devonian Siltstone (Risser et al. 2005) and laminated shale (Woods and Wright 2003)

3.Values indicated for undeformed Hawkesbury Sandstone in Sydney metropolitan area and elsewhere (Tammetta and Hewitt 2004)

4.Values for interburden to base of Illawarra Coal Measures indicated by unpublished results for Permian coal measures within the Western and Hunter Coalfields

Table 13 Modelled specific yield over same geological extent as covered by the pumping tests near the Hume Coal Project

Model Layers	Lithology	Median Modelled Specific Yield (EIS Model – Coffey, 2016b)	Pumping Test – Average Optimised Specific Yield	Modified EIS Model - Median HydroSimulations Modelled Specific Yield
2 - 11	Top of Hawkesbury Sandstone – Base of Wongawilli Seam	0.004	0.015	0.012

5.3 FLOW BUDGET (MODIFIED EIS MODEL)

The global water balance for the Modified EIS Model for the prediction period is shown in **Table 14**, averaged over the prediction period of 19 years.

Rainfall recharge accounts for about 72% of groundwater system inputs, the balance being provided by river leakage (about 23%) and Wingecarribee Reservoir leakage (about 5%). About half of the groundwater losses are to “Drains”, meaning creeks, mines and the escarpment. Evapotranspiration consumes about 25%, baseflow to rivers is about 10% and pumping from private bores is about 16% of groundwater use.

The values in **Table 14** are not significantly different from those in **Table 7** for the Preliminary EIS model (before storage parameter changes were made), apart from an increase in the “Drains” component by 3.2 ML/day (12%), more evapotranspiration (by 15%) and a higher average loss from the groundwater system.

Table 14 Simulated Average Water Balance During the Prediction Period

Component	Groundwater Inflow (Recharge) (ML/day)	Groundwater Outflow (Discharge) (ML/day)
Rainfall Recharge	34.9	-
Evapotranspiration	-	15.2
Rivers	11.1	6.5
Drains	-	30.3
Constant Head	2.4	-
Wells	-	10.1
TOTAL	**48.5**	**62.1**
Storage	**13.7 LOSS**	
Discrepancy (%)	**0.00**	

Notes:

“Rivers” = Wingecarribee River and Medway Dam
“Drains” = Creeks, Berrima Mine, Escarpment, Hume Coal Project
“Constant Head” = Wingecarribee Reservoir
“Wells” = Landholder Bores

5.4 KEY CALIBRATION OUTPUTS FOR MODIFIED EIS MODEL

Key outputs demonstrating the ongoing calibration of the Revised EIS Model are presented in the following section.

The modelled water table elevation average residual at target locations for the Modified EIS Model at the end of the calibration period is displayed in **Figure 4**. The lack of data in the eastern domain of the model should be noted as well as the distribution of low calibration residuals near the proposed Hume Coal Project area.

Time series hydrographs presenting observed and modelled hydraulic head are presented in **Figure 5** to **Figure 15** (at bore locations shown in **Figure 66**. As was seen for the EIS model, observed heads are generally well reproduced.

Increasing the specific yield values resulted in some deterioration of the calibration statistics. In going from the Preliminary Modified EIS (USG) Model to the Modified EIS Model, with increases in both specific storage and specific yield, the statistics changed from 10.76 to 11.00 %RMS and 15.41 to 15.75 mRMS.

Following the model updates and revisions by HydroSimulations the model remains appropriately calibrated and is fit-for-purpose to assess the impacts of Hume Coal Project mining.

6 D CLIMATE SCENARIO ANALYSIS

In accordance with standard practice, the EIS model predictions were based on average climate into the future. As the climate impacts for large groundwater systems, such as the Southern Coalfield, are long-term, it is appropriate to use long-term average climate data within groundwater models used to simulate the impacts of mining.

As requested by DI Water in their submission and in the subsequent consultation with them, scenario analysis has been conducted on the prediction model during mining and recovery for the 108 climate sequences adopted by the surface water modellers (WSP PB, 2016).

The climate scenarios were run in the cloud using AlgoCompute software, with outputs presented as aggregate statistics based on all model runs.

Outputs are:

- Mine inflow.
- Baseflow interception for watercourses within the model domain.
- Number of impacted bores and spatial extent of greater than 2m drawdown.
- Wianamatta Group to Hawkesbury Sandstone water exchange.
- Hume Coal Project induced release of groundwater from adjacent Management Zones and water sources.

Separate to the cloud scenario runs, the rainfall data used in each climate run were analysed to select the 'wettest' and 'driest' scenarios (as outlined below in Section 6.2.2). The results of these most extreme wet and dry runs are also presented in this section.

6.1 CLIMATE SCENARIOS

The Modified EIS groundwater model was analysed to determine the time that maximum impacts for the selected outputs occurred. From this, the model length was shortened from a 100-year run length to 35 years. The shortened length of the prediction period reduced model run times despite increased complexity in using time variable rainfall and evapotranspiration factors.

6.1.1 RAINFALL AND EVAPOTRANSPIRATION

The climate scenarios are derived from historical rainfall and Morton actual evapotranspiration rates from 1889 to 2014. A 35-year sliding window beginning in 1889 is used to derive each climate sequence:

- Scenario 1: 1889 – 1923
- Scenario 2: 1890 – 1924
- ….
- Scenario 107: 1995 – 2014, then wrapping back to 1889 – 1903
- Scenario 108: 1996 – 2014, then wrapping back to 1889 – 1904

6.1.2 RAINFALL RECHARGE

Although rainfall recharge varied dynamically, the rainfall recharge rate was held at 1.8% of rainfall throughout each simulation (the calibrated value used in the EIS model). No change was considered necessary as the value was constrained by calibration to baseflows.

6.1.3 RIVER STAGE

As is stated in the EIS model report, only the Wingecarribee River and Medway Dam are simulated using the MODFLOW River package, due to their near-permanent retention of water and their proximity to the proposed mine area. The stage height of a river can be transiently altered within the River package (as could possibly be observed due to climatic influence), allowing for variation in the interaction between surface and groundwater to be examined.

The influence of climate on stage height at Medway Dam and Wingecarribee River was investigated to determine the merit of transiently altering stage height in line with periods of wet and dry climate indicated in the 108 scenarios. All other drainage channels were simulated using the Drain package, indicating their ephemeral nature, with the elevation of the drain inverts set using topographic data, generally LiDAR over a large portion of the modelled area (as discussed in HydroGeoLogic, 2017).

No information on the transient stage height or storage volume of water within Medway Dam is available. Therefore, no relationship between stage height and climate in Medway Dam was able to be established.

The investigation into the impact of climate on the stage height of the Wingecarribee River within the model domain found near-permanent pools with consistent water levels that showed minimal level change in response to periods of above or below average rainfall conditions.

The investigation utilised time series stage height data for two sites on Wingecarribee River downstream of Wingecarribee Reservoir (Berrima Weir and Bong Bong Weir) and one site upstream (Yarrunga Creek) (BoM, 2017). It also considered stipulated release requirements from Wingecarribee Reservoir from *the Water Sharing Plan for the Greater Metropolitan Region Unregulated River Water Sources* (NSW Government, 2011) (further reported in **Appendix C**).

Man-made environmental controls, such as multiple weirs, serving to control stage height, and a 4 ML/day minimum release requirement from the Wingecarribee Reservoir (NSW Government, 2011) into the Wingecarribee River have been identified as the key influences on the stable river stage observed within the model domain.

Upstream of the reservoir, the gauging station at Yarrunga Creek demonstrates more variation in stage height, frequently recording near zero water levels in periods of low rainfall. While this site has a smaller catchment area than the two farther downstream, it serves as a useful comparison to show the nature of a nearby watercourse that does not have the same 'man made' controls on stage height as the modelled reach of the Wingecarribee River.

6.2 CLIMATE SCENARIO ANALYSIS USING CLOUD COMPUTING

Traditional methods of evaluating 108 climate scenarios in individual model runs, each taking several hours on an individual modern computer, would be both cost and time prohibitive. It is neither cost nor time effective to fully explore the sensitivity of a model to historical fluctuations in climate using these traditional computing methods.

Recent offerings in the field of cloud computing have greatly increased the availability and accessibility of computing resources. These developments allow hundreds of model runs to be evaluated simultaneously. AlgoCompute (HydroAlgorithmics, 2018; Merrick, 2017) allows for large-scale modelling in the cloud utilising the Microsoft Azure cloud to launch many simultaneous runs. This eliminates the limitations of attempting a similar assessment on a local computer.

The climate scenario evaluation for the Hume Coal project was undertaken using cloud computing for the Modified EIS Model with the newly developed AlgoCompute software.

6.2.1 AGGREGATE SCENARIO MODEL OUTPUTS

Key aggregate metrics and peak baseflow impacts from the climate sensitivity runs on the Modified EIS Model are given in **Table 15**. These are presented in terms of the absolute change either side of the median value, out to the 5th and 95th percentile results.

Table 15 Absolute differences between 5th and 95th percentile results for key metrics within the climate scenario analysis

Key aggregate metric	Difference in key metrics between the 5th percentile and median climate scenario analysis	Difference in key metrics between the 95th percentile and median climate scenario analysis
Number of bores affected by 2m drawdown or more	-2	2
Maximum mine inflow “to sump” (ML/day)	-0.090	0.118
Maximum total mine inflow (ML/day)	-0.068	0.067
Peak baseflow impact (ML/day)		
Medway Rivulet (whole source)	-0.044	0.161
Medway Rivulet (excluding tributaries)	-0.045	0.141
Oldbury Creek	0.000	0.003
Belanglo Creek	0.000	0.000
Wells Creek	-0.009	0.018
Wells Creek Tributary	-0.012	0.025
Lower Wingecarribee River (whole source)	-0.015	0.015
Lower Wingecarribee River (excluding tributaries)	-0.009	0.012
Black Bobs Creek	-0.002	0.013
Longacre Creek	-0.002	0.005
Upper Wingecarribee River	-0.008	0.008
Lower Wollondilly River	0.000	0.001
Nattai River	0.000	0.000
Bundanoon Creek	-0.002	0.003

It is noted that the uncertainties in the number of bores affected by more than 2m drawdown and mine inflow are very low (<5% change); indicating that these results are insensitive to climate. The uncertainties for Medway Rivulet are about 4-12% from the median impact. The uncertainties for all other streams are very low in terms of their absolute magnitudes (see **Table 17**).

6.2.2 INDIVIDUAL SCENARIO MODEL OUTPUT

Of the 108 modelled climate sequences used within the sensitivity analysis, the ‘wettest’ and ‘driest’ scenarios were selected to be modelled separately from the cloud computing runs. This allowed for results from individual ‘extreme’ historical climate scenarios to be compared against the average climate inputs used in the EIS Model. The EIS Model used a single long-term average rainfall value derived from historical data and applied this to each stress period; the basecase “Average” climate scenario analysis replicated this method.

Table 16 shows information for the selected climate scenarios and key results from the selected runs are presented in **Table 17.**

Table 16 Variation in average daily rainfall between the 'wettest' and 'driest' climate scenarios

Scenario	Scenario number	Date range for historical rainfall data (35 year period)	Average Daily Rainfall During Scenario (mm/day)
Wet	61	1/1/1949 - 1/1/1984	2.52
Dry	103	1/1/1991-31/12/2014, and 1/1/1889-31/12/1899	2.03

The results from these scenarios demonstrate that overall, the model is not sensitive to changes in climate. The greatest change between the wet and dry climate scenarios is observed for Medway Rivulet, with 30% greater baseflow loss reported for the wet scenario compared to the dry scenario. However, this loss is less than 6% higher than the value reported under average climate, similar to what is observed in the rest of the waterways with impacts to baseflow. The differential absolute effects are very low in all cases.

The number of impacted bores is insensitive to climate extremes, with a variation of only about 1%.

Figure 16 shows minimal variation in the spatial extent of the maximum greater than 2m drawdown between the average (basecase), wet and dry climate scenarios. The maximum drawdown displayed in **Figure 16** is a composite of the maximum drawdown at each cell in the model experienced at any time during the simulation.

Table 17 Climate Scenarios - Key Metrics

Key metric	Difference between Wet (Scenario 61) and Average (Basecase)	Difference between Dry (Scenario 103) and Average (Basecase)
Number of bores affected by > 2m drawdown	0	2
Maximum mine inflow rate (ML/day)	0.010	-0.070
Peak baseflow impact (ML/day)		
Medway Rivulet (whole source)	0.042	-0.141
Medway Rivulet (excluding tributaries)	0.024	-0.098
Oldbury Creek	0.001	-0.001
Belanglo Creek	n/a[1]	
Wells Creek	0.057	-0.008
Wells Creek Tributary	0.061	-0.009
Lower Wingecarribee River (whole source)	-0.008	-0.011
Lower Wingecarribee River (excluding tributaries)	-0.001	0.001
Black Bobs Creek	-0.002	-0.011
Longacre Creek	0.000	-0.001
Upper Wingecarribee River	-0.091	-0.012
Lower Wollondilly River	n/a	
Nattai River	n/a	
Bundanoon Creek	0.000	0.000

[1] n/a indicates no baseflow intercepted by stream during Null or Mining scenario

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7 E – UNCERTAINTY ANALYSIS OF HYDRAULIC CONDUCTIVITY PARAMETERS

7.1 METHODOLOGY

The uncertainty analysis addresses hydraulic conductivity parameter uncertainty by stochastic modelling using the *Monte Carlo* method. This method operates by generating numerous alternative sets of input parameters to the deterministic groundwater flow model (realisations), executing the model independently for each realisation, and then aggregating the results for statistical analysis.

A traditional drawback to the Monte Carlo method is that its successful application often necessitates many hundreds or thousands of model runs, each of which may take several hours of run time on an individual modern computer. More complex variants of Monte Carlo analysis exist that aim to explore the parameter space more efficiently than the basic Monte Carlo approach, such as Null Space Monte Carlo (NSMC) (Doherty, 2015) and Markov Chain Monte Carlo (MCMC) approaches (e.g. Vrugt *et al.,* 2009).

Recent offerings in the field of cloud computing have greatly increased the availability and accessibility of computing resources, allowing hundreds of model runs to be evaluated simultaneously. The uncertainty analysis undertaken for the Hume Coal Project has been performed utilising the latest available software and computing technology.

The uncertainty analysis was able to be undertaken using a basic Monte Carlo approach, which places no reliance on a linearisation of the model. This allows for each individual model run to be kept relatively simple and with predictable run time (with no additional calibration steps as in the NSMC method) and is free from the problem of autocorrelated samples that may occur with MCMC approaches.

AlgoCompute (HydroAlgorithmics*,* 2018; Merrick*,* 2017) was used as the platform for executing the model runs in parallel; batches of up to 255 realisations were evaluated simultaneously, each being allocated to a single CPU core of a virtual machine in the cloud. The model-independent uncertainty quantification software HGSUQ (Miller *et al.,* 2018) was used to generate the Monte Carlo parameter realisations and orchestrate the model runs within the AlgoCompute environment.

7.1.1 PILOT POINTS

To assess the uncertainty in the hydraulic conductivity parameters in the model, a *pilot point* approach was applied. Lateral (Kx) and vertical (Kz) hydraulic conductivity values were permitted to vary spatially throughout the model domain by taking representative values at 256 locations (pilot points) in each of the 13 model layers and giving each point a depth value based on the depth below ground to the middle of the layer for the cell the pilot point is in.

For each realisation generated by the Monte Carlo process, every pilot point was assigned a Kx value and a Kx/Kz ratio, for a total of 6,656 parameters (256 points * 13 layers * 2 parameters). Each model cell was assigned a Kx and a Kz value through interpolation from surrounding pilot point values by *kriging*.

Hydraulic conductivity values at each pilot point were sampled from a log-normal distribution with a mean and standard deviation based on the depth of the pilot point below ground. These distributions were derived from field measurements, as described in **Section 7.2** below.

The locations of the pilot points were distributed approximately equidistantly throughout the model domain, with an average distance of 1.7km between neighbouring points. This was accomplished by starting with 256 points placed in initially random locations within the model extents, and then using the optimisation algorithm for mesh generation in the AlgoMesh software tool (Merrick and Merrick, 2015) to distribute the points according to a uniform distance function. The resulting pilot point locations are depicted in **Figure 17**. Each pilot point is replicated at the same location – but different depth – for each of the 13 model layers.

7.1.2 BASELINE MEAN K RUN

Prior to execution of the suite of Monte Carlo runs, a representative run was undertaken locally to provide a baseline for calibration checks. For this run, the mean values of Kx and Kz were used at all pilot points. The root mean square (RMS) calibration fit of this realisation was computed to be 16.15m, equivalent to 11.3% scaled RMS (SRMS). These figures were used in determining appropriate cut-off limits for further runs in the Monte Carlo suite, as detailed below in the individual run procedure.

In order to determine an appropriate relationship between Kx and depth, packer and specific capacity field test data from the Hume Coal Project and neighbouring areas were analysed (**Figure 18**). The green crosses shown in **Figure 18** mark the Kx values used in the EIS Model, which were assigned constant values per layer, irrespective of varied depth of the layer. The blue boxes in **Figure 18** represent the median depth of each layer (over the entire model extent) and the Kx value assigned in the EIS Model.

The depth function describing the distribution mean of Kx was derived from a regression fit to field test results, depicted in **Figure 18**. The resulting function is Kx=exp [(29.675-depth)/21.346]. This function is capped to 10^{-4}m/day as a minimum (to honour the average value at depth from Southern Coalfield packer data) and 1m/day as a maximum (to honour the average value near surface from Hume specific capacity data). Without capping to these values, the Monte Carlo process could assign unrealistic Kx values at the extremes.

Table 18 shows the mean and median horizontal hydraulic conductivity values of each layer in the Mean K Model run and compares them with the values used in the EIS Model (Coffey, 2016b). The last column (Median : EIS) is a ratio that indicates the relative difference between the old and new models. Aside from Layer 12, which is an order of magnitude higher in the Mean K Model than the EIS Model, the horizontal hydraulic conductivity values show a good match with the calibrated EIS values, as shown by the blue boxes aligning with the solid red line in **Figure 18**. The mean and median values for Layer 12 derived from the depth function are higher than those applied in the EIS Model due to the capping of horizontal conductivity at10^{-4}m/day in conjunction with the shallower depth of cover to the west of the model domain.

The spatial distribution of horizontal hydraulic conductivity values across the active model domain for the Mean K Model are shown **Figure 19** to **Figure 25.**

Table 18 Comparison of horizontal hydraulic conductivity values from the EIS model with the mean and median values of each model layer using the depth function at pilot point locations

Horizontal Hydraulic Conductivity (Kx)				
Layer	**EIS Model**	**Median**	**Mean**	**Median : EIS**
1	1	1	0.86	1
2	0.6	0.45	0.52	0.75
3	0.05	0.1	0.26	2
4	0.03	0.022	0.11	0.73
5	0.01	0.0084	0.055	0.84
6	0.005	0.0068	0.048	1.36
7	0.005	0.0062	0.045	1.24
8	0.005	0.0029	0.043	0.58
9	0.005	0.0026	0.042	0.52
10	0.005	0.0025	0.041	0.5
11	0.005	0.0022	0.039	0.44
12	0.0001	0.0014	0.032	14
13	0.0001	0.0001	0.005	1

7.1.3 FLOW BUDGET (MEAN K BASELINE MODEL)

The global water balance for the Mean K Baseline Model for the prediction period is shown in **Table 19**, averaged over the prediction period of 19 years.

Rainfall recharge accounts for about 72% of groundwater system inputs, the balance being provided by river leakage (about 24%) and Wingecarribee Reservoir leakage (about 4%). About half of the groundwater losses are to “Drains”, meaning creeks, mines and the escarpment. Evapotranspiration consumes about 19%, baseflow to rivers is about 16% and pumping from private bores is about 17% of groundwater use.

There are some significant differences between the values in **Table 19** (for spatially varying hydraulic conductivities) and those in **Table 14** for the Modified EIS model (with uniform layer hydraulic conductivities): evapotranspiration is reduced from 15.2 to 9.4 ML/day (38%); the “Drains” component is reduced from 30.3 to 23.9 ML/day (21%), and average loss from the groundwater system has been reduced almost to zero.

Table 19 Simulated Average Water Balance During the Prediction Period

Component	Groundwater Inflow (Recharge) (ML/day)	Groundwater Outflow (Discharge) (ML/day)
Rainfall Recharge	34.9	-
Evapotranspiration	-	9.4
Rivers	11.8	7.8
Drains	-	23.9
Constant Head	1.8	-
Wells	-	8.2
TOTAL	**48.5**	**49.3**
Storage	**0.7 LOSS**	
Discrepancy (%)	**0.01**	

Notes:

"Rivers" = Wingecarribee River and Medway Dam
"Drains" = Creeks, Berrima Mine, Escarpment, Hume Coal Project
"Constant Head" = Wingecarribee Reservoir
"Wells" = Landholder Bores

7.1.4 RUN PROCEDURE

For each Monte Carlo realisation, a procedure was executed on a virtual machine in the cloud, initiated by a HGSUQ "slave" worker process. The following summarises the procedure:

1. Convert Kx value and Kx/Kz ratio to a Kx and a Kz value at each pilot point.
2. Interpolate Kx and Kz values to model cells by kriging with PLPROC (Doherty, 2016).
3. Run steady-state model (no Hume mining) to obtain appropriate initial conditions.
4. Run calibration model using steady-state initial conditions.
5. Compute SRMS error of the outputs of the calibration model at a set of observation locations with respect to observed values at those locations, and additionally RMS error at a selected subset of those locations.
6. If the global SRMS error exceeds 13%, stop processing and reject the run. (The 13% figure represents a 15% allowed deviation from the baseline Mean K run's figure of 11.3%.)
7. If the RMS error at more than one of the selected subset locations exceeds 16.15m, stop processing and reject the run. (The 16.15m RMS figure corresponds to the baseline Mean K run's global RMS figure.)
8. Run prediction model with Hume mining inactive (the null model).
9. Run prediction model with Hume mining active (the mining model).
10. Aggregate drawdown (null model minus mining model), number of bores affected by ≥2m drawdown, mine inflow and stream baseflow results from the null and mining models and return these to the HGSUQ "master" process for amalgamation with other run results.

7.1.5 ASSUMPTIONS OF NOTE

The following assumptions should be noted in assessing the information on the uncertainty analysis presented in this report:

- To limit the large number of possible realisations, the stochastic modelling was limited to hydraulic conductivity values, considered to be the most important determinants of groundwater behaviour. Other less significant model parameters, such as rainfall, storage and recharge, were considered through sensitivity or other forms of analysis elsewhere in this report (refer to Sections 5, 6 and 8, and the original EIS report).

- Mean Kx values are assumed to decrease logarithmically with increasing depth below ground surface. The hydraulic conductivity Kx vs depth function is derived from field data and described later in this section (Refer to Section 7.2).

- Kz values are assumed to correlate to Kx according to a spatially-varying linear ratio. Refer to Section 7.2 for details on the distributions adopted.

- Each calibrated realisation was assumed to be equally likely in the analysis of the model outputs; i.e. apart from rejecting particularly poorly-calibrated runs, no weighting was applied to distinguish models based on how well they fit the observed data.

7.2 INPUT PARAMETER DISTRIBUTIONS

Two sets of parameter distributions are presented in this section:

- **Prior distributions**: are continuous distributions from which the Monte Carlo process builds random samples for evaluation. This process produces a finite number of sample sets, some of which are rejected during evaluation due to failing calibration checks.

- **Posterior distributions**: are discrete distributions that define the actual hydraulic conductivity distributions evaluated after sampling and rejection are taken into account.

Prior and posterior parameter distributions are the statistical distributions of hydraulic conductivity values at each pilot point. A prior distribution is a continuous mathematical function describing the range of hydraulic conductivity values that may be assigned at a pilot point, and the relative probability of each value in that range. The Monte Carlo process uses the prior distributions to generate random hydraulic conductivity values at every pilot point in accordance with these probabilities. For each set of values generated (one Kx and one Kz at every pilot point), a model run is performed. If the model run is within acceptable calibration error limits, its results are accepted as part of the Monte Carlo analysis; otherwise, the run is rejected. The set of hydraulic conductivity values at each pilot point from all accepted model runs form the posterior distributions. Each posterior distribution is a discrete set of hydraulic conductivity values, indicating the spread of values that were used at a given pilot point over all accepted model runs.

Comparing prior and posterior distributions may be useful for two reasons:

A posterior distribution that does not approximate the shape of the corresponding prior distribution (e.g. log-normal for Kx, or uniform for Kx/Kz ratio) may indicate that an insufficient number of model realisations have been evaluated.

A posterior distribution showing an obvious gap, translated mean or scaled range relative to the corresponding prior distribution may indicate the presence of a certain range of model input values that results in poor model calibration. This may in turn indicate a misfit between the prior distribution and the parameter values that most accurately represent physical reality.

For ease of analysis, we organise the pilot points into bins based on their depth below ground level (0-50m, 50-100m, and so on down to 450m+).

The results presented in this section confirm that the posterior distributions are very similar in shape, mean and range to their respective prior distributions. This is consistent with expectations, as fewer than 6% of model runs were rejected due to poor calibration.

For concept design purposes, over 2,200 realisations were run on an earlier version of the groundwater model, in order to establish the number of runs needed for adequate convergence of key model metrics. In all, 510 realisations were evaluated as part of the Monte Carlo process. Of these, 481 (94.3%) were accepted and 29 (5.7%) were rejected by the prescribed calibration criteria.

7.2.1 PRIOR DISTRIBUITIONS

The prior distribution of lateral hydraulic conductivity (Kx) at each pilot point is log-normal with mean and standard deviation calculated as a function of the pilot point's depth below ground surface irrespective of which model layer the pilot point is within. Kx prior distribution standard deviations were derived by grouping the field data into 50m depth groups (grouped bins) and computing the standard deviation of log10(Kx), with the results presented in **Table 20.** Note the 450m+ bin extends to approximately 530m to include the small set of data points present beyond 500m. Also listed in **Table 20** are the number of field data and pilot points in each depth range.

Table 20 Prior distribution - standard deviation of log10(Kx), binned by depth.

Depth	Stdev Log10(Kx)	# Field Data Points	# Pilot Points
0-50m	0.84	156	498
50-100m	1.06	96	560
100-150m	0.92	83	854
150-200m	1.15	66	552
200-250m	0.70	62	459
250-300m	0.80	52	227
300-350m	0.84	57	96
350-400m	0.71	84	64
400-450m	0.86	92	12
450m+	0.77	44	6

Vertical hydraulic conductivity (Kz) is determined at each pilot point by a vertical anisotropy ratio Kx/Kz. This ratio was assigned a uniform distribution from 3 to 100. This is believed to be conservative relative to the EIS Model, in which most layers were given a Kx/Kz ratio of between 5 and 100 (except layers 2, 12 and 13 which were given ratios of 600, 1, and 1, respectively).

7.2.2 POSTERIOR DISTRIBUTIONS

Table 21 summarises the posterior distributions of Kx, organised in 50m depth bins and compared to the prior distribution statistics. Very little difference is noted between prior and posterior, which is as expected with fewer than 6% of runs being rejected due to the calibration criteria.

Table 21 Posterior Kx compared to prior means and standard deviations, arranged in 50m depth bins.

Depth	Posterior Mean Kx	Prior Mean Kx[1]	Posterior Stdev	Prior Stdev
0-50m	8.6×10^{-1}	8.6×10^{-1}	0.85	0.84
50-100m	1.1×10^{-1}	1.1×10^{-1}	1.10	1.06
100-150m	1.2×10^{-2}	1.2×10^{-2}	0.96	0.92
150-200m	1.1×10^{-3}	1.2×10^{-3}	1.18	1.15
200-250m	1.4×10^{-4}	1.4×10^{-4}	0.72	0.70
250-300m	1.0×10^{-4}	1.0×10^{-4}	0.80	0.80
300-350m	9.8×10^{-5}	1.0×10^{-4}	0.84	0.84
350-400m	1.0×10^{-4}	1.0×10^{-4}	0.71	0.71
400-450m	1.0×10^{-4}	1.0×10^{-4}	0.86	0.86
450m+	9.9×10^{-5}	1.0×10^{-4}	0.76	0.77

1. Prior means are taken from the mean of log10(Kx) at all pilot points within the depth bin.

The posterior mean and standard deviation of the vertical anisotropy ratio (Kx/Kz) are reported in **Table 22**. The comparative prior distributions of these are uniform and constant with depth, with a mean of 51.5 and standard deviation of 28.0. The posterior distributions are reported in the same depth bins as Kx for consistency.

Table 22 Posterior mean and standard deviation of the vertical anisotropy ratio (Kx/Kz), binned by depth.

Depth	Posterior Mean Kx/Kz	Posterior Stdev Kx/Kz
0-50m	51.46	27.99
50-100m	51.52	27.96
100-150m	51.50	27.99
150-200m	51.52	28.00
200-250m	51.41	28.01
250-300m	51.47	27.99
300-350m	51.51	28.00
350-400m	51.37	28.14
400-450m	51.79	28.13
450m+	51.63	27.95

Histograms of the posterior Kx values in each depth bin are presented from **Figure 26** to **Figure 29.**

Histograms of the posterior Kx/Kz anisotropy ratios in each depth bin are presented in **Figure 30** to **Figure 33**. Note that the vertical axes do not begin at 0, and that the scale differs in each chart, for better visibility of the variation of the values.

7.3 PRESENTATION OF RESULTS

In March 2018, the Independent Expert Scientific Committee (IESC) released a draft Explanatory Note on Uncertainty Analysis in Groundwater Modelling (Middlemis & Peeters, 2018). The explanatory note establishes some 'key guiding principles' for undertaking uncertainty analysis in accordance with the *IESC Information Guidelines*. The note is currently in a draft format. The IESC has since sought feedback from the greater groundwater modelling industry with a view to finalising the explanatory note later in 2018.

Within the draft explanatory note, the importance of effective communication in the presentation of model results was highlighted, in a way that could be understood by all stakeholders. Narrative descriptors devised by the IPCC (2013) that directly relate to probability classes reflecting uncertainty have been combined with risk-based visualisation methods to develop an approach that enhances communication effectiveness (Richardson *et al.,* 2017).

This approach is shown in **Table 23** and is a composite of:

- narrative descriptors on the likelihood of a given outcome;
- quantitative ranges in probability from an uncertainty analysis; and
- qualitative visual methods presented as risk-assessment style colour-coding.

The quantitative ranges from the uncertainty analysis on hydraulic conductivity are presented in reverse order to those within the draft explanatory note (Middlemis & Peeters, 2018).

Table 23 Combined numeric, narrative and visual approaches to describing likelihood

Narrative Descriptor	Probability Class	HydroSimulations Percentile Class	Description	Colour Code
Very likely	90-100%	0-10%	Likely to occur even in extreme conditions	
Likely	67-90%	10-33%	Expected to occur in normal conditions	
About as likely as not	33-67%	33-67%	About an equal chance of occurring as not	
Unlikely	10-33%	67-90%	Not expected to occur in normal conditions	
Very unlikely	0-10%	90-100%	Not likely to occur even in extreme conditions	

7.4 RESULTS OF UNCERTAINTY ANALYSIS

An uncertainty analysis was undertaken to provide context for interpreting the results of the original EIS Model (Coffey, 2016b) and revised modelling by HydroSimulations in 2018. The uncertainty analysis gives insight into the likelihood of project impacts exceeding or coming in under those modelled, given the uncertainty inherent in the choices of model parameters. Overall, the results of this analysis indicate a relatively narrow band of uncertainty around the key impact metrics, highlighting the suitability of the modelled results for the assessment of project impacts.

Statistics on a number of key metrics were computed from the results of the 481 accepted model runs and are presented in this section. Aggregate metrics are summarised with 33rd, 50th (median), 67th and 90th percentile values. Time-series results are reported as 10th, 33rd, 50th, 67th and 90th percentiles.

The term "aggregate metric" is used here to describe a value that is summarised over all modelled times from the accepted Monte Carlo runs. Aggregate metrics reported include the number of bores affected by at least 2m drawdown at any time, the maximum inflow into the mine at any time, and the maximum magnitude of reduced baseflow to streams due to mining at any time.

For each accepted Monte Carlo run, one value is calculated for each aggregate metric. The set of all such values for a given metric is then used to compute a single value for each of the percentiles considered (90%, 67%, 50%, 33% and 10%). The 90% value, say X, is determined such that 90% of the runs have a metric value less than or equal to X, and 10% of the runs have a metric value higher than X – and similarly for the other percentiles.

It is important to note that the set of Monte Carlo runs comprising a percentile value for one metric may be different to the set of runs comprising the same percentile for a different metric. For example, the 90% value for the number of bores affected by 2m drawdown does not necessarily correspond to the same modelled conditions as those that generated the 90% value of maximum total mine inflow, as each value may come from a different subset of the Monte Carlo runs. Thus, each of the aggregate metric percentile values should be considered independently; it is not valid to combine them directly by addition, subtraction or other operations.

Percentile results, denoted by convention as "10%ile", "33%ile", "50%ile", "67%ile" and "90%ile", were calculated strictly on a conservative "round to higher value" basis. To clarify, a 90%ile value of X for a particular metric should be interpreted to mean "90% of realisations from the set of accepted realisations resulted in a value for this metric no larger than X".

The colour coding of charts relating to this section is as follows: **green** represents the 10th percentile, **yellow** represents the 33rd percentile, **black** represents the 50th percentile, **orange** represents the 67th percentile, and **red** represents the 90th percentile.

7.4.1 SUMMARY OF AGGREGATE METRICS

Key aggregate metrics and peak baseflow impacts from the Monte Carlo runs are given in **Table 24**. The model outcomes for the 67th percentile set of results are seen as the most appropriate in terms of a conservative prediction of the impacts caused by Hume Coal Project mining. While useful when considering worst-case outcomes, percentile results higher than the 67th when considered in line with IESC guidelines are considered 'unlikely', or 'not expected to occur' (Table 25) and are therefore not appropriate for licensing or make-good. For those purposes, the median is appropriate.

Table 24 Summary of aggregate metrics and peak baseflow impacts

	33%ile		50%ile		67%ile		90%ile	
Key aggregate metric								
Number of Bores with Active Licence affected by 2m drawdown or more	75		84		93		118	
Maximum mine inflow "to sump" **(ML/day | ML/year)**	2.573	940	2.672	976	2.784	1017	2.984	1090
Maximum total mine inflow **(ML/day | ML/year)**	5.42	1980	5.647	2063	5.904	2156	6.396	2336
Calibration error **(%SRMS)**	10.15%		10.60%		11.03%		11.82%	
Peak baseflow impact (ML/day | ML/year)								
Medway Rivulet (whole source)	0.793	290	0.883	323	0.982	359	1.207	441
Medway Rivulet (excluding tributaries)	0.768	280	0.865	316	0.961	351	1.176	429
Oldbury Creek	0.000	0	0.003	1	0.021	8	0.062	23
Belanglo Creek	0.000	0	0.000	0	0.000	0	0.000	0
Wells Creek	0.000	0	0.000	0	0.000	0	0.000	0
Wells Creek Tributary	0.000	0	0.000	0	0.000	0	0.000	0
Lower Wingecarribee River (whole source)	0.205	75	0.230	84	0.254	93	0.318	116
Lower Wingecarribee River (excluding tributaries)	0.138	50	0.158	58	0.184	67	0.252	92
Black Bobs Creek	0.044	16	0.054	20	0.063	23	0.091	33
Longacre Creek	0.009	3	0.013	5	0.018	7	0.030	11
Upper Wingecarribee River	0.005	2	0.007	3	0.008	3	0.013	5
Lower Wollondilly River	0.005	2	0.007	2	0.006	3	0.012	4
Nattai River	0.000	0	0.000	0	0.000	0	0.001	0
Bundanoon Creek	0.004	1	0.005	2	0.008	3	0.016	6

7.4.2 DRAWDOWN

Aggregate outputs for water table drawdown from the uncertainty analysis are computed on a cell-by-cell basis and represent the maximum drawdown experienced by a model cell at any time within a run. It is important to note that this is different from the method used for the spatial drawdown plots displayed in the EIS (Coffey, 2016b). In Coffey (2016b), the water table drawdown is plotted for a particular year, in particular mine year 17 when the area of active mining is at its greatest; the spatial extent of areas impacted by mining before and after this time area may not be represented adequately.

Figure 34 shows a comparison between the extent of greater than 2m drawdown at mine year 17 in the Wongawilli Seam from the EIS Model, and the extent of aggregate maximum water table drawdown greater than 2m at the 67th percentile from the uncertainty analysis. While this is not a direct comparison of the same outputs between the two model runs, it is still useful in demonstrating the variations between the models of the spatial extent of greater than 2m drawdown. The near vertical head and drawdown contours shown in cross section and plan view for mine year 17 in the EIS model (Coffey, 2016b) indicate the spatial extent of drawdown in the Wongawilli Seam is very close to the spatial extent of water table drawdown.

Figure 35 to **Figure 40** show groundwater level and drawdown hydrographs from the 67%ile aggregate results at locations around the Hume Coal Project displayed on **Figure 66**.

The Wongawilli Seam drawdown extent derived from the uncertainty analysis also does not display the irregular shape of drawdown seen for the water table in the EIS Model. In order to understand the difference in shape of drawdown extent between the two models, an analysis of the modelled heads compared to layer elevation within the EIS Model and the Preliminary Modified EIS Model (using MODFLOW SURFACT V4 software) was conducted. The results were compared with outputs from the Preliminary Modified EIS model that had been converted to USG and had the pseudo soil function enabled. The irregular drawdown pattern within the EIS Model and SURFACT V4 revision was caused by a tendency for layers to maintain small positive head values in areas that should be reporting as "dry", indicated by nearby hydraulic gradients. This tendency is a function of the older software and is not present within the MODFLOW-USG converted models with the pseudo soil function enabled. The full analysis and supporting figures are presented in **Appendix B**.

The range of impacts determined by the uncertainty analysis for the number of impacted bores and the extent of greater than 2m drawdown is shown in **Figure 41**. Probability class is linked with risk analysis style colouring and narrative descriptors to provide a visualisation of the spatial extent of impacts that may be caused by the Hume Coal Project.

Figure 42 displays the aggregate outputs for maximum drawdown and number of bores impacted by at least 2m drawdown for the 67th percentile. As indicated by the Richardson *et al*. (2017) approach to the communication of uncertainty analysis results, numbers greater than the values presented for the 67th percentile are not expected to occur.

7.4.3 TRANSIENT MINE INFLOW

Figure 43 and **Figure 44** show 10%ile, 33%ile, 50%ile, 67%ile and 90%ile simulated mine inflows over time. The period charted is restricted to 25 years following the beginning of mining, after which flows are negligible.

The water requiring pumpout from the mine is expected to increase gradually, almost linearly, to mine year 17, at which time the mine inflow should range between 2.4 and about 3.0 ML/day (**Figure 43**). Total mine inflow, which includes water pumped out and water flowing into undrained portions of the mine, is expected to be variable with time with distinct peaks at mining years 3, 10-12 and 17 (**Figure 44**). The maximum total mine inflow is expected to peak in the range between 4.8 and about 6.4 ML/day.

7.4.4 TRANSIENT STREAM BASEFLOW IMPACTS

Figure 45 to **Figure 55** show 10%ile, 33%ile, 50%ile, 67%ile and 90%ile baseflow impacts induced by Hume mining over time. All are shown over a 100-year period. Stream catchments with zero baseflow impact – Belanglo Creek, Wells Creek and Wells Creek Tributary – are omitted from this section (see **Table 24** for reference to the peak baseflow impact values).

For Medway Rivulet, the peak loss of water should range between 0.6 and about 1.2 ML/day around mining year 20 (**Figure 45**). The Lower Wingecarribee River is expected to lose about 0.2 to 0.3 ML/day at peak, which is expected to occur at 20-25 years after commencement of mining (**Figure 48**).

7.4.5 IMPACT TO GROUNDWATER MANAGEMENT ZONES

Table 25 shows the maximum rate of groundwater take from each Groundwater Management Zone within the model domain for results from the 67th percentile of the uncertainty analysis.

Table 25 Maximum rate of groundwater take from Groundwater Management Zones within the model domain.

Groundwater Source	Maximum rate of release from groundwater storage at the 67th percentile (ML/day)	Time to maximum rate from the 67th percentile (years)
Nepean Management Zone 1	5.64	17
Nepean Management Zone 2	0.018	72
Sydney Basin South	0.020	25

7.4.6 MONTE CARLO CONVERGENCE

It is important that a sufficient quantity of realisations have been evaluated to ensure that the results reported are accurate – that is, that the stochastic process has *converged*.

In addition to the 510 runs reported, 2,229 realisations were evaluated using an earlier version of the Modified EIS model. Of these, 2,093 (93.9%) were accepted, and 136 (6.1%) were rejected by the prescribed calibration criteria. Although these runs were evaluated using an earlier version of the model, they acted as a proof of concept and a useful tool for estimation of the number of runs needed for convergence of the adopted Monte Carlo methodology.

From the preliminary runs, it was noted that the key output metrics did not change substantially between approximately 500 and 2,000 runs – generally by less than 1-2% for flow results and by a single bore for the number of affected bores. This suggested that around 500 runs would be sufficient to ensure reasonable confidence in the convergence of the Monte Carlo process.

To gain further confidence that the reported results were sufficiently close to their correct values after 510 runs, 99.7% confidence intervals were computed for the 10th, 50th and 90th percentiles of key aggregate metrics.

Confidence interval bounds for the $(100 \times p)^{th}$ percentile may be approximated by the formula $p \pm \sqrt{p(1-p)c^2/n}$, where c is the desired confidence in standard deviations of the normal distribution – $\mathrm{e.g.}\, c = 3$ for 99.7% confidence – and n is the number of runs (see e.g. Mood *et al., 1974* for derivations of confidence interval bounds). For example, it may be said with 99.7% confidence after 481 successful runs that the true 90th percentile value lies between the 85.9th and 94.1st percentile estimates ($= 100 \times \left(0.9 \pm \sqrt{0.9 \times 0.1\ x\ 9/481}\right)$).

The charts for this section are presented in **Figure 56** and **Figure 57** illustrating the convergence of key aggregate bore count, mine inflow and baseflow impact metrics. Baseflow impact metrics are limited to the two most significantly affected catchments: Medway Rivulet and Lower Wingecarribee River.

Two types of chart are presented in **Figure 56** and **Figure 57**. **Figure 56** shows the values of the 10th, 33rd, 50th, 67th and 90th percentiles as they evolve with the number of runs evaluated. **Figure 57** shows the 10th, 50th and 90th percentile values surrounded by their computed 99.7% confidence intervals, also as they evolve with respect to the number of runs evaluated. Note that 33rd and 67th percentile confidence intervals have been omitted from these charts to improve readability; the intervals in these cases were similar or narrower in width than those of the 10th, 50th and 90th percentiles shown.

The colour coding of the convergence charts follows the same scheme as the other charts presented earlier: **green** represents the 10th percentile, **yellow** represents the 33rd percentile, **black** represents the 50th percentile, **orange** represents the 67th percentile, and **red** represents the 90th percentile. Solid lines in the convergence charts represent the actual sampled percentile values, and dashed lines represent the 99.7% confidence intervals of the percentile corresponding to their colour.

7.5 SENSITIVITY ANALYSIS: NUMBER OF PILOT POINTS

The uncertainty analysis of hydraulic conductivity parameters utilised a *pilot point* approach to vary Kx and Kz values spatially throughout the model domain. The number of pilot points used in this approach determines the effective resolution at which conductivity changes may be represented.

Using only a few pilot points would result in the interpolation of a smoother, more uniform K-field. Adding more pilot points would permit this K-field to vary more substantially over shorter distances. This may result in a more accurate representation, particularly if K is determined primarily by depth, and can better capture the uncertainty present in the input parameters, but it also increases the number of parameters required for the Monte Carlo process, increasing its complexity and potentially the number of runs required for convergence.

256 pilot points per layer were used in the uncertainty analysis, resulting in a total of 3,328 pilot points throughout the model. This section provides the results of the sensitivity analysis that investigated the effects of altering the number of pilot points used.

Six scenarios were constructed for this purpose and named PP16, PP32, PP64, PP128, PP256 and PP512, with the number in the scenario name specifying the number of pilot points in each case (i.e. PP256 refers to the test case with 256 pilot points) In each case, the pilot points were distributed uniformly throughout the domain using AlgoMesh (see **Figure 58**). The PP256 scenario, highlighted in red, was the distribution used in the uncertainty analysis.

A single realisation was evaluated for each pilot point scenario, in which the mean Kx and Kz values of the input distributions from the uncertainty analysis were taken and then calculated at each pilot point according to its depth. A number of key metrics were then calculated from the outputs of each scenario and compared to assess their variability with respect to changes in the number of pilot points. These are presented and analysed in the following subsections.

7.5.1 AGGREGATE RESULTS

Table 26 summarises the key aggregate metric results from each of the pilot point scenarios.

A trend is seen where the models become better calibrated as more pilot points are used; indeed, the PP16 and PP32 cases would fail the calibration checks used for the uncertainty analysis runs. PP512 is noted to be the "best" case, both because it most finely represents the changes in hydraulic conductivity with depth, and because it is the best calibrated of the six scenarios.

Some fluctuations are seen in the number of affected bores, but these are stable within about 4% (a range of 3 bores maximum) in the PP128 case and beyond.

Maximum mine inflow matches quite closely between the PP256 and PP512 cases (within 1%), suggesting that there is only minor benefit to be gained by doubling the number of pilot points after 256. This effect is clear also in the time series charts reported in the remainder of this section.

Higher percentage variations are observed for baseflow impacts but the magnitudes are very low. For example, the Lower Wingecarribee impact ranges from 0.10 to 0.13 ML/day from PP128 to PP512, with 0.12 ML/day for the adopted P256 scenario.

Table 26 Variations of aggregate metrics from those found for the adopted pilot point scenario

	PP16	PP32	PP64	PP128	PP256	PP512
Calibration error (%SRMS)	13.89%	11.55%	11.26%	11.48%	11.28%	11.20%
Number of selected calibration bores with error >16.15m RMS	4	2	1	0	0	0
Number of bores with active licences affected by 2m drawdown or more (%)	-5.4	10.8	-5.4	-2.7	Model Selected for Uncertainty Analysis	-4.1
Maximum mine inflow "to sump" (ML/day) (%)	-9.5	5.3	0.0	-3.0		-0.76
Maximum total mine inflow (ML/day) (%)	1.3	8.9	10.2	-0.55		0.73
Peak baseflow impact: Medway Rivulet (whole source) (ML/day) (%)	-26.2	-4.8	2.4	4.86		2.4
Peak baseflow impact: Lower Wingecarribee River (whole source) (ML/day) (%)	-25.0	-25.0	-8.3	-16.7		8.3

7.5.2 MINE INFLOW

Transient inflow curves (**Figure 59** and **Figure 60**) match well for all cases where the number of pilot points is at least 64.

Peak total inflow appears to be overestimated in the PP32 and PP64 scenarios, while the PP128, PP256 and PP512 scenarios match each other quite well.

7.5.3 BASEFLOW IMPACTS

PP256 and PP512 are seen to match fairly closely in the two most significantly affected catchments (**Figure 61** and **Figure 62**), Medway Rivulet and Lower Wingecarribee River, particularly around the peak.

PP128 noticeably falls short of the PP512 peak baseflow impact to Lower Wingecarribee River, and slightly overshoots the peak baseflow impact to Medway Rivulet.

7.5.4 SUMMARY

The scenarios using 64 pilot points or more all exhibit somewhat similar outputs, with an overall trend towards improved calibration fit as the number of pilot points increases.

The 256 pilot point case was chosen for the uncertainty analysis as an appropriate trade-off between complexity and spatial resolution, as the differences exhibited by increasing beyond 256 pilot points are small.

8 F – SENSITIVITY ANALYSIS

The sensitivity analysis in the EIS Model focused on the key areas of known sensitivity and uncertainty in the data and provided efficiency to the modelling process. As part of the submissions on the Hume Coal Project and subsequent consultation with the NSW DI Water it was agreed to undertake some additional sensitivity runs for the model.

Apart from the investigation of specific storage and specific yield values, additional sensitivity analysis has been conducted by HydroSimulations on the Modified EIS model for:

- Simulations with or without the **pseudo soil function**, which found that the pseudo soil function is required to be enabled in order to allow calibration convergence of the Modified EIS model.
- Simulating Hume Coal Project mining with a **drain conductance** increased by 1 order of magnitude. This indicated that the calibrated drain conductance applied in the EIS Model is considered appropriate and fit for purpose.
- A simulation testing the efficacy of the **Horizontal Flow Barrier** by removing the drain cells associated with the simulation of the basalt body south of the Hume Coal project area. The simulation found the representation of horizontal flow barriers within the EIS Model is considered appropriate and fit for purpose.

The results of the above sensitivity analysis are presented in the following sections.

8.1 PSEUDO SOIL SENSITIVITY

The EIS Model (Coffey 2016b) was run without the pseudo soil function enabled. It is likely that the EIS Model was unable to converge with the pseudo soil function enabled, a phenomenon well-known to experienced modellers. A pseudo soil function was introduced into MODFLOW-SURFACT to mitigate the instabilities that arise in standard MODFLOW versions when dry cells occur. However, the function does not always alleviate the instabilities. Subsequently, a similar function was introduced into MODFLOW-USG, where it seems to perform more reliably.

Figure 63 shows a cross section view of the behaviour of a groundwater model without the pseudo soil function enabled. By way of contrast, **Figure 64** shows a cross section view of the behaviour of a groundwater model segment with the pseudo soil function enabled.

The USG converted HydroSimulations groundwater model failed to converge without the pseudo soil function activated. For this reason, it has not been possible to compare simulations with and without this function in order to assess the sensitivity of key outputs of interest. The pseudo soil function was enabled for the Modified EIS model.

8.2 DRAIN CONDUCTANCE SENSITIVITY ANALYSIS

The 0.05 m^2/day conductance value used in the EIS model was based on the calibration of drain cell conductance to discharge volumes from the Berrima Mine void, taking into consideration the relative area of the cell sizes between Berrima Mine and the Hume Coal Project within the model domain (Coffey, 2016b). The EIS modelling report also highlights that similar drain conductance values (0.1 m^2/day) were used to simulate non-collapsing development headings for proposed mining at Dendrobium Area 3B (Coffey, 2012).

Drain conductance of 0.05 m^2/day can be converted to more meaningful terms such as hydraulic conductivity (K) or leakage coefficient (K/b) by taking into account the dimensions of plunges and roadways relative to model cell dimensions, and allowing for the area of seeps from the roof or sidewalls being much less than roof or wall face areas. When this is done, the effective leakage coefficient adopted in the Hume model is $5x10^{-5}$ d^{-1} at Hume and $2x10^{-5}$ d^{-1} at Berrima, where drain conductance has been calibrated. This compares favourably with estimates applied at other Southern Coalfield mines which range from $4x10^{-5}$ to $1x10^{-3}$ d^{-1}. Consultation on this matter with DPI Water occurred on 25 August 2017.

As part of the groundwater model revision, a parameter sensitivity run that increased the drain conductance to 0.5 m^2/day (a factor of 10) was conducted. The results of the sensitivity run are presented in **Table 27**.

Importantly, if this increase in conductance was similarly applied to the drains simulating mining at Berrima, the modelled inflow would far exceed the observed discharge from the Berrima mine void and the conductance values would no longer be calibrated, indicating that this is an unrealistic mine conductance value.

Table 27 Percentage difference in key metrics due to increase in drain conductance

Key metric	Percentage Difference in key metrics[1]
Number of bores affected by 2m drawdown or more	10.4%
Maximum mine inflow “to sump” (ML/day)	93.8%
Maximum mine inflow “to void” (ML/day)	-5%
Maximum total mine inflow (ML/day)	32.5%
Peak baseflow impact (ML/day)	
Medway Rivulet (whole source)	15.9%
Medway Rivulet (excluding tributaries)	17.4%
Oldbury Creek	32.9%
Belanglo Creek	9.0%
Wells Creek	0.1%
Wells Creek Tributary	0.8%
Lower Wingecarribee River (whole source)	30.9%
Lower Wingecarribee River (excluding tributaries)	37.7%
Black Bobs Creek	13.3%
Longacre Creek	30.1%
Upper Wingecarribee River	35.6%
Lower Wollondilly River	-54.2%
Nattai River	24.6%
Bundanoon Creek	29.8%

1. Positive percentage values indicate an increase in metric as a result of increasing drain conductance.

Increasing the drain conductance by an order of magnitude has resulted in a near doubling of the ‘to sump’ mine inflow within the sensitivity run. This is the inflow intercepted by drains at the Hume Coal Project (See **Section** 5 for further information on the revised simulation of mining). Other key parameters such as total mine inflow and increases to the number of impacted bores are much lower, showing the model is overall not particularly sensitive to changes in mine drain conductance for these key outputs of interest.

The similarities in the conductance values for other models within the Southern Coalfield, as well as the indication that conductance can become uncalibrated with an order of magnitude change, serve to show that the calibrated conductance values used in the EIS Model are reasonable and fit for the purpose of predicting the impacts of the mine.

8.3 IMPACT OF HORIZONTAL FLOW BARRIER ON DRAWDOWN PROPAGATION

To replicate the hydraulic head field within the Robertson Basalt, the EIS Model (Coffey, 2016b) utilised both the MODFLOW Horizontal Flow Barrier and MODFLOW Drain packages to simulate an interpreted structural feature and the underlying unsaturated zone to the south of the feature (Coffey, 2016a). The barrier has been given a relatively high permeability (0.0001 m/day), and drain cells have been used to simulate the partial desaturation of the upper Hawkesbury Sandstone.

In the submissions on the EIS, some concerns were raised that the utilisation of the Horizontal Flow Barriers would limit the extent of drawdown within the basalt, and provide protection from drawdown impacts to bores located within the basalt. However, as indicated in the data analysis by Coffey (2016a), large drawdowns to the top of the Hawkesbury Sandstone would only have small drawdown impacts in the basalt that would be satisfied in time by decreased baseflow to streams.

A sensitivity analysis was conducted to assess the ability of the Horizontal Flow Barriers to restrict the movement of drawdown in the basalt. This analysis utilised a run with global specific yield values close to a half order of magnitude lower than used in the EIS Model (Coffey, 2016b), and a whole order of magnitude lower than what was found to be most appropriate in the final Modified EIS Model. By decreasing the specific yield to unrealistically low values, the extent of the drawdown footprint increases to source the water needed to fill in the void space created by mining of the Hume Coal Project. The lowering of the specific yield values by this magnitude was an attempt to ensure that interaction between the drawdown footprint and the simulated basalt occurred.

Figure 65a shows the interaction of drawdown with the basalt using unrealistic model parameters. As is conceptualised, drawdown in the surrounding and underlying Sydney Basin units does not result in significant drawdown within the basalt to the south of the interpreted structure. It also appears that the drain cells, used to simulate the partial desaturation of the upper Hawkesbury Sandstone, are responsible for the limiting of the drawdown footprint to a greater extent than the horizontal flow barrier.

Further sensitivity analysis assessing the efficacy of the horizontal flow barrier was conducted by removing the drain cells associated with the partially saturated upper Hawkesbury Sandstone. **Figure 65b** shows that, without the drains, the drawdown moves much further into the basalt, indicating that the barrier has only limited ability to restrict the extent of drawdown within the basalt.

These sensitivity runs show that the method used to simulate the interpreted structure and associated unsaturated zone has resulted in a limited ability of drawdown to propagate through the basalt. This is consistent with the Coffey (2016a, 2016b) conceptualisation that appears to be a strong interpretation of the available evidence. The barriers in the model alone are shown not to provide the protection that was raised in the submissions as a concern (i.e. they are not effective barriers to the overall groundwater flow).

8.4 EVAPOTRANSPIRATION SENSITIVTY ANALYSIS

Separate to the climate scenario analysis, sensitivity analysis was conducted on the extinction depth of evapotranspiration as requested in the HydroGeoLogic (2017) report. A run was conducted on the Modified EIS Model that increased the extinction depth from 1.5 m to 2.5 m and adopted an evapotranspiration rate of 1.8 mm/day.

A comparison was made between the sensitivity run and the Modified EIS Model in terms of the area over which evapotranspiration was occurring in the model (**Table 28**). The total evapotranspiration volumes of the model from the water balance were also compared (**Table 29**).

Table 28 Model area where evapotranspiration occurs with varying extinction depth

Stress Period	17		34		54	
Scenario	**Basecase**	**ET Sensitivity**	**Basecase**	**ET Sensitivity**	**Basecase**	**ET Sensitivity**
Area of ET (m^2)	2.07×10^7	2.82×10^7	19.3×10^7	25.9×10^7	18.6×10^7	25.0×10^7
% difference	**36 % Increase**		**34 % Increase**		**34 % Increase**	
%area of whole model where ET occurs	2.8	3.8	2.6	3.4	2.5	3.3

Despite an approximate increase of 35% in the area of the model over which ET was occurring, the insignificant difference in volume of water taken by ET shows the model is overall insensitive to changes in the extinction depth of ET.

Table 29 Evapotranspiration volume comparison

Volumes	ET volume m^3	Difference (m^3)	Volume (ML)
Sensitivity	4.2182×10^8	37,144	37
Basecase	4.2178×10^8		
%Difference	0.0088		

9 CONCLUSIONS

HydroSimulations was engaged initially by Hume Coal to undertake a detailed model audit and verification, following on from Dr Noel Merrick's[3] role as a peer reviewer of the EIS modelling. Consequent to the audit, HydroSimulations was engaged to update, revise and undertake sensitivity analysis on the groundwater model developed by Coffey Geoscience (2016b) for the EIS. These updates, revisions and sensitivity analyses were undertaken in response to submissions from the NSW Government and interest groups to respond directly to those issues raised in submissions.

The model revision and updates that have been included in the additional groundwater modelling, undertaken in response to submissions, have increased the ability of the model to realistically simulate the groundwater system, and provide additional confidence in the model results. This is both in relation to model features, such as TVM (allowing the implementation of realistic void properties) and the activation of the pseudo soil function (allowing for realistic recovery of groundwater level), and model properties, such as the increasing of both specific storage and specific yield to values closer to what was observed in field data.

The groundwater models simulated following these revisions and updates, in line with submissions, contain properties that are consistent with real world observations, and use the most up-to-date simulation methods available. The simulations are acceptably calibrated and contain a near zero mass balance error. They are therefore fit for the purpose of simulating the response of the groundwater system to the mining of the Hume Coal Project.

The similarities in the results of the additional groundwater modelling, including the uncertainty analysis conducted on hydraulic conductivity, serve to support the EIS groundwater model as fit-for-purpose, and provide additional confidence in the results. The sensitivity analysis conducted on model features, as well as the climate scenario analysis, reduce the uncertainty of model outputs and show that the conceptualisation and simulation of the original EIS model are appropriate.

A new approach to uncertainty analysis has been introduced in this study which is compliant with directions advocated in a recent Explanatory Note issued by the IESC. In particular, the approach (using AlgoCompute software in the cloud) demonstrates that convergence has been achieved for key outputs of interest by quantifying the uncertainty in nominated percentiles as the number of Monte Carlo runs increases. About 500 runs were required for satisfactory convergence, with each run taking about 8 hours of computer time. As this would take about 6 months of continuous time for a single computer, rigorous uncertainty analysis is only achievable by running simulations in the cloud.

[3] Dr Noel Merrick is a Director of HydroSimulations

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FIGURES

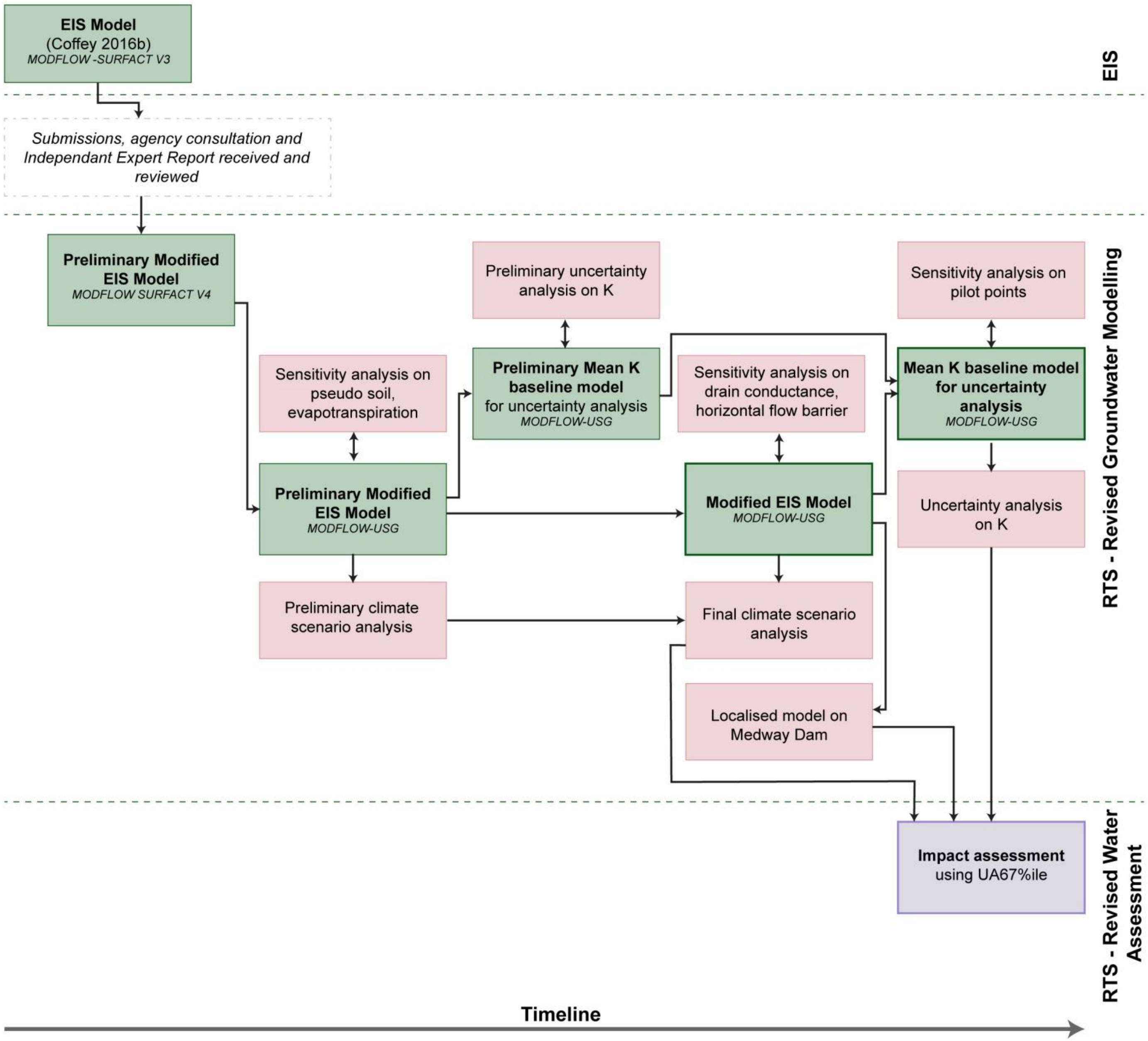


Figure 1 **Hume Coal Project numerical groundwater model versions**

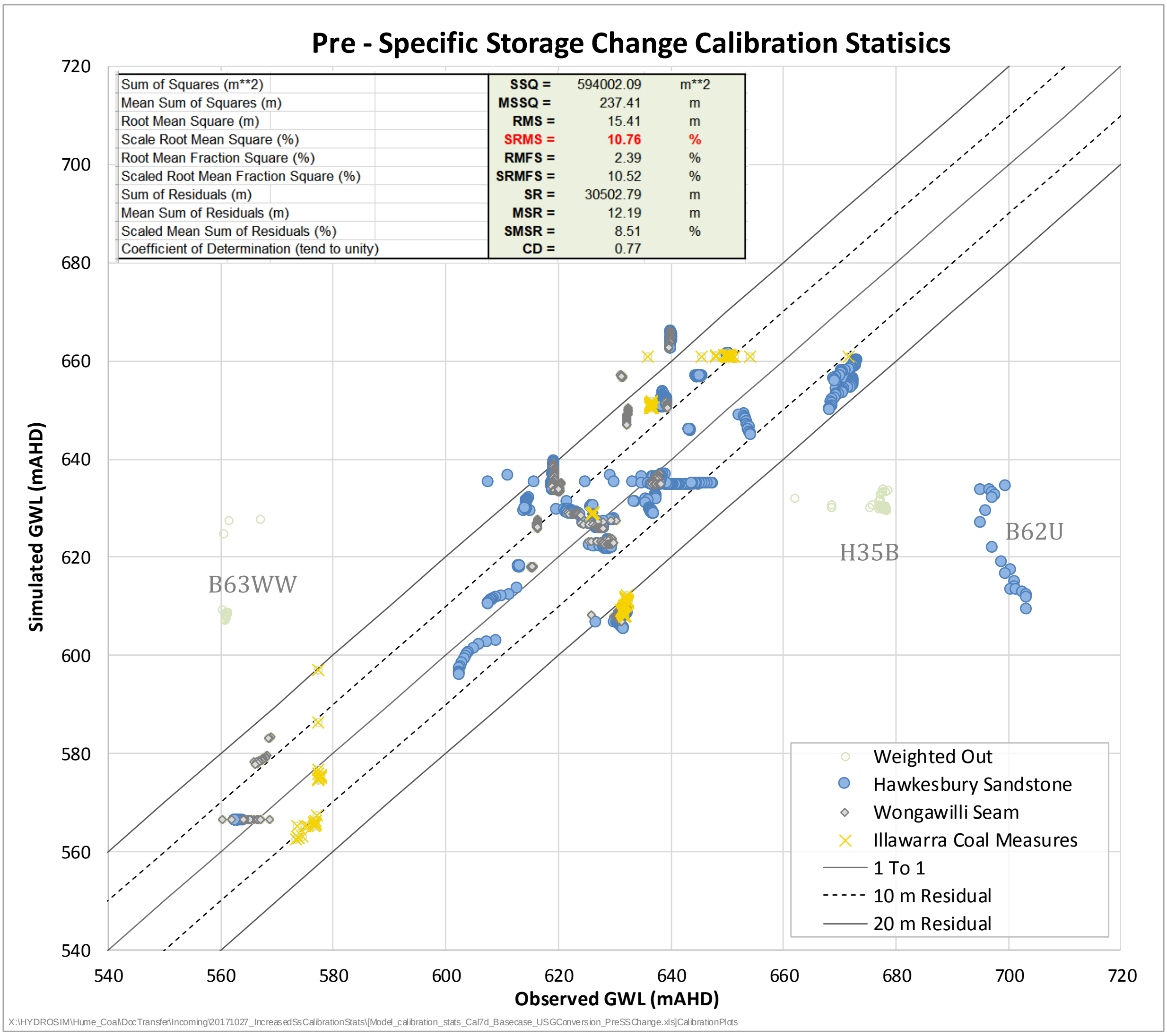


Figure 2 Observed vs modelled groundwater levels for the HydroSimulations revision of the EIS model using MODFLOW USG [Preliminary Modified EIS Model – USG]

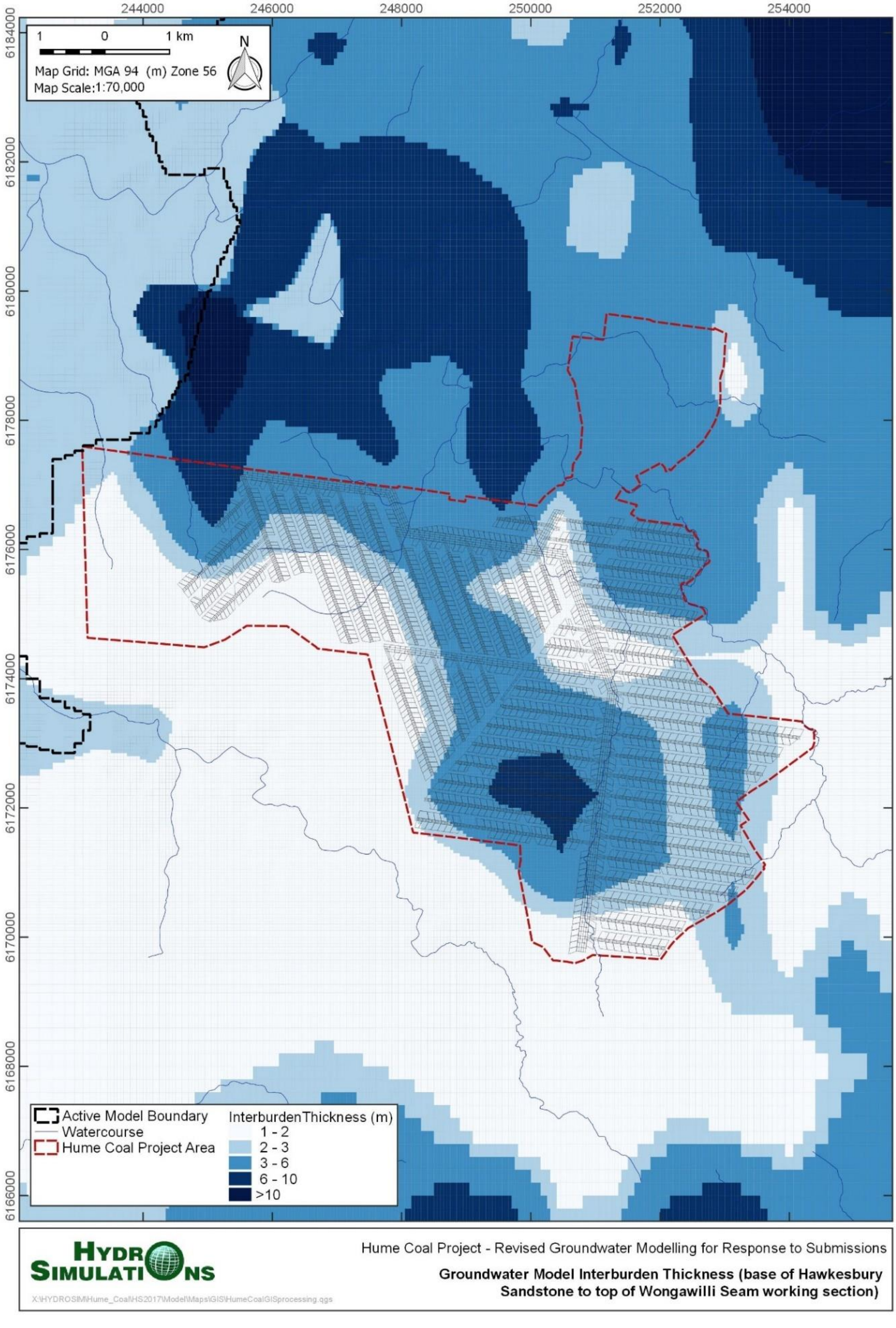


Figure 3 Groundwater model 'interburden' thickness

(Note: no changes to model layer geometry within revisions)

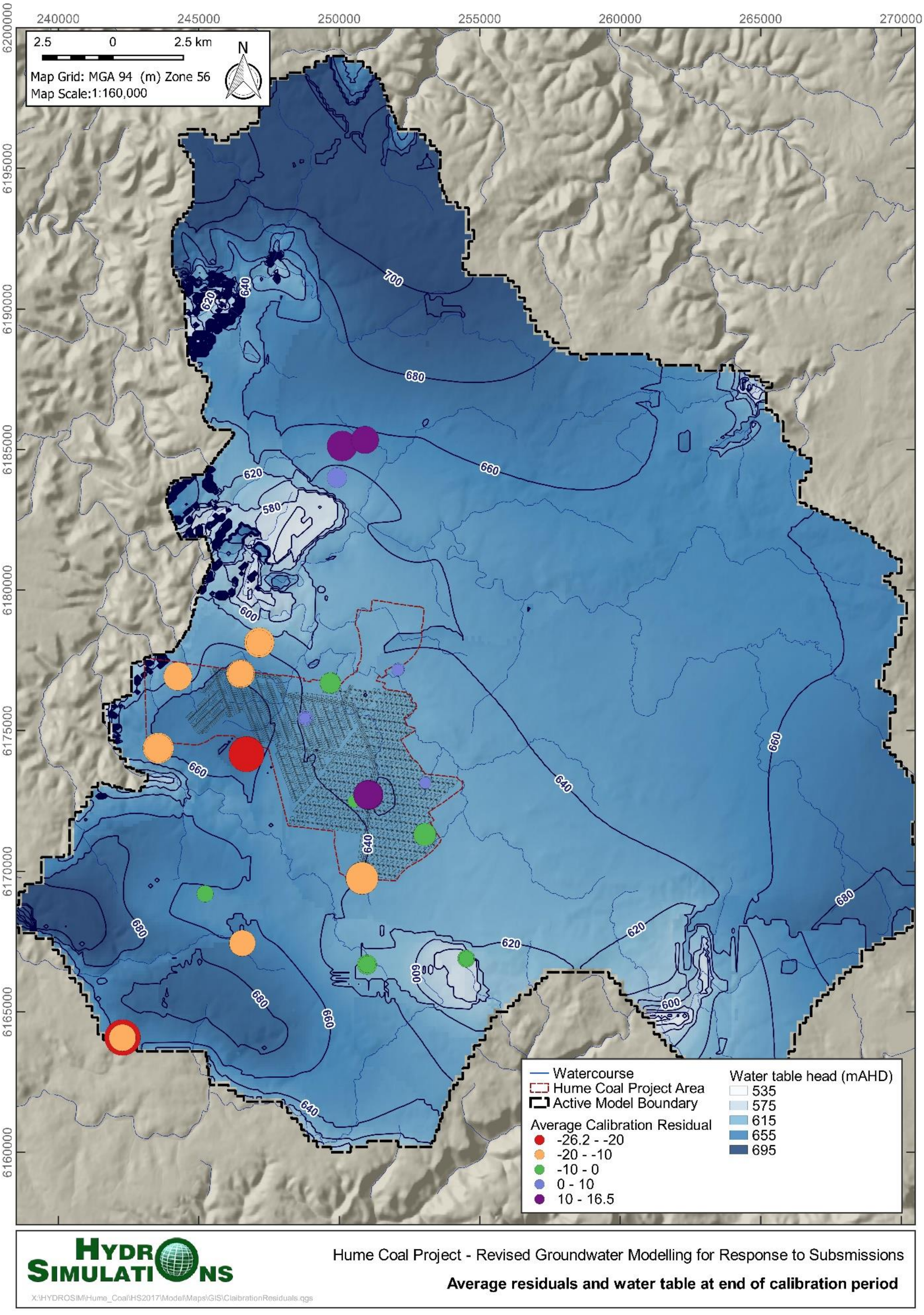
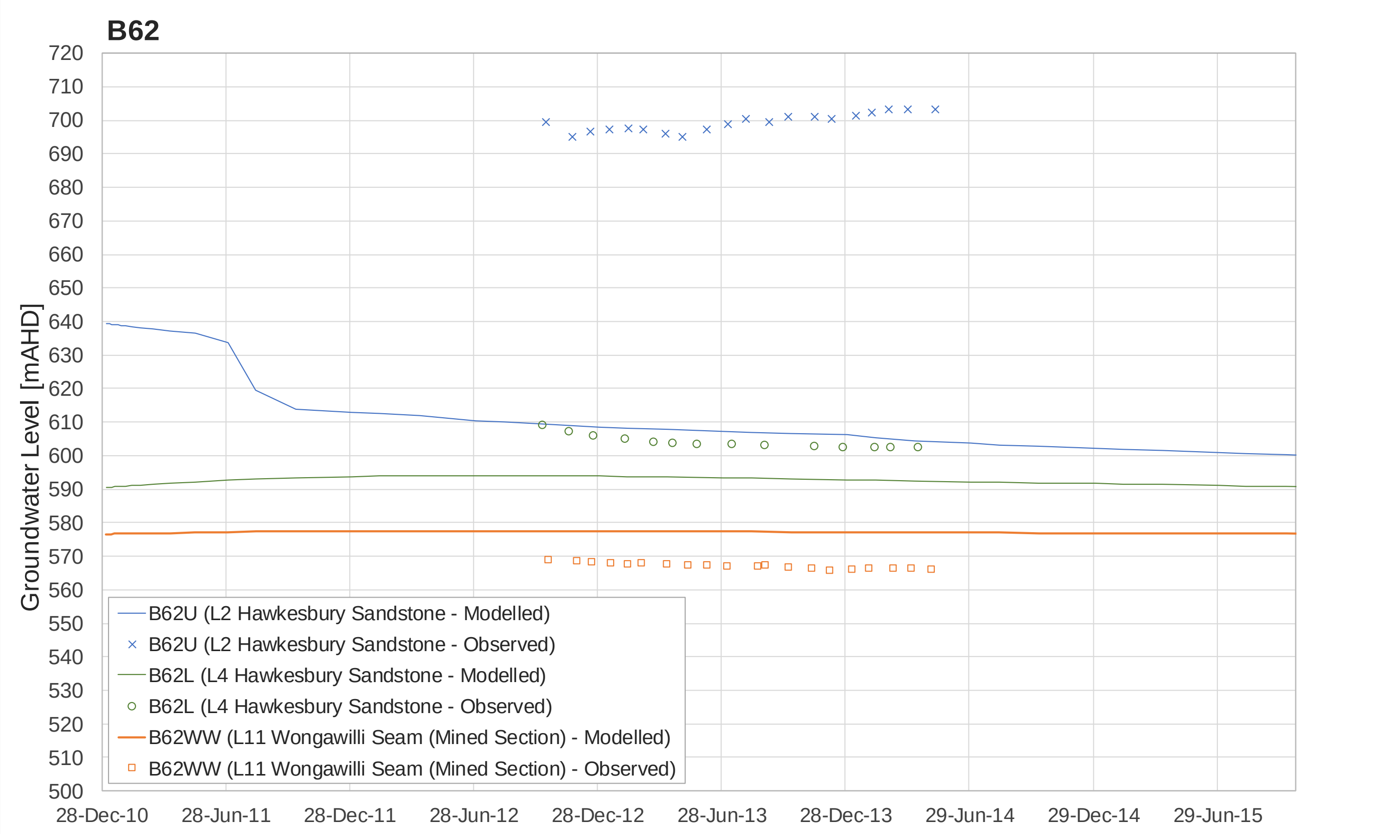


Figure 4 Average residuals at bores and water table elevation at the end of the calibration period

[Modified EIS Model – MODFLOW USG]

CALIBRATION HYDROGRAPHS (MODIFIED EIS MODEL – MODFLOW USG)



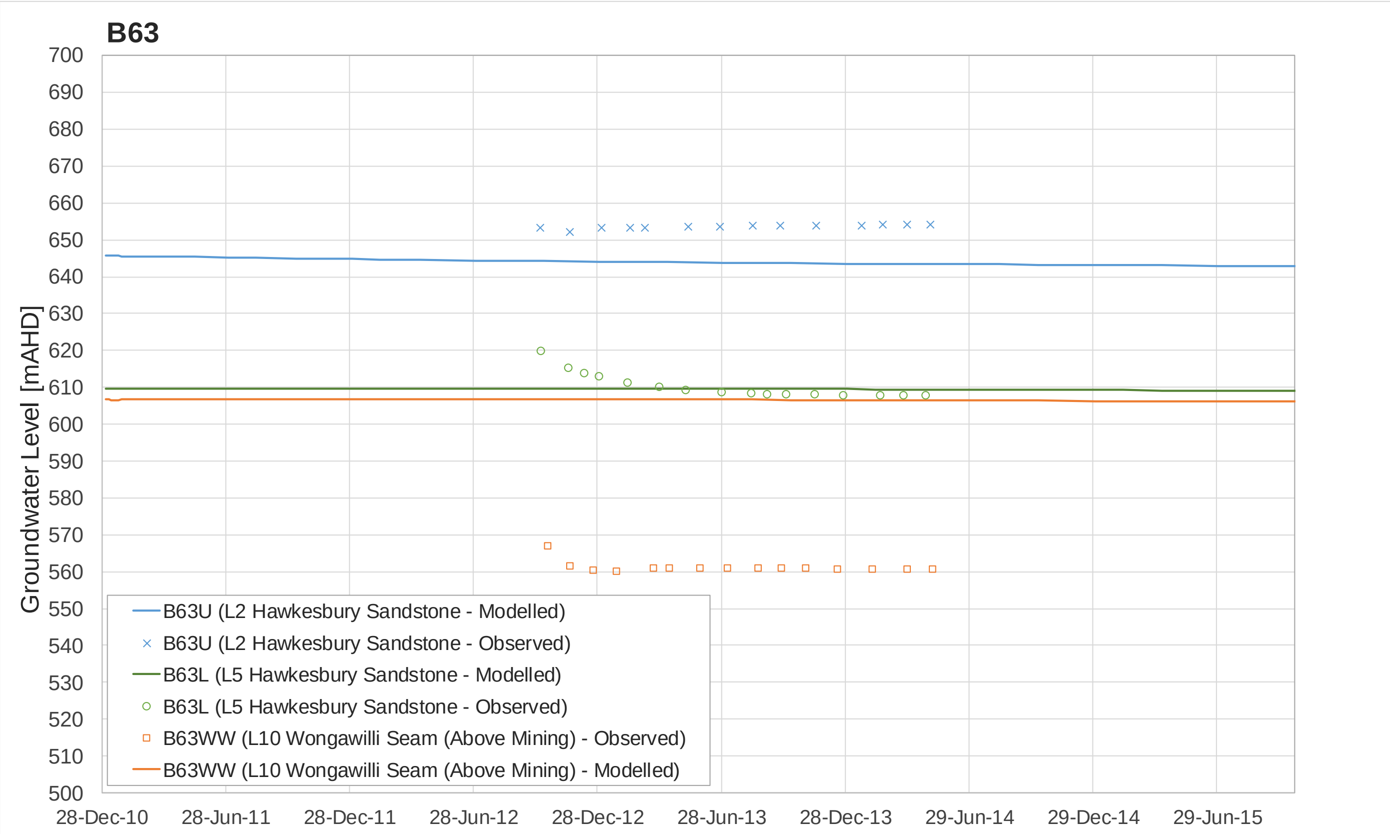
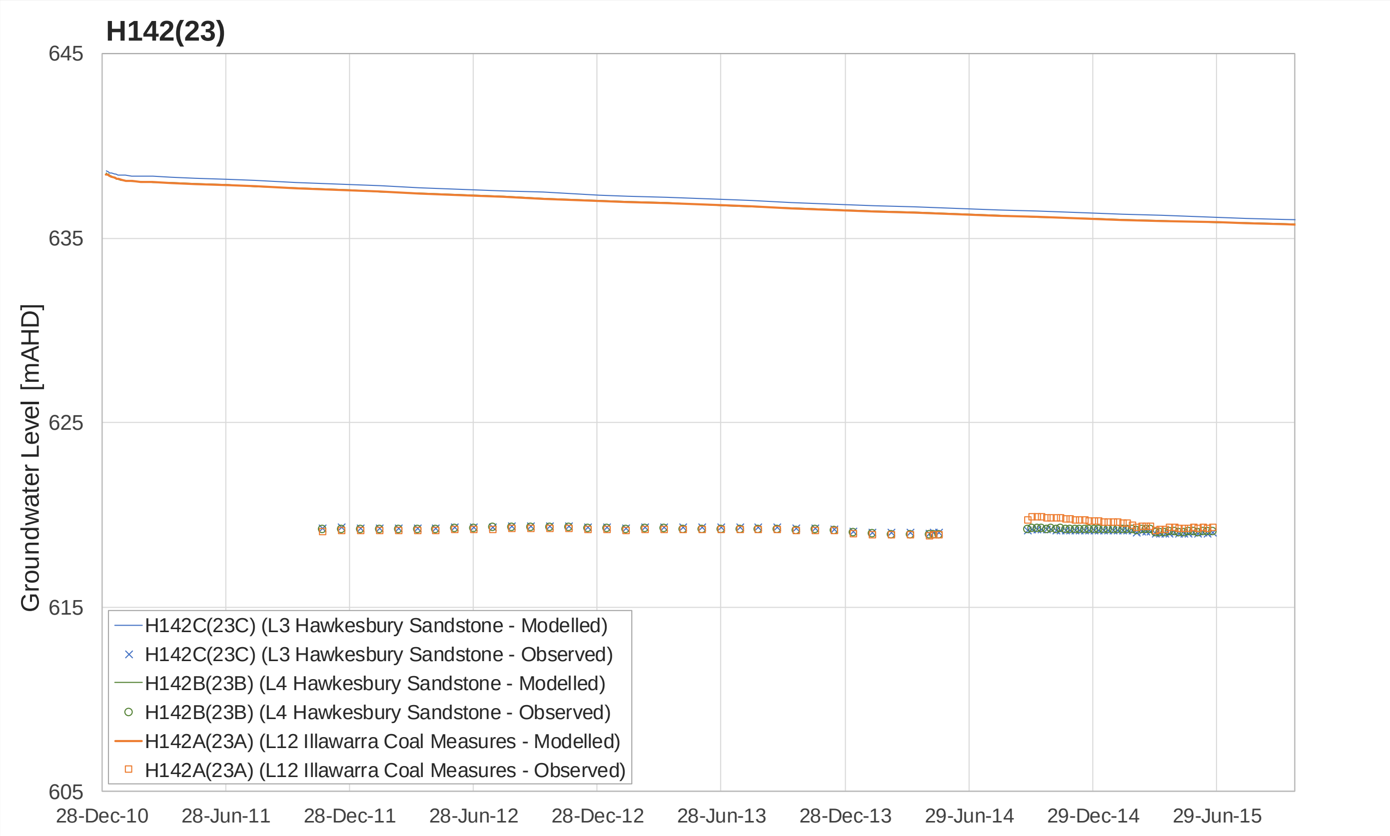


Figure 5 Multi sensor calibration hydrographs for B62 and B63



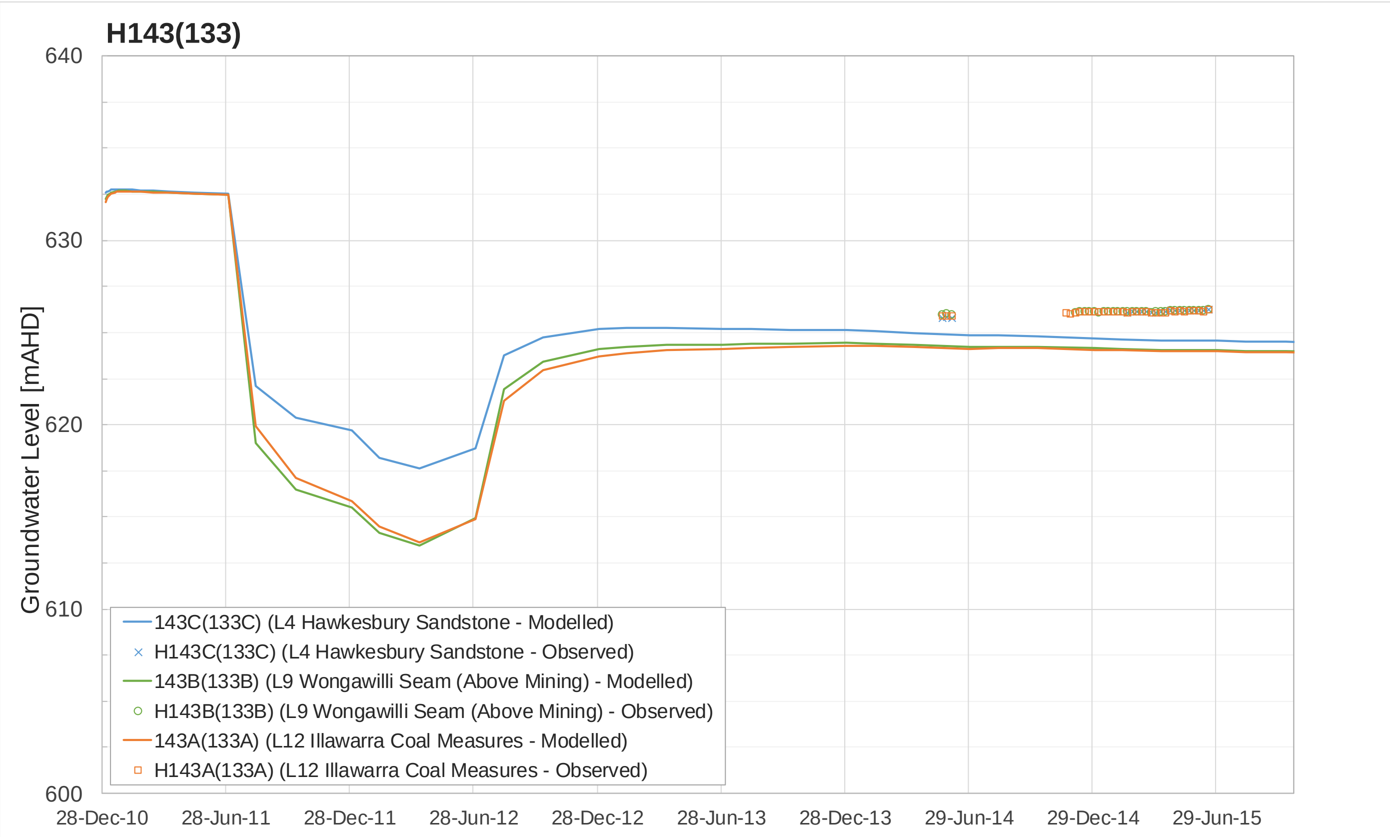
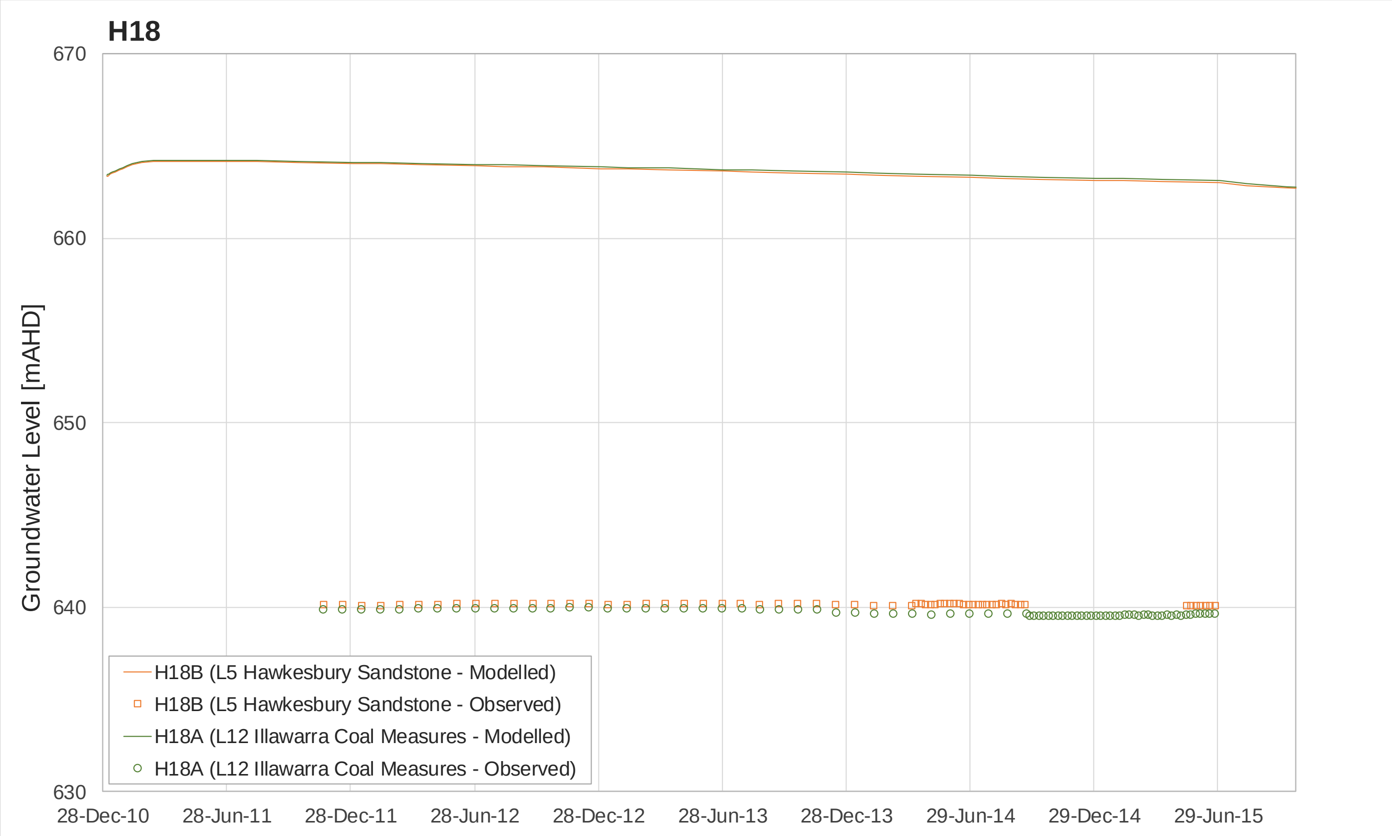


Figure 6 Multi sensor calibration hydrographs for H142(23) and H143(133)



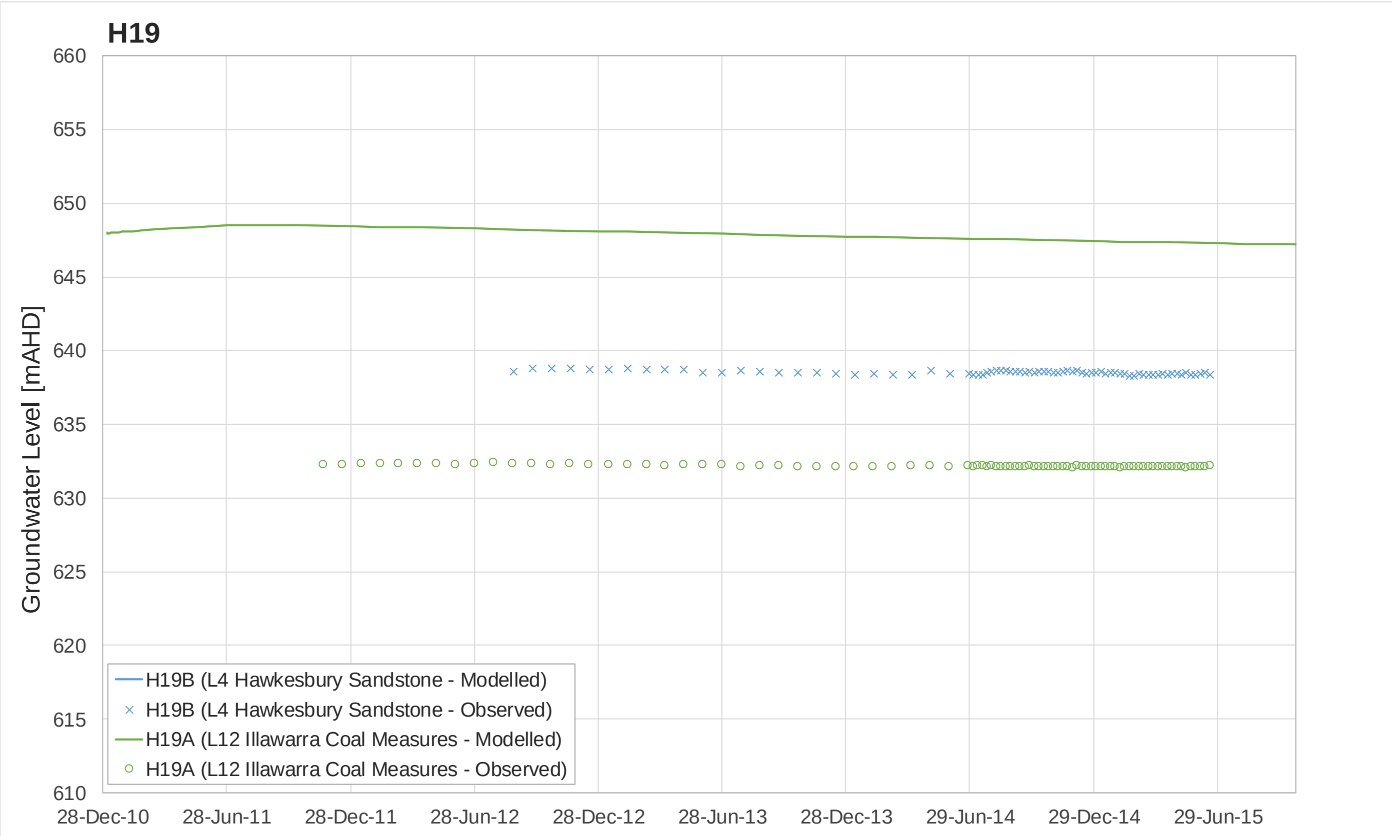
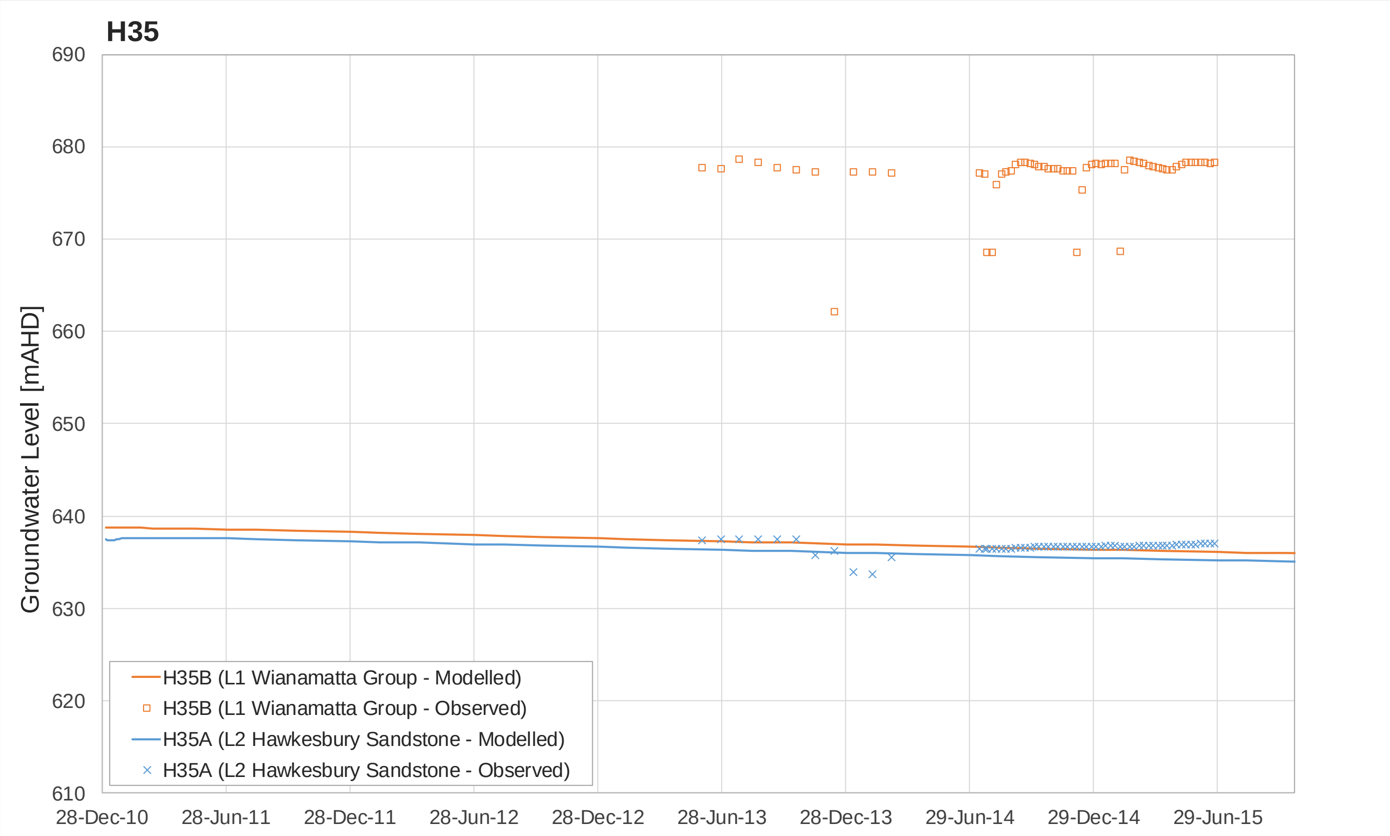


Figure 7 Multi sensor calibration hydrographs for H18 and H19



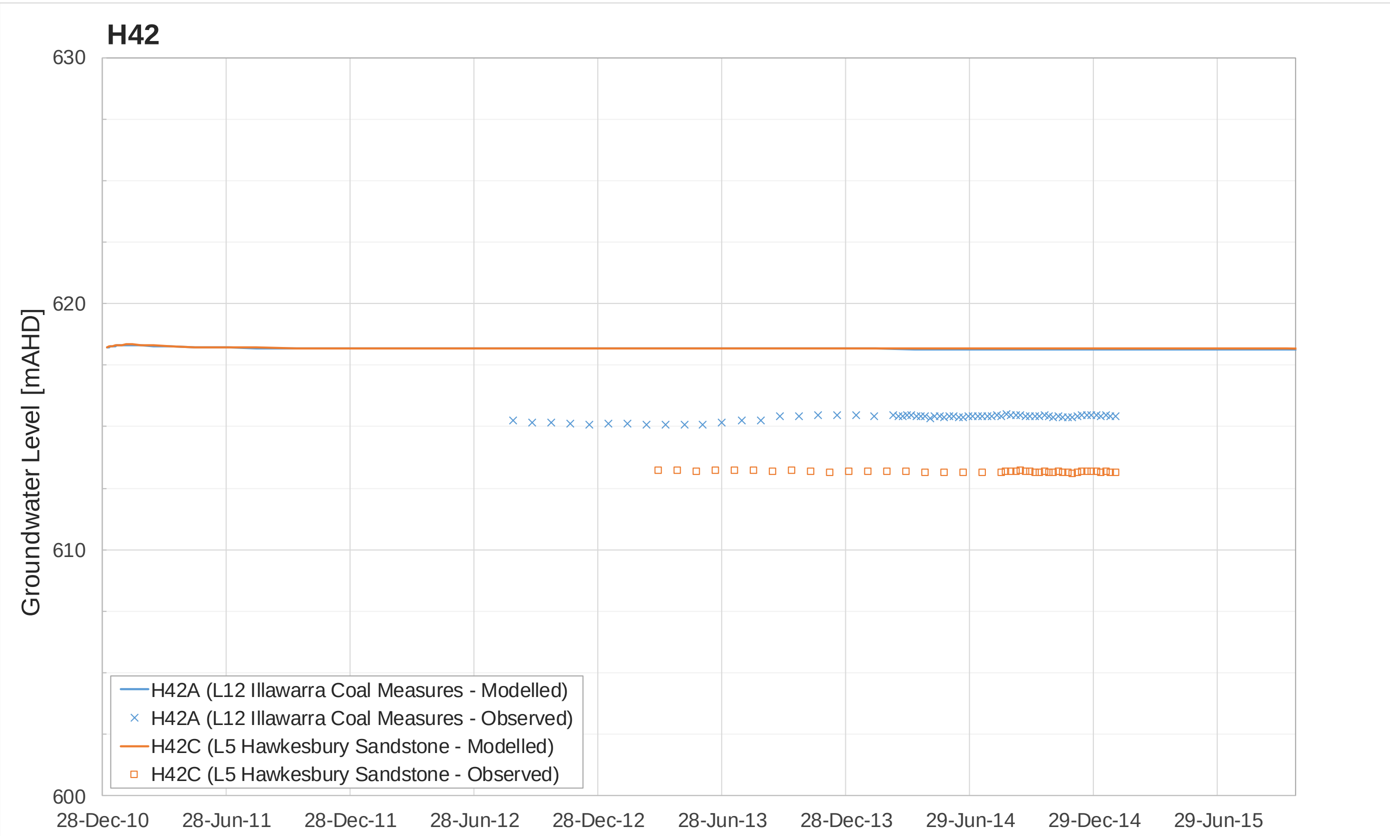


Figure 8 Multi sensor calibration hydrographs for H35 and H42

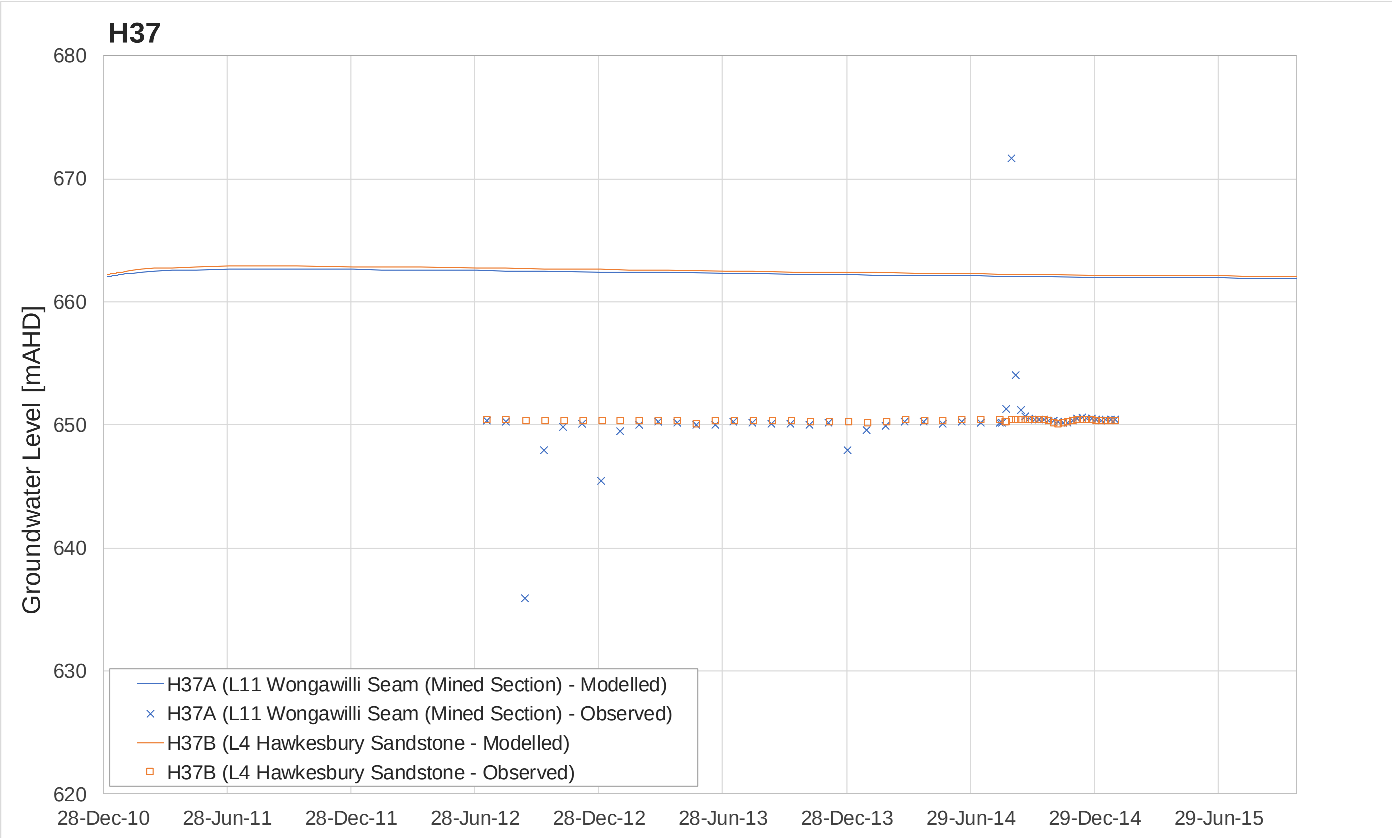


Figure 9 Multi sensor calibration hydrographs for H37 and H38

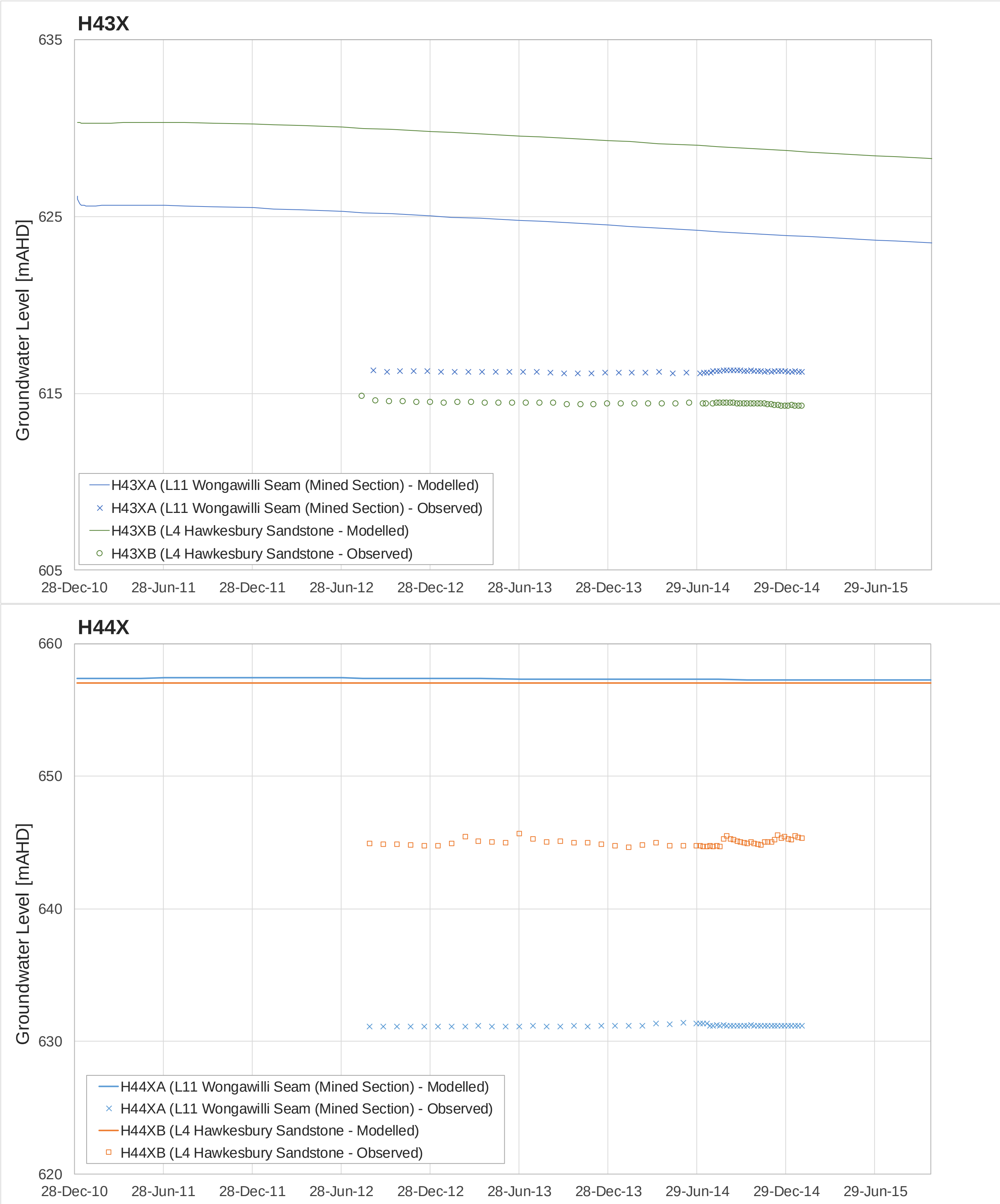
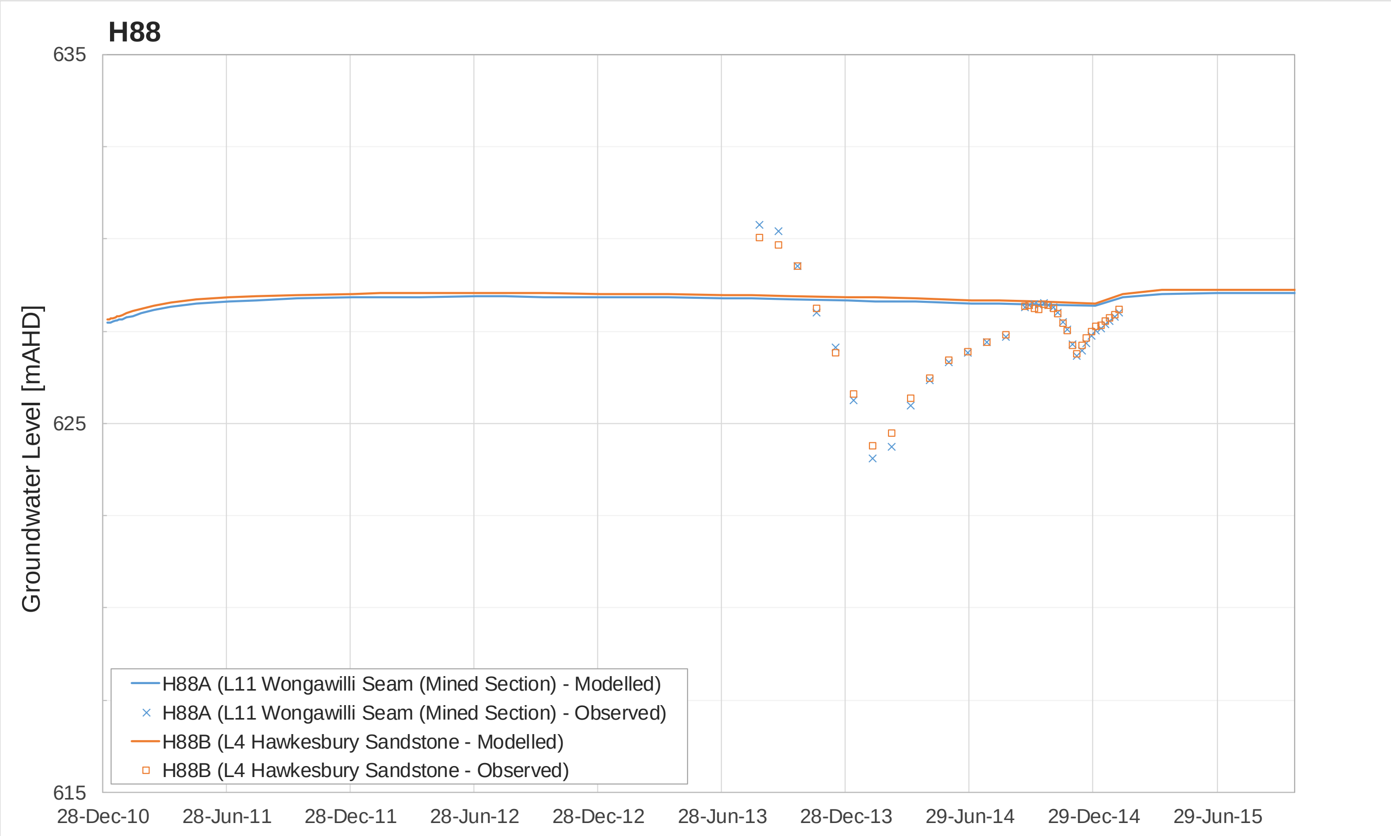


Figure 10 Multi sensor calibration hydrographs for H43X and H44X



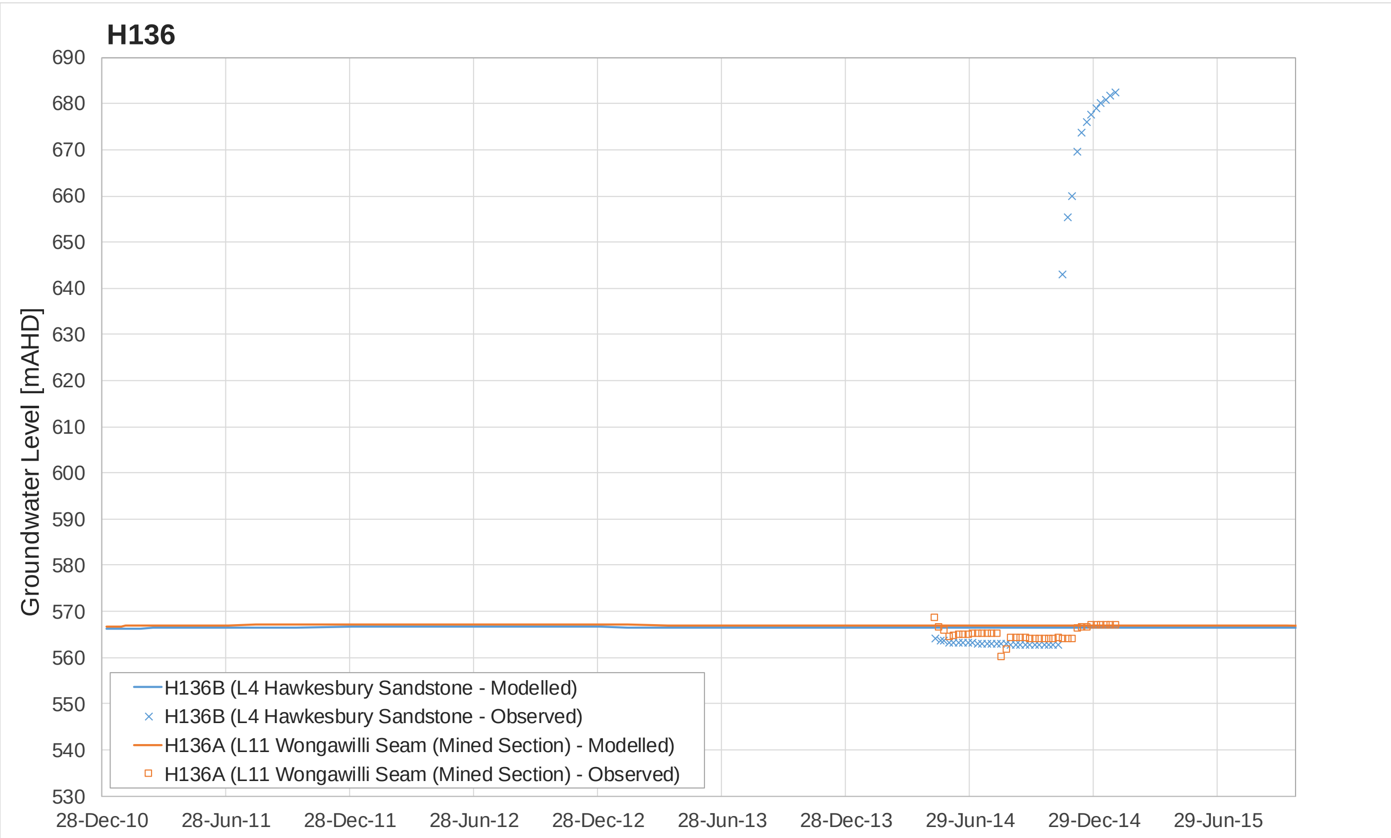
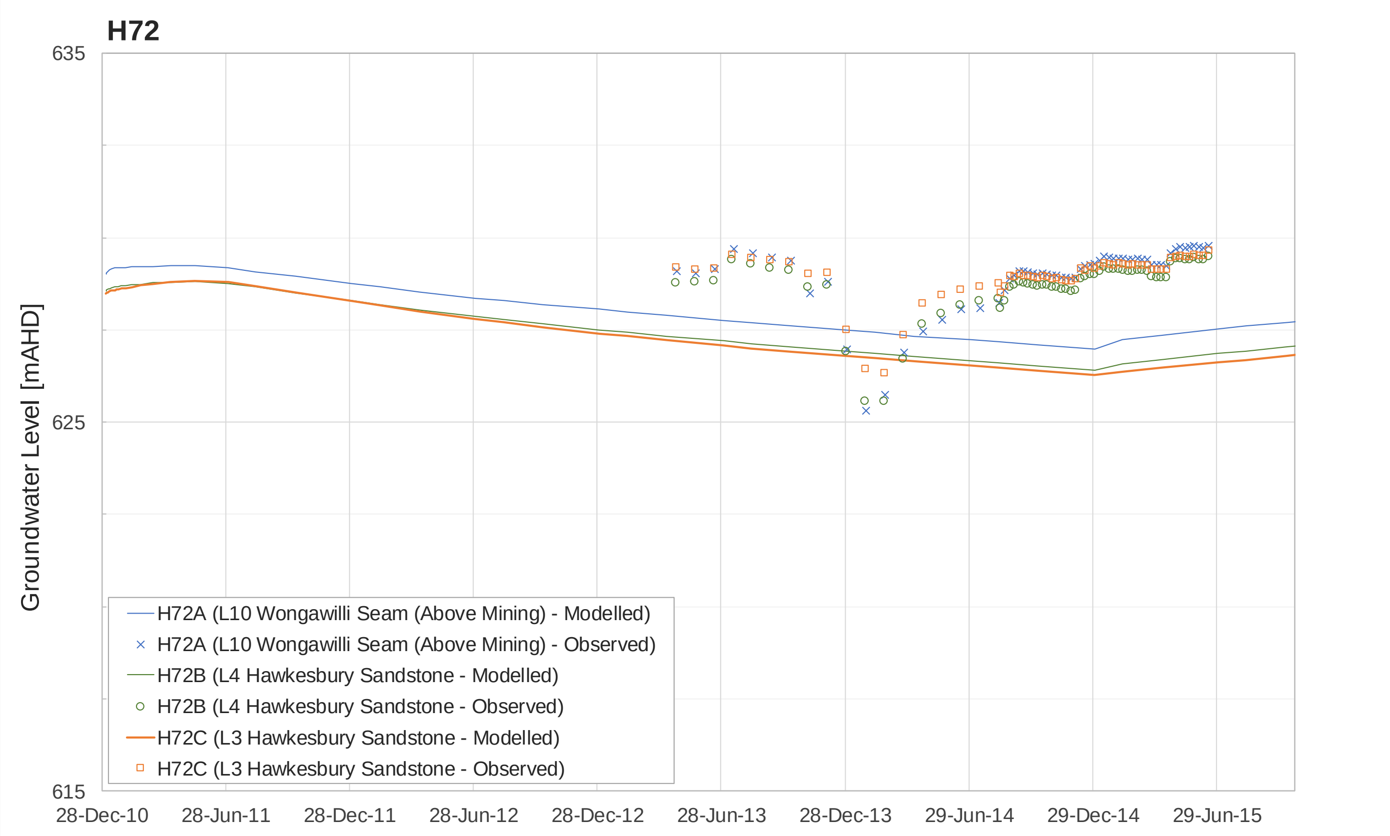


Figure 11 Multi sensor calibration hydrographs for H88 and H136



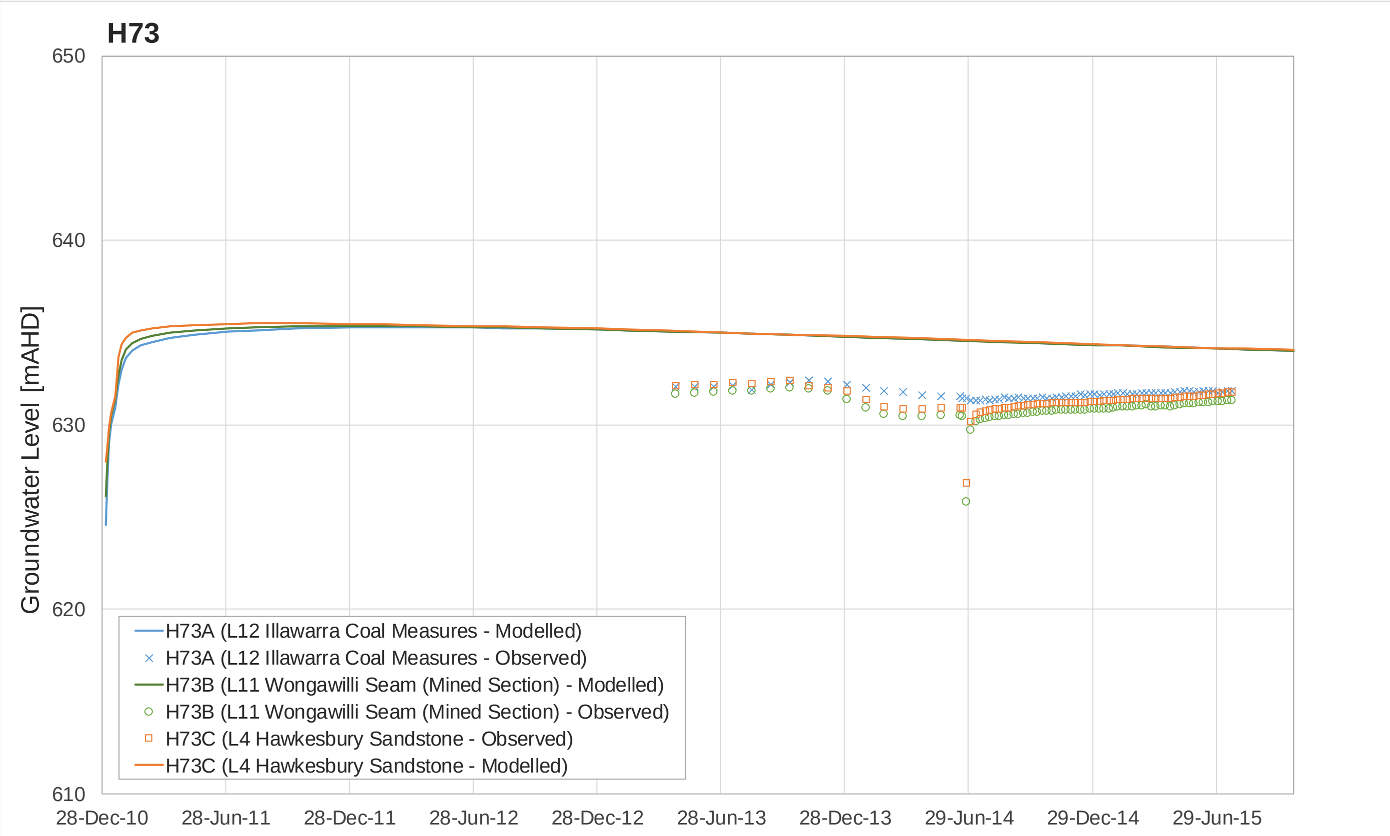


Figure 12 Multi sensor calibration hydrographs for H72 and H73

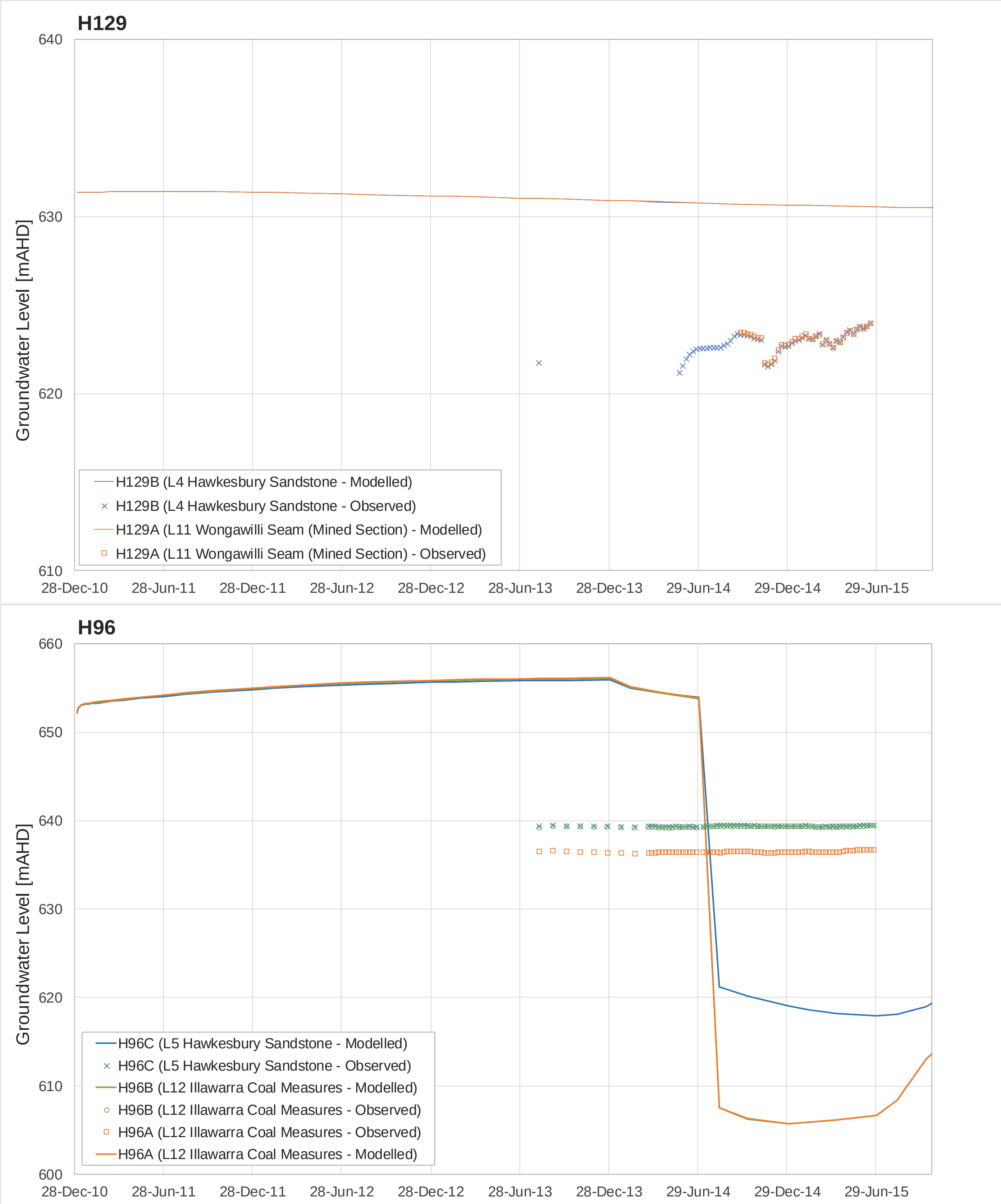


Figure 13 Multi sensor calibration hydrographs for H129 and H96

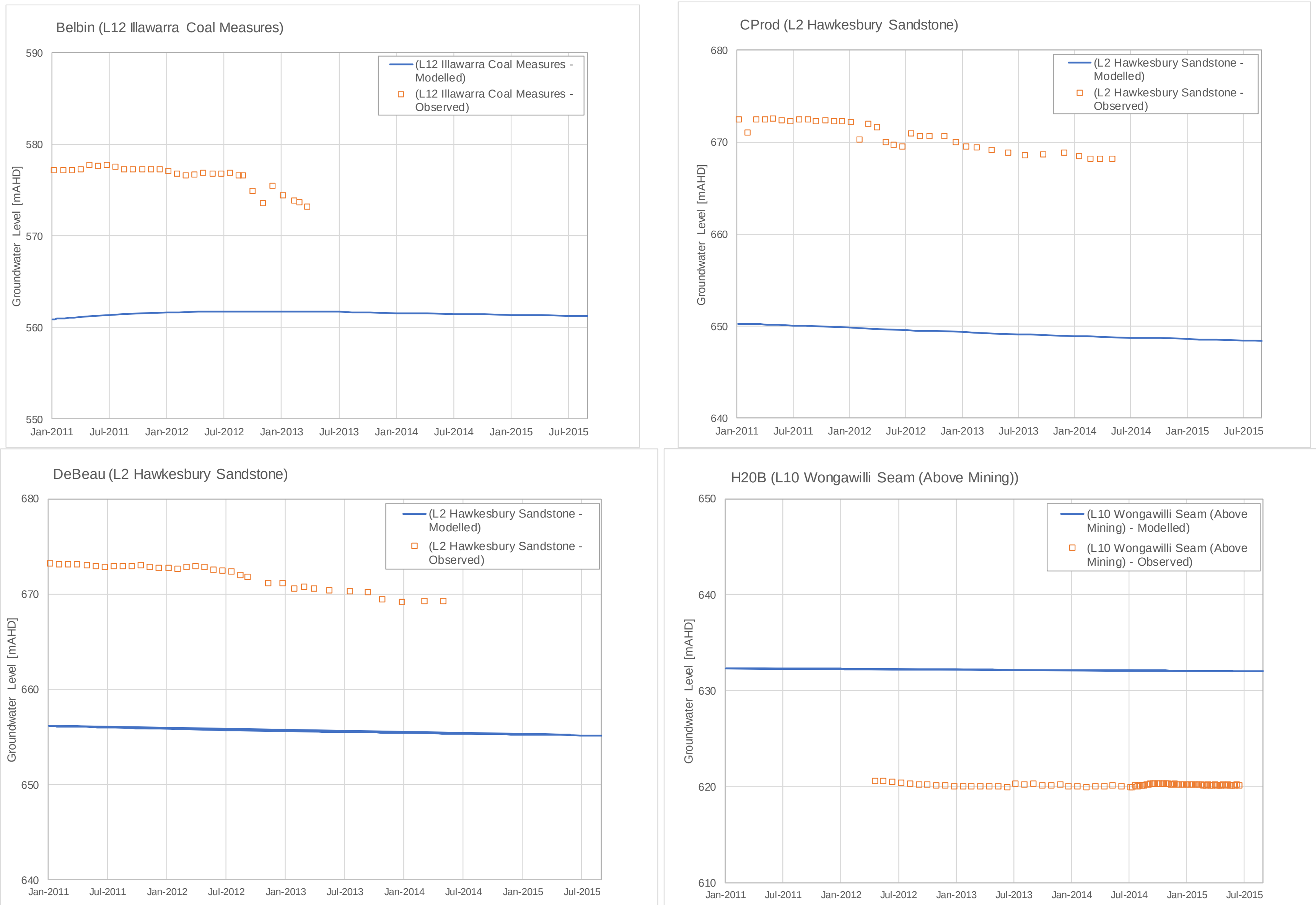


Figure 14 Calibration hydrographs for Belbin, CProd, DeBeau, H20B

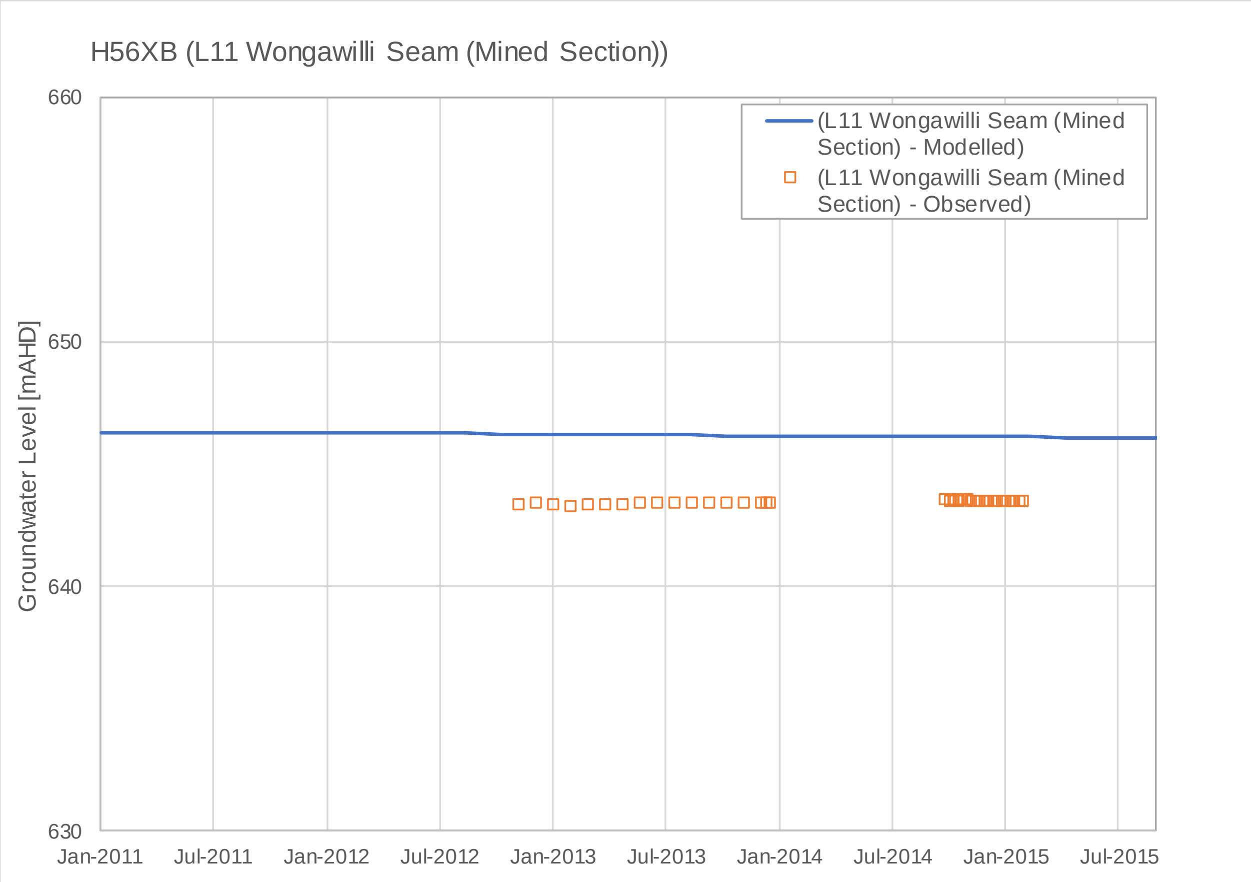


Figure 15 Calibration hydrograph H56XB

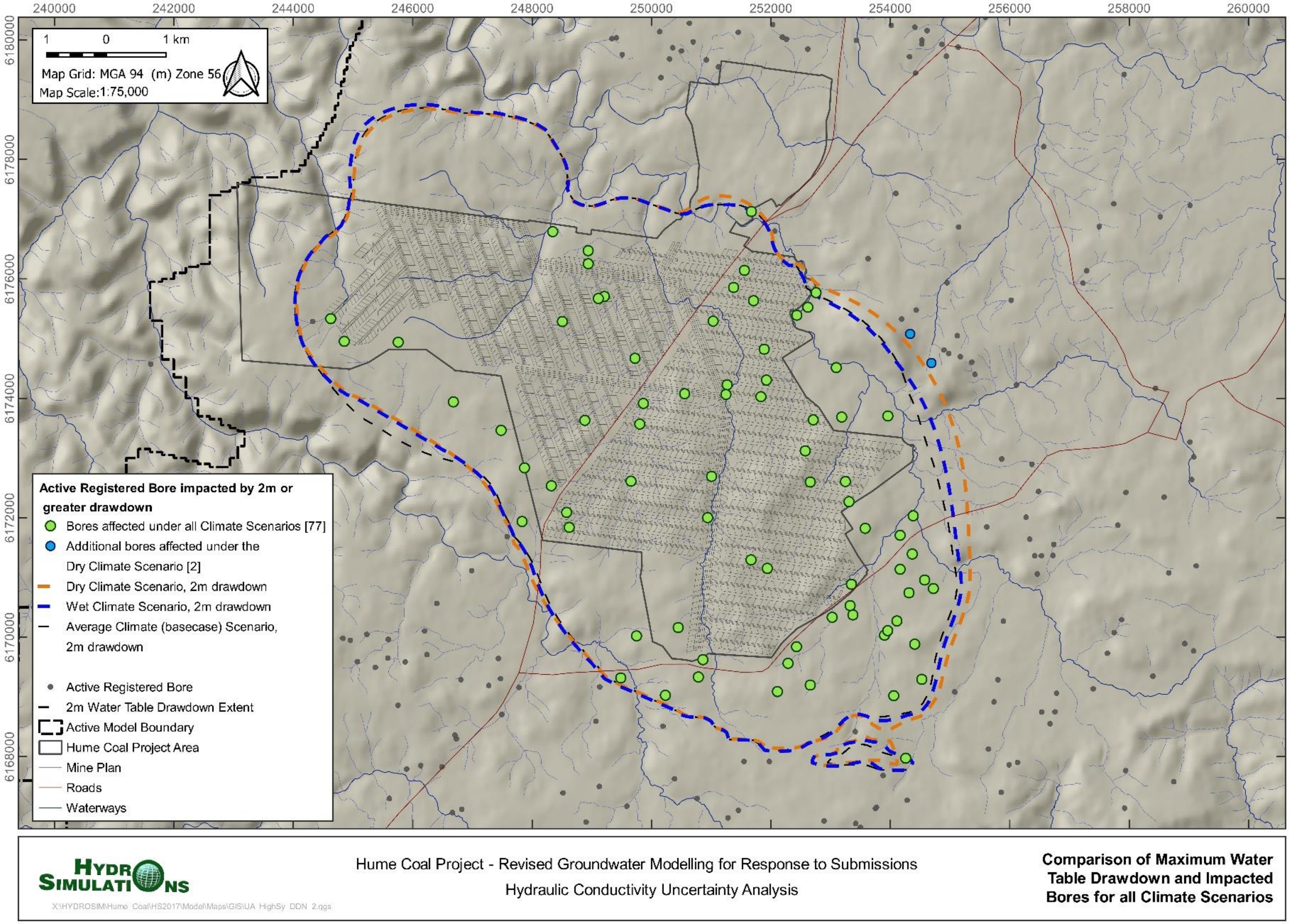


Figure 16 Comparison of water table drawdown and number of impacted bores during mine year 17 for climate scenarios (Modified EIS Model)

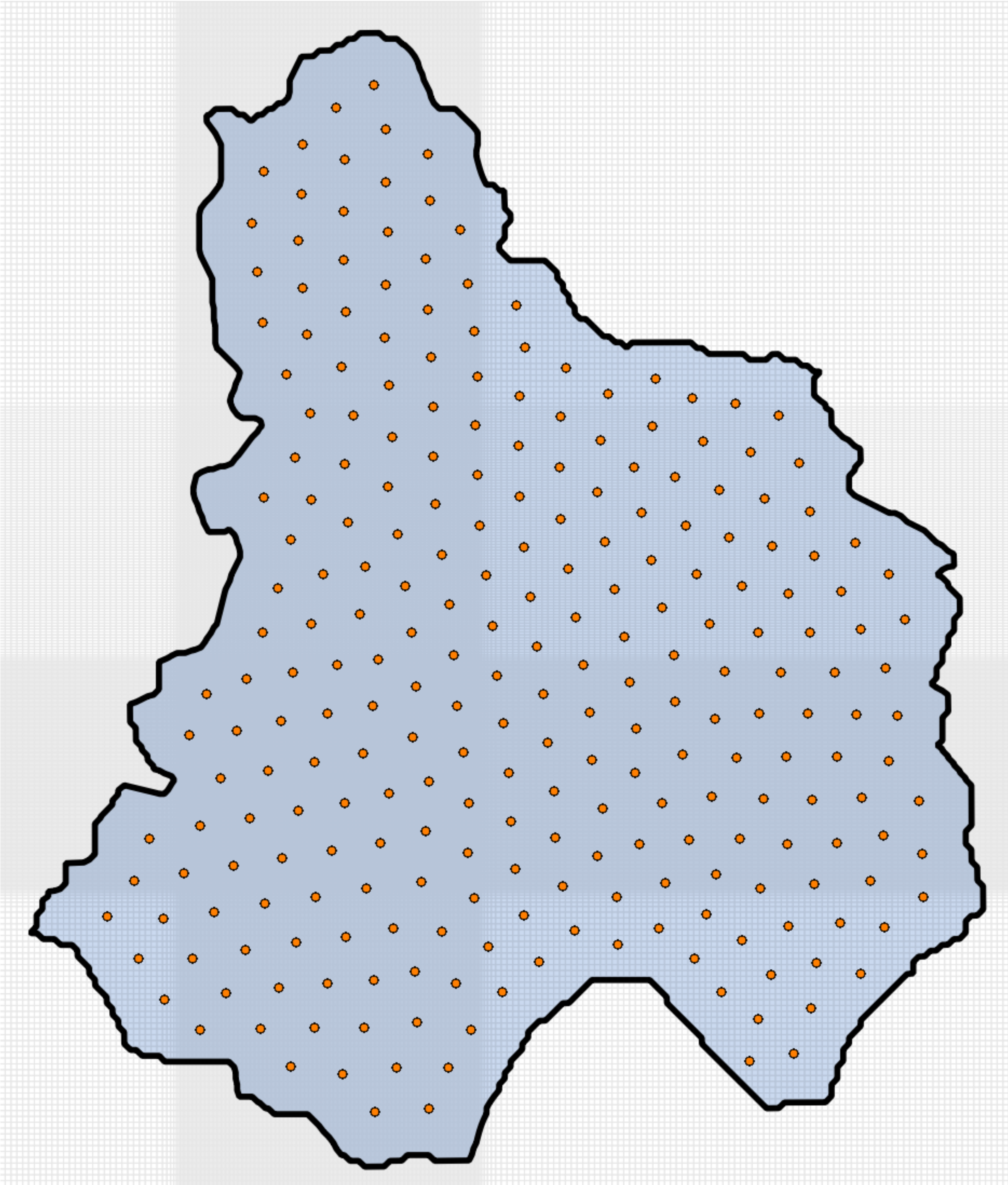


Figure 17 256 pilot point locations used to represent spatially-varying hydraulic conductivity.

UNCERTAINTY ANALYSIS FIGURES

BASELINE MEAN K

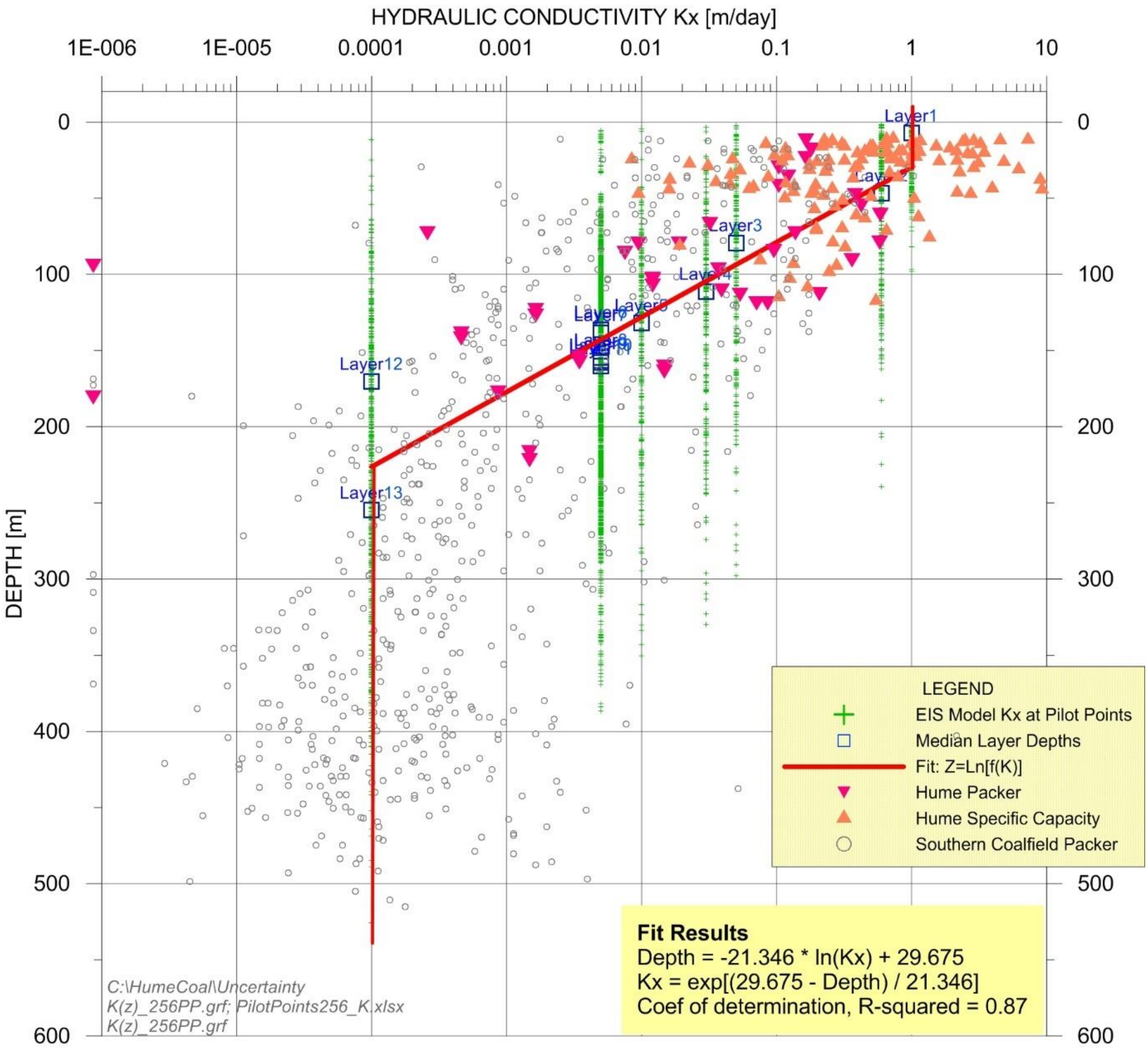


Figure 18 Prior mean Kx versus depth, fit to Hume and surrounding Southern Coalfield data.

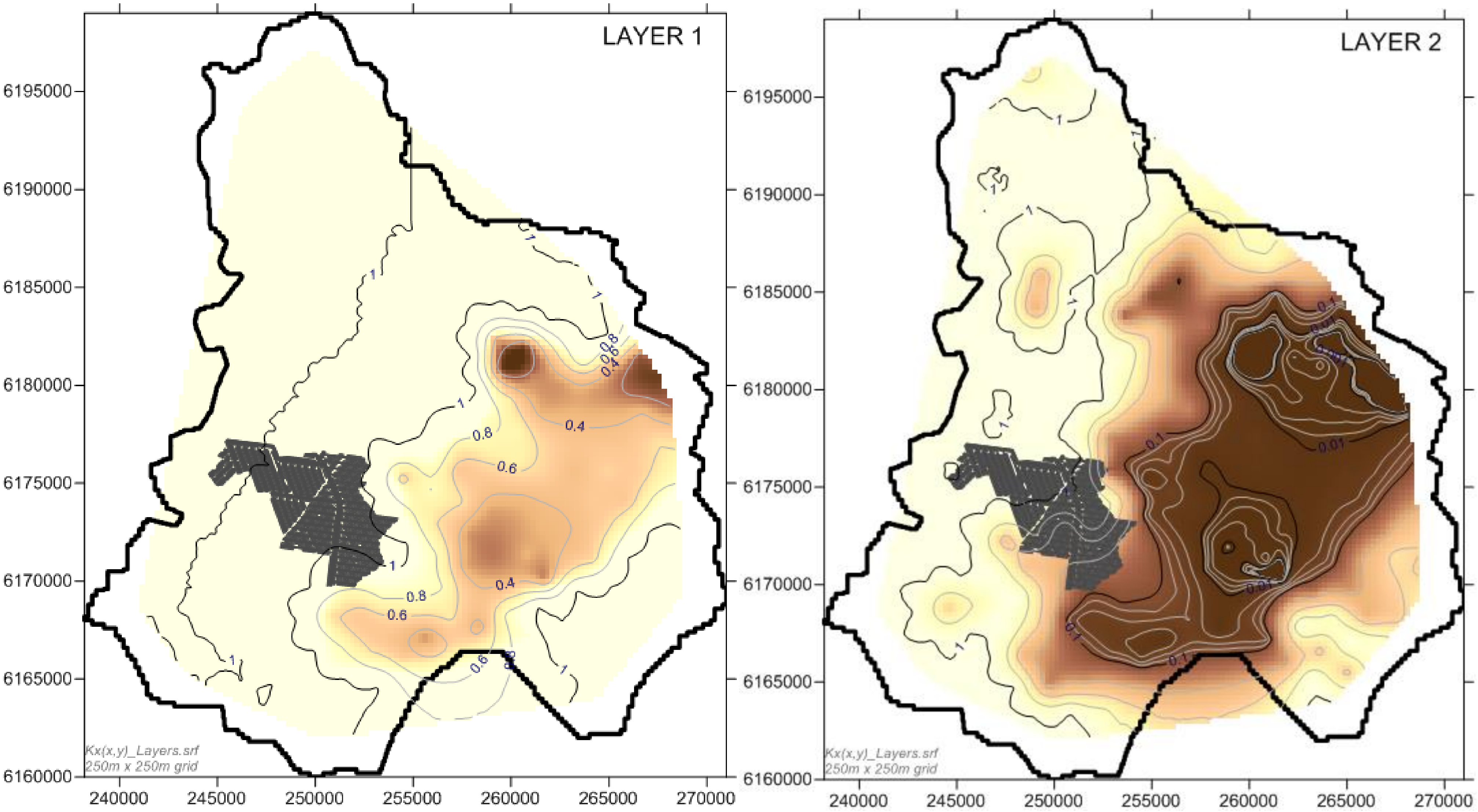


Figure 19 **Spatial Distribution of Hydraulic Conductivity using depth function in Layer 1 and Layer 2**

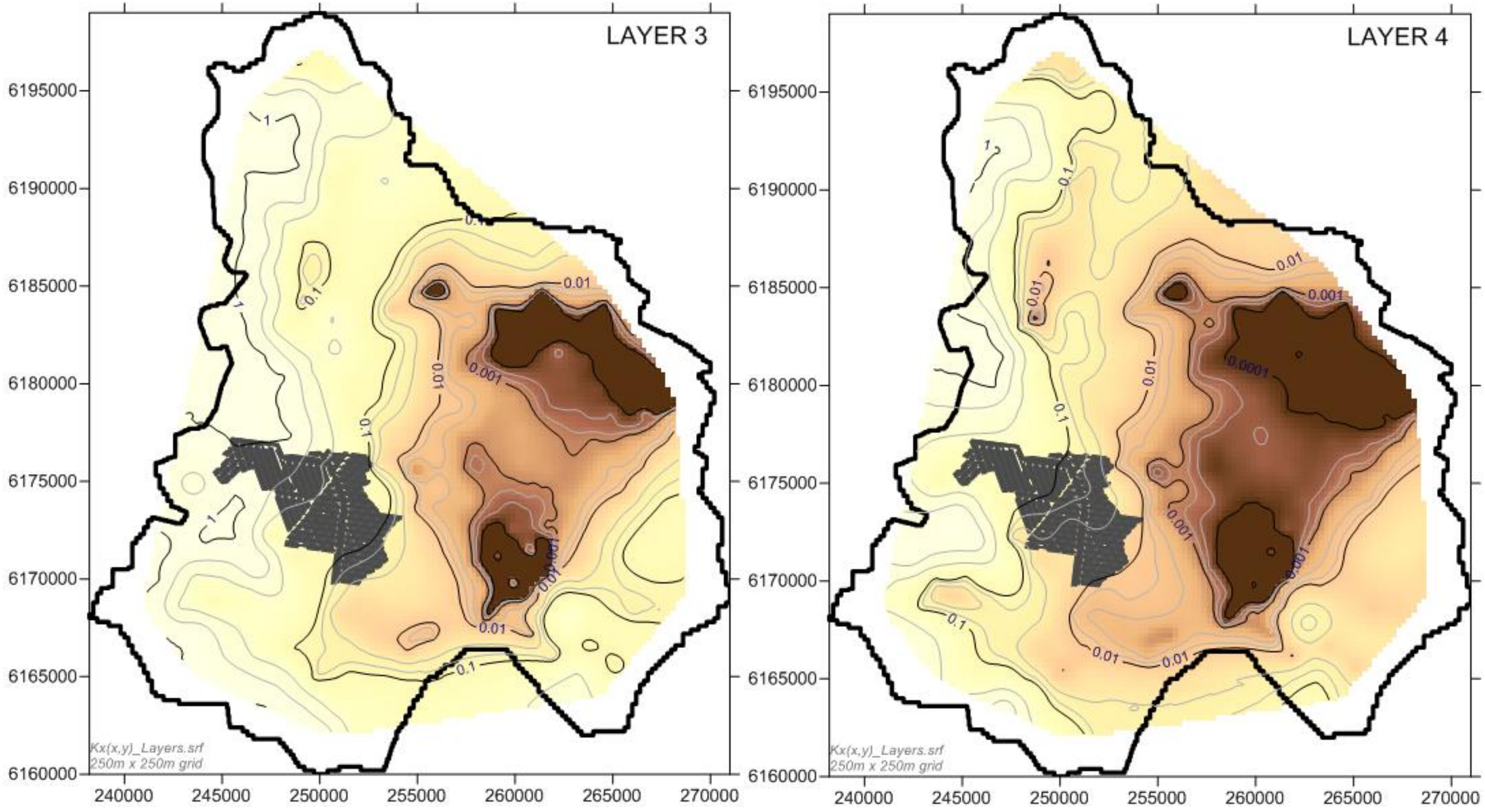


Figure 20 **Spatial Distribution of Hydraulic Conductivity using depth function in Layer 3 and Layer 4.**

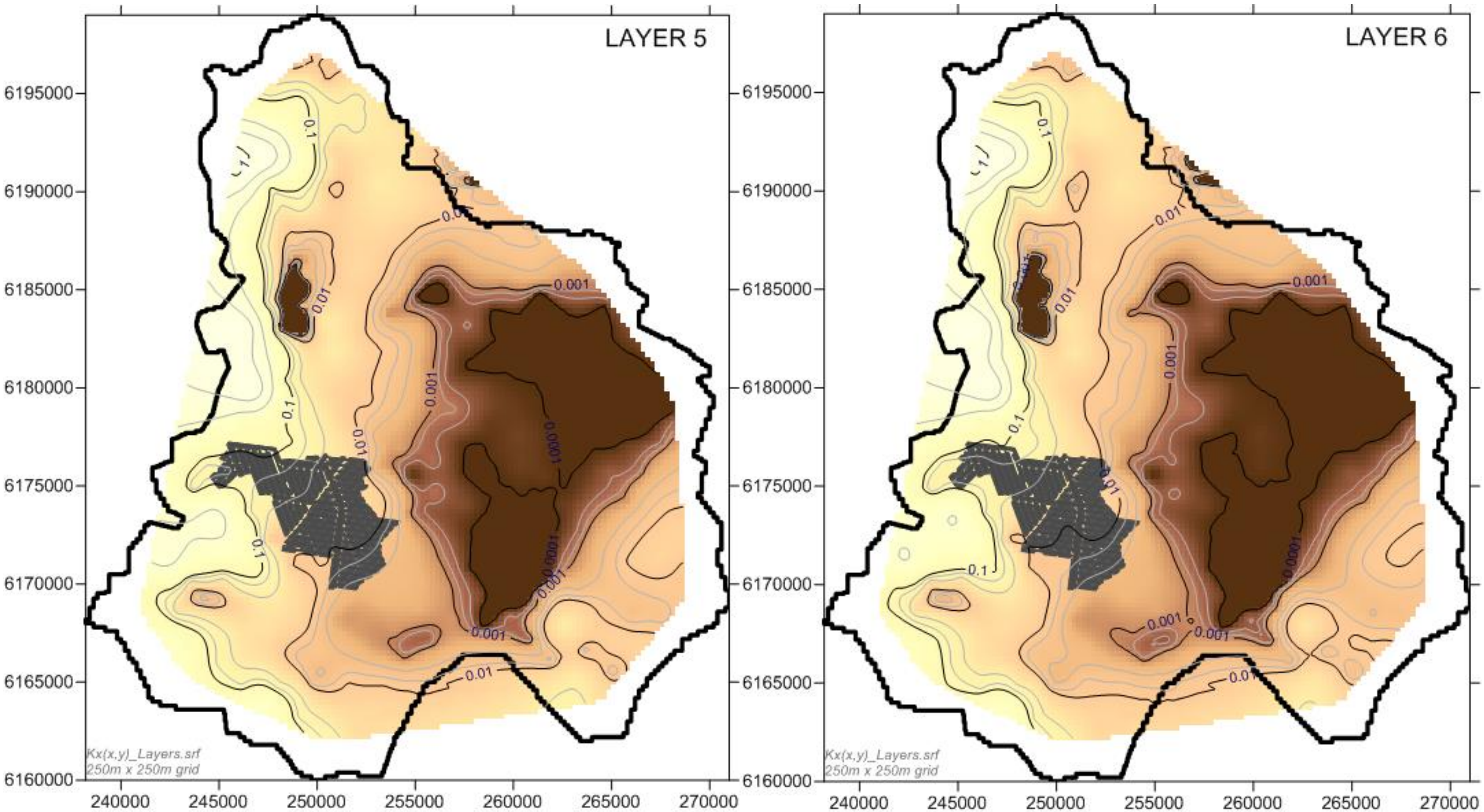


Figure 21 Spatial Distribution of Hydraulic Conductivity using depth function in Layer 5 and Layer 6

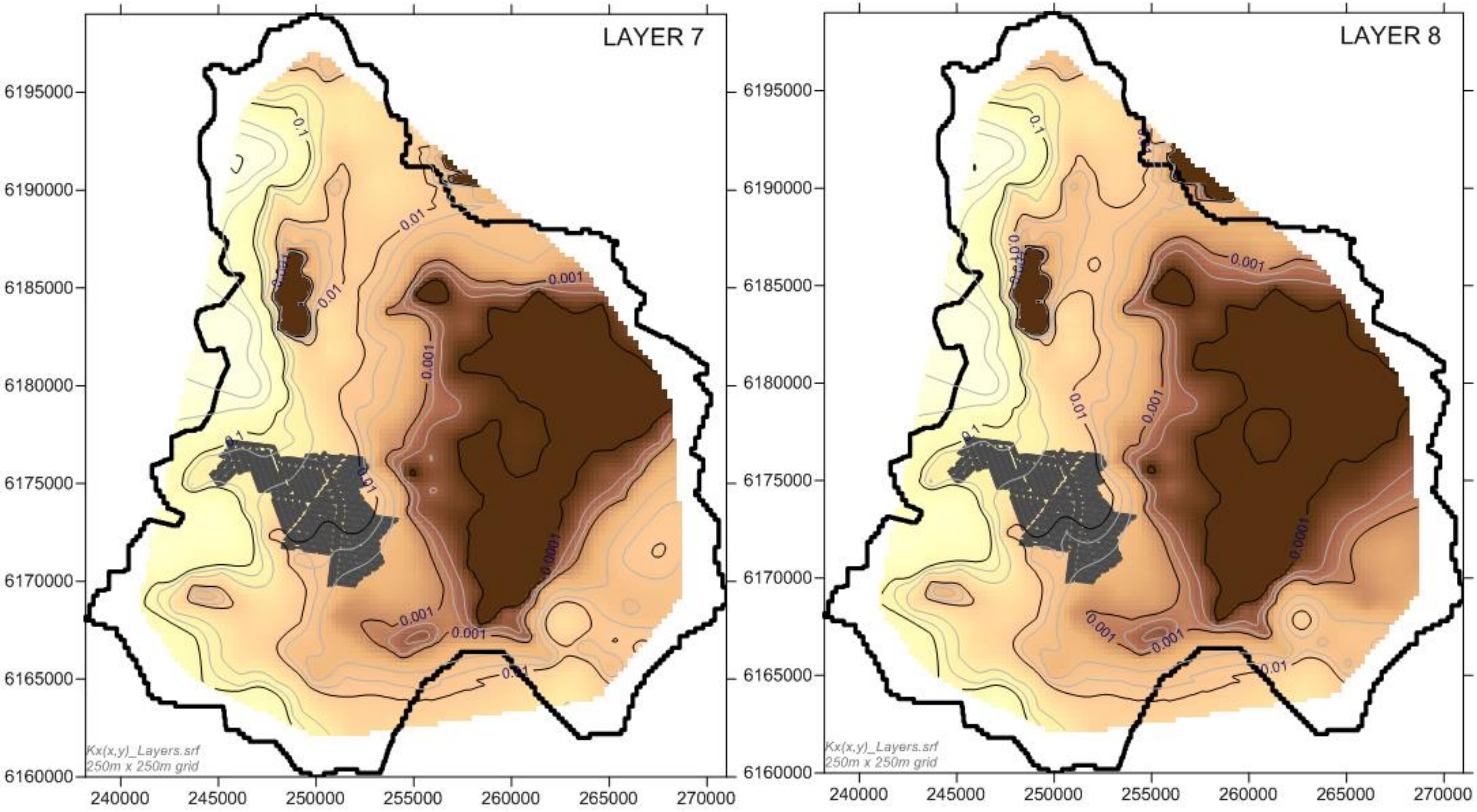


Figure 22 Spatial Distribution of Hydraulic Conductivity using depth function in Layer 7 and Layer 8

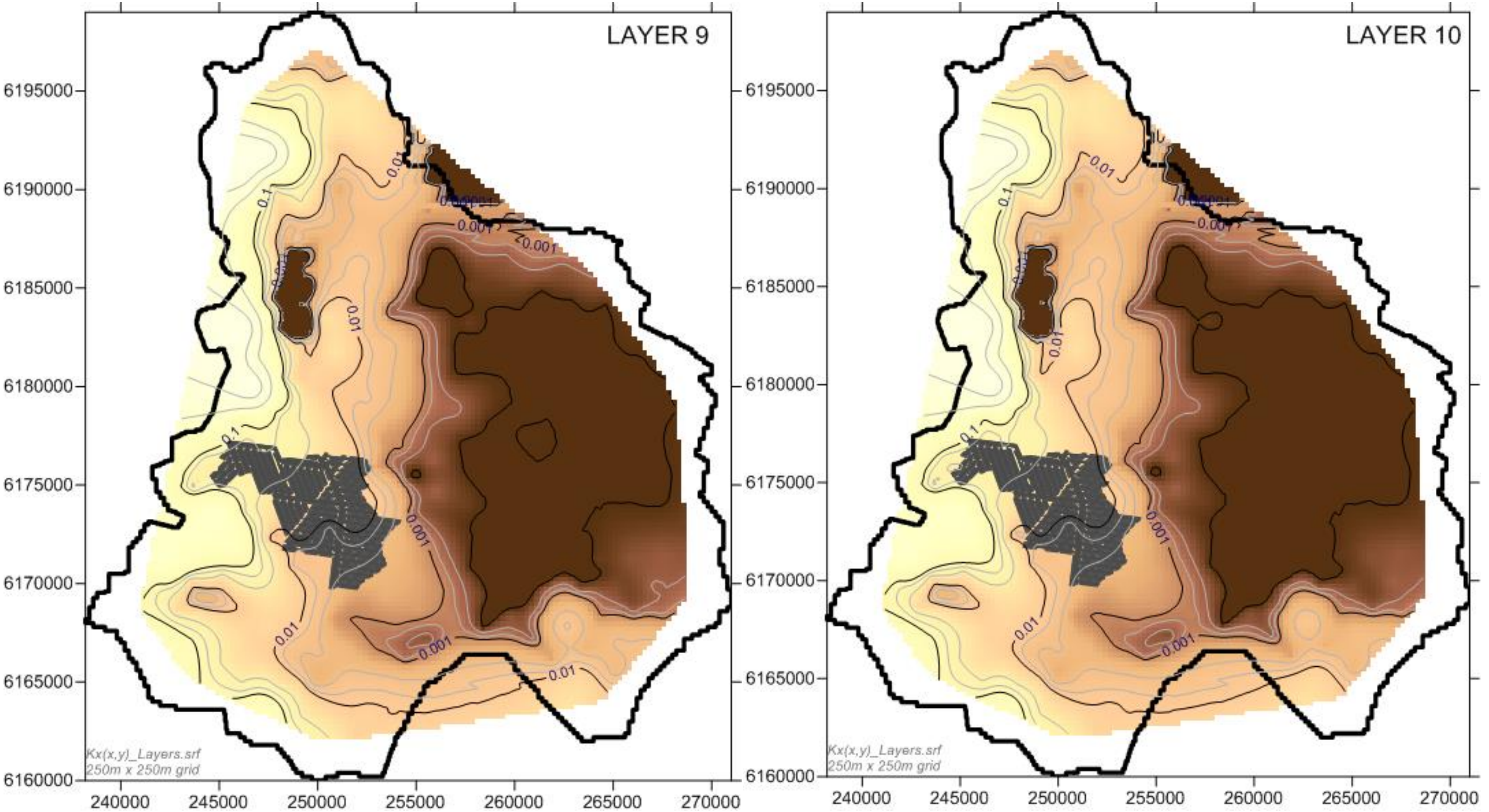


Figure 23 Spatial Distribution of Hydraulic Conductivity using depth function in Layer 9 and Layer 10

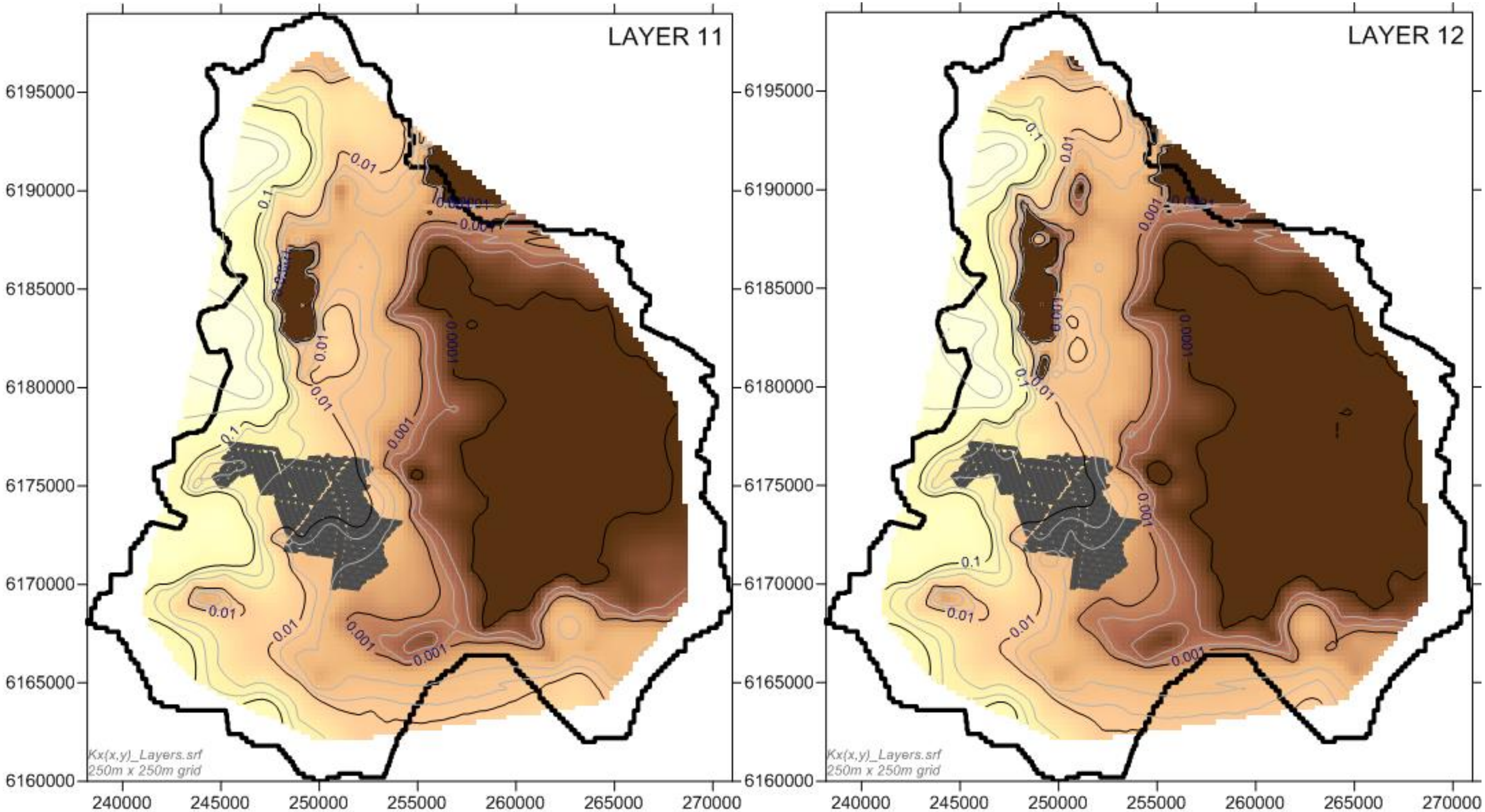


Figure 24 Spatial Distribution of Hydraulic Conductivity using depth function in Layer 11 and Layer 12

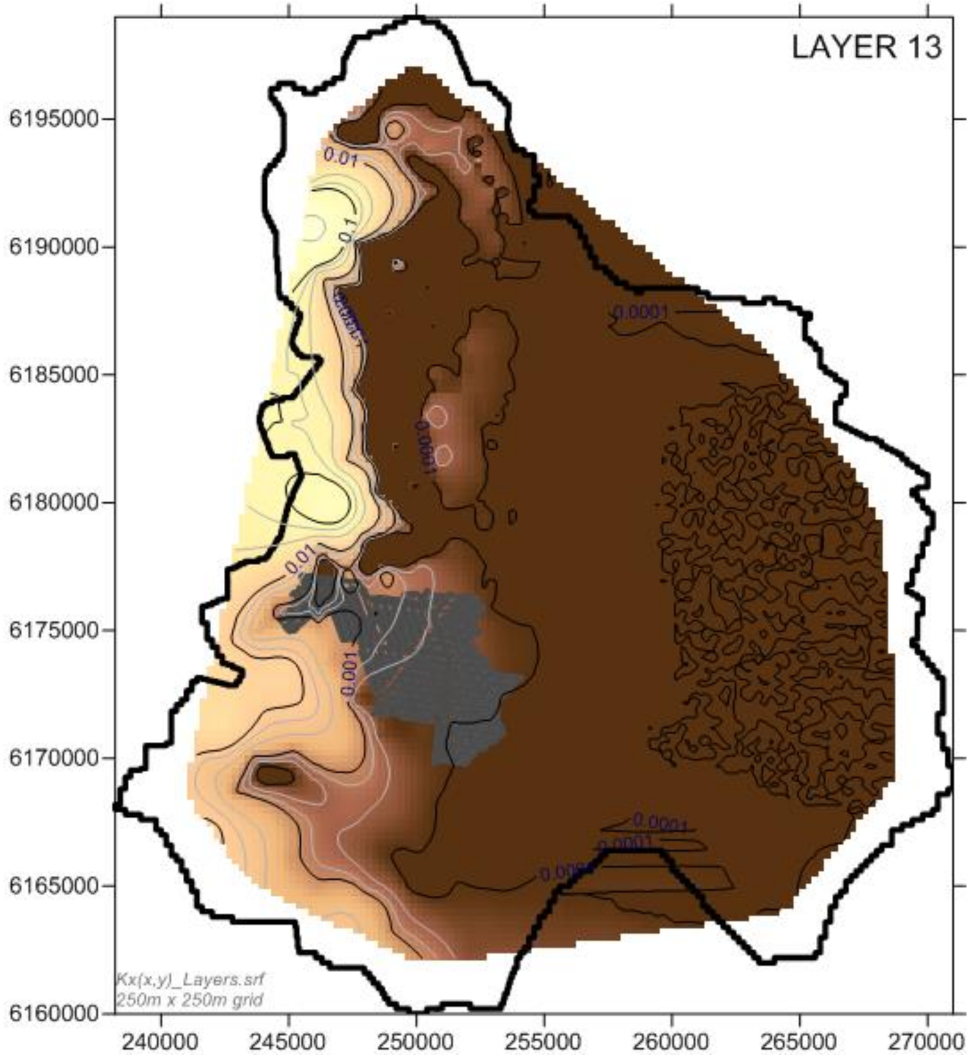


Figure 25 **Spatial Distribution of Hydraulic Conductivity using depth function in Layer 13**

POSTERIOR KX HISTOGRAMS

The following charts present histograms of the posterior Kx values in each depth bin. Each distribution is uni-modal, with gradually decreasing mean with depth as expected.

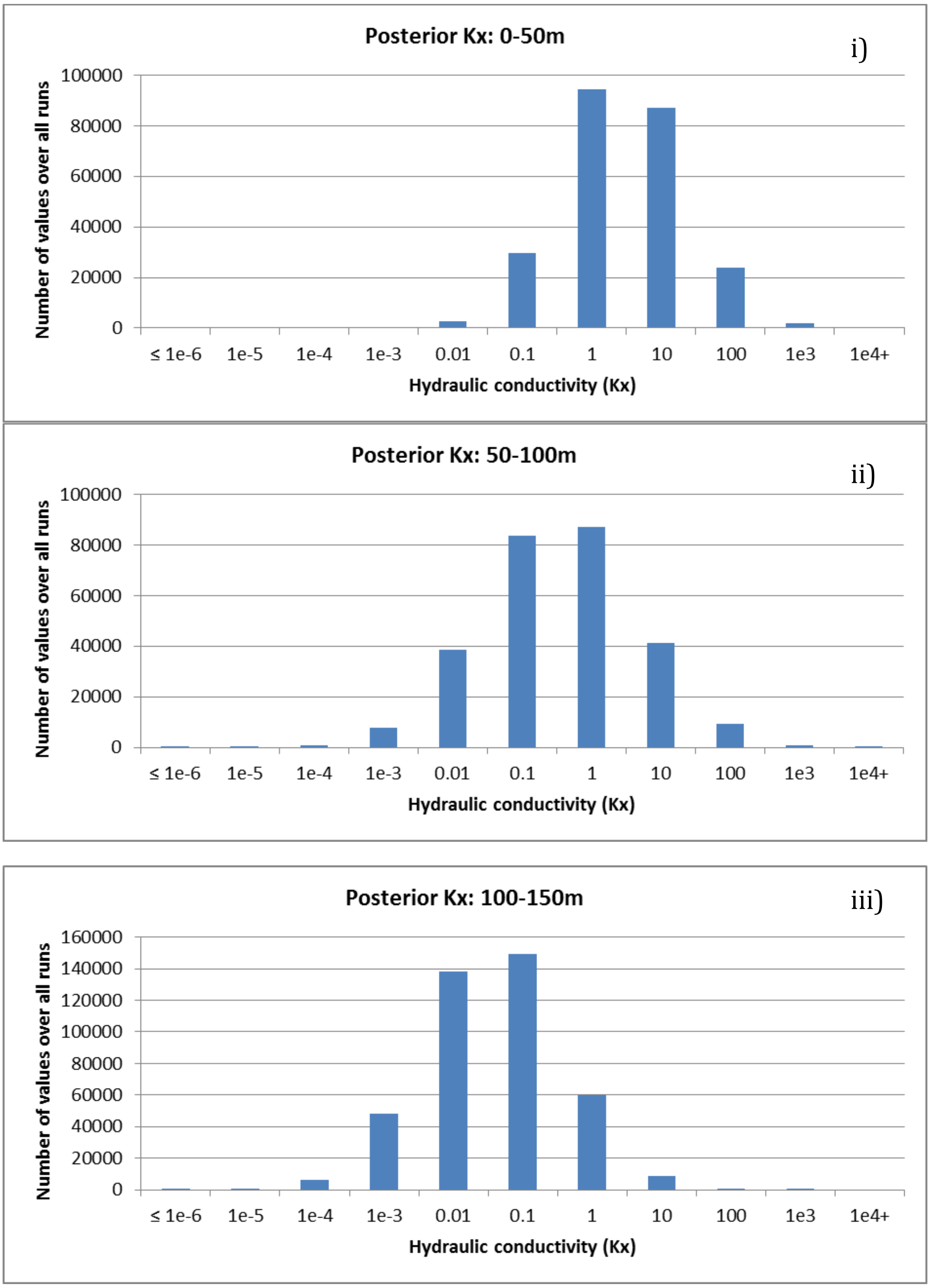


Figure 26 Posterior Kx values for i) 0-50 m; ii) 50 m-100 m; iii) 100 m-150 m.

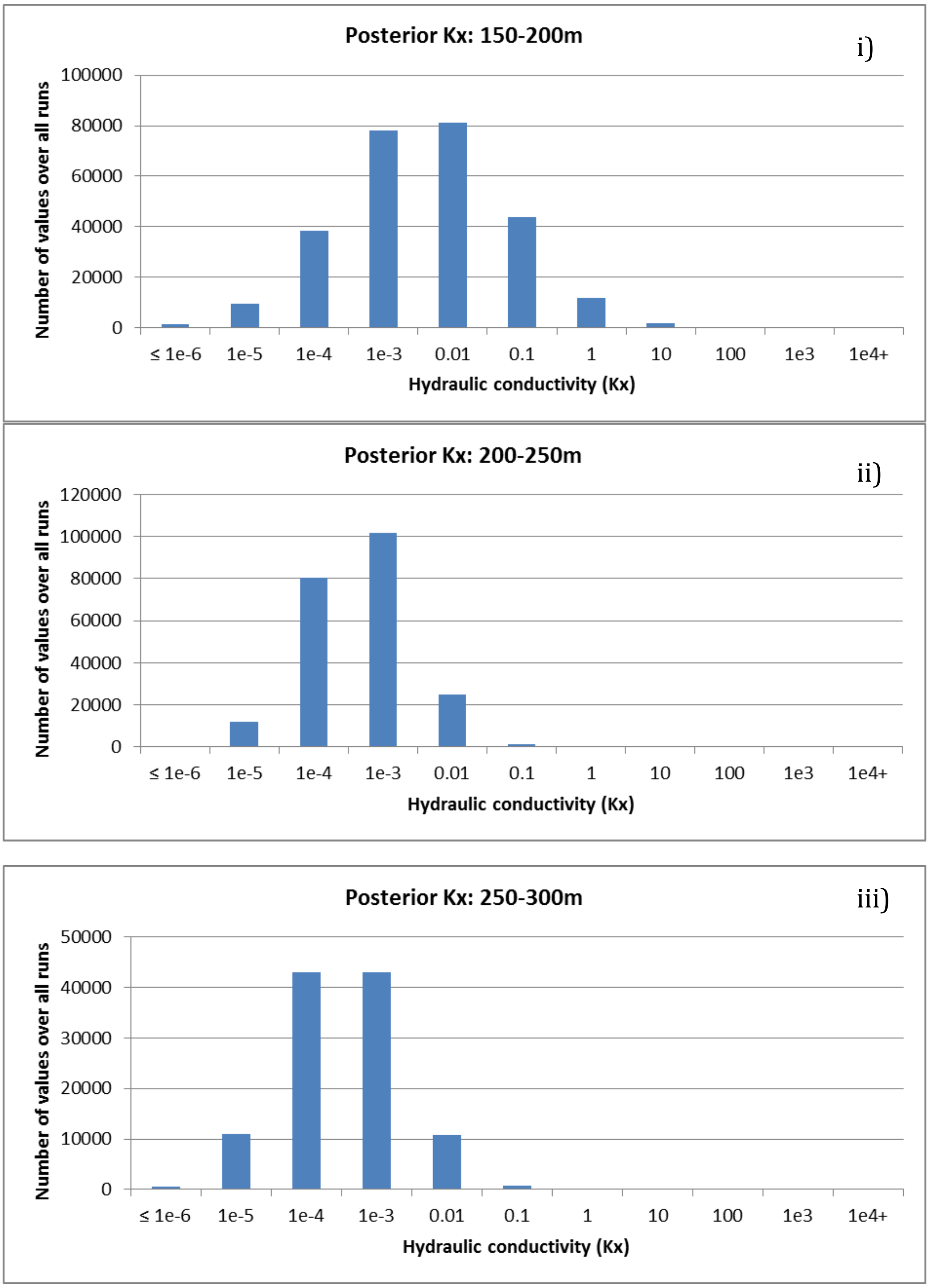


Figure 27 Posterior Kx values for i) 150-200 m; ii) 200 m-250 m; iii) 250 m-300 m.

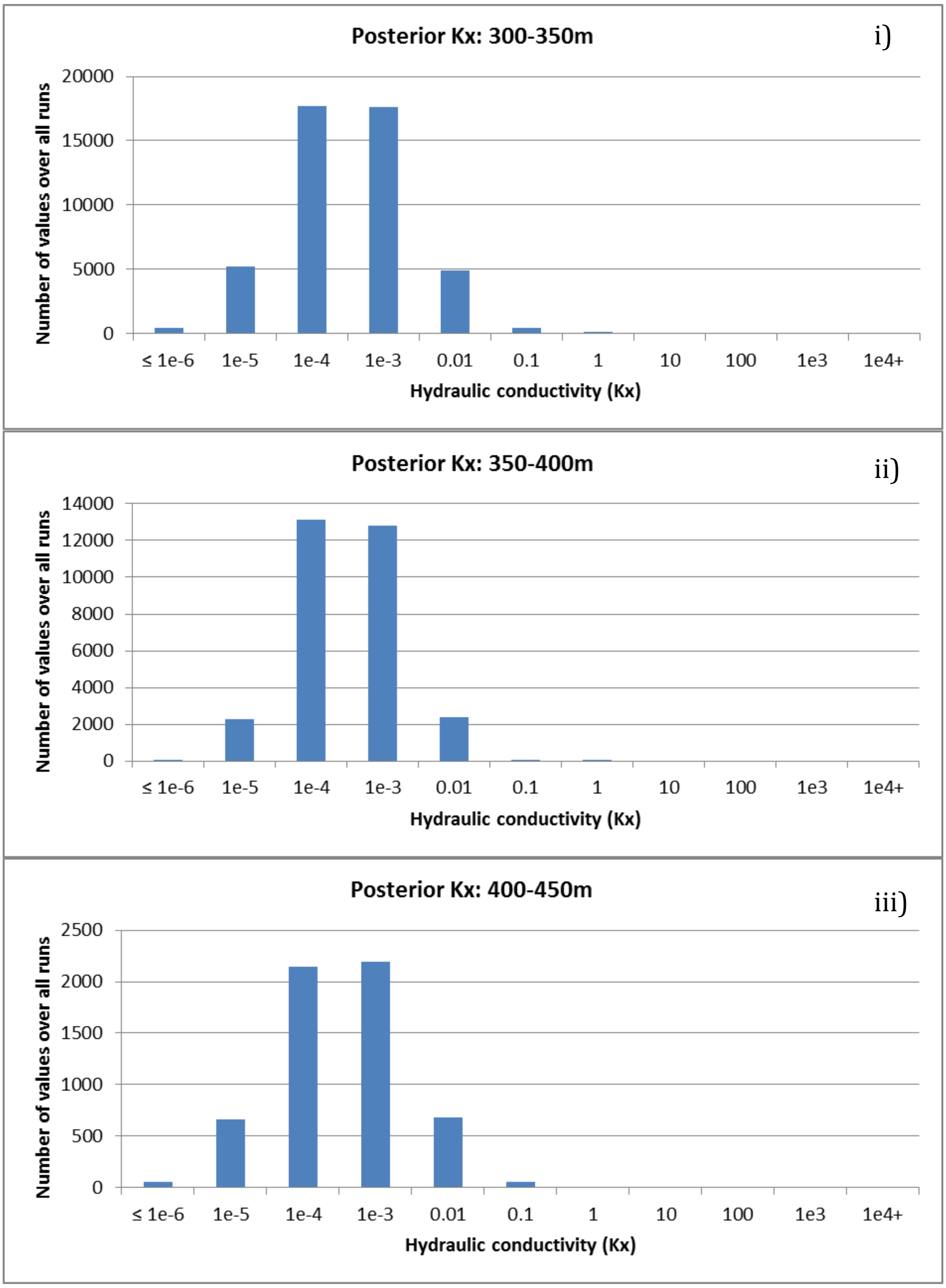


Figure 28 Posterior Kx values for i) 300-350 m; ii) 350 m-400 m; iii) 400 m-450 m.

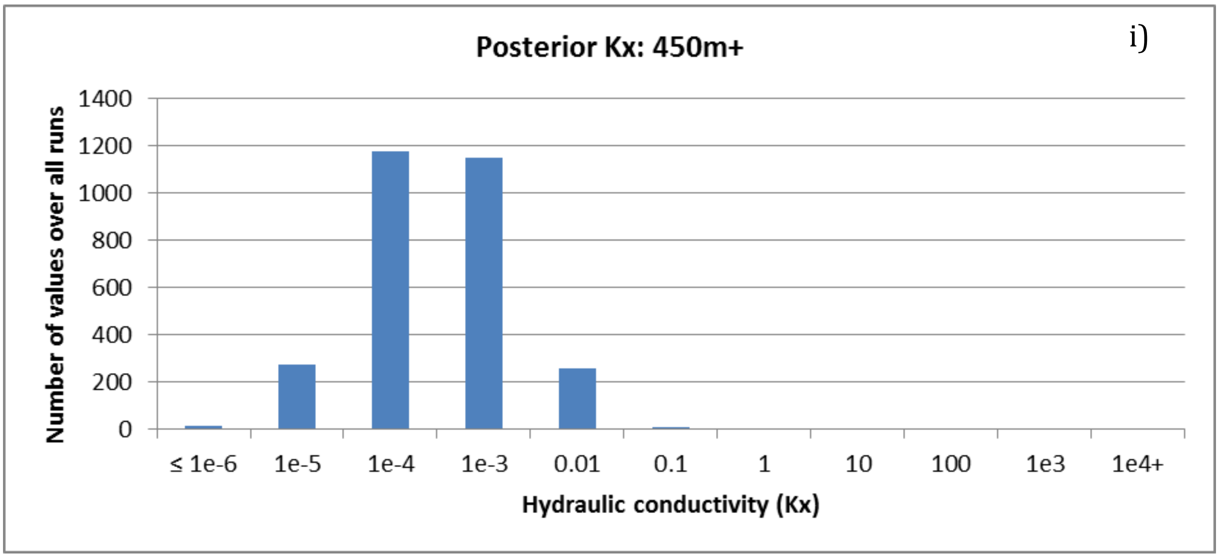


Figure 29 Posterior Kx values for i) 450 m and greater.

HISTOGRAMS OF POSTERIOR KX/KZ ANISOTROPY RATIOS

The following charts present histograms of the posterior Kx/Kz anisotropy ratios in each depth bin. Note that the vertical axes do not begin at 0, and that the scale differs in each chart, for better visibility of the variation of the values. The distributions are not uni-modal and display no systematic pattern in going to progressively greater depths.

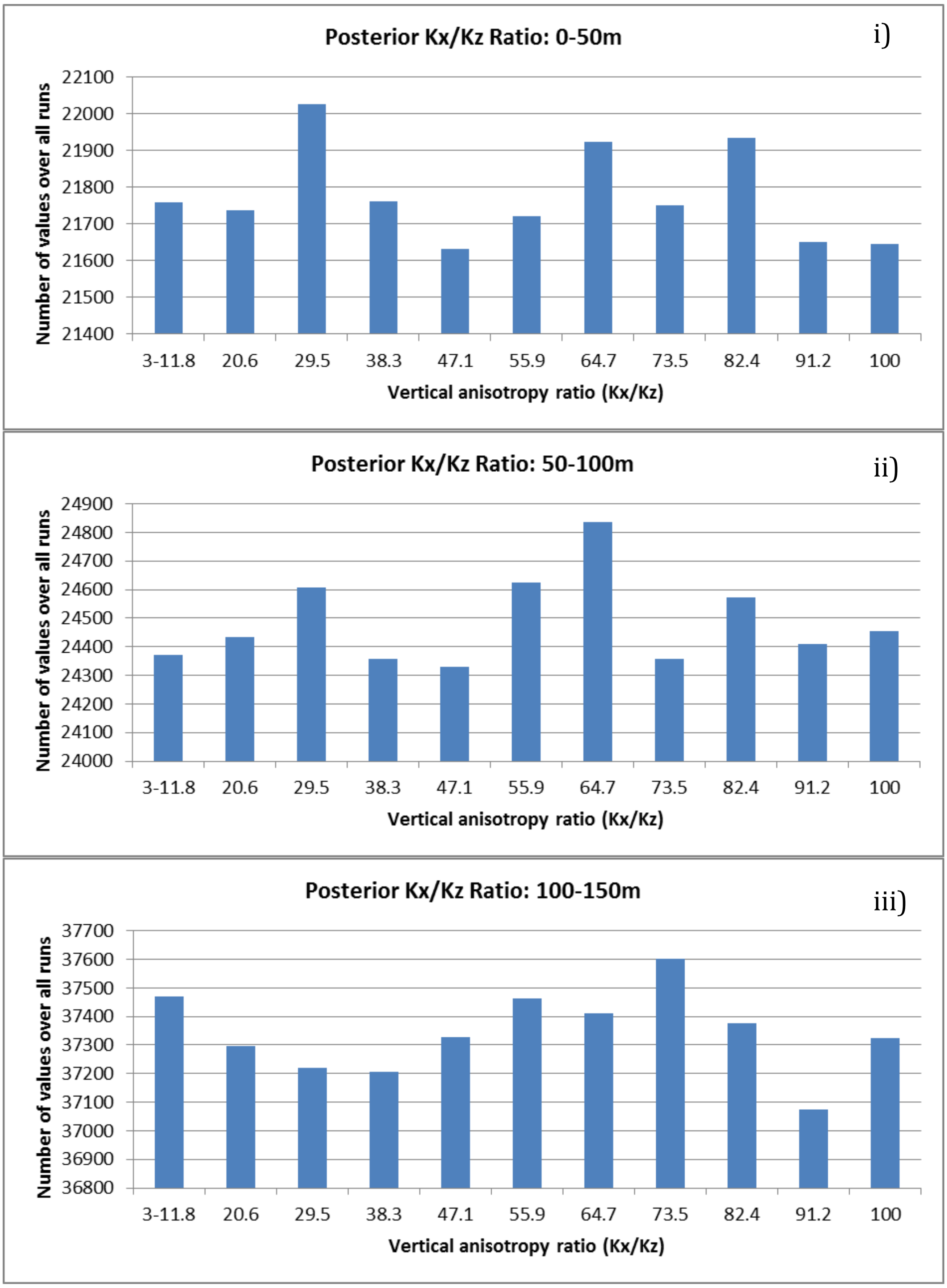


Figure 30 Posterior Kx/Kz ratio for i) 0-50 m; ii) 50 m-100 m; iii) 100 m-150 m.

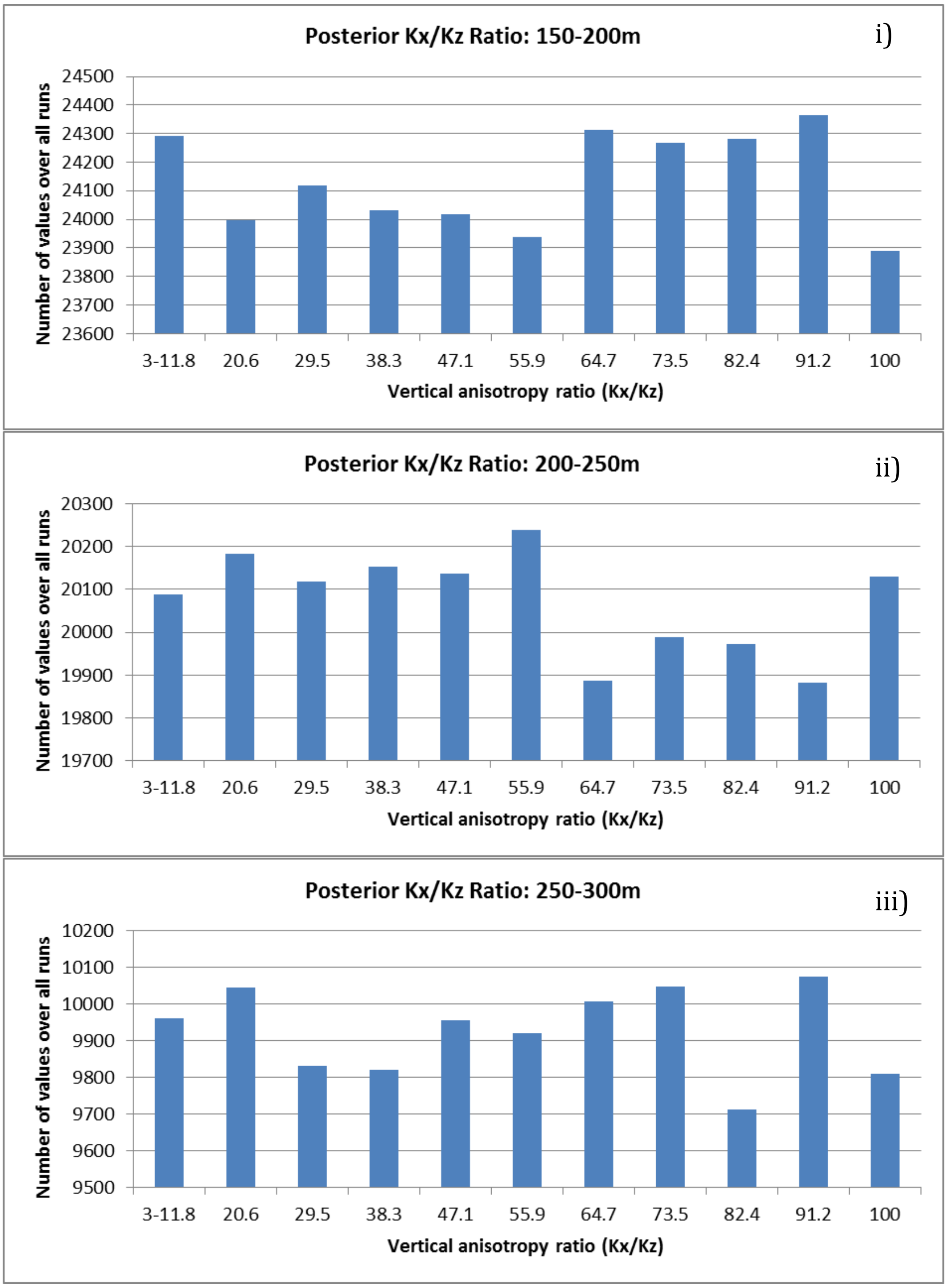


Figure 31 Posterior Kx/Kz ratio for i) 150-200 m; ii) 200 m-250 m; iii) 250 m-300 m.

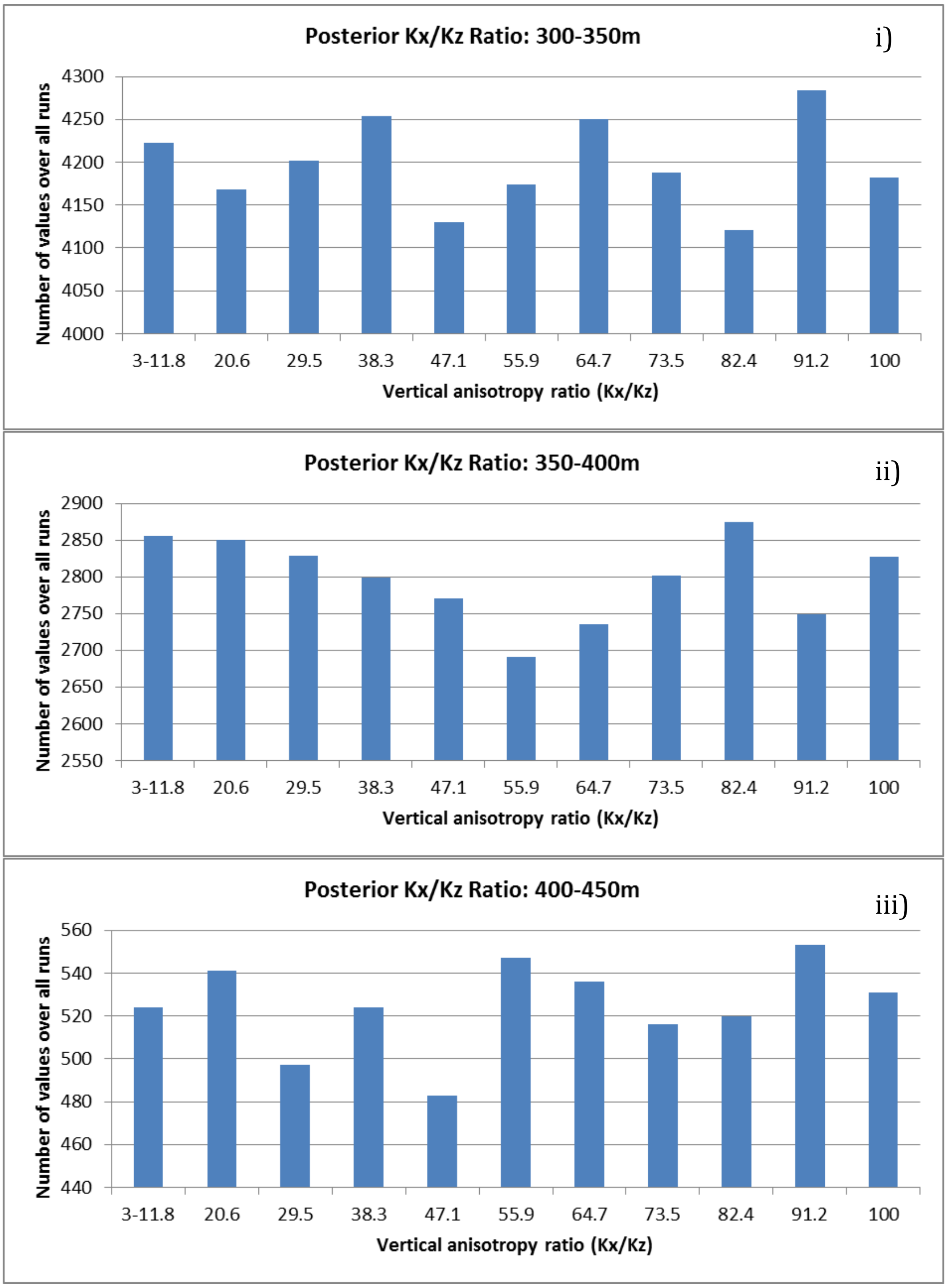


Figure 32 Posterior Kx/Kz ratio for i) 300-350 m; ii) 350 m-400 m; iii) 400 m-450 m.

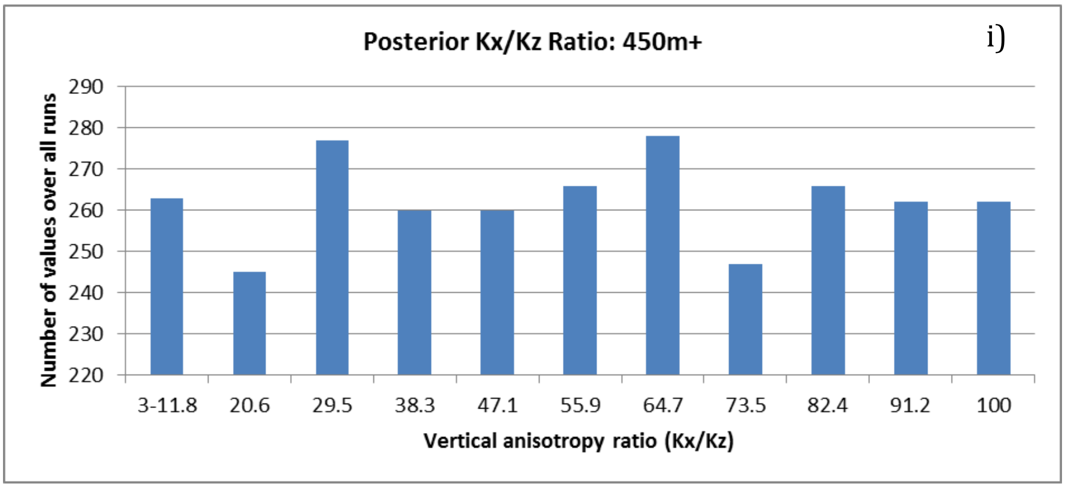


Figure 33 Posterior Kx/Kz ratio for i) 450 m and greater.

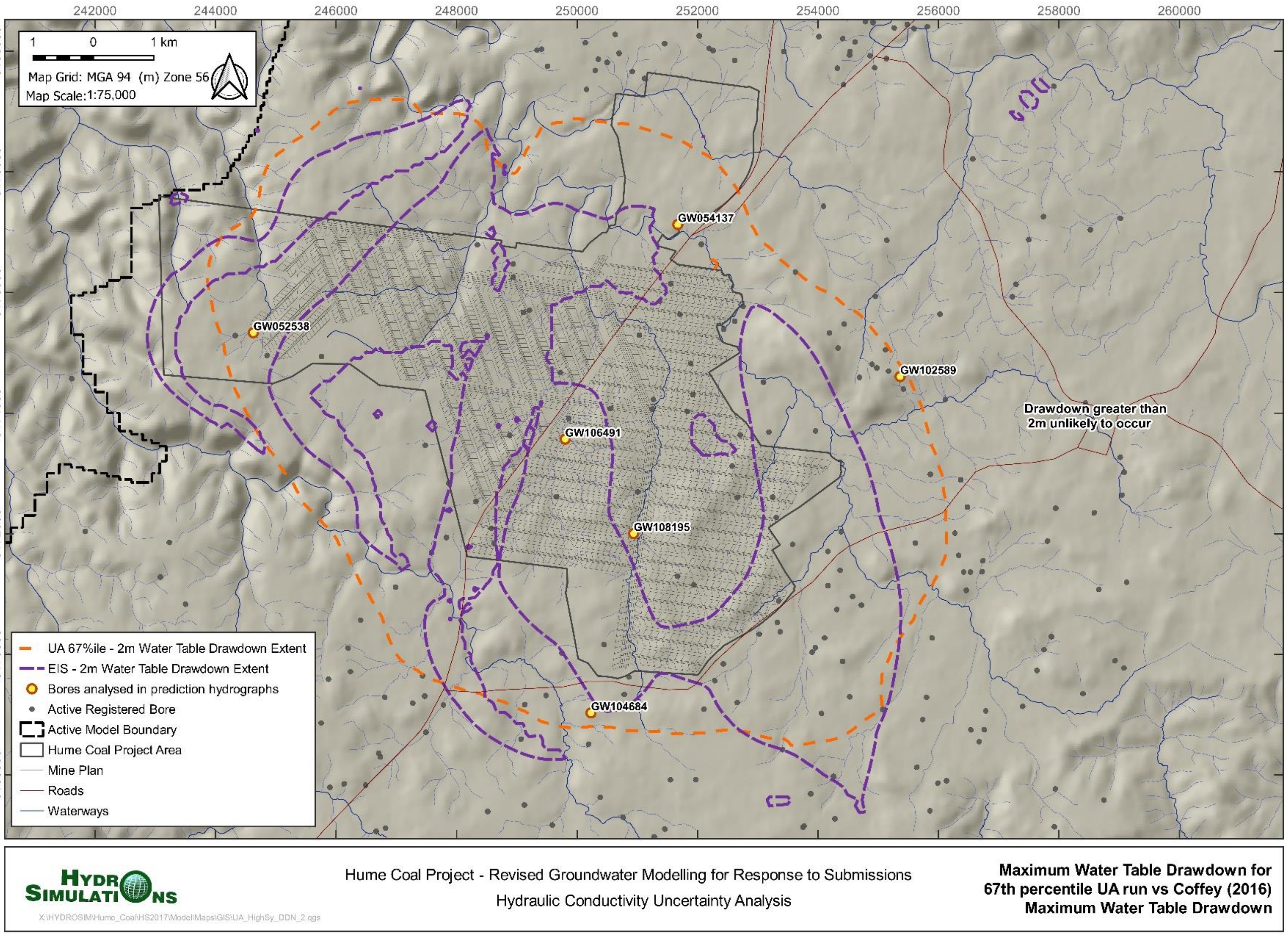


Figure 34 Maximum water-table drawdown for 67th percentile vs EIS Model (Coffey, 2016b) Wongawilli Seam 2m drawdown during mine year 17

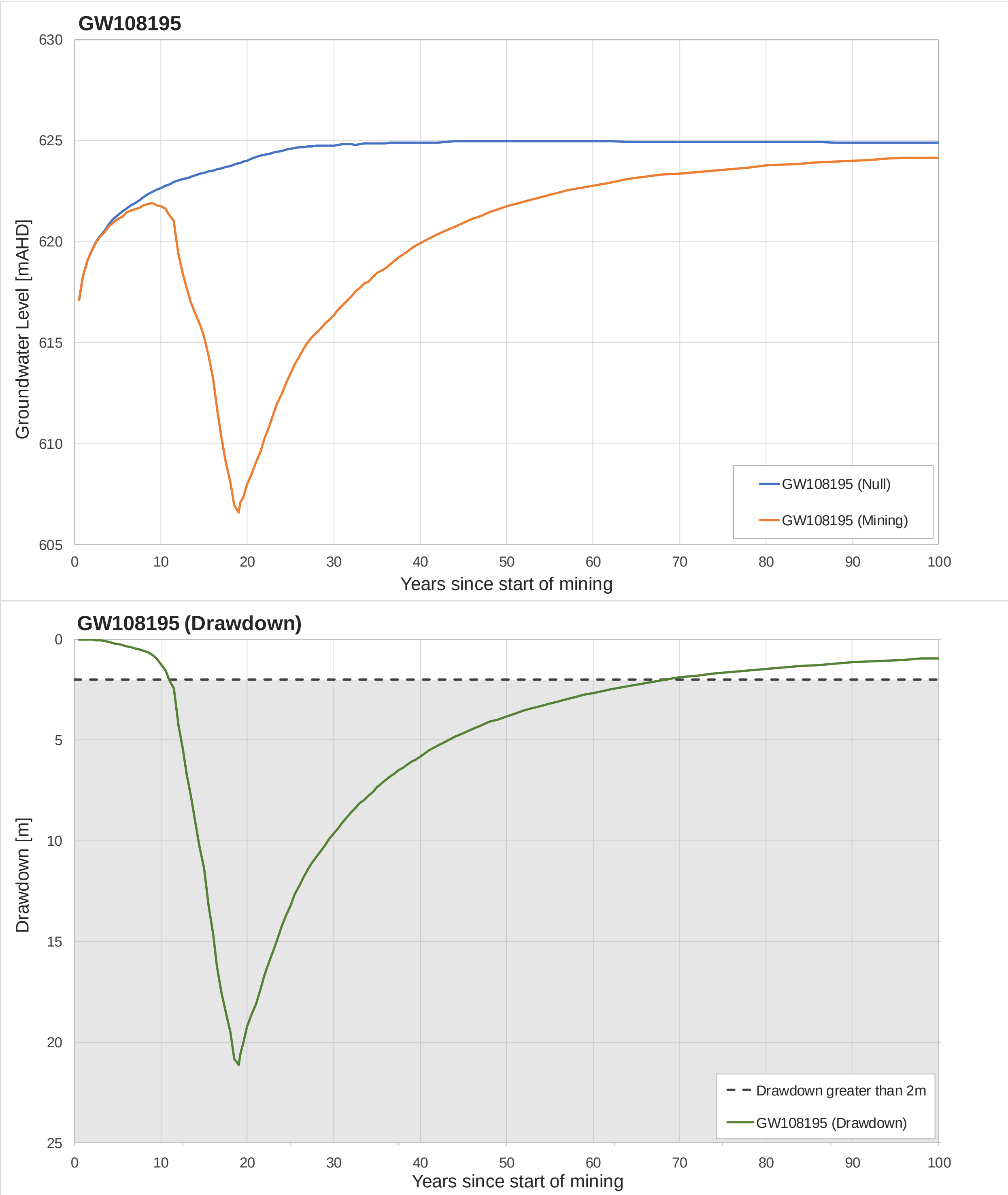


Figure 35 Modelled groundwater level and drawdown at GW108195 from 67%ile aggregate data

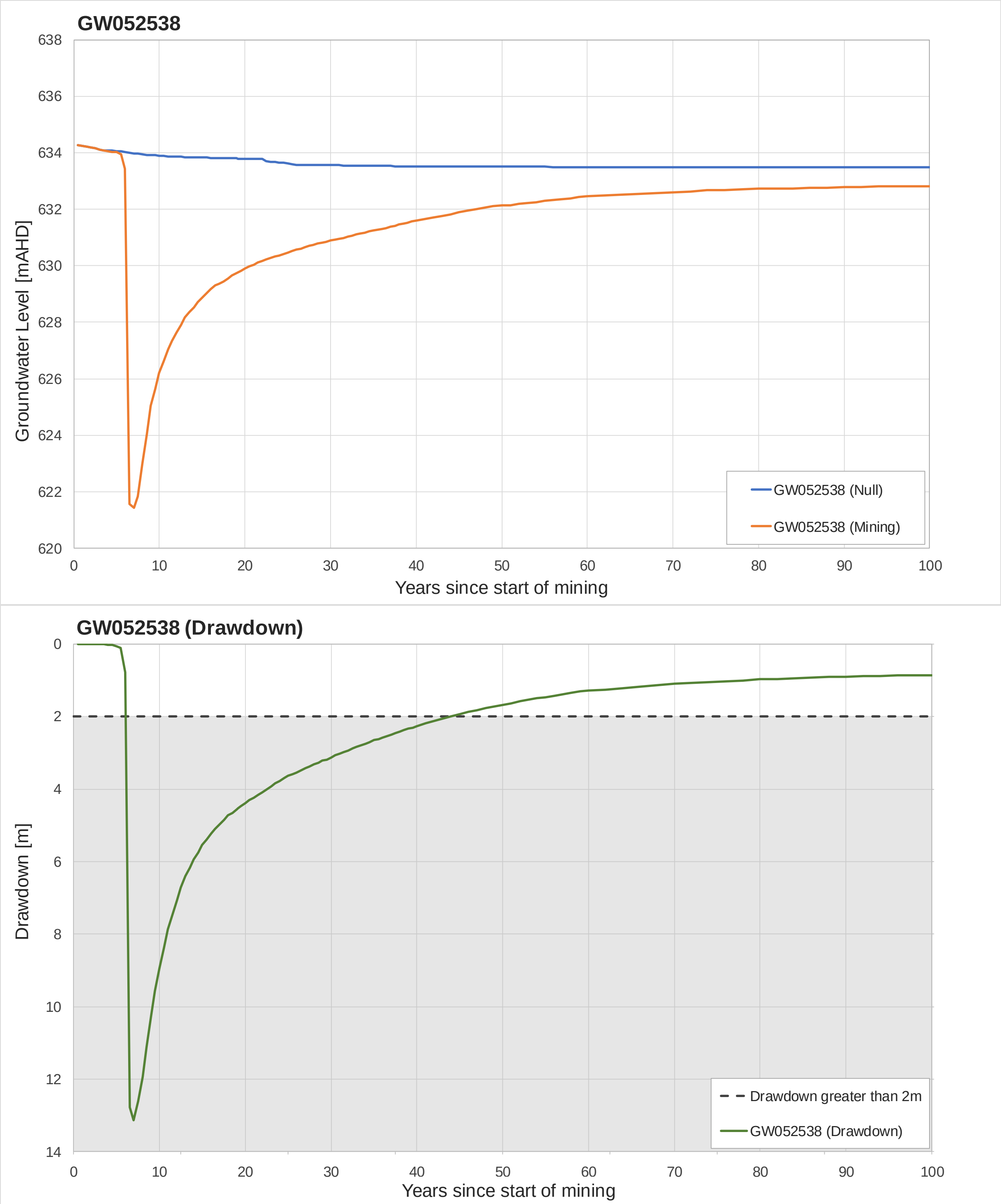


Figure 36 Modelled groundwater level and drawdown at GW052538 from 67%ile aggregate data

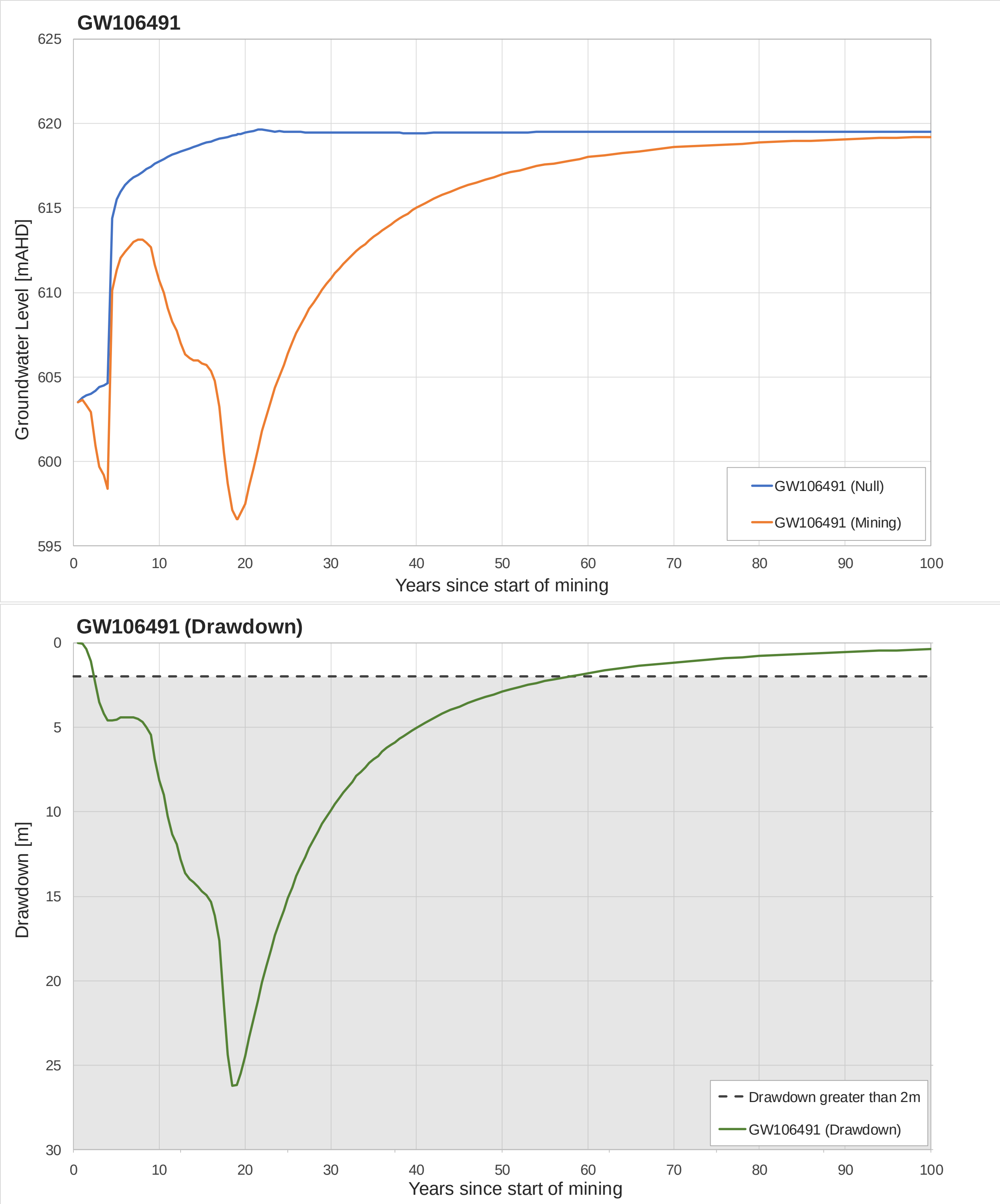


Figure 37 Modelled groundwater level and drawdown at GW106491 from 67%ile aggregate data

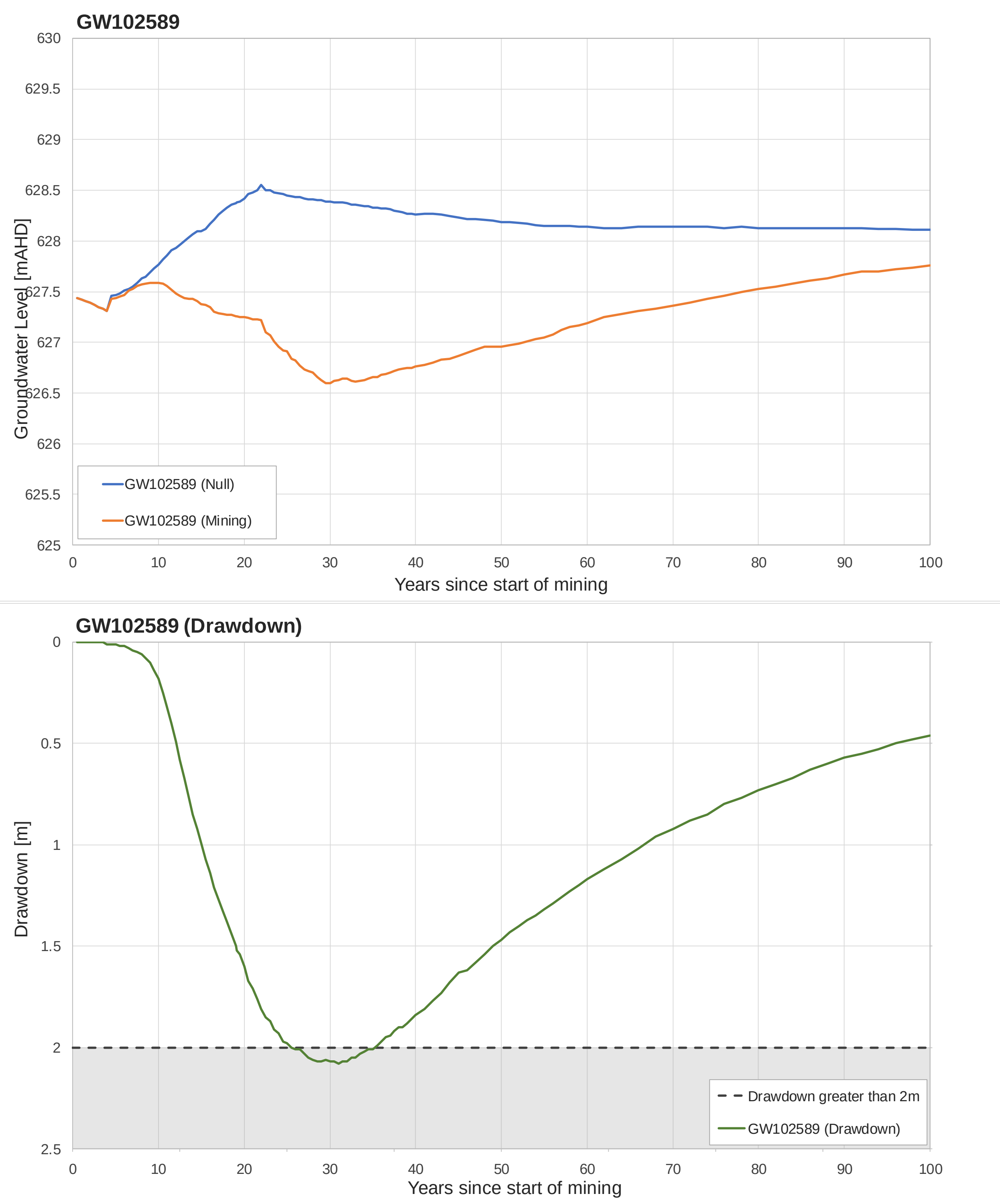


Figure 38 **Modelled groundwater level and drawdown at GW102589 from 67%ile aggregate data**

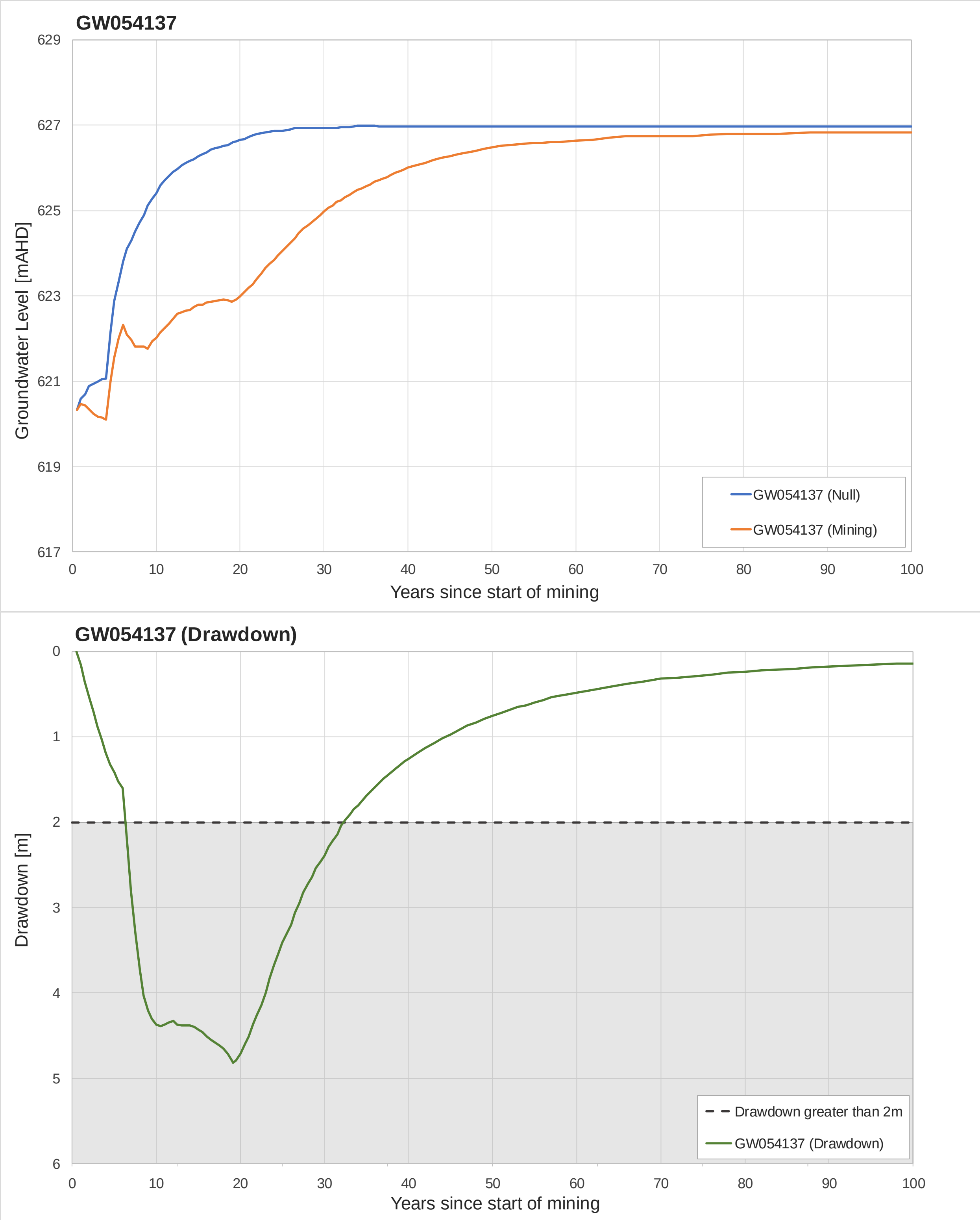


Figure 39 Modelled groundwater level and drawdown at GW054137 from 67%ile aggregate data

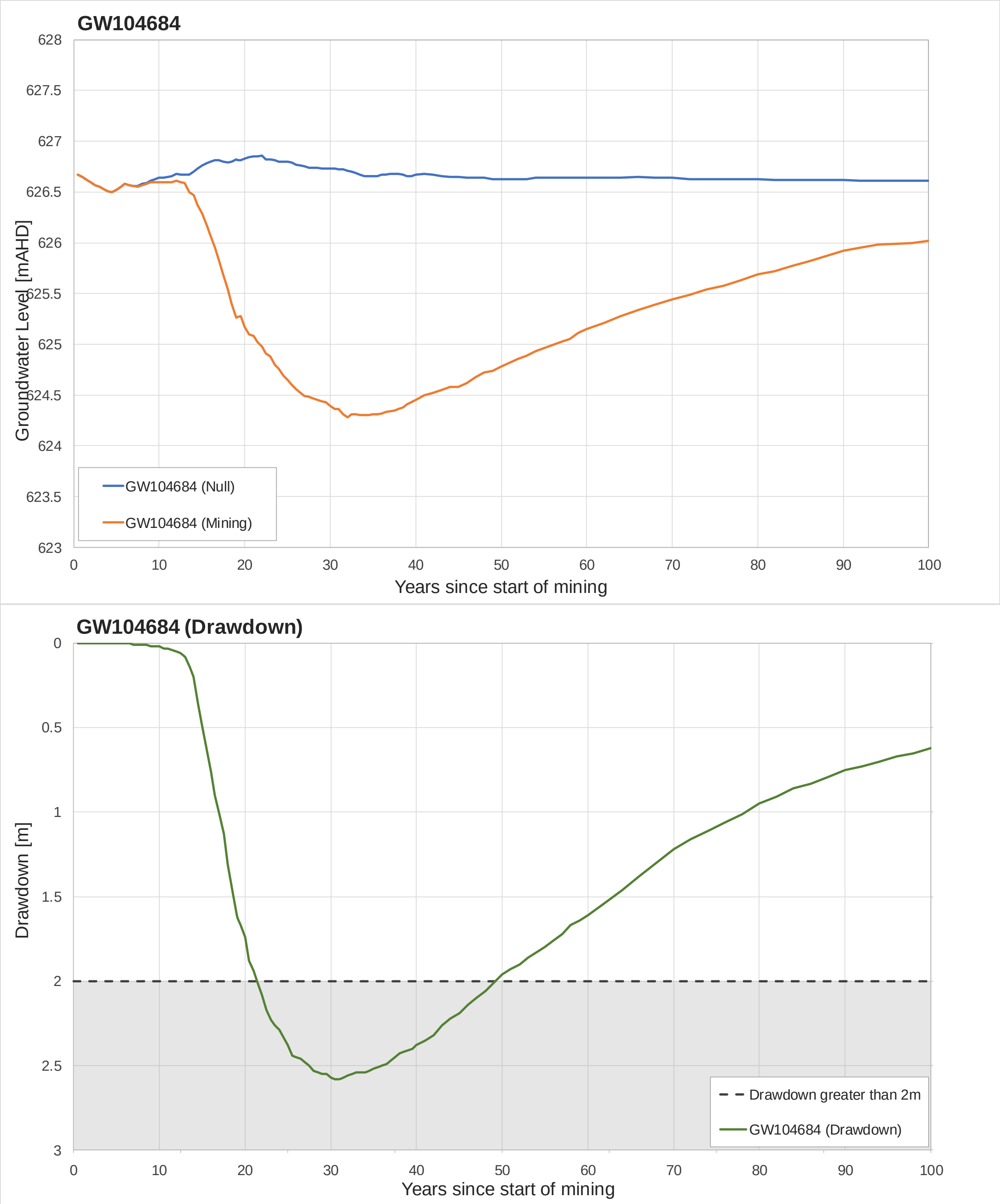


Figure 40 Modelled groundwater level and drawdown at GW104684 from 67%ile aggregate data

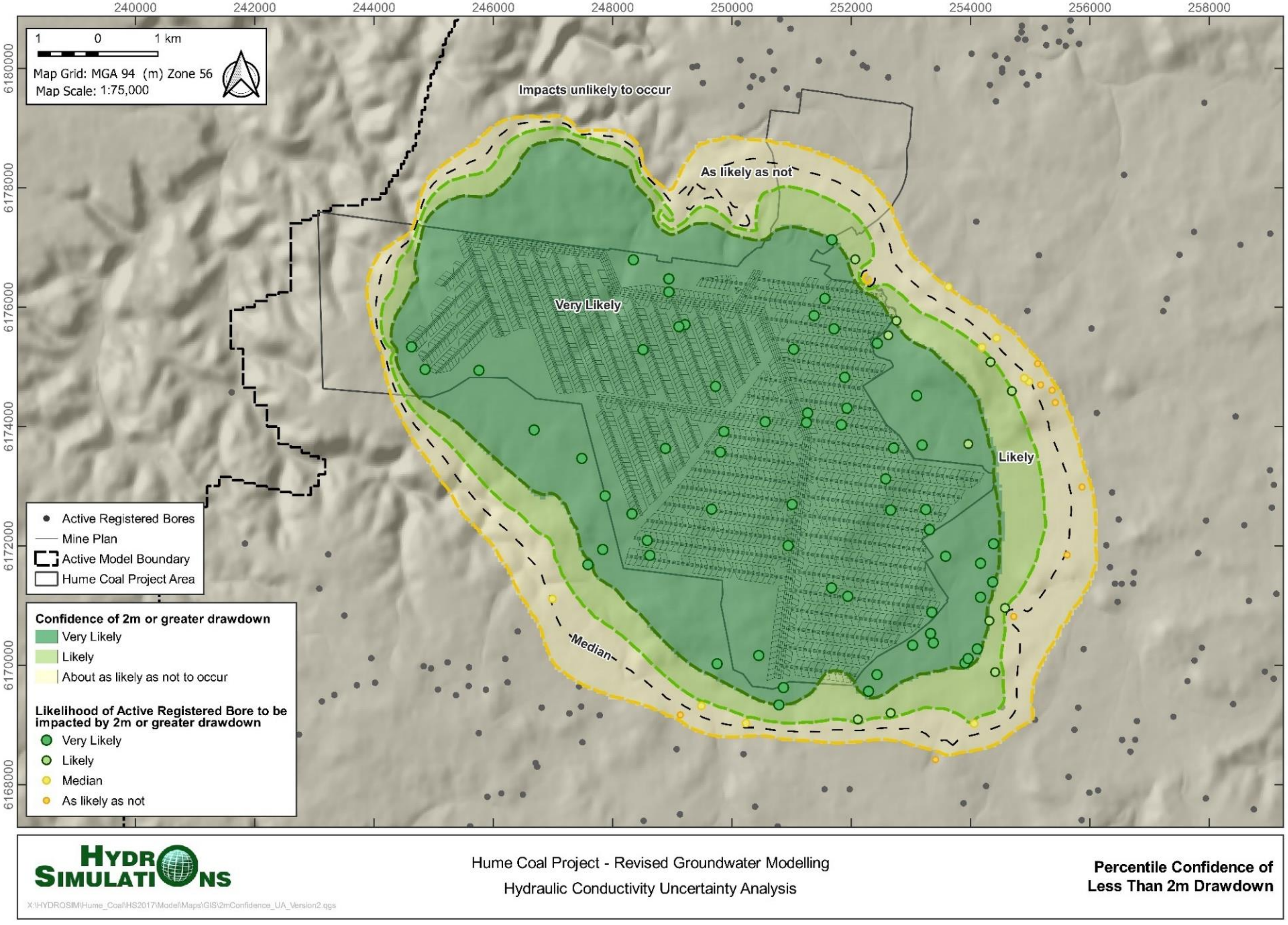


Figure 41 Percentile confidence of less than 2m drawdown at water table and bores

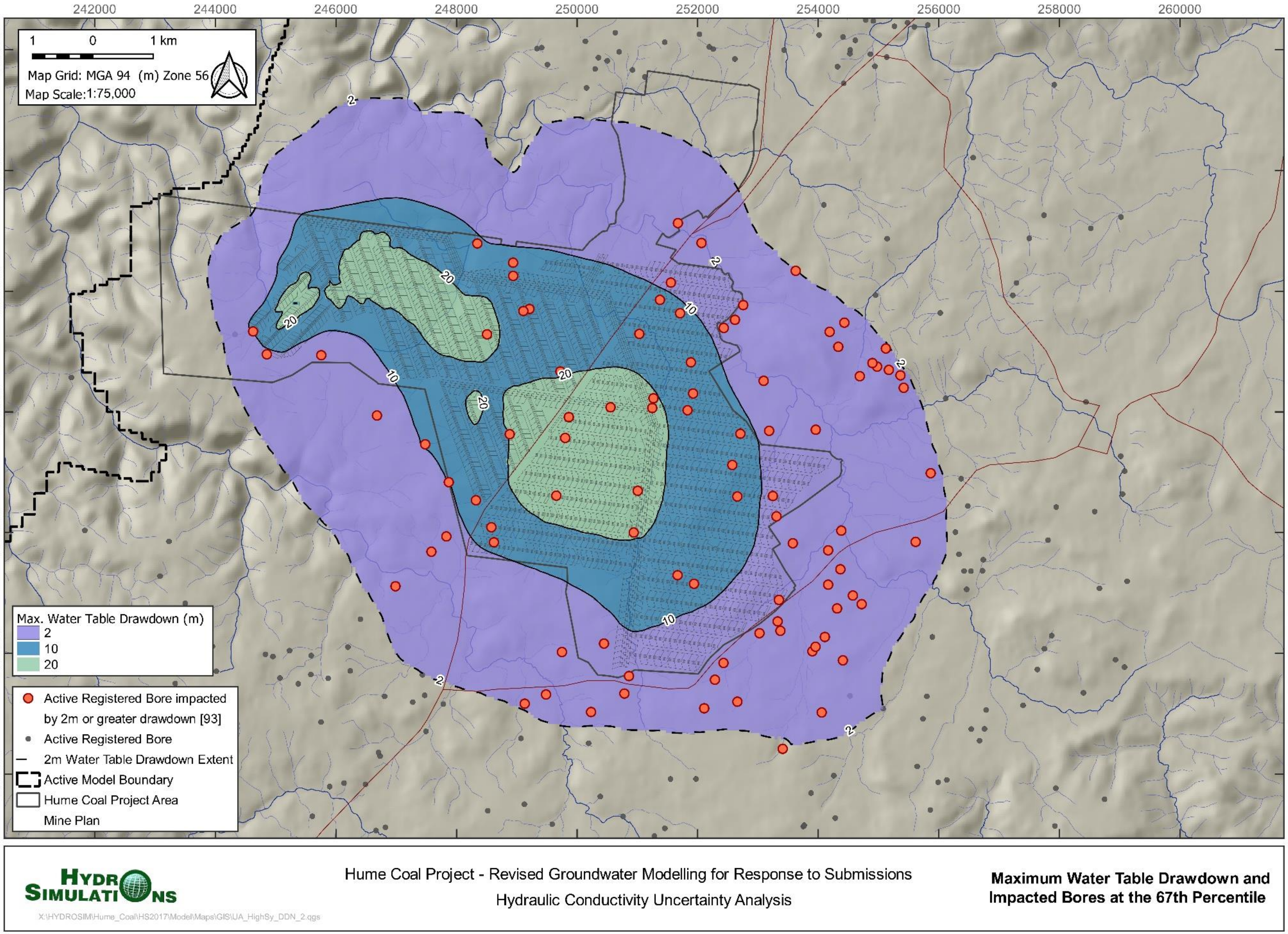


Figure 42 Maximum drawdown and number of impacted bores at the 67th percentile

TRANSIENT MINE INFLOW

The following charts show 10%ile, 33%ile, 50%ile, 67%ile and 90%ile simulated mine inflows over time. Both “to sump” inflows and total flow into the mine area are reported. The period charted is restricted to 25 years from commencement of mining, after which flows are negligible.

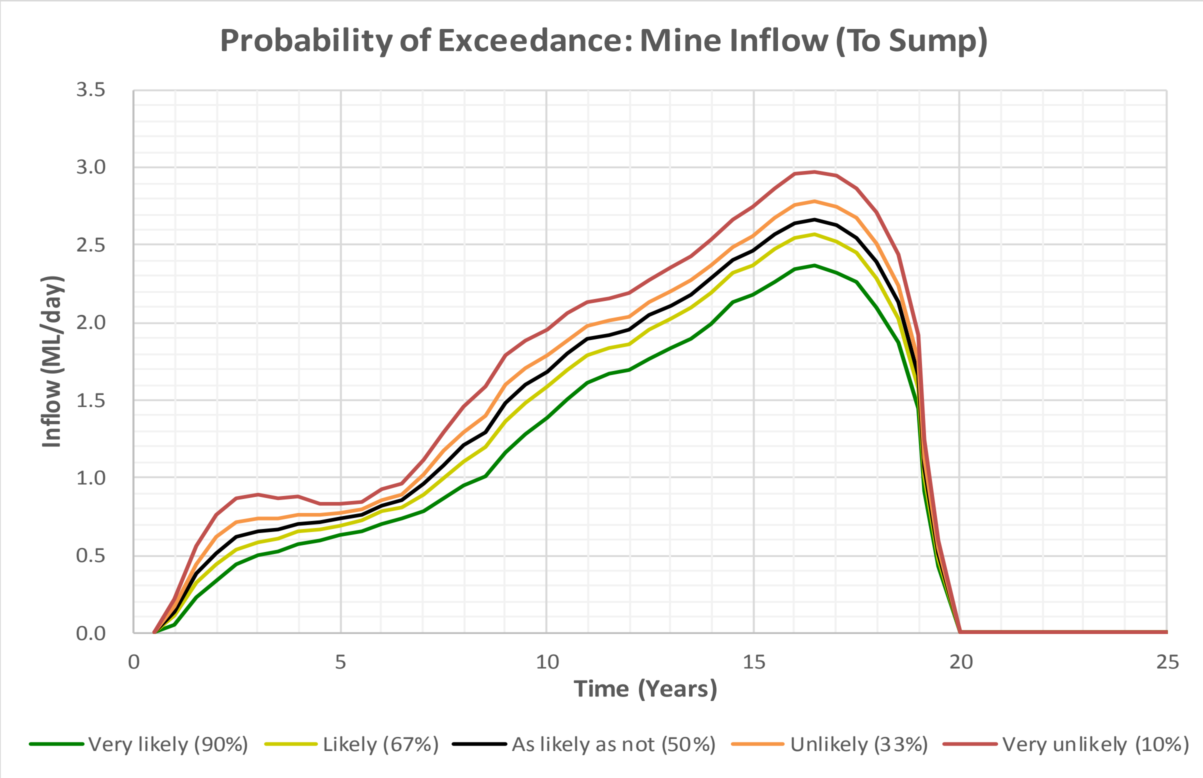


Figure 43 Uncertainty Analysis – Mine inflow (to sump)

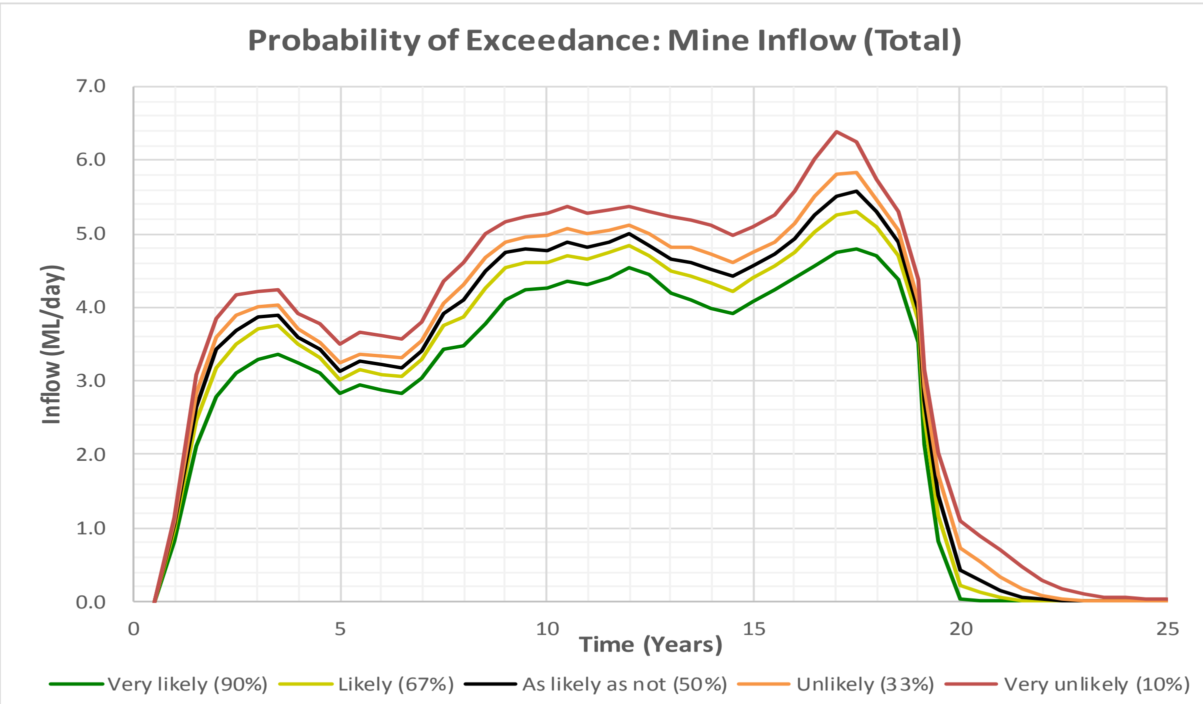


Figure 44 Uncertainty Analysis – Mine inflow (total)

TRANSIENT STREAM BASEFLOW IMPACTS

The following charts show 10%ile, 33%ile, 50%ile, 67%ile and 90%ile baseflow impacts induced by Hume mining over time. All are shown over a 100-year period. Stream catchments with zero baseflow impact – Belanglo Creek, Wells Creek and Wells Creek Tributary – are omitted from this section (see **Section 7.3** for reference to the peak baseflow impact values).

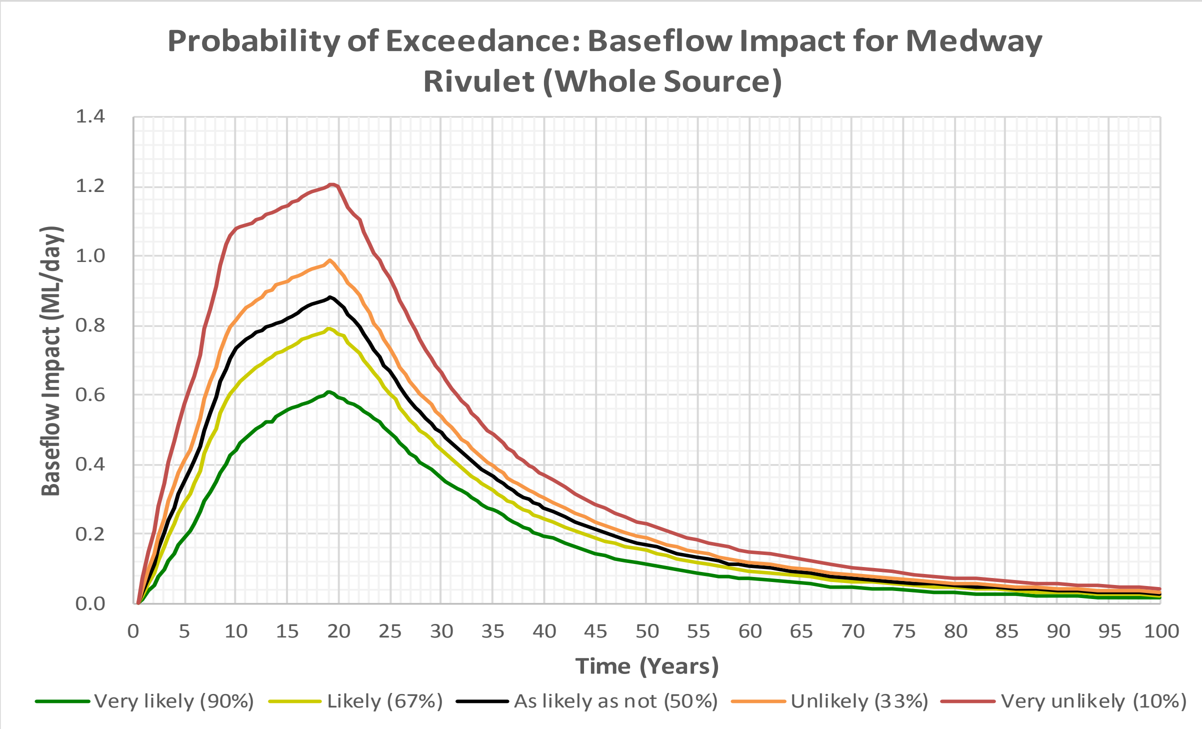


Figure 45 Uncertainty Analysis – Baseflow impact for Medway Rivulet

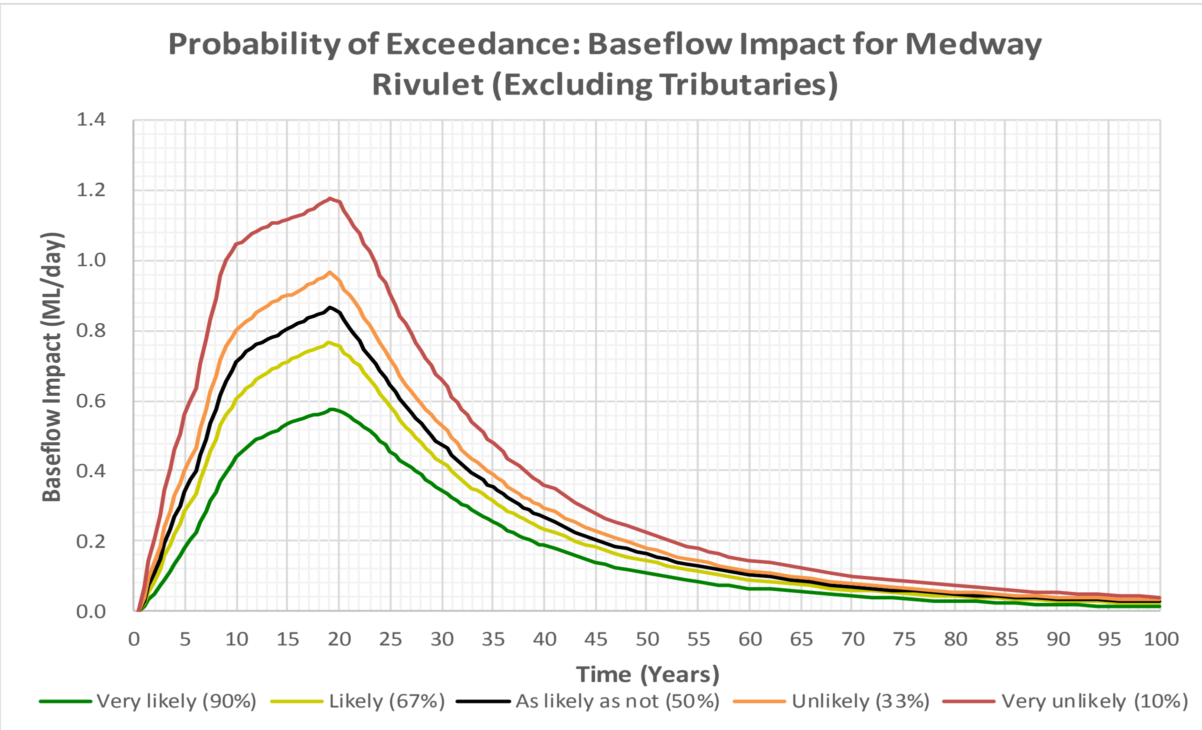


Figure 46 Uncertainty Analysis – Baseflow impact for Medway Rivulet (Excluding Tributaries)

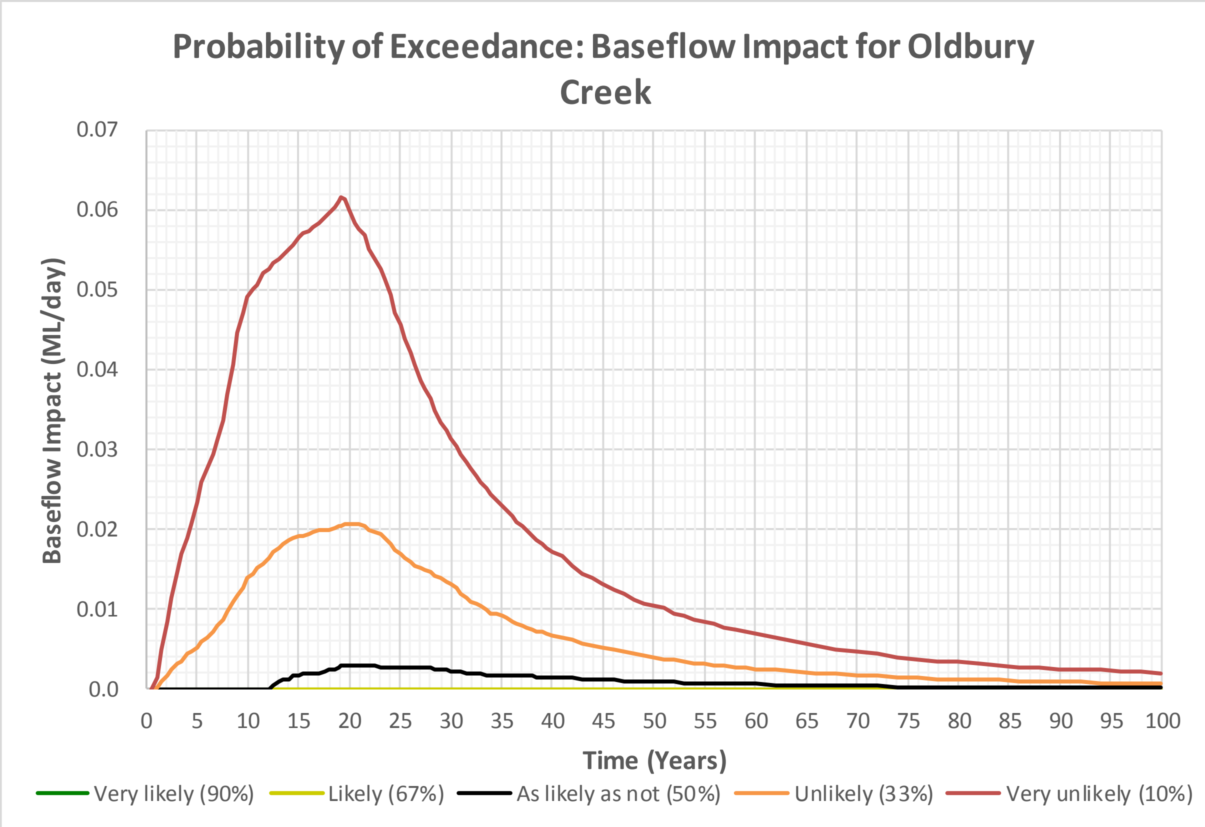


Figure 47 Uncertainty Analysis – Baseflow impact for Oldbury Creek

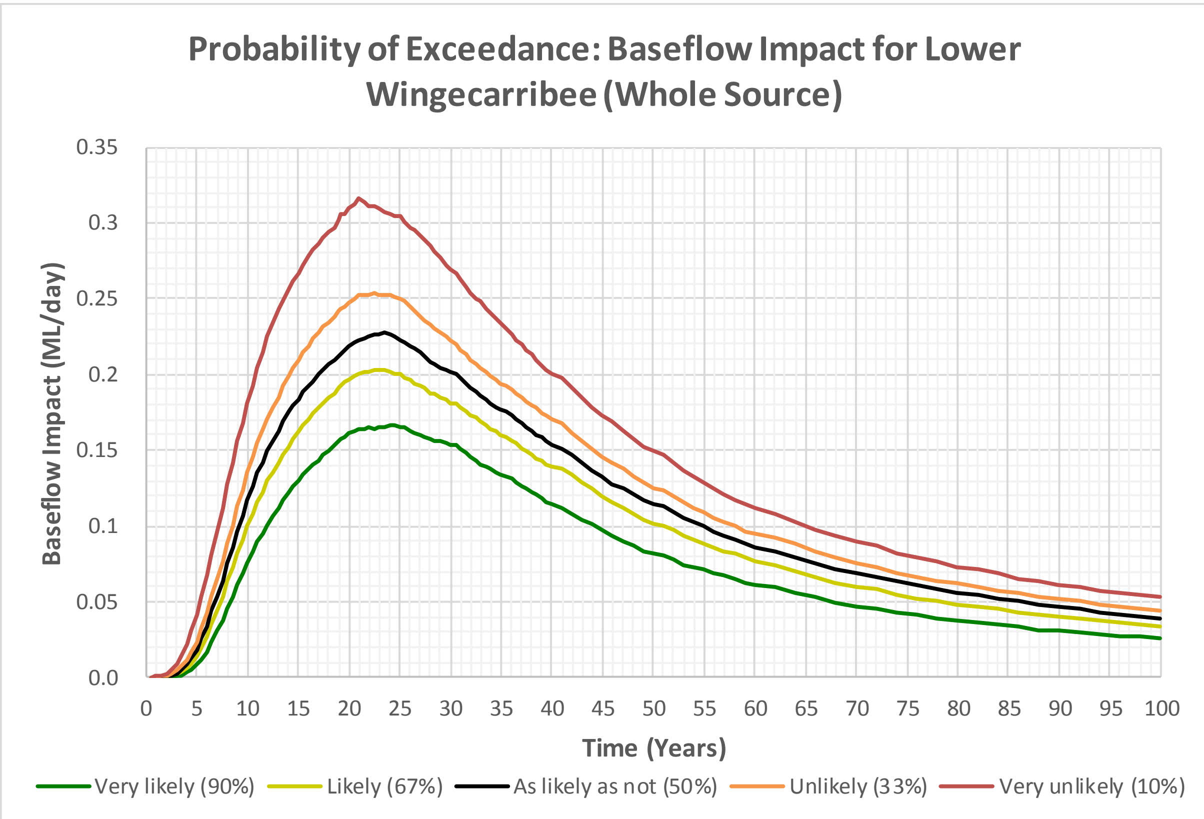


Figure 48 Uncertainty Analysis – Baseflow impact for Lower Wingecarribee

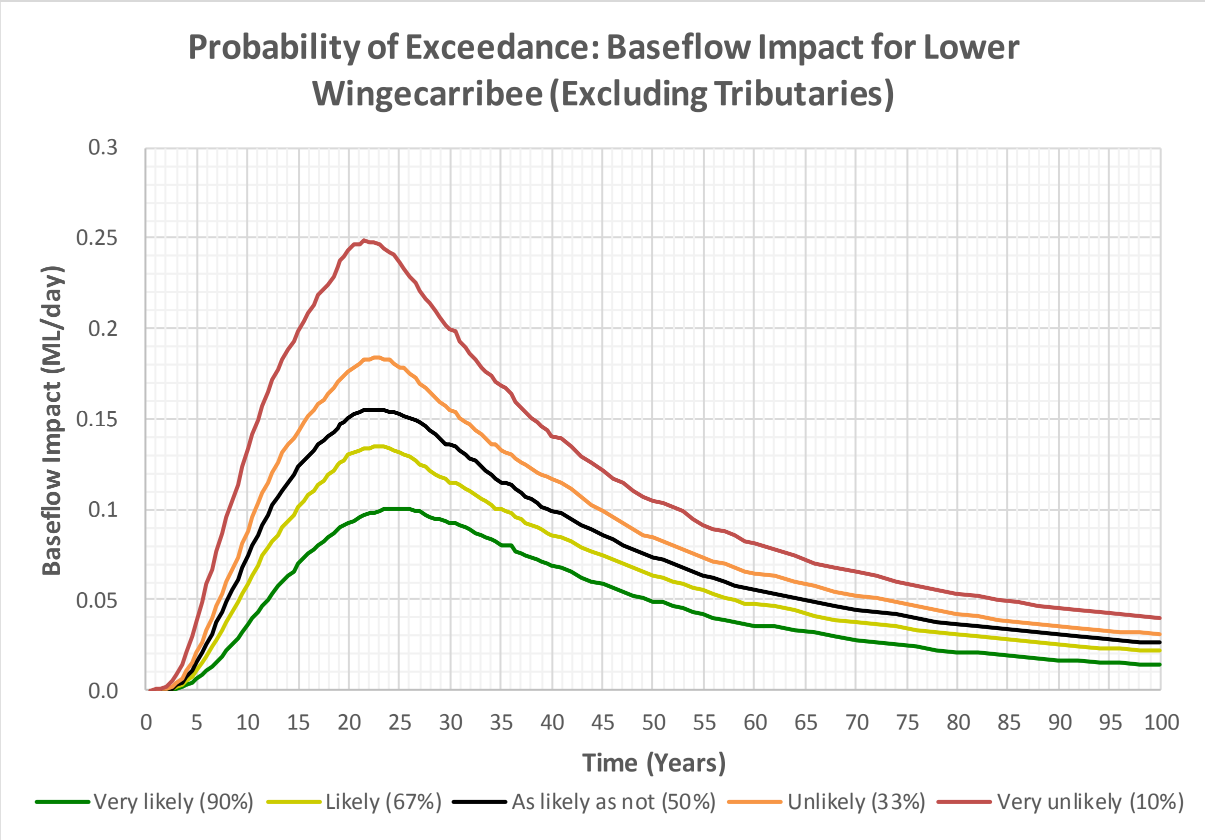


Figure 49 **Uncertainty Analysis – Baseflow impact for Lower Wingecarribee (excluding tributaries)**

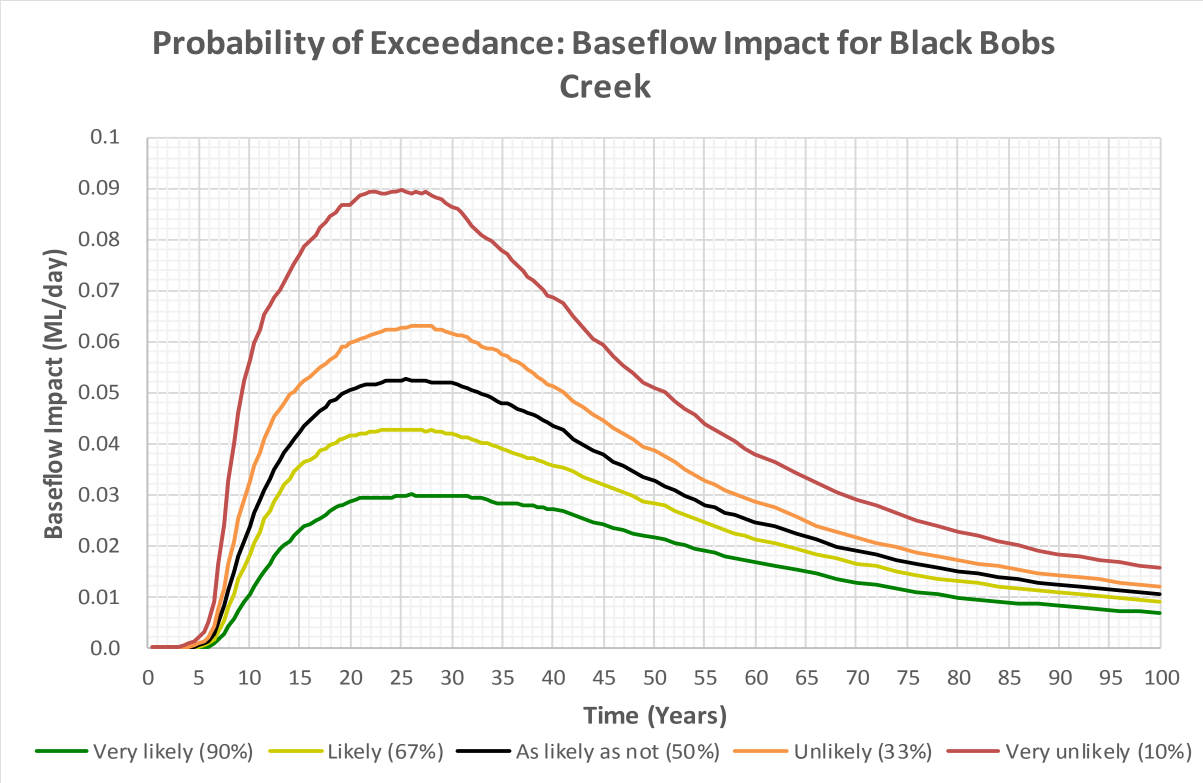


Figure 50 Uncertainty Analysis – Baseflow impact for Black Bobs Creek

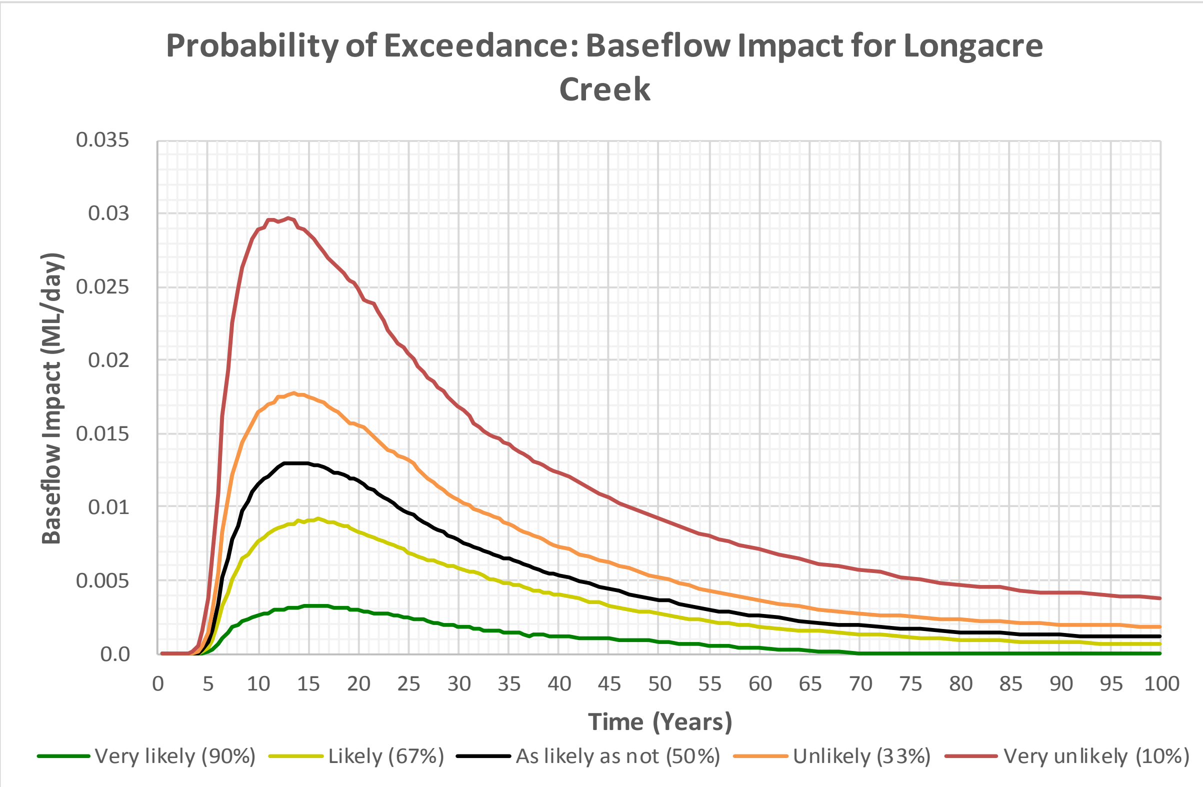


Figure 51 Uncertainty Analysis – Baseflow impact for Longacre Creek

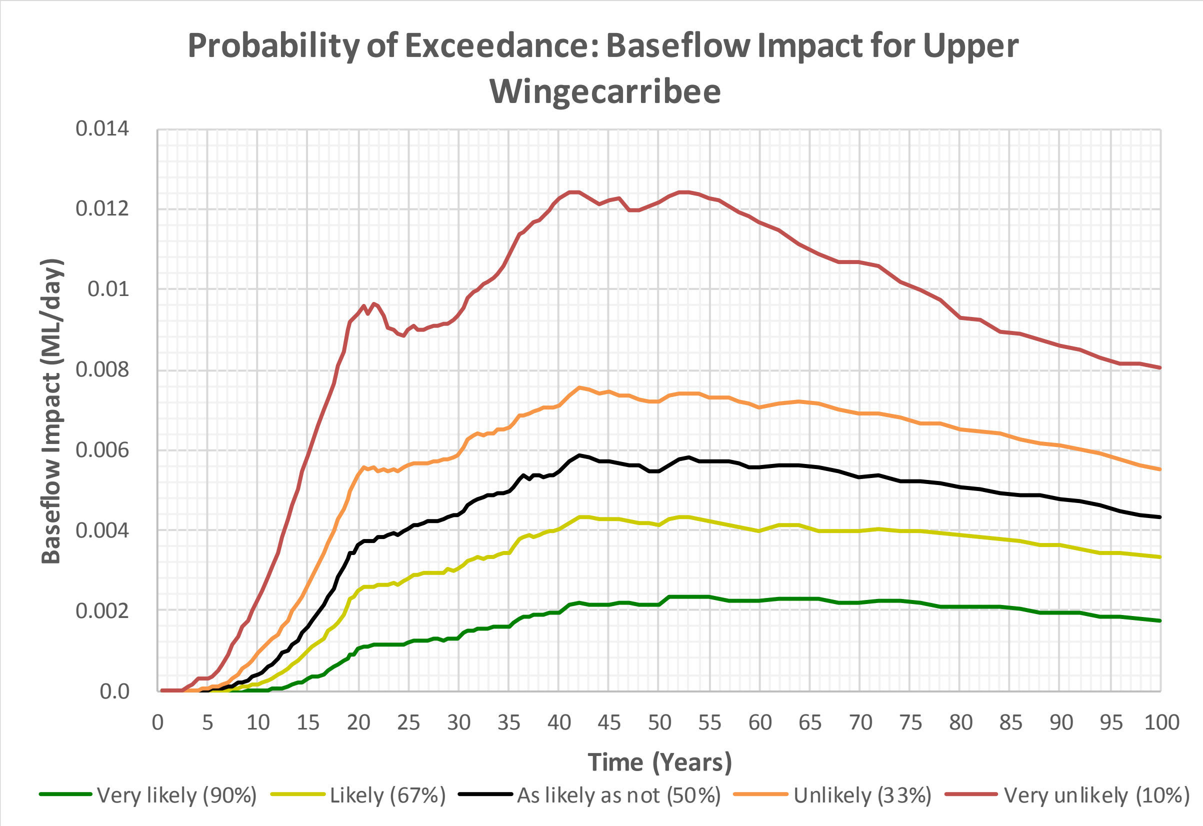


Figure 52 Uncertainty Analysis – Baseflow impact for Upper Wingecarribee River

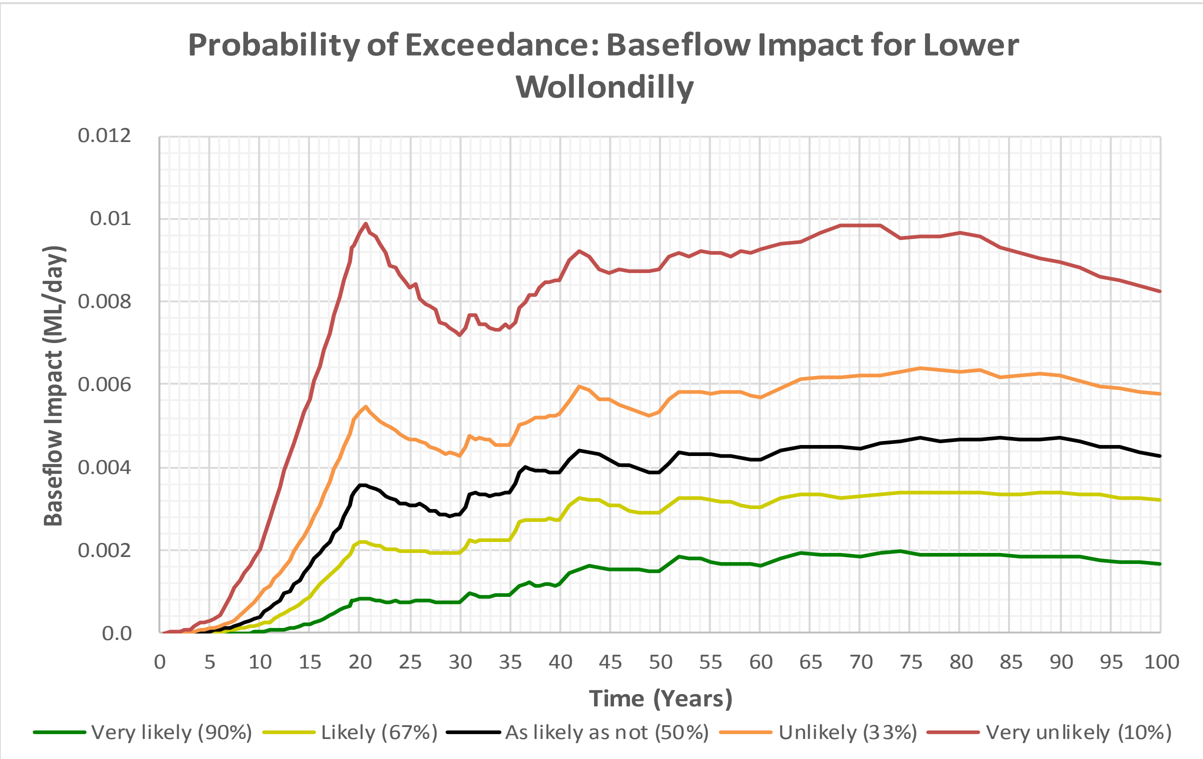


Figure 53 Uncertainty Analysis – Baseflow impact for Lower Wollondilly

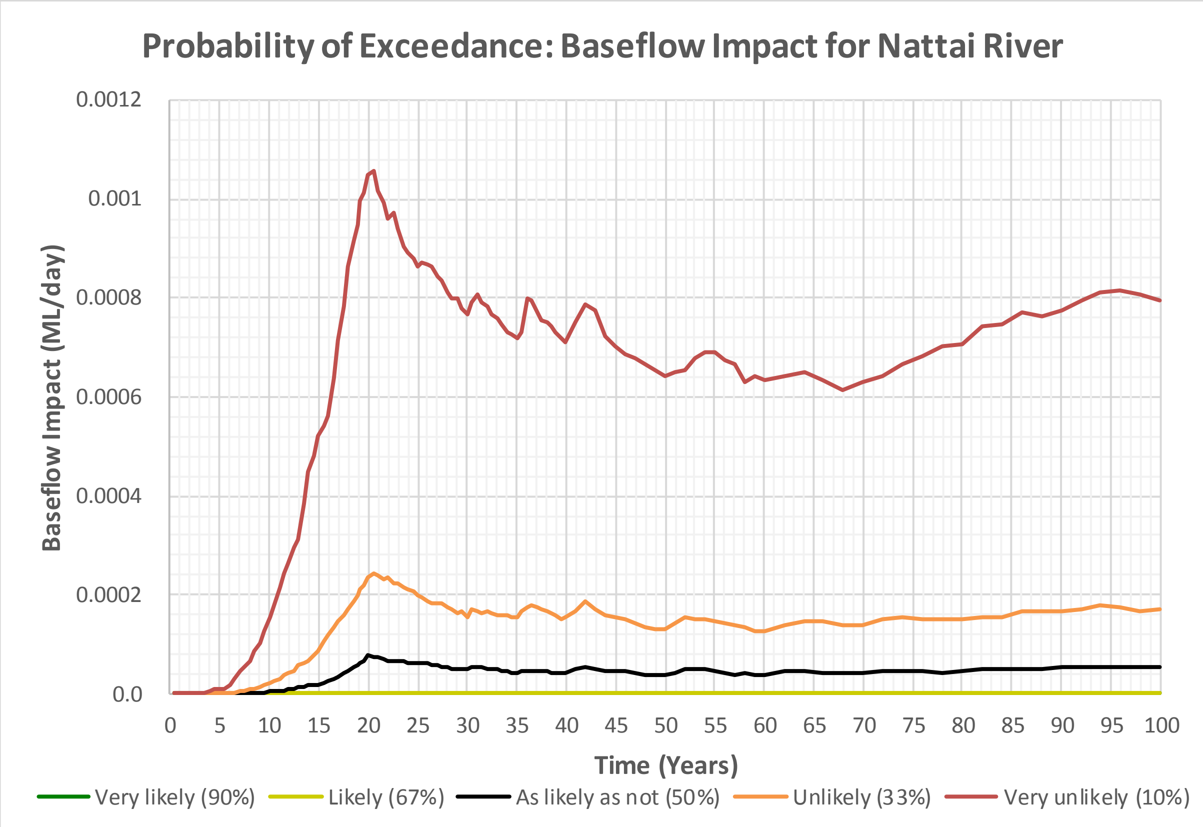


Figure 54 Uncertainty Analysis – Baseflow impact for Nattai River

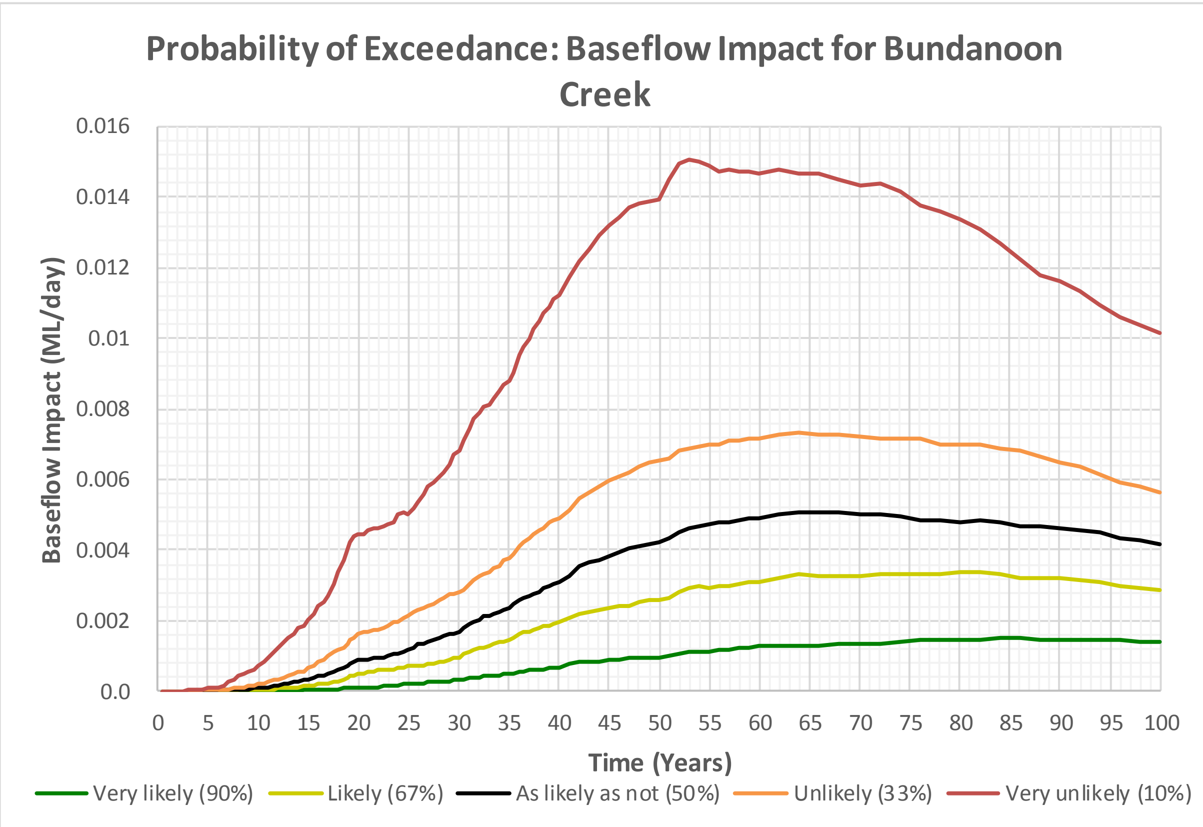
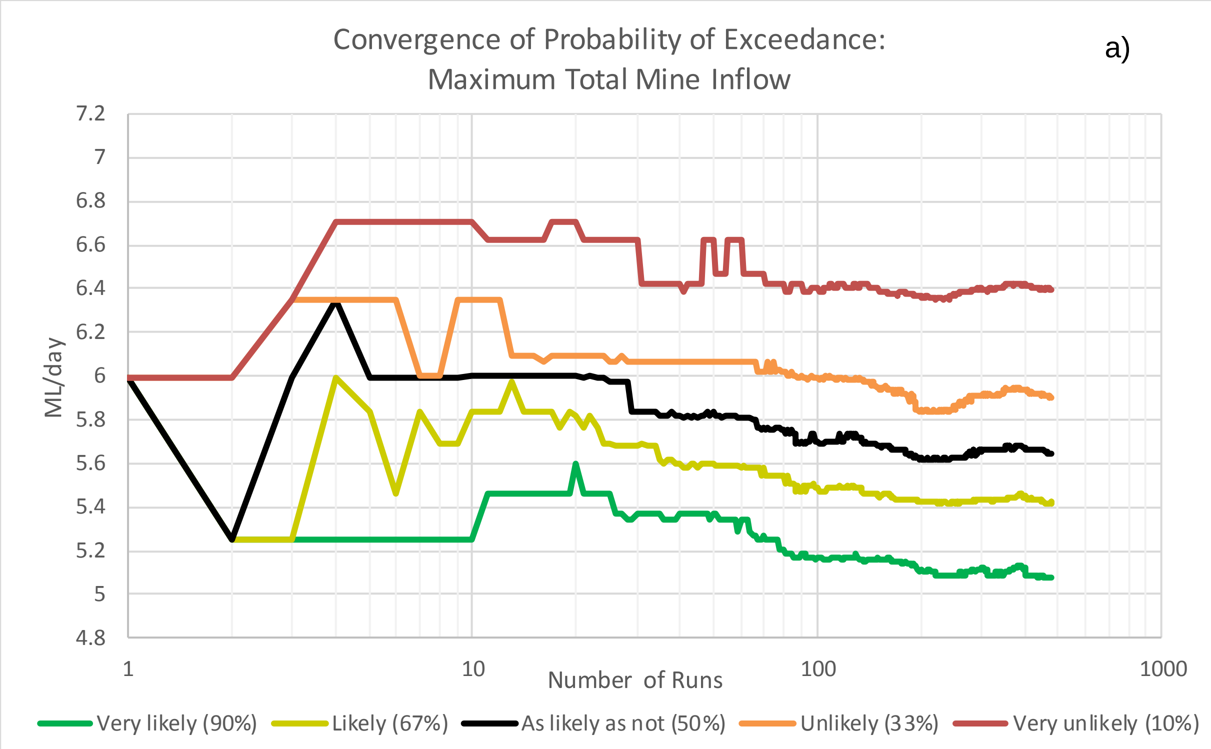


Figure 55 Uncertainty Analysis – Baseflow impact for Bundanoon Creek

MONTE CARLO CONVERGENCE

Number of bores with active licences affected by 2m drawdown or more

The 99.7% confidence intervals indicate that the reported numbers of affected bores are likely within 2-4 bores of the true values.



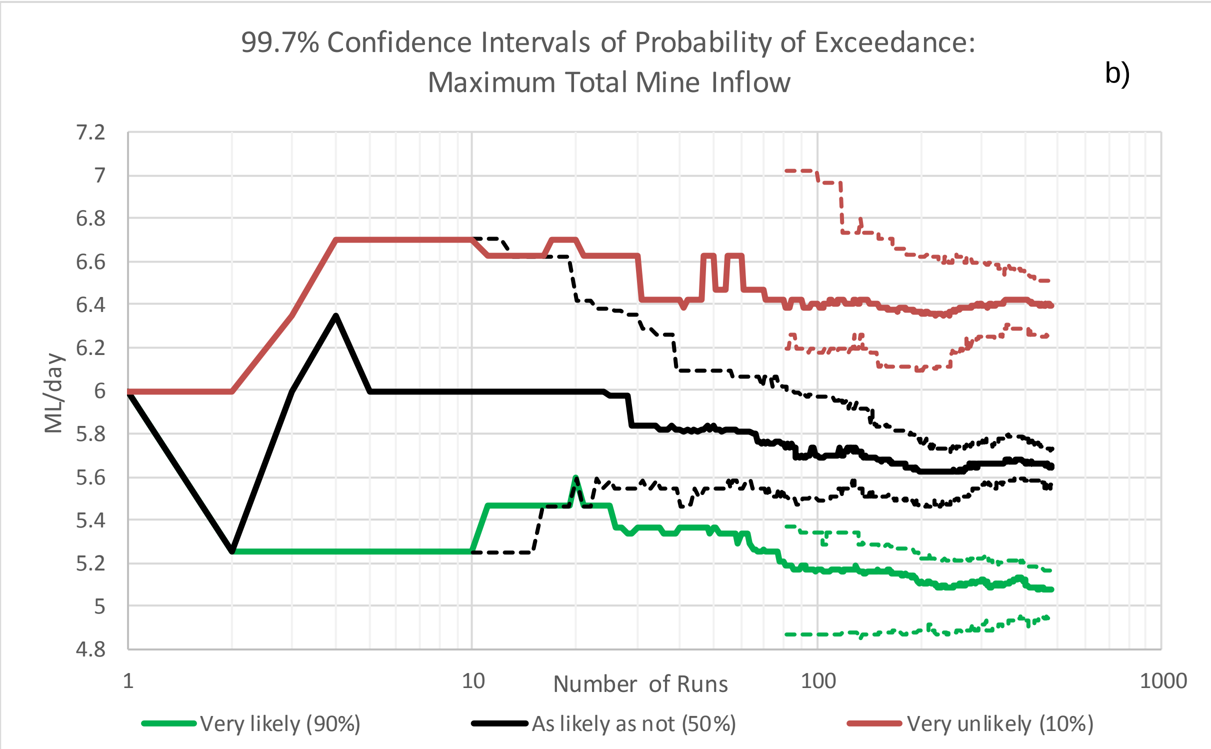


Figure 56 Convergence chart (a) and confidence interval (b) for number of impacted bores

Maximum total mine inflow

The reported maximum total mine inflow values are within 0.11 ML/day (1.7%) of the true maxima with high probability.

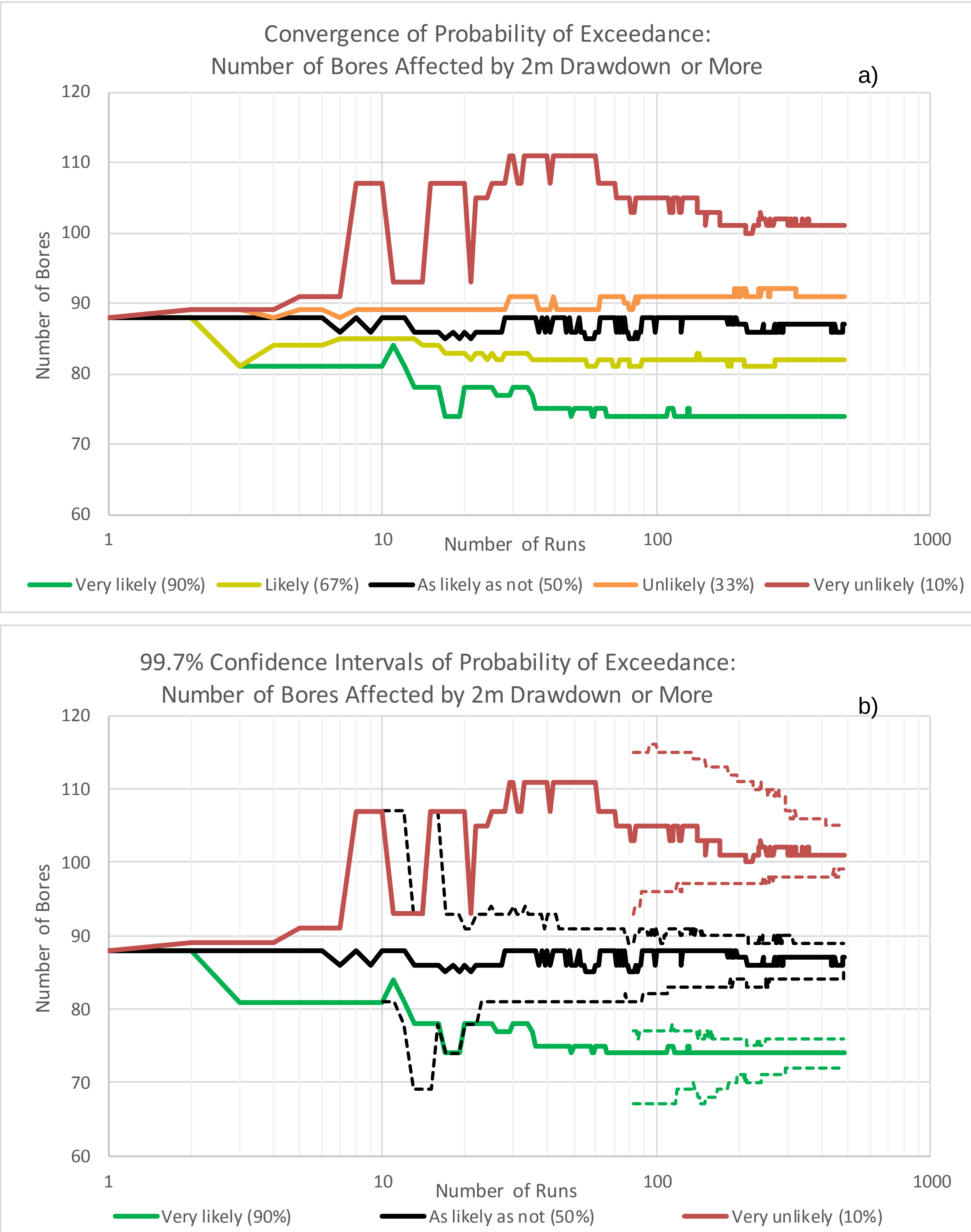


Figure 57 Convergence chart (a) and confidence interval (b) for 'Total' mine inflow.

SENSITIVITY ANALYSIS FIGURES

PILOT POINTS

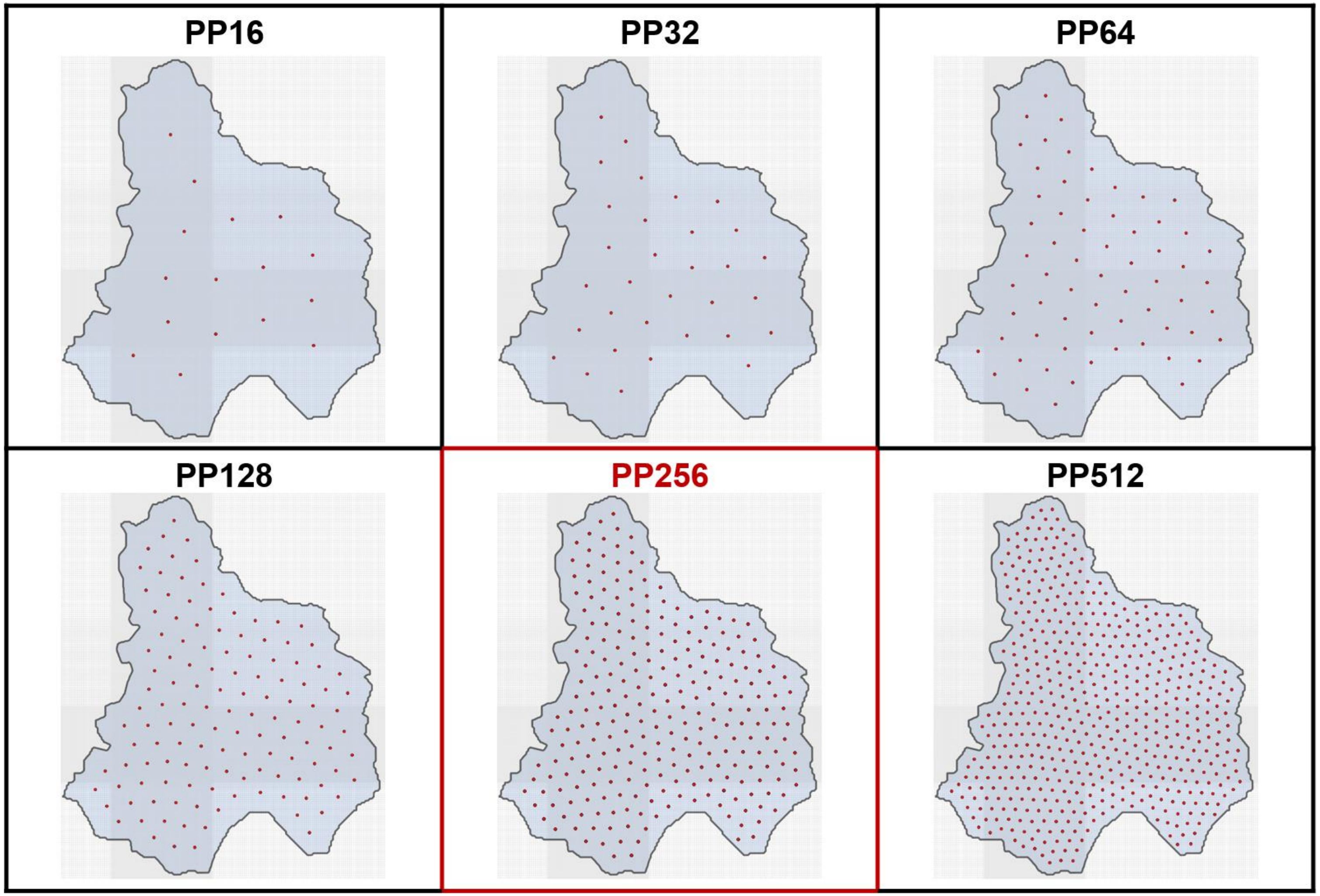


Figure 58 Pilot point spatial distributions in each of the six scenarios. The PP256 scenario, highlighted in red, was the distribution used in the uncertainty analysis.

MINE INFLOW

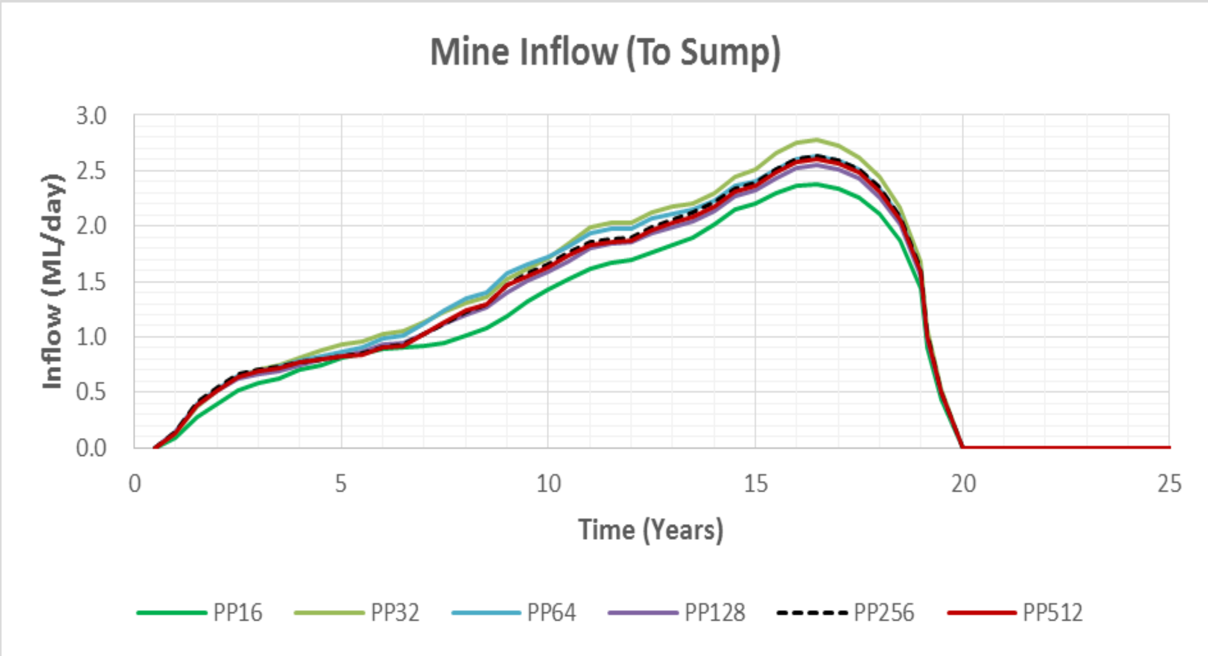


Figure 59 Mine Inflow to sump for pilot point sensitivity analysis

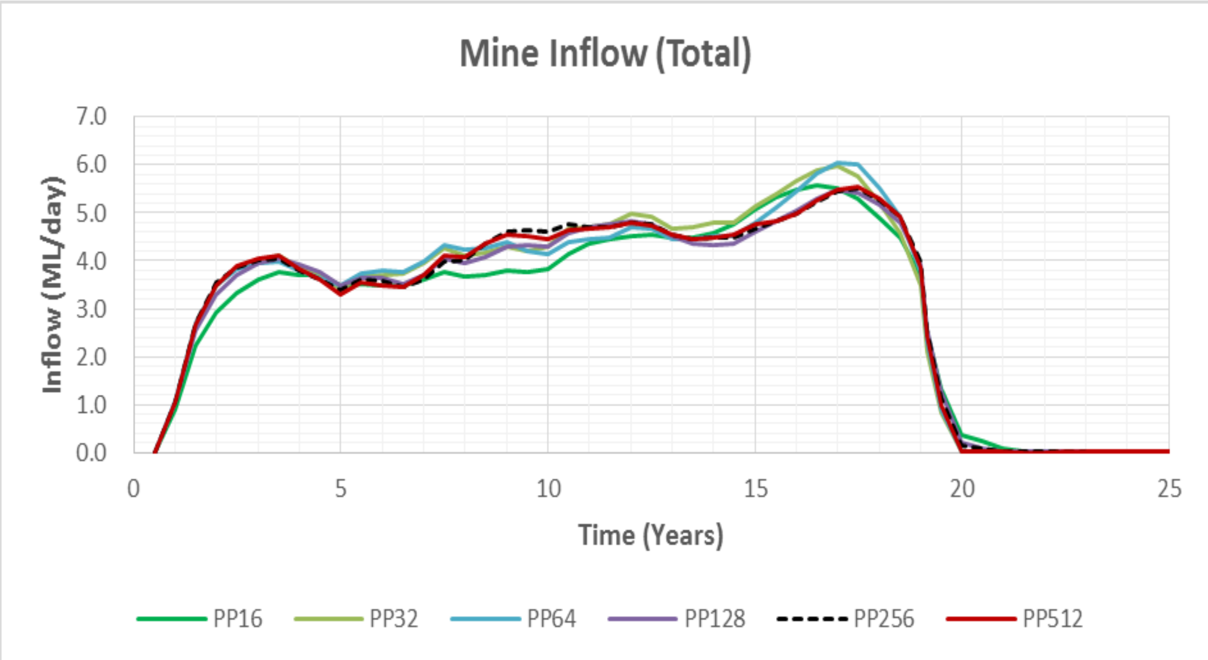


Figure 60 Total Mine Inflow for pilot point sensitivity analysis

BASEFLOW IMPACTS

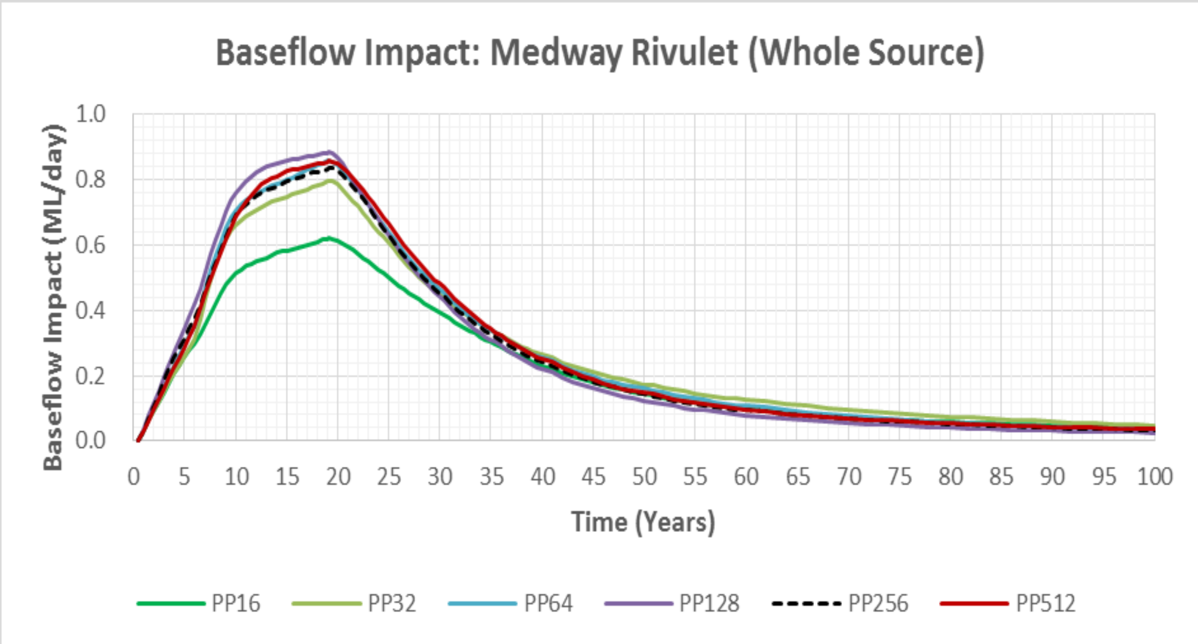


Figure 61 Medway Rivulet baseflow impact for pilot point sensitivity analysis

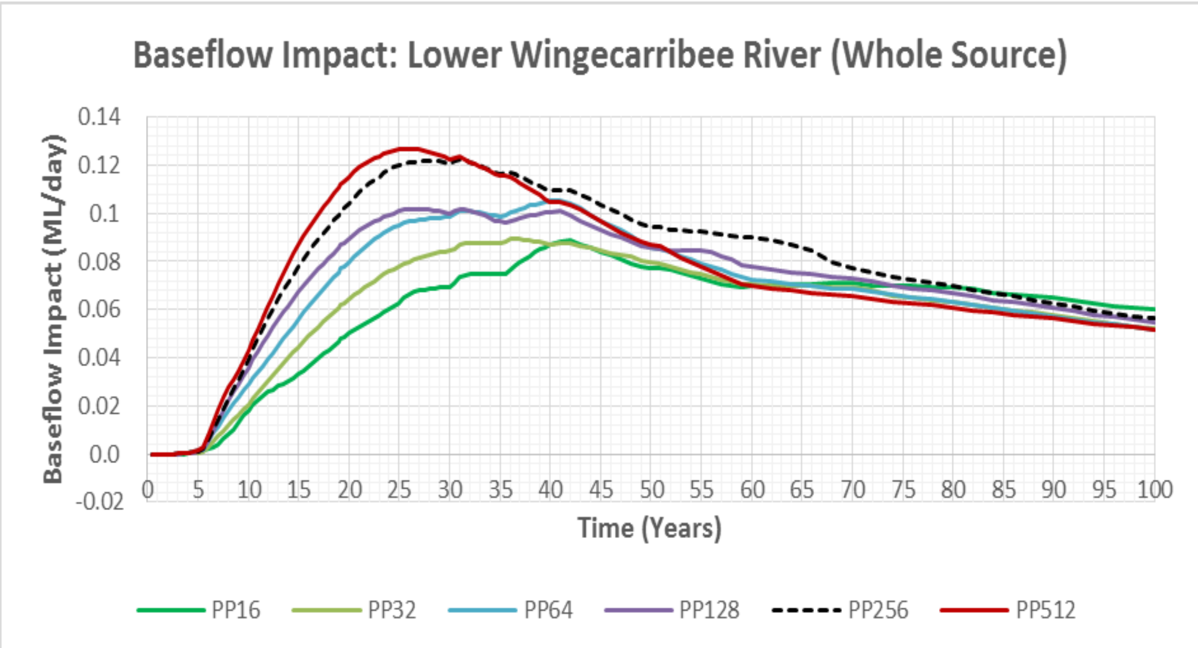


Figure 62 Lower Wingecarribee River baseflow impact for pilot point sensitivity analysis

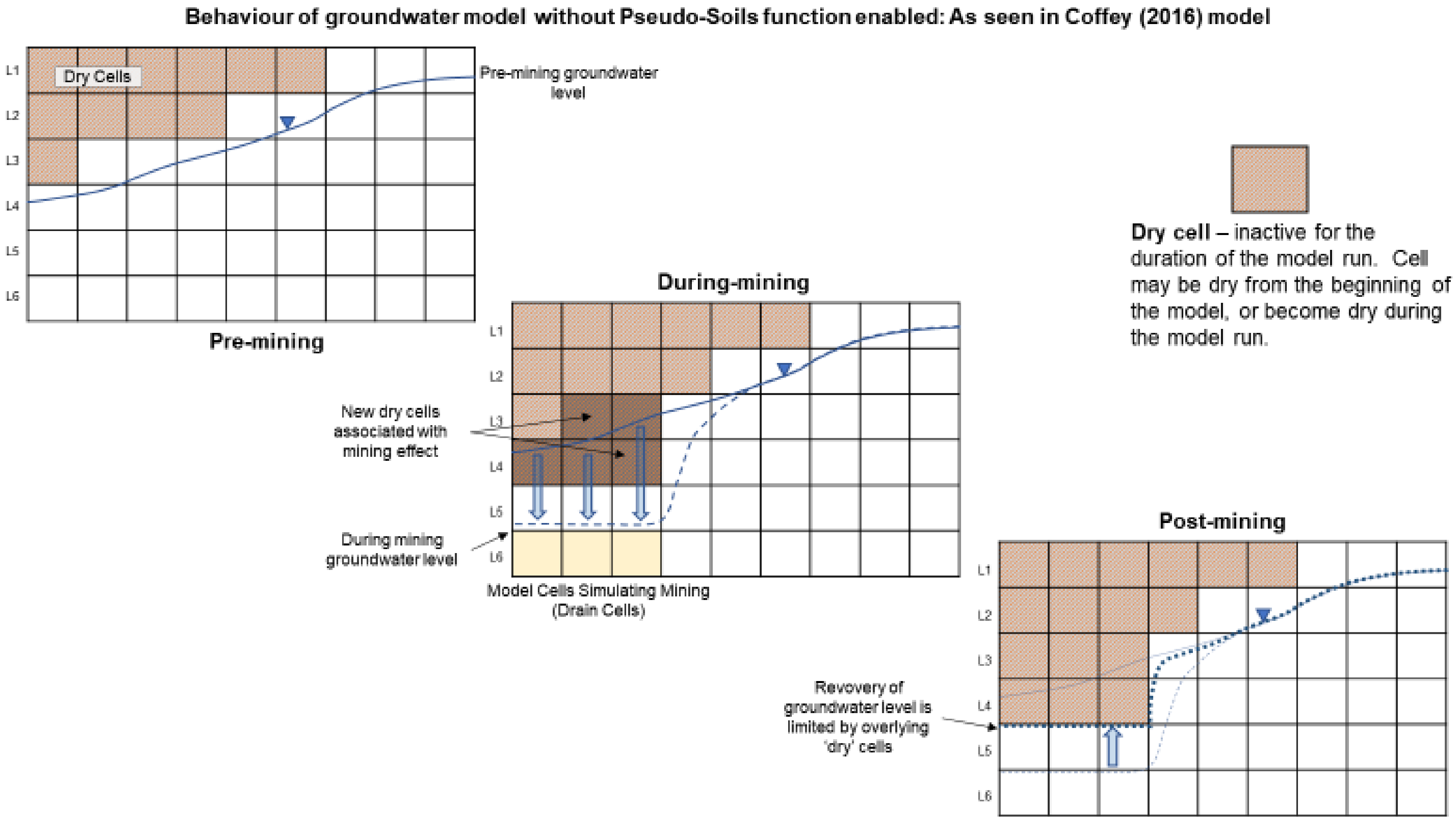


Figure 63 Cross section showing the behaviour of a groundwater model without pseudo soil function enabled (EIS Model)

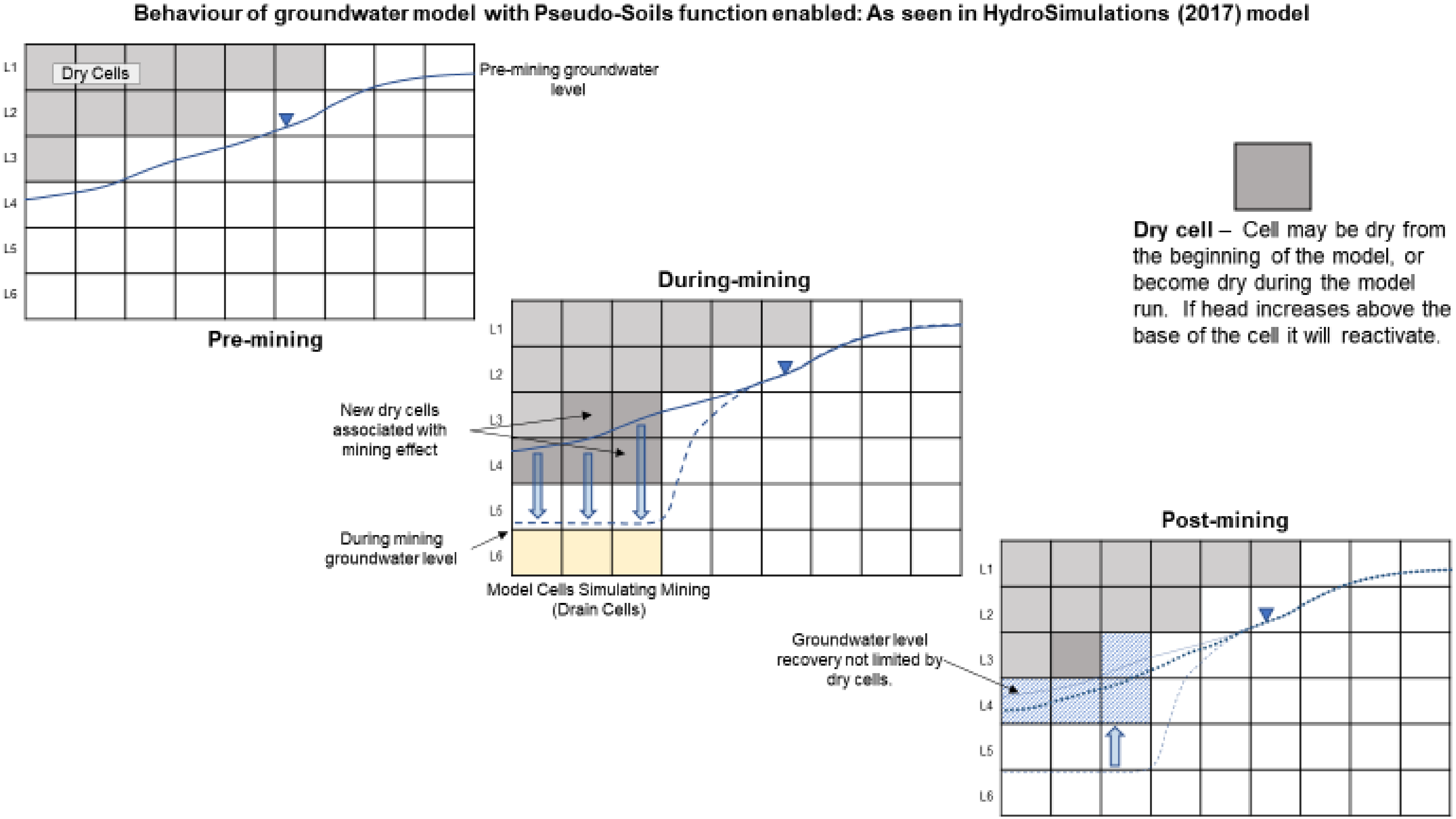


Figure 64 Cross section showing the behaviour of a groundwater model with the pseudo-soil function enabled (Modified EIS model).

HORIZONTAL FLOW BARRIERS

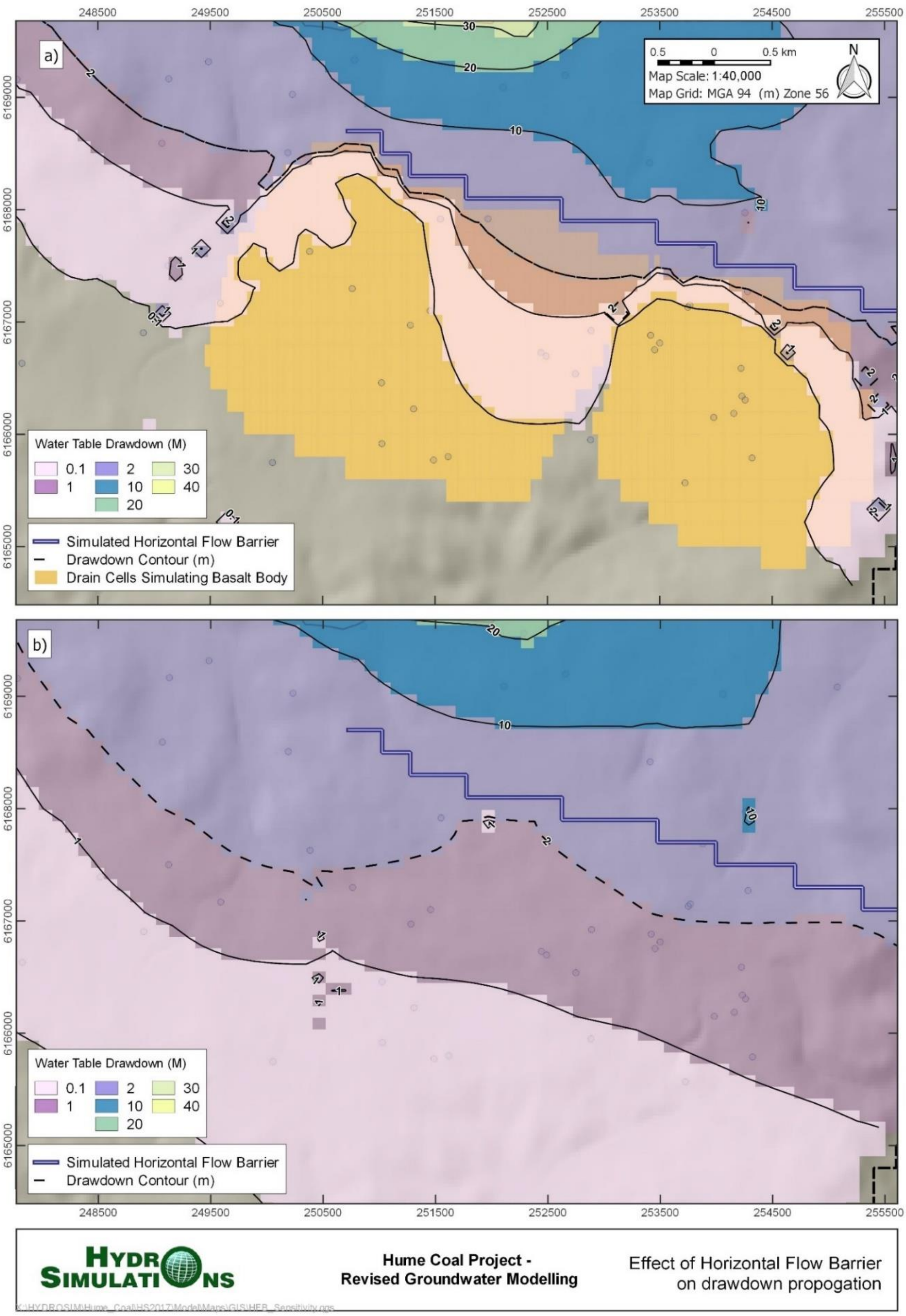


Figure 65 a) Spatial interaction of drawdown with basalt body simulated using Drain and Horizontal Flow Barrier cells b) spatial interaction of drawdown when only Horizontal Flow Barrier cells are present.

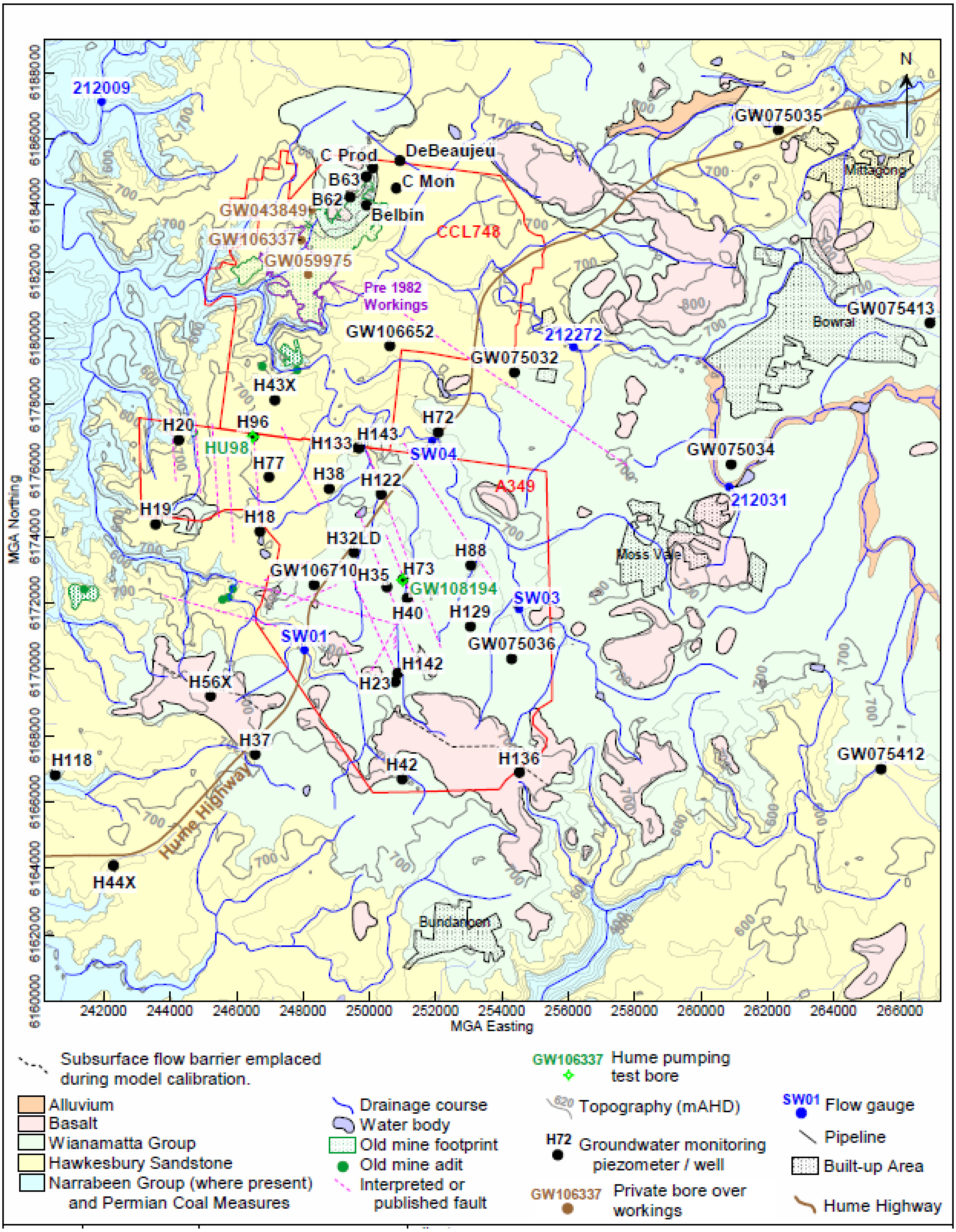
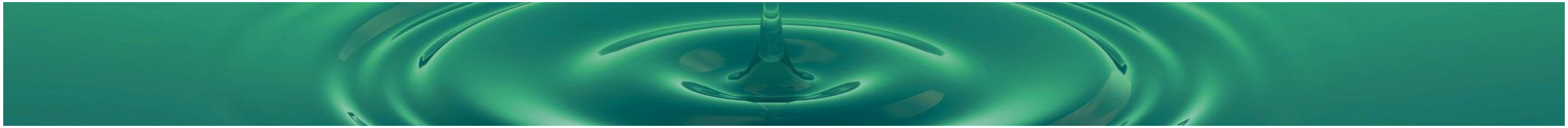


Figure 66 Monitoring piezometer and well locations [from Coffey, 2016a, Figure D1]



APPENDIX A – HYDROGEOLOGIC REVIEW SUMMARY TABLE

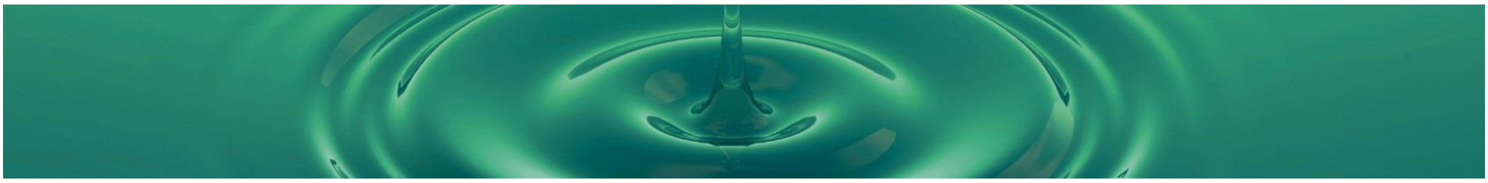
Issues Log — Hume Coal Project (SSD 7172) - Groundwater Model

Item	Context	Comment/Question/Issue from Independent Peer Review by Hugh Middlemis (HM) August 2017, updated 5 & 11 October 2017	Response from Groundwater Assessment Team (5 Oct 2017)
1	Evidentiary Basis	Coffey (2016) Groundwater Assessment Volume 2: Numerical Modelling and Impact Assessment; supported by: Coffey (2016) Groundwater Assessment Volume 1: Data Analysis	*not required*
2	Model Confidence Class (s.4.3.5)	Report claims Class 2/3 (30%/70%). DPI disagrees, suggesting Class 1, citing 2012 guideline commentary that any element of Class 1 renders entire model Class 1. Important because DPI rely on this demonstrably false premise to base their claims of inadequate modelling. Merrick concurs with Class 2/3, suggesting weighted score of decision table in guidelines. Independently assessed by HM (see tab "Class" herein), indicating Class 2 overall (with some Class 1 and some Class 3 elements), and thus appropriate for impact assessment. That the Hume model can be improperly labelled Class 1 with apparent justification from the guidelines is not the fault of the model; it is fault of the inadequate guidelines and their internally inconsistent commentary on the model confidence classification. The guidelines Table 2.1 on model confidence level classification is itself not unreasonable, but the related commentary and guidance is poor & internally inconsistent, such that cherry-picking one comment (rather than considering the table attributes) does not constitute a valid argument.	We agree that the Groundwater Modelling Guidelines are in error in regard to labelling a model as Class 1 on these stated grounds: "If a model falls into a Class 1 classification for either the data, calibration or prediction sectors, it should be given a Class 1 model, irrespective of all other ratings." This statement is inconsistent with other statements in the same guide; e.g. "In general, it should be acknowledged that if a model has any of the characteristics or indicators of a Class 1 model it should not be ranked as a Class 3 model, irrespective of all other considerations." This implies that a model could be labelled as Class 2, though it has Class 1 characteristics. Our assessment (adjacent) shows 16% Class 1, 36% Class 2, 48% Class 3. Two of the Class 1 attributes have moved to higher classes following model revision by HydroSimulations: mass balance is now Class 3 and performance (excluding unreliable VWP measurements) is <10%RMS (Class 2).
3	Implementation of mining s.3.2.5	Good calibration to effects of mining at Berrima (inflows, heads, dewatering /depressurisation) gives confidence that such mining features applied to Hume would be adequate, except for unclear reporting of implementation at Hume re volumes. s.3.2.5 outlines some introductory info on non-caving workings, including that the conductance of drains is used to simulate mine openings and the overlying drained zones; illustrated later in fig 5.4 (see "mining" tab). OK. s.5.3 confirms that pre-mining parameters apply to the horizon from surface to mined zone, with drain features/parameters used to represent drained zone. OK subject to subsidence report. Drained zone comprises mine opening excavation of 3.5m (thickness of Layer 11) plus relaxation zone of 2m (s.3.2.5), which would be Layer 10 generally (2m thick and present in Hume lease area; see Table 2). Layer 8 (interburden), and Layers 9 & 10 are all present in Hume lease area (see Table 2, s.3.1). OK in principle, but s.4.1 of Volume 1 (groundwater data) states that interburden is absent in south-western half of lease (see also Fig.4.3 of Vol.1; see "params" tab). However, Fig 4.3 of Vol.1 shows bore HU0016CH has 1.3m of interburden although Fig.4.1 shows it within the zero interburden thickness. Reports do not state what happens to Layers 9 & 10 where interburden (Layer 8) is absent, and this needs clarification, as the interburden thickness/extent is a significant point of difference between Hume and Berrima, and it has hydrological effects in situ, and affects how the drained zone should be represented in the model. Fig 5.2 (see "mining" tab) indicates that relaxation zone extends up into layer 8 in some areas(?), which is not consistent with text (which is itself inconsistent). For example, s.3.1. says layers 6 & 7 accommodate roof relaxation where interburden layer 8 is absent, but relaxation should be hosted in Layer 10 as it is 2m thick generally (Table 2 in s.3.1). Fig 5.4 does not specify which layers drain treatments are applied to. Q&A needed. Subsequent comment (post-response): The title of Table 2 (Appendix I, groundwater model) is "Model layer thicknesses", but the column heading in the table does say "average layer thickness". This is not as clear as it should be. Table 2 data indicates that layers 9 & 10 are 2m thickness in the Hume lease area and layer 8 is 4m thick, and the footnote indicates "minimum model layer thickness is 0.1m". This is not consistent with Groundwater Assessment Team response opposite, including that minimum layer thickness is 0.4m (Triassic) or 0.29m (Permian). There are other references in report to effect that "constant offsets" were used to establish layer top/bottom surfaces, and "proportional thicknesses" although that term is not explained. It is report content such as this that causes confusion and reduces confidence in the modelling tool. Having said that, the model audit explanations in the response, and the additional figures, do provide good detail, confirming the need for model revision as outlined. Further review required once results are available.	Agreed that Berrima Mine provides the best control on likely inflows at Hume Mine. Table 2, s.3.1 gives indicative thicknesses for Layers 8-10 in the Hume lease area, whereas reviewers have interpreted these as constant values. A model audit shows that the thicknesses vary over the lease area and over the model extent (see Tab "New_Figures"). Triassic interburden [Layer 8] geometry: thickness is spatially variable and is consistent with Figure 4.3 (Vol.1). In the model, a minimum thickness of 0.4m is applied; as the properties are those of lower Hawkesbury Sandstone, the absence of interburden (as in Figure 4.3 of Vol.1) is represented properly. The thicknesses of Layers 9 and 10 (Permian above the coal seam) are a minimum of 0.29m each. Allowing for the minimum thickness of Layer 8, there is at least 0.99m between the roof of the coal seam and the base of the Hawkesbury Sandstone layer. Figure 4.1 (Vol.1) shows a log of HU0016CH but the thickness of 1.3m is not associated with this bore but is stated as an overage "over the mine lease". Section 3.1: "The bottom two layers for the Hawkesbury Sandstone (Layers 6 and 7) are to accommodate roof relaxation from mining where the interburden or piles above the working section are absent." - a check of the model shows that Drains have been applied only to Layers 10 and 11 in the model. Over a small area (see Q10 below) drain cells should have been applied to Layers 7-11. This will be corrected in the revised modelling.

4		Conductance (C) of drains used to simulate mine openings (layer 11) and overlying drained zones (nominally layer 10, 2m thick). s.5.1: Calibrated C = 0.05 m^2/d (suggests very low K=6.e-5m/d for cell size of 50x50m and assumed thickness of 3m). May be OK? s.5.3: Drains set to 0.1m above floor in any layer/cell intersected by drained zone in mined zone and above (see also fig.5.1). s.5.3.1: No material volumes of injection of water to bulkheads (so only tailings volumes injected). s.5.3.1: Backfilling of co-disposed tailings comprise 36% of void volume (Table 7) and reported as inert re groundwater fluxes (non-draining/non-storing). Extraction from recovering voids (behind bulkheads): s.5.2.1 & fig.5.3 very confusing - see "mining" tab herein. Key issue: s.5.3.1. states that drain cells active only for time for total drained water volume to match residual void after co-disposal of tailings. This suggests that model does not simulate dewatering of excavation and 3m relaxed zone, but that it limits the volume drained to the volume of the excavation. Could this be part of the explanation as to why the drawdown pattern (figures 6.6 & 6.7) is so chaotic? Discussion and clarification required. Subsequent comment: the application of the DRN facility for the immediate post-mining period until the residual void volume has been extracted was also clarified (in a similar way) in discussion with Paul Tammetta. This reviewer was confused by the less than crystal clear reporting (e.g. including descriptions of DRN features post-mining (s.5.3.1) within a discussion of the implementation of mining in the model in s.5.3). Further review needed when the corrected drawdown plots are available (hence orange "traffic light" colour retained).	Drain conductance: It is not correct to assume the full cell area in converting conductance to hydraulic conductivity (K), or leakage coefficient (K/b). Allowance must be made for the dimensions of the plunges, and for the much smaller area of seeps in the roof of a void. A comparison of adopted leakage coefficients at other mines in the Southern Coalfield (adjacent) shows that a conductance of 0.05 m2/day is comparable with other mines when a correction is made for actual void width. The conclusion that the model "limits the volume drained to the volume of the excavation" is not correct. The model extracts water during the period of excavation, and then the DRN facility is used to calculate the time required for the void to fill with water. This volume is incorrectly withdrawn from the groundwater system in the model, whereas in reality the water remains in the void. The unusual drawdown patterns in Figures 6.6 and 6.7 are due to the descent of the water table through different layers in the model. This requires correction, as the drawdown of the water table should be smooth.
6	Water Balance Tables 4, 10 & 11	Refer to tab "WatBal" for questions about water balance issues that require discussion/explanation please. 1. Inconsistent water balance effects need discussion and explanation. 2. What does "period of active stress" really mean? [Table 9] Is it the period when drain cells are active to represent mining? 3. Is active stress limited to the volume of the excavation void? The language/terminology is not clear and transparent (but it needs to be). Subsequent comment: In discussion with Paul Tammetta, it is understood that the (previously) reported water balances were not direct outputs from the model at specific stress periods (recommended in the guidelines to assess model performance with a criterion of discrepancy less than 1%). Rather, they were calculated as cumulative volumes (presumably between stress periods) divided by elapsed time. Hence the "discrepancy" term was not an indication of potential problems with the mass balance in model performance terms (rather it was an indication of either mining-induced or post-mining recovery changes to aquifer storage). It is good to note that re-running the model resolved the question of the model mass balance performance, which also appeared to confuse third parties reviewing the reports. Also good to have a clear explanation of the "active stress" term, and clarification of how the DRN facility is used during and post-mining (i.e. to address issue 3). Details should appear in the model audit report. The revised model approach outlined is sound and endorsed for implementation, with the results requiring further review (hence orange "traffic light" colour retained).	1. Inconsistent water budgets: A re-run of the calibration, null and prediction models with improved solver settings (and finer time steps) gives consistent water balance components (see adjacent) with very low mass balance discrepancy (0.15-0.19%). Previously reported water balances had high discrepancies of 4.1-6.8%. 2. 'Active stress' consists of two periods during which DRN cells are active in the model: (1) During mining, giving "to sump" volumes; (2) Post-mining until the local void fills with water, giving "to void" volumes. 3. The "to void" volume is limited to the volume of the excavation void, allowing for the portion of the void occupied by waste. The two volumes are accounted and reported independently in the model. The "to sump" volume is considered taken from the groundwater source and used for mining, whereas the "to void" volume remains in the groundwater system and is available for other users. Post-mining DRN cells are really a convenient accounting method for calculating the time taken for the void to fill with water, after which time the DRN cells are removed and the water in the model can recover rapidly (in the void) at host properties. More realistic void properties were not applied because the TMP facility in SURFACT was not available to the modeller. A better approach, being adopted in the model revision, is to have DRN cells active only during mining with recovery allowed immediately afterwards in the void at enhanced permeabilities and specific yields using the TMP facility in SURFACT or the TVM facility in MODFLOW-USG. There is no need to calculate the "to void" volume. The "to void" volume is wrongly reported by MODFLOW as a loss from the groundwater system. It is not pumped out, in reality, and remains underground. The revised modelling will deactivate drain cells as soon as a mined section is sealed. Hume Coal will license both the "sump water inflow" and the "void water inflow" as per the AIP requirements. This is a very conservative approach as there is no precedent (at other mines) for regarding void-refill as licensable. In order to calculate the "to void" volume, one run will be conducted for prolonged drain cells post-mining. The model audit report will revise and re-word the language/terminology on water balance concepts so they are clearer and more transparent to a reader.

6	Topography	SRTM data (+/-8m), reportedly benchmarked to Lidar on lease, but acknowledged as inaccurate. Hence data uncertainty on bore levels, stream drainage levels, EVT process. Hence uncertainty applies to water balances and analyses, although scenario difference method reduces uncertainties. Links to water balance issues. Subsequent comments: a) in high risk context projects such as this, where surface-groundwater interaction is a critical issue (evapotranspiration and stream baseflow are the major discharge elements in the model water balance), this reviewer considers that the cost of high accuracy Lidar data is warranted to reduce uncertainties b) the merging of Lidar with SRTM products is indeed "normal practice" but that is not best practice in my view in a high risk context (coal mining in high value agricultural/natural areas with strong surface and groundwater interactions); subsequent info from Noel Merrick indicates that Lidar covers main area of interest of the model (see graphic opposite); OK/adequate c) Issues 7 and 8 below allude to the potential for an alternative model arrangement (conceptualisation and/or parameterisation), one that has higher recharge, which could still be benchmarked against the very good baseflow estimates (and the Berrima mine flows) by allowing for some variation in the relatively uncertain evapotranspiration rates, especially with the benefit of improved Lidar topography in the riparian zones; investigation of such an alternative arrangement would be a reasonable way to investigate uncertainties, and is recommended. After meeting Dr Merrick on 9 October: plans to run 130 climate scenarios and to do a formal uncertainty analysis, with some further slected sensitivity runs whould address this "alternative model" issue (hence orange "traffic light" colour retained).	The model topography is based on merging the 1 arc-second (~30m) gridded smoothed version of DEM-S Version 1.0 obtained from the Shuttle Radar Topographic Mission (SRTM) with LIDAR that covers an approximate 400 sq km over the proposed mining area and adjacent surrounds. This is normal practice. The more accurate (and expensive) LIDAR data are not usually available over areas broader than a mining lease. The LIDAR survey has a stated accuracy of +/- 150 mm. Geoscience Australia: "DEM-S represents ground surface topography, excluding vegetation features, and has been smoothed to reduce noise and improve the representation of surface shape. An adaptive smoothing process applied more smoothing in flatter areas than hilly areas, and more smoothing in noisier areas than in less noisy areas." Geoscience Australia determined the accuracy relative to permanent survey marks as 1.3m mean, 1.7m median and 7.6m at the 95th percentile (GA, 2011, 1Second SRTM Derived Products User Guide). Cell sizes of 50-200m necessarily add approximation to the single topographic level that must be applied in the model over the entire area of a cell.
7	Recharge (RCH) s.4.3.3.	Report states RCH at 1.8% of annual average rainfall (no seasonality, no climate change effects). RCH benchmarked to baseflow and weighted a little higher to allow for recharge from basalt (both worthy methods). RCH lower than applied to Berrima model (4% general, 8% over mine). WSP assumes 6%. Would higher average RCH and/or seasonality (as an uncertainty assessment) result in increased or decreased mine inflow and drawdown impacts? Subsequent comment: the climate scenarios will assess uncertainties relating to recharge (and, presumably, evaporation), but the alternative arrangement suggested above (Issue 6) would test uncertainties to parameterisation (noting that recharge is correlated with Kh). For example, the model should arguably be used to provide objective evidence (results of scenarios) that pose questions such as: - what parameter value/combination would increase the current prediction of third party bores affected, and how likely is such a set of parameters? - what higher dewatering rate/duration would it take for the mine water balance to be compromised (in terms of zero discharge aims), and what parameters (or combinations) would cause those higher dewatering volumes/durations, how likely is that eventuality and what would be the regional impacts?. To discuss October 9th. Subsequently: see comment at Issue 6.	This study has ground-truthed rainfall recharge against baseflow analysis for consistency. Other referenced recharge estimates do not have this control. Seasonality is considered during calibration but not during prediction, but the fraction of rainfall remains the same. Climate scenario analysis is to be undertaken (for 108 climate sequences) to assess the uncertainty in mine inflow and baseflow impacts.
8	Aquifer parameters s.4.3.2, Table 3, Figure 4.5	Kh arguably a little on the low side (reasonable given RCH arguably a bit low). Kv a bit on the high side, hence Kv/Kh high at 0.2 in model, compared to 0.02-0.002 from pump tests. Higher Kv arguably OK given number of boreholes in area. Specific storage (Ss) value of 5.e-7 m^-1 is arguably too low in a physical sense (compressibility of water alone yields Ss of approx. 4.5e-7 m^-1). Pells 2017 in his fig.2.8 suggests Ss too low by far, but this is relevant only to software based on compressibility (bulk modulus values not specified by Pells and warrant double-checking). However, in this case the Ss value is valid and acceptable, in that Modflow is a quasi-3D model (does not work on basis of compressibility) that coverts Ss to S by multiplying by layer thickness. The values of S used by Modflow are thus reasonable in a composite and individual layer sense (e.g. composite S = 1.e-4 for layers 2-5 (124m thick), and S = 1.e-5 for layers 6-11 (17.5m thick), but S = 1.e-6 for 2m thick interburden layers). OK. Subsequent comment: Discussion around parameters not unreasonable, and points re Ss and Poissons Ratio appear quite valid (i.e. Pells argument is questionable and hence so is some of UNSW review comment, especially inconsistent references to specific storage and confined storage values). Monte Carlo calibration-constrained uncertainty analysis results required to provide objective information on review comments about potential for alternative conceptualisation or parameterisation to result in significantly different impact assessments. Adoption of Ss at 5.e-7 m^-1 is almost at low end of physical limit, and pumping test results provided (thank you) indicate Ss in order of 3.e-6 m^01. This suggests that the uncertainty effects of a higher confined storage (by a factor of 10) have not yet been explored. In other words, despite the well-constrained calibration achieved, and given the feedback loops between parameter settings, impact predictions with Ss at least a factor of 10 higher may be warranted. Having said that, dewatering volumes are likely insensitive to confined storage values (but may be sensitive to unconfined specific yield values). Uncertainty analysis would have provided the information in question. For discussion on 9 October. Subsequently: uncertainty analysis in progress OK (but orange "traffic light" colour retained accordingly)	Field K values always cover several orders of magnitude. The applicable regional K values are best determined by calibration to broad groundwater levels and hydraulic gradient patterns. The calibrated Kh values [Figure 4.5] lie roughly in the middle of the field K spread. Kv is generally 1-2 orders of magnitude lower. In this study, the choice of aquifer property values has been constrained considerably due to the three-pronged approach of simultaneously honouring observed groundwater levels, measured Berrima mine inflow and inferred steam baseflows. Accordingly, Hume Coal is confident that there is strong support for the adopted K values but recognise uncertainty and non-uniqueness as being ever-present. It is not unusual in mining models to allocate a single K value per model layer, as long as the RMS calibration statistic is acceptable (9%RMS without VWP measurements). Monte Carlo calibration-constrained uncertainty analysis is planned to assess the effects of spatial variability. The adopted Ss and inferred S values are similar in magnitude to those adopted in other mining models. Generally, the unavailability of geotechnical tests precludes direct calculation of Ss from one of many empirical relationships. The Pells argument is based on an assumed Poisson's Ratio (PR) of 0.2. This could be higher, in which case the model-adopted values are closer to theoretical expectations. The literature has many reported values of similar magnitude (and lower) to those adopted. The adjacent graph of Bulk modulus vs Specific storage shows extreme bounding lines for PR of 0.31 (blue) and 0.40 (red); also literature values (green spade), incompressible limit (red spade), and pumping test (blue spade - accurate to no better than a half order of magnitude).

9	Pumping Tests and Berrima Inflows	1-day test at H98, 7-day test at GS108194 (Wongonbra). Sy = 0.015 (incorrectly listed as 0.15 in draft issues log), Ss = 3.e-6 m^-1, Kv/Kh = 0.002-0.02. No details of pumping tests provided, and no long term tests undertaken (other than one 7-day test at Wongonbra). However, good calibration to Berrima mine inflows and to baseflow estimates, along with head values. Berrima inflows similar in scale to predicted Hume inflows. Subsequent comments: - thank you for providing the pumping test information from PB memo of 2014 ("pumping_tests" tab) - agree Sy should have been indicated as 0.015 in draft issues log comment (my mistake) - 2 pumping tests, but only one "long term" test, of 7-days duration (i.e. report in s.5.1.1. is exaggerating the "long term pumping test" claim); not questioning the other tests, just pointing out that there is little by way of a large scale stress test on the aquifer (only the one 7-day test) - note that Ss from 7-day test over a 100m interval resulted in Ss value of 3.e-6 m^-1, which is 10 times higher than the Ss applied to the model of 5.10-7 m^-1; the S values obtained from the test of 3.e-4 and 1.e-5 are not inconsistent with the model-calculated composite S value for layers 2-5 (124m thick) of 1.e-4, and 1.e-5 for layers 6-11 (nominally 17.5m thick). Key issue is that, while the S parameter used in the model is consistent with pumping test data, uncertainties have not been investigated. For discussion 9th October. Subsequently: a sensitivity run is planned to evaluate effect of a higher Ss value - need to review results in due course.	Volume 1 notes 28 packer tests, two long-term pumping tests on the lease (pumping bores HU0098 and GW108194 (Wongonbra) with multiple observation piezometers monitored), six long-term pumping tests from private bores in the wider area, 129 estimates of hydraulic conductivity from specific capacity data in government records for private water bores, and laboratory tests on 39 cores. Details of the two pumping tests are summarised in a Memo from Parsons Brinckerhoff dated 19 December 2014. Data were analysed using Aqtesolve software assuming either unconfined or leaky-confined conditions, and also analysed using MODFLOW-USG on an 8-layer model for the longer pumping test. Of interest for the latter analysis is an interpreted storage coefficient of 5E-6, suggesting a specific storage an order of magnitude lower (consistent with what has been adopted in the model). The field data and Aqtesolv analyses are at Tab "Pumping_Tests". Coffey re-interpreted the pumping test data using USGS WTAQ software. The field data and WTAQ analyses are at Tab "Pumping_Tests". Of interest is an interpreted specific storage of 3E-6 m^-1 and specific yield of 0.015 (not 0.15).
10	Calibration Performance s.4.3	Performance stated for validation period to August 2015: SRMS = 12% exceeds guideline upper limit of 10%, but probably affected by outliers B62 upper and B63 lower (not unreasonable that there is a poor match to 2 VWPs out of 6 VWPs at Berrima), and given topo data issue. What is performance statistic excluding outliers? Time series plots show some good matches, some poor; overall OK (given data issues). Figure 4.6 shows reasonable calibration match to post-2012 measured flows at Berrima gauge (when good data quality available from cut-throat weir). What is performance during warm-up model run to 2011 (match to factored gauge data shown by purple line on fig. 4.6 - see "Berrima" tab herein) ? No presentation of model performance at Dec 2014 (end of calibration) in terms of groundwater contours and head residuals plot; this would be helpful to judge performance. Subsequent comment: changed issue colour to green based on extra info provided (thank you), even though data on Berrima flows pre-2011 was not provided.	VWP data are commonly known to vary by up to 10m. In the model two VWPs are outliers and do not calibrate well. When these are removed the SRMS is reduced to 9.0% (and 12.9 mRMS). All head calibration data at 2432 points are now included in the calculation of performance statistics. The scattergram is adjacent. Groundwater head contours (water table) and head residuals are provided in the "New_Figures" tab.
11	Reporting	s.7.1.1 Model Results: "indicate that 98% of total inflow to Hume mine workings is satisfied by interception of baseflow to streams and release of groundwater storage". No mention of recharge, which would presumably play a role as a component of inflow. Explanation required please as to how this statement is justified. s.7.2, last para needs explanation please: "drawdown calculated as transmissivity-weighted average of drawdown in each model layer intersected by bore hydraulic interval". s.8 Parameter Sensitivity; bullet 2, sub-bullet 2: report asserts that calibrated Kv of layers 1-5 comprise Wianamatta Group and Hawkesbury SST between water table and mine workings, but Hawkesbury SST extends to layer 7, and then layer 8 is the interburden (relaxation zone in some areas?). This sensitivity run does not test Kv profile to the top of the workings as suggested by the text. Potential for fracturing to extend up into layers 6 & 7 is arguably high, hence this sensitivity run may not explore uncertainty adequately. May need discussion. Subsequent comment: issue colour changed to orange - s.7.1.1. Appendix I (model report) section 7.1.1 does indeed state 98%. The statement in the report is lacking the explainer provided in the response that is linking mine inflows to dependencies on mine activity. Recharge also plays a role in mining-induced impacts in terms of the long term regional extent and magnitude of the cone of depression, which is a key issue given the number of third party bores affected; mainly an issue of report clarity (not material) - s.7.2 - would it not be better to interrogate the model and report the water table drawdown at the bore location, rather than a "transmissivity-weighted drawdown"? For example, in groundwater engineering terms, water is lifted from the water table (not the screened interval of the bore), and the predicted water table is a robust indicator in this case of water accessibility for 3rd parties. - s.8 revised modelling results are required to provide objective information on impacts (hence orange "traffic light" colour retained)	s.7.1.1: There is no mention of "98%" in the report. The water entering the mine comes directly from storage in adjacent rocks, which are replenished in part by baseflow losses and rainfall recharge. The latter, however, is independent of the mining activity. s.7.2: Table 1 in Appendix G shows the model layers that are "open" to each production bore. The model returns a separate drawdown in each layer. In reality, a bore would experience a single drawdown, and that value is best estimated as some average of the reported layer drawdowns; instead of a simple average, the drawdowns have been weighted according to transmissivity as thicker and more permeable layers would dominate the actual drawdown in a bore. s.8: It is acknowledged that the full extent of Hawkesbury Sandstone was not included in the sensitivity analysis for Kv. The thickness of material between the roof of the coal seam and the floor of the Hawkesbury Sandstone ranges up to 8m (see adjacent contours). It is true that DRN cells should have been placed in Layers 7, 8 and/or 9 for a small portion of the mine plan. In the revised modelling, enhanced time-varying properties will be applied in those layers where required.



APPENDIX B - DRAWDOWN PATTERN INVESTIGATION

Drawdown Pattern Investigation

The water table, as presented by a groundwater model, is a composite field comprised of the elevation head from the uppermost non-dry layer at any location.

An investigation has been conducted to identify the apparently unusual drawdown pattern presented for the water table within the EIS Model (Coffey, 2016b). Modelled head data from the EIS Model were exported and compared with early model revisions run in MODFLOW-SURFACT V4 that displayed similar unusual patterns in spatial drawdown. These outputs were then compared with results from a model that had been updated and run in MODFLOW-USG with the pseudo soil function enabled. Following the update to MODFLOW-USG and the implementation of the pseudo soil function, more regular concentric spatial patterns of water table drawdown were observed.

Initial examinations of water table contours from the EIS and revised SURFACT V4 models showed that some mounding of head was occurring close to the edge of where a layer was reporting dry. These areas of mounding, occurring near the edge of the saturated extent of a model layer, are also coincident with the unusual shapes seen in the water table drawdown. Figure B 1 shows these patterns over the proposed Hume Coal Project area, as well as the location of cross section A - A' that has been used to compare modelled heads in relation to layer elevation for a number of model runs.

Figure B 2**,** Figure B 3**,** and Figure B 4, show modelled groundwater level elevation for layers 1 to 5 and computed water table elevation in relation to the bottom layer elevations through cross section A-A'. These figures have been annotated to highlight key trends. The heads and water table within the figures come from the Preliminary Modified EIS Model using MODFLOW-SURFACT V4. As the modelled groundwater level for a layer approaches the bottom of its layer, nearing zero pressure head, there is a tendency for the groundwater level to follow the layer bottom before going dry. This is regardless of, and often counter to, the gradient of the water level before it approached the layer bottom. This behaviour is not an accurate representation of a real-world groundwater system and is incorrect. It is expected that the gradient of the groundwater level within a layer should be maintained despite approaching the bottom of a layer.

Both 'Null' (Figure B 2) and 'Mining' (Figure B 3) runs demonstrate this unrealistic behaviour, with overlap in the areas between the runs where groundwater level is following a layer bottom shown in Figure B 4. Water table drawdown is calculated by subtracting the water table calculated for Mining run from the water table calculated for the Null run, so the areas where the water table is hugging a layer bottom in both runs would report a near-zero water table drawdown. Above the active area of the Hume Coal Project, there are large sections where the water table elevation in the Null and Mining runs are hugging the bottom of layers. These areas would report near-zero drawdown, while areas where the layers have a greater pressure head but are outside the mine area would give drawdown of approximately 10m. When compared to the trends seen in underlying layers and areas where layers have more pressure head, it is clear the reporting of zero drawdown is physically and conceptually incorrect.

Water table elevations at year 17 in the EIS model (Coffey, 2016b) for the Null and Mining runs are displayed in Figure B 6. The same tendency for the modelled head to follow the base of a layer, despite the trends in gradient before going dry is observed, with overlap in the areas where the Null and Mining runs are hugging the bottom of a layer. Incorrect, near-zero values are returned when water table drawdown is calculated.

Figure B 7, Figure B 8, and Figure B 9 show modelled groundwater level and calculated water table elevations for the Preliminary Modified EIS Model using MODFLOW USG with the pseudo soil function enabled. Groundwater levels in both the Null (Figure B 7) and Mining (Figure B 8) runs do not follow the layer bottoms before going dry.

Figure B 9   Water table **comparison in mine year** 17 for '**Null'** and 'Mining' runs using MODFLOW-USG Software with pseudo-soil function enabled indicates no overlap of calculated water tables near layer bottoms, and shows a large continuous difference between the Null and Mining run water tables over the active area of Hume Coal Project. This continuous difference results in the continuous spatial pattern of water table drawdown as seen in Figure 42.

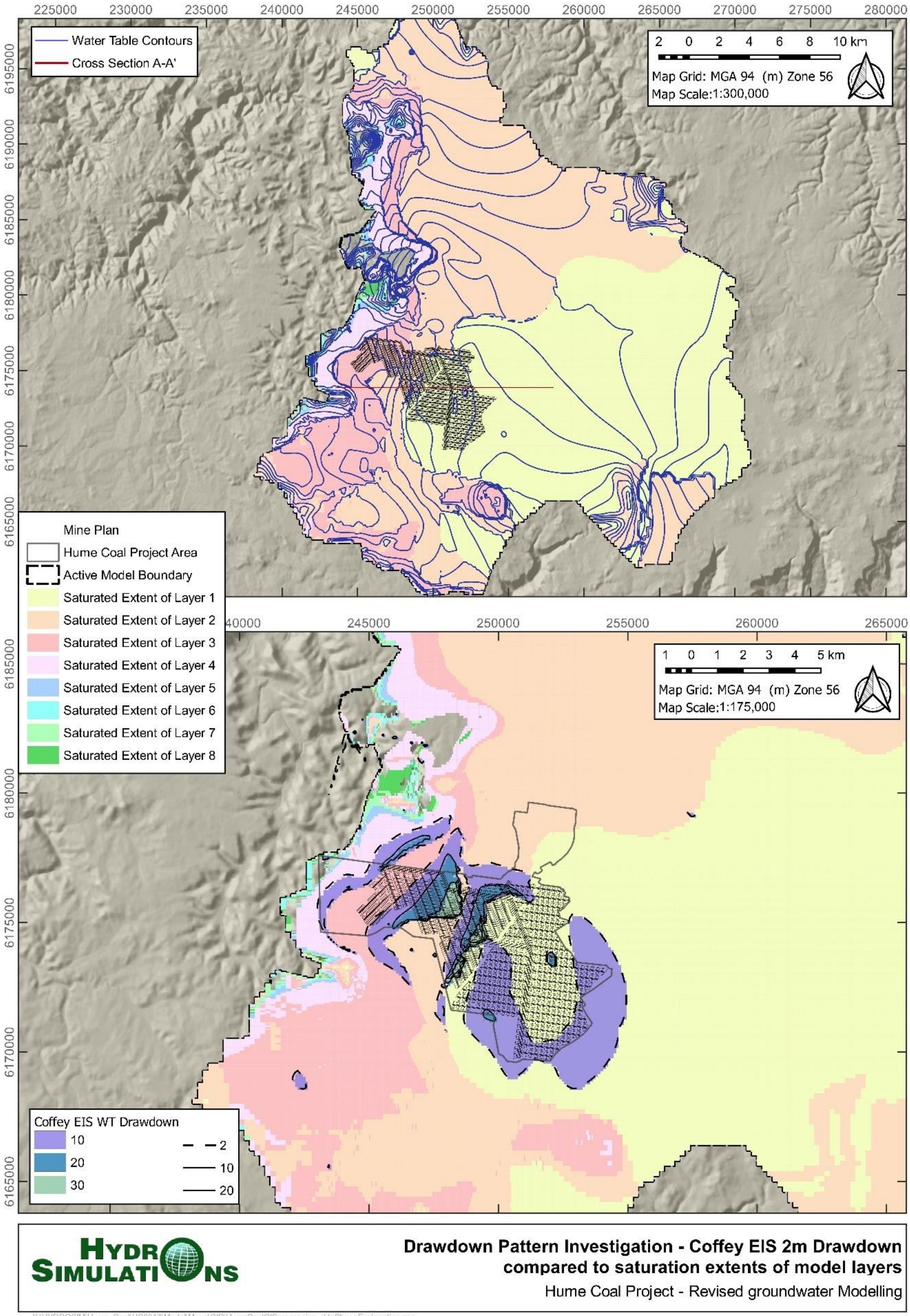


Figure B 1 Saturated extents of each model layer

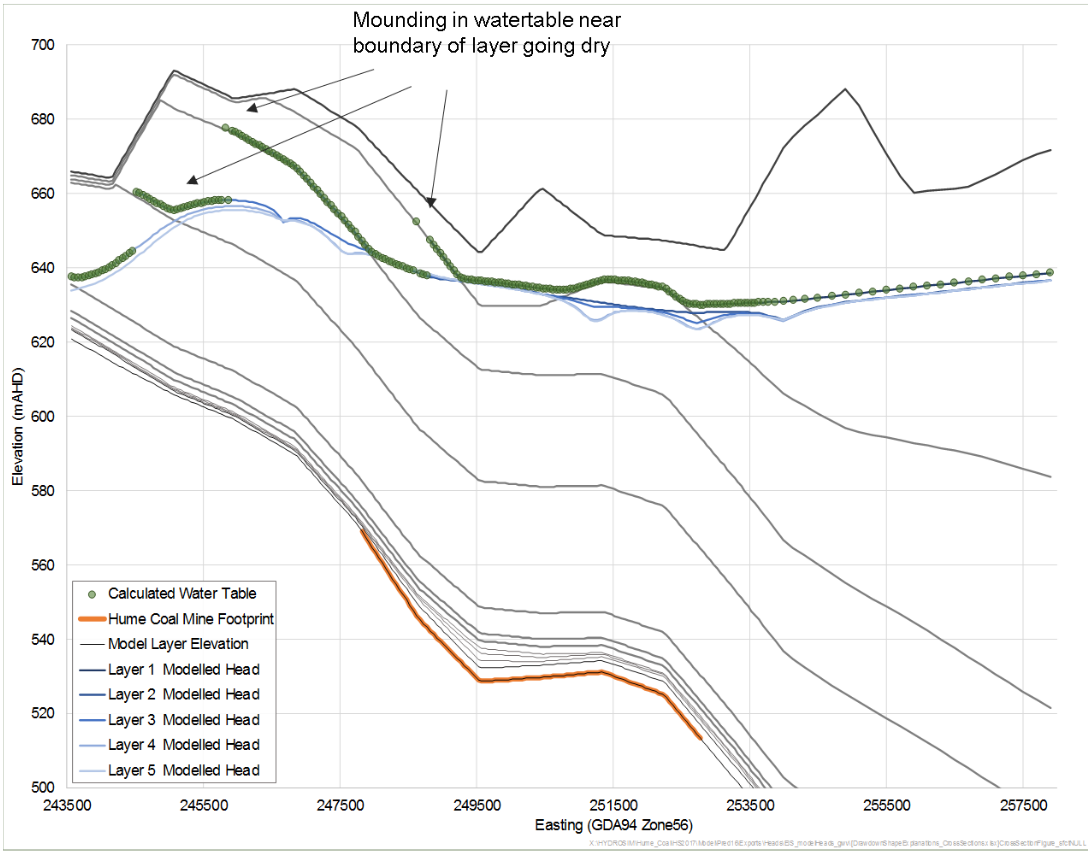


Figure B 2 Modelled head and water table elevation in mine year 17 for a 'Null' run using MODFLOW-SURFACT V4 Software

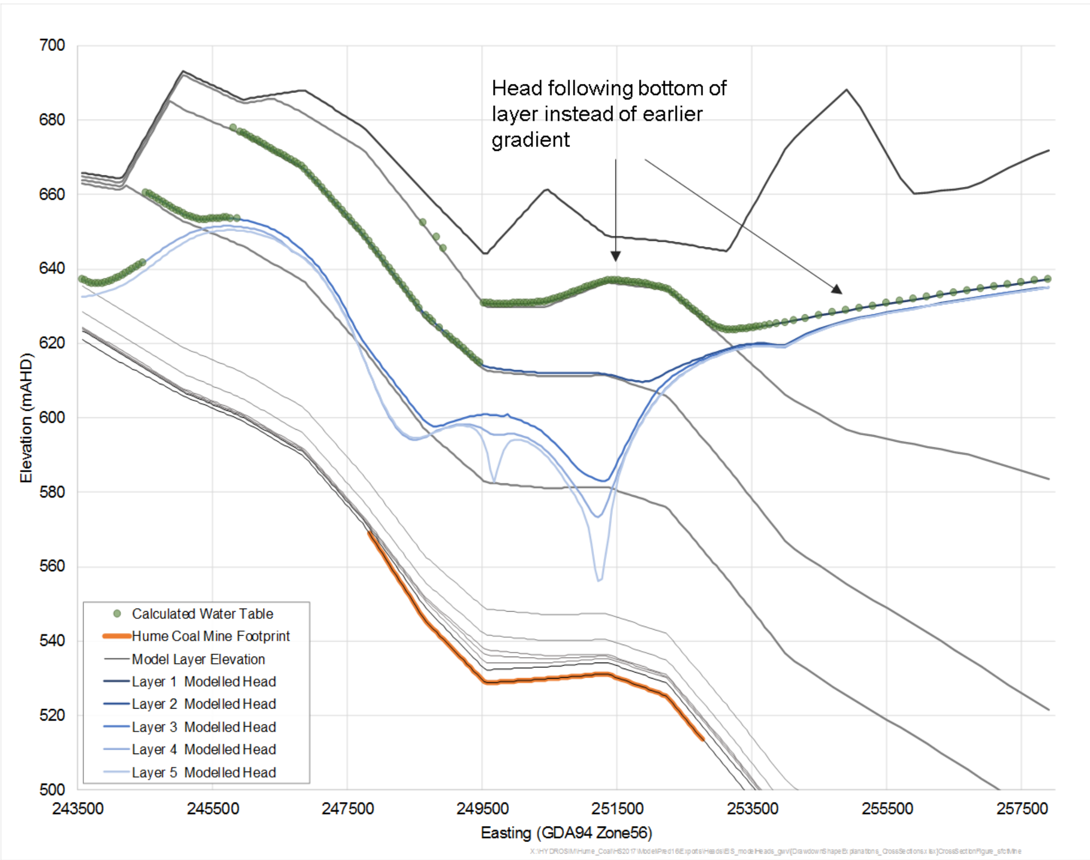


Figure B 3 Modelled head and water table elevation in mine year 17 for a Hume Coal 'mining' run using MODFLOW-SURFACT V4 Software

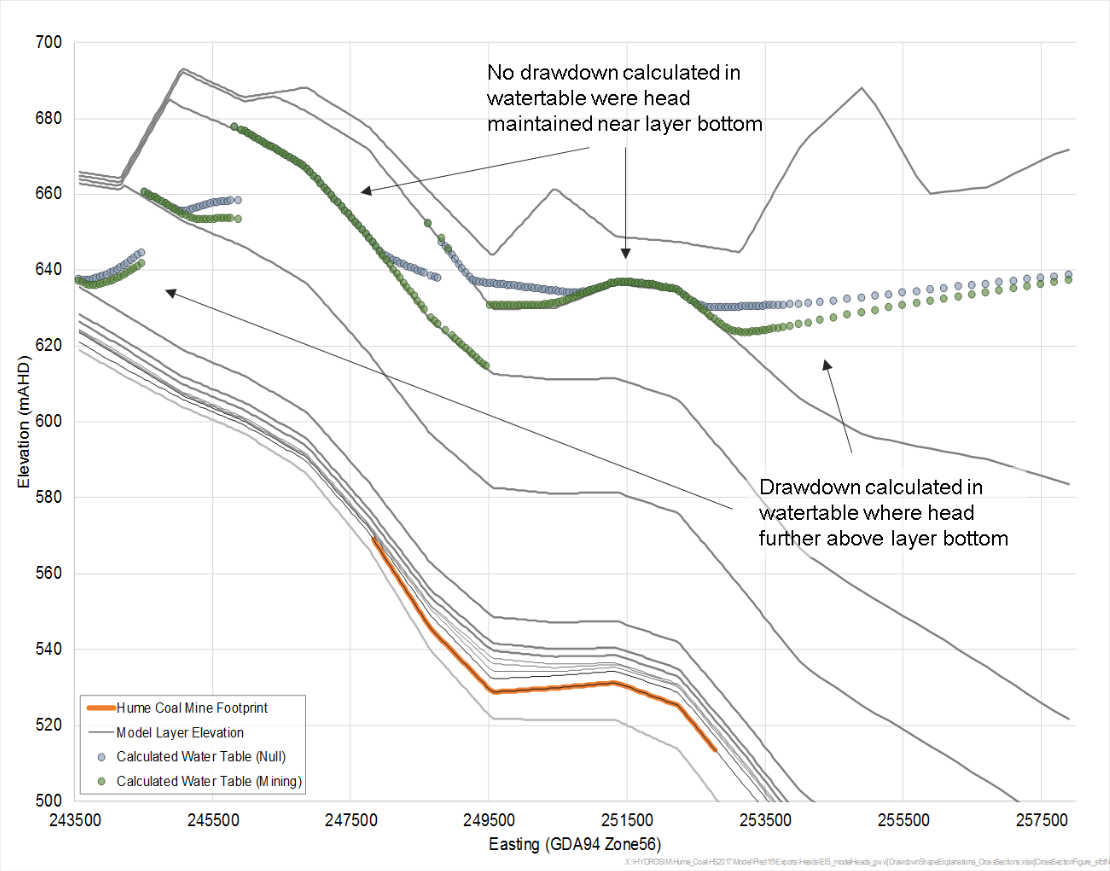


Figure B 4 Water table comparison in mine year 17 for the 'Null' and 'Mining' runs using MODFLOW-SURFACT V4 Software

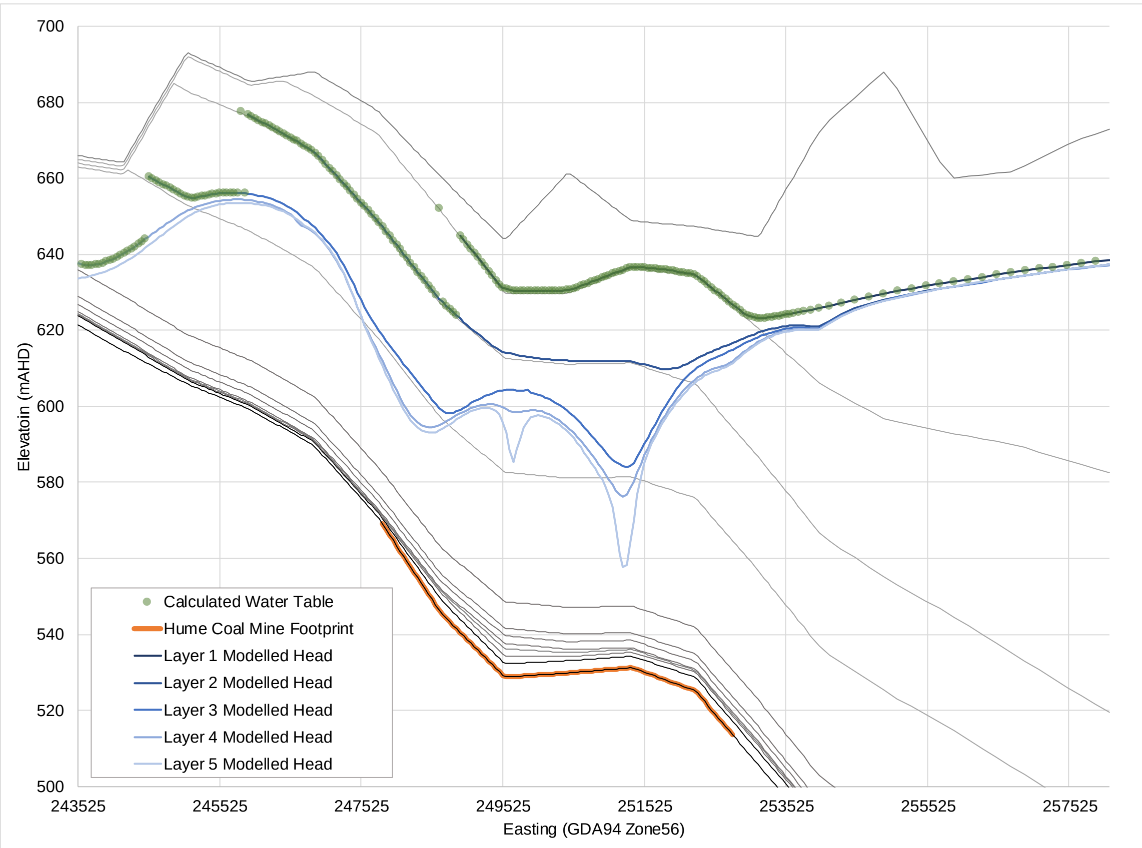


Figure B 5 Modelled head and water table elevation in mine year 17 from the EIS model 'mining' run using MODFLOW-SURFACT V3 Software

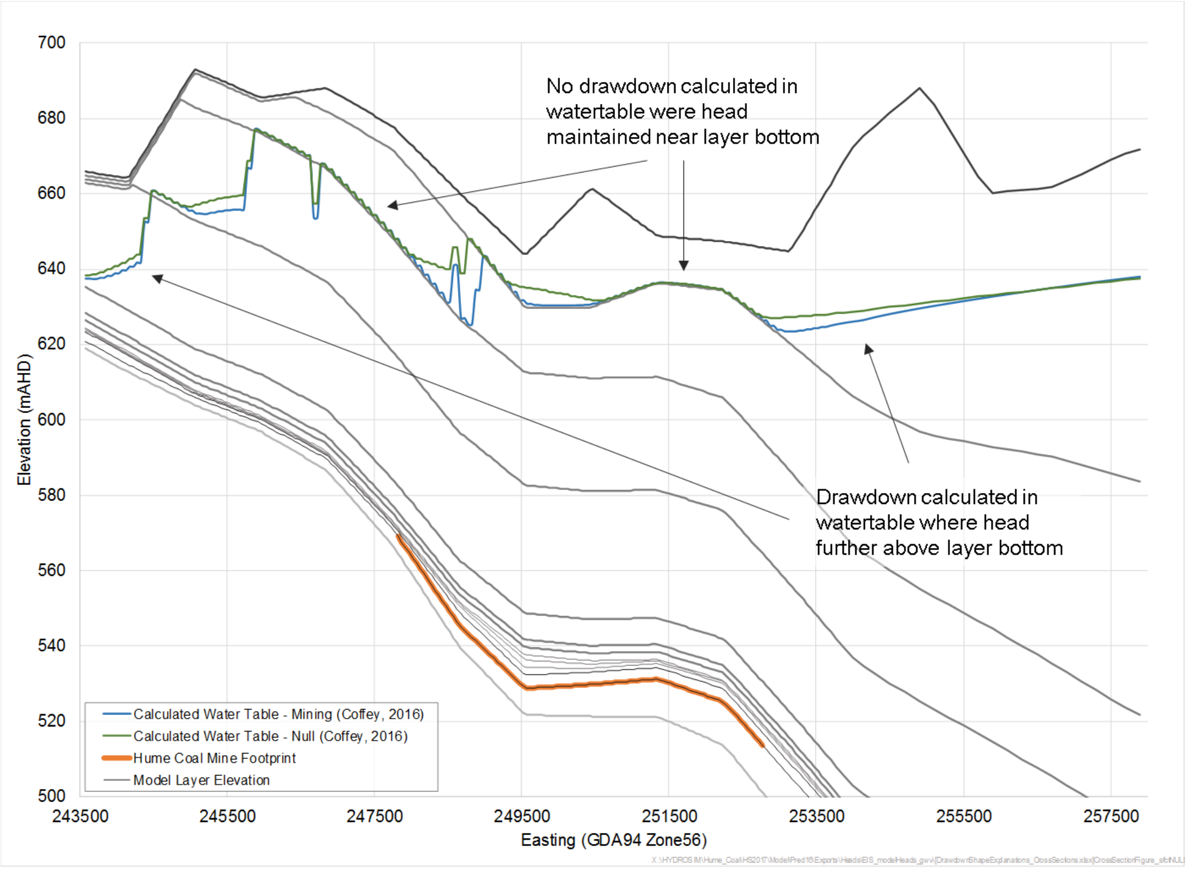


Figure B 6 Water table comparison in mine year 17 from the EIS Model for the 'Null' and 'Mining' runs using MODFLOW-SURFACT V3 Software

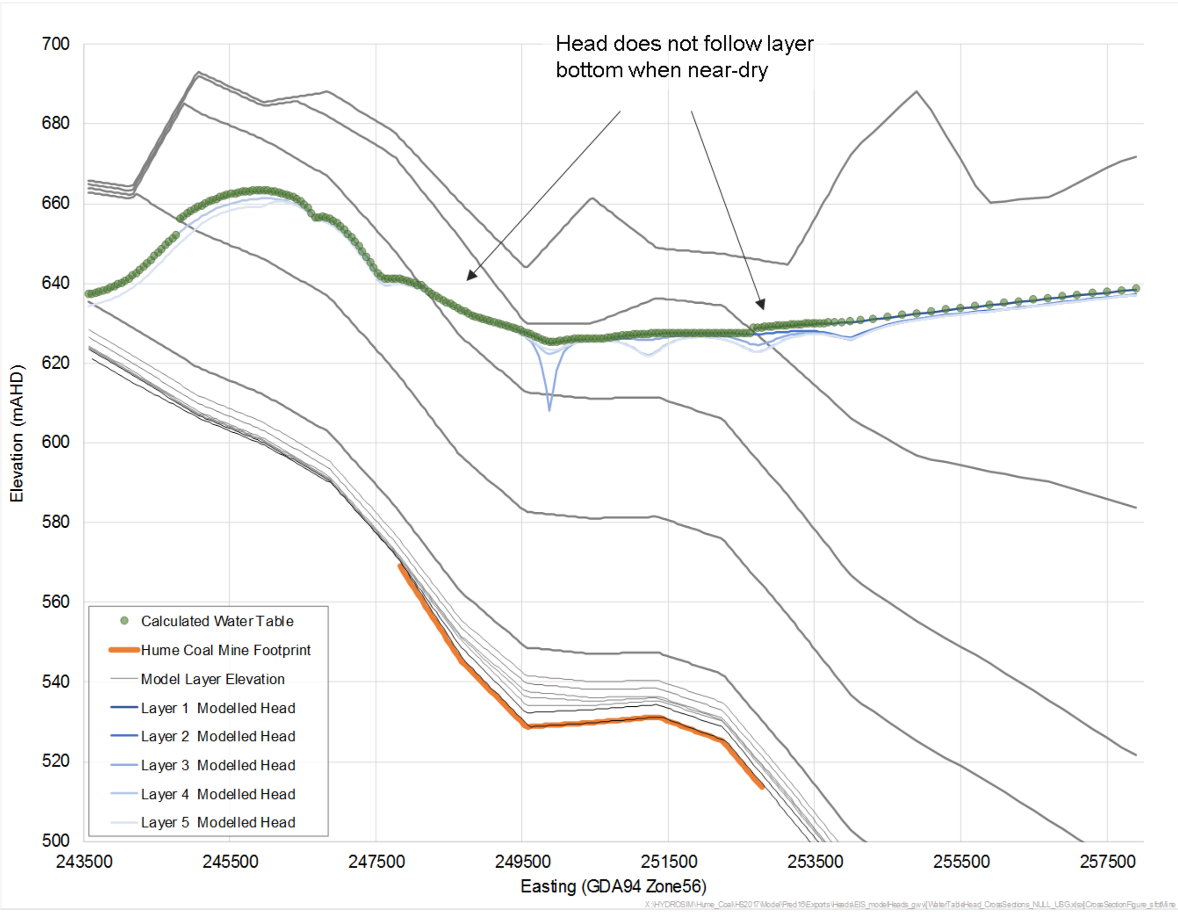


Figure B 7 Modelled head and water table elevation in mine year 17 for a 'Null' run using MODFLOW-USG Software with pseudo-soil function enabled

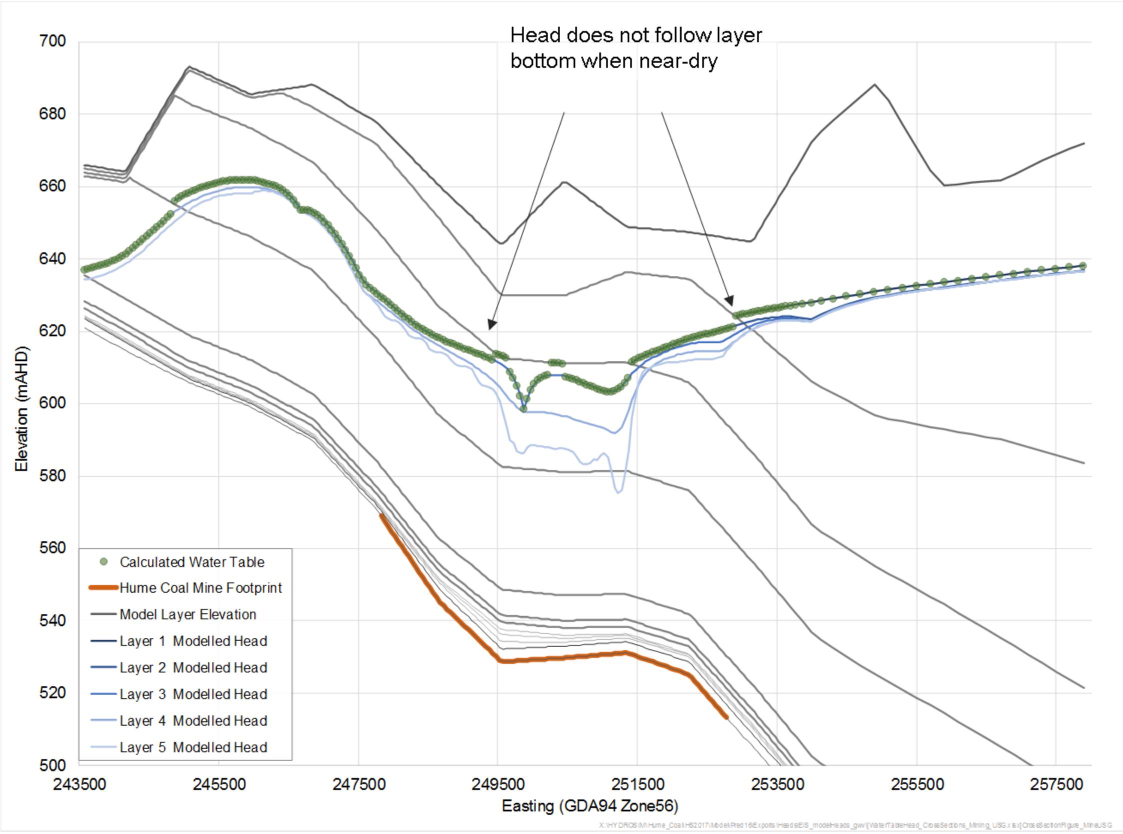


Figure B 8 Modelled head and water table elevation in mine year 17 for a Hume Coal 'mining' run using MODFLOW-USG Software with pseudo-soil function enabled

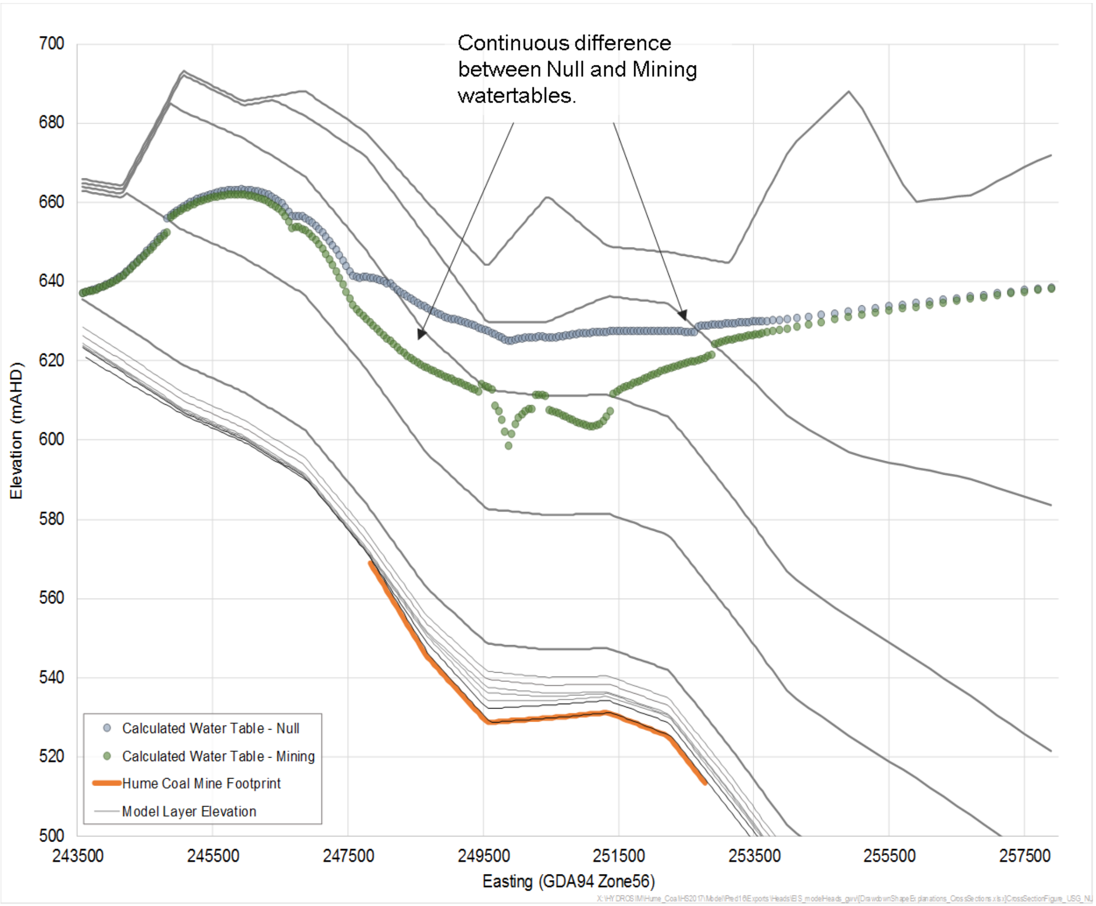


Figure B 9 Water table comparison in mine year 17 for 'Null' and 'Mining' runs using MODFLOW-USG Software with pseudo-soil function enabled

APPENDIX C - ASSESSMENT OF STAGE HEIGHT IN WINGECARRIBEE RIVER

Stage Height in Wingecarribee River

A question was raised within submissions and subsequent consultation (DPI, 2007) to determine whether the stage height in watercourses represented using the MODFLOW River package would require variation according to climatic conditions in the climate scenario analysis. It was hypothesised that wet conditions may raise the stage height of the rivers, causing a greater hydraulic gradient between the river and the mining affected groundwater system, resulting in a greater loss from the river due to mining.

An investigation was conducted to determine the necessity or otherwise of varying the river stage between modelled climate scenarios. It was found that the Wingecarribee River maintains a relatively consistent stage height independent of climatic conditions and it is justifiable to maintain the stage originally set in the EIS Model (Coffey, 2016b) in all climate scenario runs. As no data were readily available for the water level elevation or storage volumes of Medway Dam, the stage height set originally in the EIS model (Coffey, 2016b) was maintained for all climate scenario runs.

Simulation of Surface Water Features in the Groundwater Model

The groundwater model currently simulates two surface water features using the 'River' boundary condition type: Wingecarribee River and Medway Dam. The "River' boundary condition can cause water to enter or leave the groundwater system dependent on the relative elevation of the groundwater and the water level within the River cell (Figure C 1). In Figure C 1 H_{bot} refers to the defined base elevation of the watercourse within a river cell and H_{ref} refers to the defined stage height of water within that cell. A river cell that is in a groundwater system with an elevation above the stage height of the river cell will 'gain' water from the groundwater system. If the groundwater level is below the stage height but above the defined base, the river cell will 'lose' water from the river cell at a rate that increases with an increasing difference between the stage height and groundwater level. The maximum loss rate occurs when the simulated groundwater level is below the base elevation of the river cell. The 'River' boundary condition is useful for simulating a perennial stream or small water storage in which a non-zero stage height is maintained. The other watercourse features in the model have been classified as ephemeral and are simulated using the 'Drain' boundary condition. Any groundwater intercepting the stream as baseflow is removed from the model.

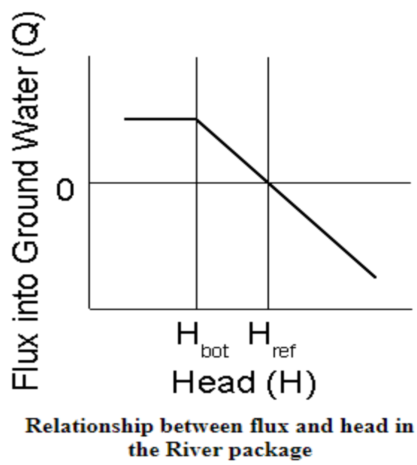


Figure C 1 Relationship between flux and head in the MODFLOW River package (USGS, 2018)

Wingecarribee River Assessment

For the investigation of Wingecarribee River, stage height data from WaterNSW were analysed for three sites: Berrima Weir (212272), Bong Bong Weir (212031) and Yarrunga Creek (215233). There was no datum reference data available. Daily rainfall data dating back to 1970 (provided by the Bureau of Meteorology) from the weather station at Berrima West (068186) was used to create a rainfall residual mass curve for assessing trends and comparisons to the stage height at the different sites.

Within the model domain, the Wingecarribee River lies downstream of the Wingecarribee Reservoir. The *Water Sharing Plan for the Greater Metropolitan Region Unregulated River Water Sources 2011* states that the Wingecarribee Reservoir is required to release at least 4ML per day into the Wingecarribee River unless natural flows are greater or equal to this amount (NSW Government, 2011). Consistent flow from the reservoir to the river downstream would serve to control the river stage independently of climate. There are also two weirs within the model domain that would similarly control the stage height of the river, particularly in drier periods. Yarrunga Creek, upstream of the Wingecarribee Reservoir, was also examined in this assessment. There are no environmental flows or water storages on Yarrunga Creek and it shows the nature of an unregulated watercourse within the same region.

Figure C 2shows the location of stage height and rainfall monitoring sites as well as the 'River' boundary condition cells within the model domain.

Figure C 3 illustrates the relationship between climate and river stage at two sites on the Wingecarribee River. While stage height is observed to respond to peaks in daily rainfall, consistent non-zero water levels are observed at both monitoring sites independent of the long-term climate trend.

The monitoring site Yarrunga Creek shows a more variable stage height that often declines to zero Figure C 4. While the water level responds to the same rainfall events seen at the weir sites, the water level is not maintained during periods of low rainfall. This highlights the regulatory factor the weirs and environmental flows from Wingecarribee Reservoir impose on the overall water level through time. This also validates the reasoning for maintaining a constant water level through time for all climate scenarios.

Figure C 5shows cumulative probability figures for stage height at both weir sites on the Wingecarribee River and Yarrunga Creek. The Berrima weir site shows a steep increase at a stage height of 1m, indicating that most observations occur at this stage height. The Bong Bong weir is nearly identical in its shape, but the majority of observations occur at a stage height of around 0.3m. The Yarrunga Creek site is less steep than the others but still shows most of the observations occurring between 0m and 0.3m stage height. This is expected as weirs control the stage height more regularly than an uncontrolled upstream site such as Yarrunga. The percentiles in Table C 1 provide the numerical ranges of the stage height at each site. There is 20% and 40% variation between the 5^{th} and 95^{th} percentile stage heights in the Berrima Weir and Bong Bong Weir sites, respectively. At the uncontrolled Yarrunga Creek site the variation is 90%.

Table C 1 Cumulative probability for stage heights at monitoring locations

	Wingecarribee River at Berrima Weir (m)	Wingecarribee River at Bong Bong Weir (m)	Yarrunga Creek at Wildes Meadow (m)
Average	1.1	0.28	0.16
Std. Deviation	0.12	0.061	0.13
Median	1.1	0.27	0.13
5th Percentile	0.97	0.23	0.034
10th Percentile	1.0	0.25	0.049
25th Percentile	1.0	0.26	0.082
50th Percentile	1.1	0.27	0.13
75th Percentile	1.14	0.29	0.21
90th Percentile	1.2	0.35	0.31
95th Percentile	1.2	0.37	0.39

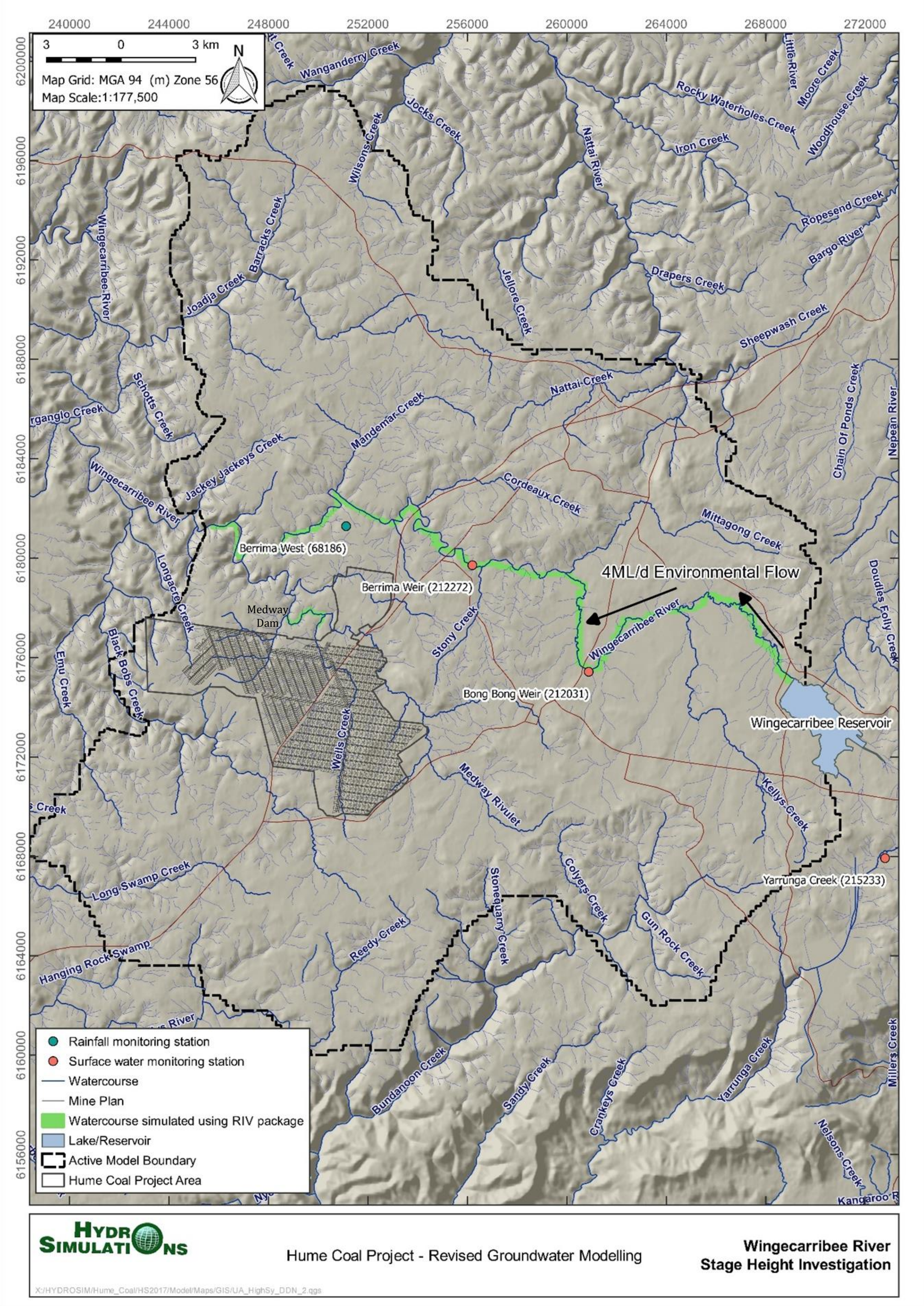


Figure C 2 Location of key features for the watercourse stage height investigation

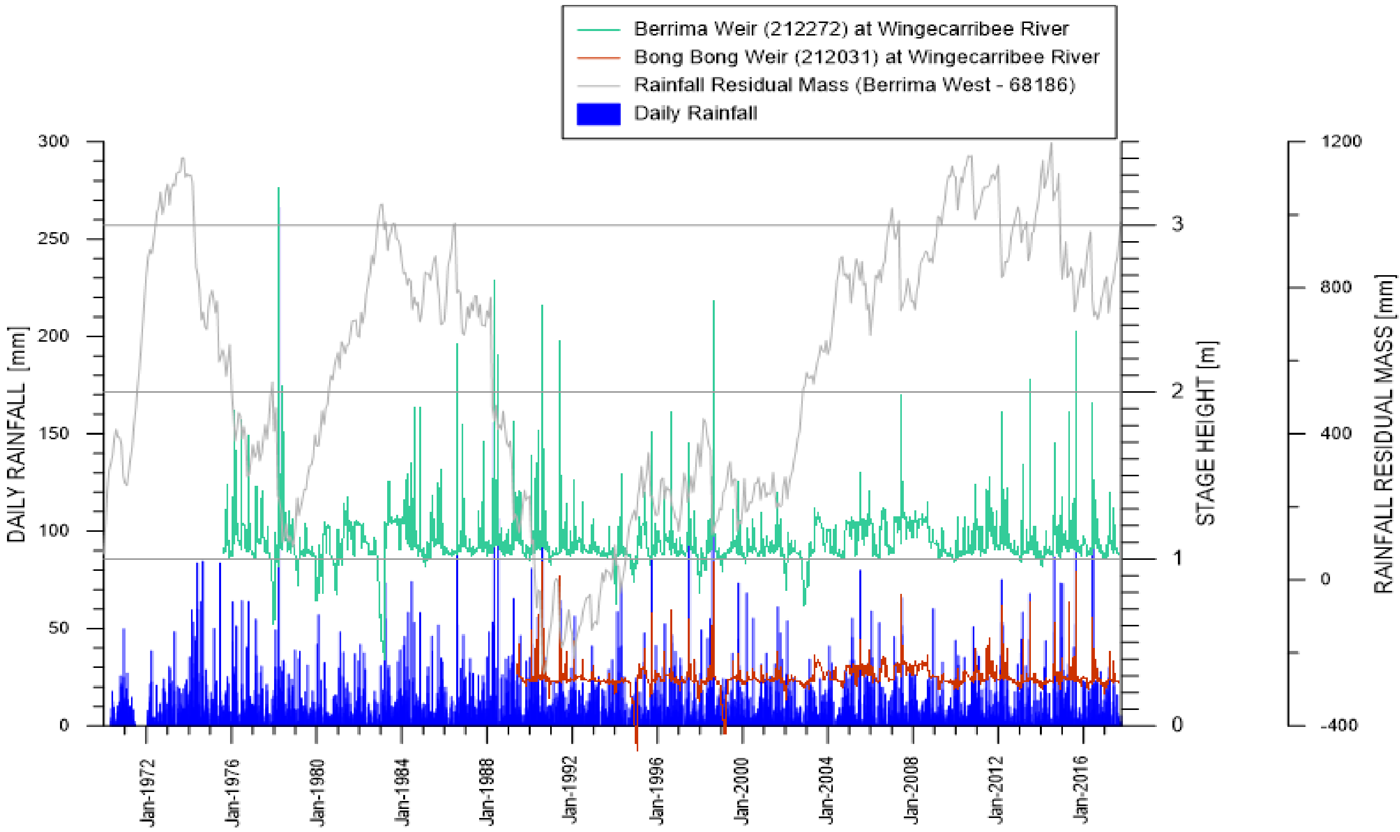


Figure C 3 Time-series stage height for Berrima Weir and Bong Bong Weir monitoring sites compared with rainfall

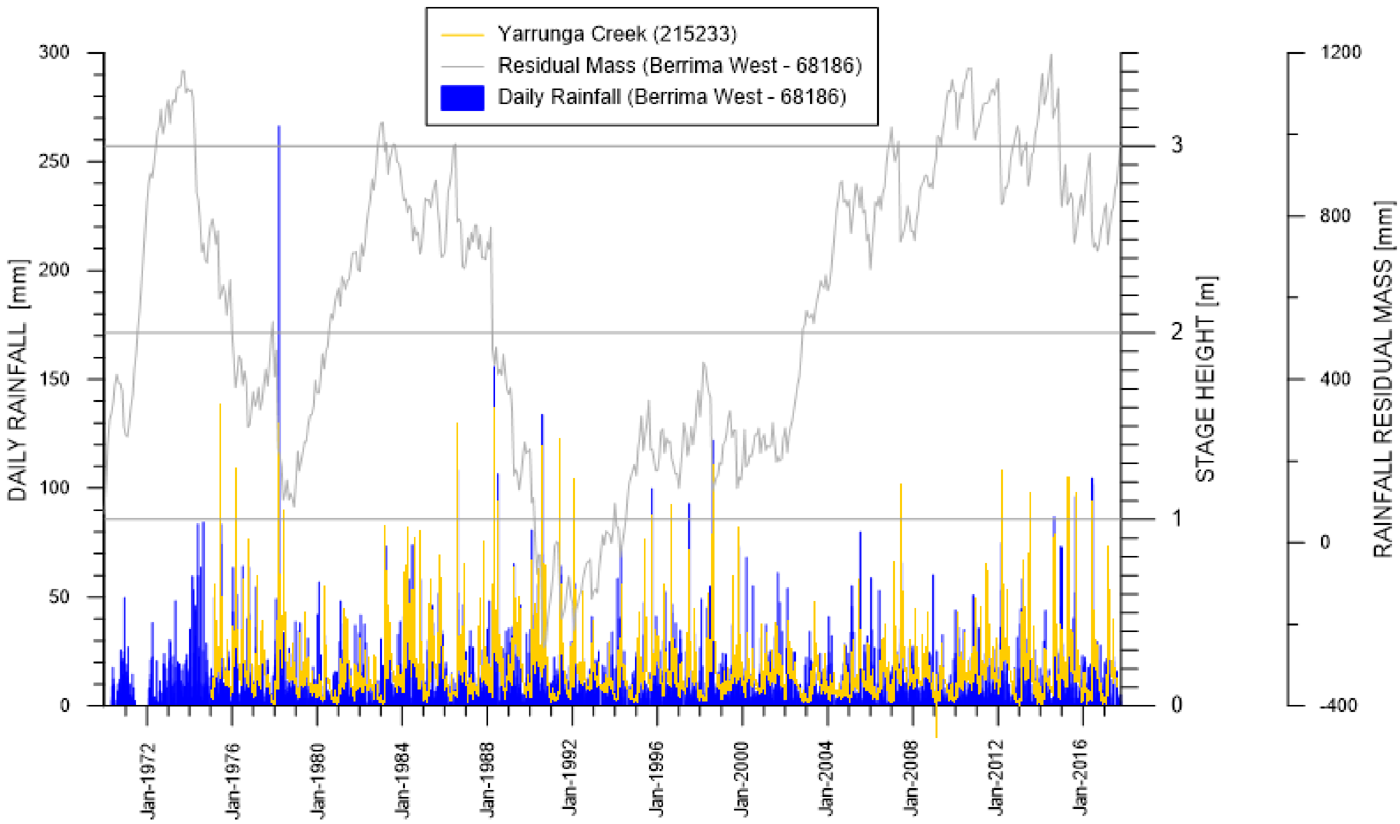


Figure C 4 -series stage height for Yarrunga Creek monitoring site compared with rainfall

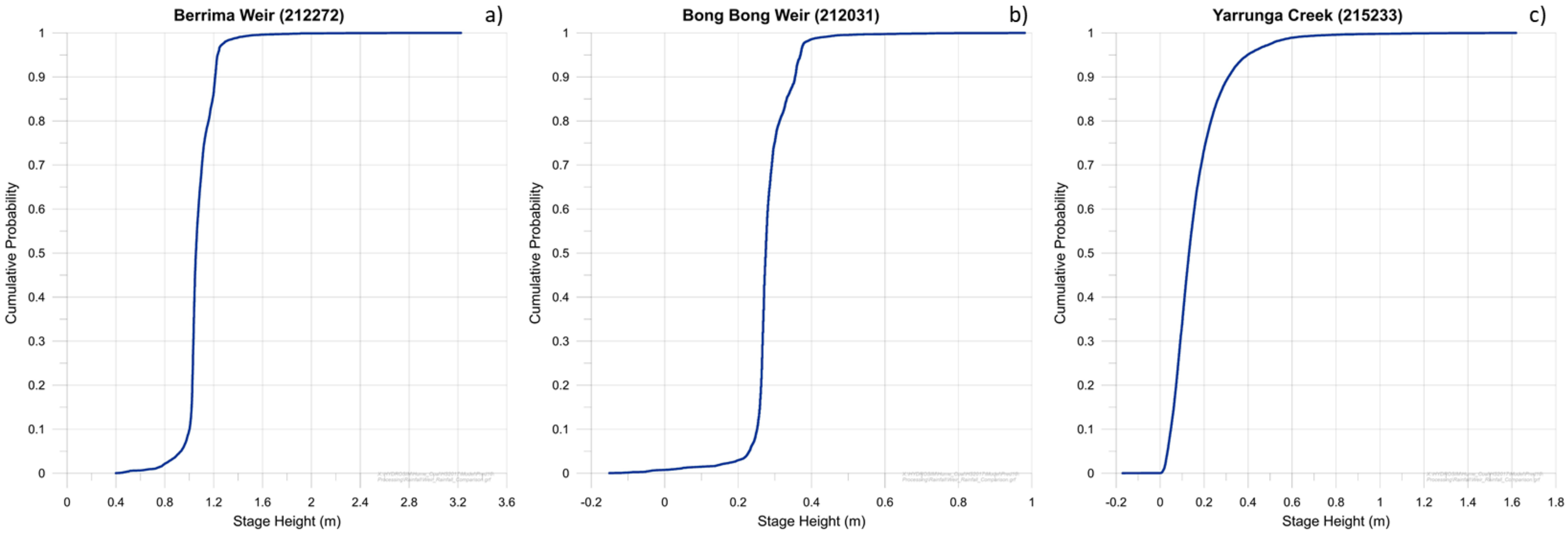


Figure C 5 Cumulative probability of stage height at: a) Berrima Weir, b) Bong Bong Weir, c) Yarrunga Creek

APPENDIX D – IMPACT PREDICTION FOR MEDWAY DAM

Impact Prediction for Medway Dam

Medway Dam is a backup water supply for Wingecarribee Council. In their *Comment on the EIS* dated 16 July 2017, the Department of Primary Industries required the proponent to undertake a secure yield analysis to assess potential impact to town water supply security due to a predicted reduction in yield and predicted increased leakage from Medway Dam. To this end, further detail on Medway Dam leakage is provided in this Appendix.

In the groundwater model, Medway Dam is simulated using the MODFLOW River package, with the generic relationship between flux and the groundwater system as shown in **Figure C 1** in Appendix C.

For the Modified EIS model, no change was made to the initial groundwater conditions adopted in the EIS Model, which showed groundwater as intersecting the stored waters of the dam. This indicates connectivity between the water stored in the dam and the regional groundwater system. Under these conditions, groundwater drawdown below the dam would result initially in capture of baseflow and ultimately in leakage of water from the dam into the groundwater system if the groundwater level falls below the base of the dam. This take is considered as a loss from the surface water storage when the primary loss mechanism is leakage.

Whether a particular model shows connectivity or not, depends on the permeability field near the dam, and the coarseness of model cells compared to natural deeply incised topography in sandstone gullies. At Medway Dam, model cells are mostly 100 m x 50 m with a single elevation over that area (a half hectare). As a result, regional groundwater models cannot represent a long narrow water body with precision.

In the uncertainty analysis, for each realisation, a separate steady state run was made prior to the calibration and prediction runs to ensure initial groundwater level conditions were appropriate for the hydraulic conductivity distribution of each individual realisation. This has the effect of variable initial status at Medway Dam – sometimes gaining, sometimes losing.

The Mean K Model (with spatially variable hydraulic conductivities) was run using the same process as an uncertainty analysis realisation. The initial conditions for the prediction run were taken from heads at the end of the calibration run, which in turn used initial groundwater levels derived from the steady state model run. Connectivity between the dam and the groundwater system was not observed for the Mean K Model, as a result of the non-uniform permeability field generated in the vicinity of the dam. In these conditions, the stored waters have a losing status and leakage from the dam would occur at a fixed rate. This rate would not increase with a decline in the groundwater level and no difference in flux would be recorded by the model.

While there is limited observation data available near Medway Dam, It is likely that there is natural connectivity between Medway Dam and the regional groundwater system. In other words, the stored waters should have a gaining status, accepting groundwater baseflow. The nearest observation bore used in model calibration is the triple sensor VWP H143, which is approximately 200 m from the upstream limit of stored waters at full capacity. Sensor H143C is within the Hawkesbury Sandstone and has 21 observations between May 2014 and June 2015, all within 30 cm of the 626.1 mAHD average water level. The maximum water level in the dam is believed to be about 625 mAHD. Hence, connectivity is to be expected under natural conditions.

Groundwater level was found to be overestimated in the calibration run for the EIS Model and the Preliminary Modified EIS Model by an average of 6 m and 5m respectively, while the Modified EIS Model underestimates by about 1.5 m **(Figure 6**). The Mean K Model (with spatially varying hydraulic conductivities) also underestimates the observed groundwater level by a few metres. This indicates that a regional groundwater model cannot be expected to be precise at the local scale, and that different models that are equally applicable regionally can have different degrees of connectivity at a local feature such as Medway Dam.

The Modified EIS Model (with uniform lateral hydraulic conductivities) predicts a maximum baseflow capture of about 5 ML/year. To ensure enduring connectivity, a localised model of Medway Dam was developed, using the Modified EIS Model as a base, by increasing the depth of water in the dam. In this case, a maximum baseflow capture of about 35 ML/year was found to be possible, with an average take of 19 ML/year during mining. This is consistent with the prediction of the EIS Model of an average increase in leakage by 36.5 ML/year.

Figure D 1 shows the predicted baseflow interception at Medway Dam. Based on flux analysis, there is a reversal of status from a gaining to a losing system (i.e. leakage) at about 10 years following start of mining. This means that the effect of mining is initially to capture natural baseflow (groundwater discharge to the dam), but after about 10 years there would be more leakage from the dam than baseflow to the dam. The amount of leakage would gradually reduce after mining ceases, but leakage would remain the primary loss mechanism (rather than baseflow capture) for another 25 years approximately, after which time baseflow would reappear.

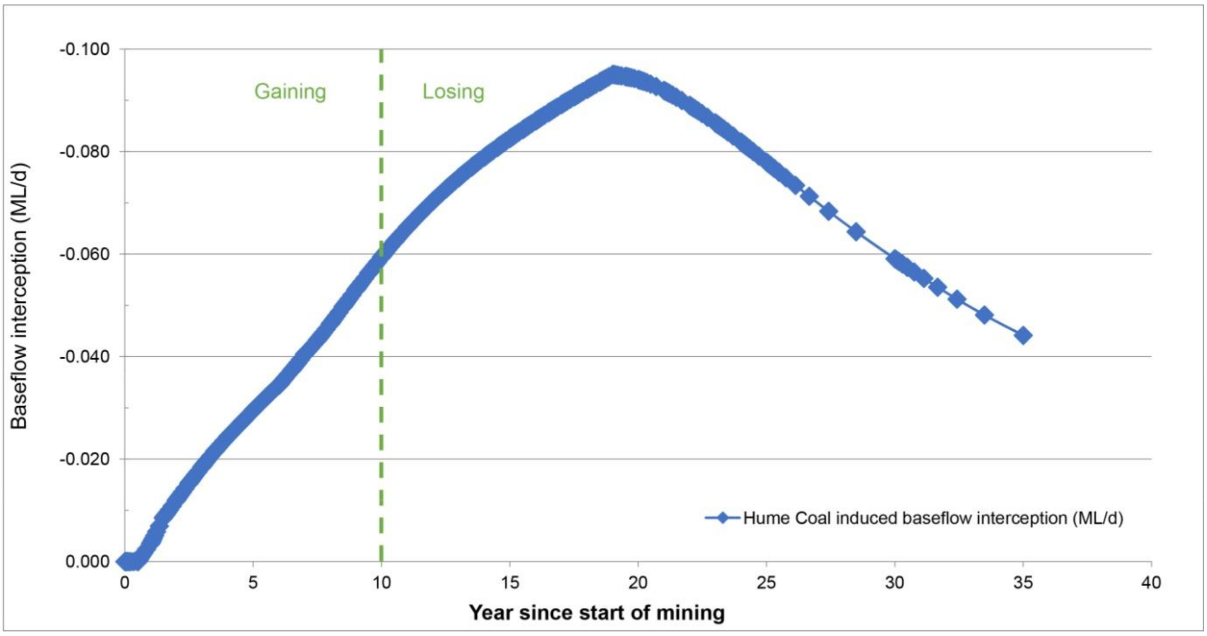


Figure D 1 Hume Coal induced baseflow interception at Medway Dam

APPENDIX E – HUME COAL PROJECT EIS GROUNDWATER ASSESSMENT VOLUME 1: DATA ANALYSIS (COFFEY 2016A)

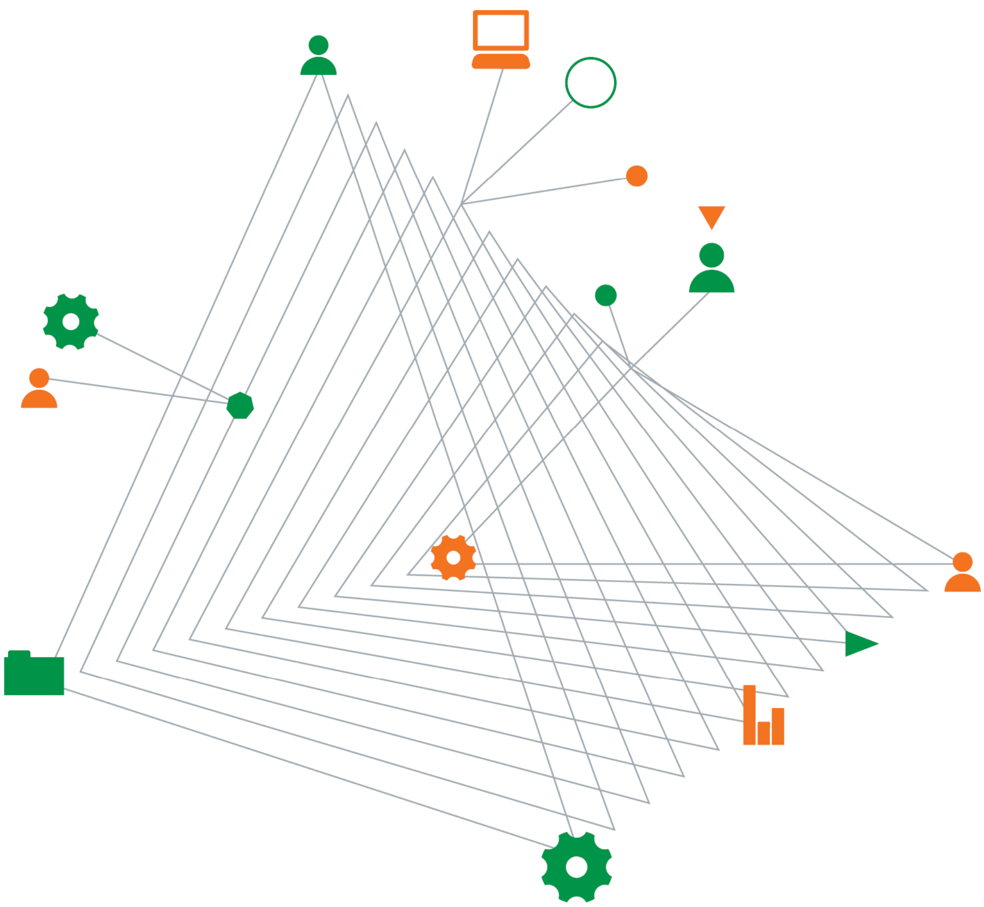
coffey
A TETRA TECH COMPANY

Hume Coal Pty Limited

Hume Coal Project

Groundwater Assessment Volume 1: Data Analysis

17 November 2016



Experience comes to life when it is powered by expertise

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Hume Coal Project

Prepared for
Hume Coal Pty Limited

Prepared by
Coffey Geotechnics Pty Ltd
Level 19, Tower B, 799 Pacific Highway
Chatswood NSW 2067 Australia
t: +61 2 9406 1026 f: +61 2 9406 1002
ABN: 93 056 929 483

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For and on behalf of Coffey

Paul Tammetta
Associate Subsurface Hydrologist

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Executive Summary

A large groundwater database has been collated for the Hume Coal Project. The purpose of the database was to support the development of a regional numerical groundwater flow model for the project. Results of the data analysis were used to develop a hydrogeological conceptual model, and to reduce uncertainty in model parameters using the large number of observations available for these parameters. Numerical model development, calibration, and predictive simulations and results, are reported separately. The database, and results interpreted therefrom, are as follows:

- Long-term rainfall observations from 20 regional stations, providing coverage of the regional area, and several years of observations from Hume's on-site rain gauge. The average long-term annual rainfall for the mine lease was estimated as 957 mm.
- Streamflow observations from four gauges on the Hume mine lease monitored by Hume (SW01, SW03, SW04, and SW08) and seven government gauges in the regional area. These were subjected to baseflow analysis. For the lease area the estimated baseflow to drainage channels is about 1.5% to 2% of annual rainfall.
- A database of hydraulic conductivity (K) measurements comprising 28 packer tests on the Hume lease, two long-term pumping tests undertaken by Hume on the lease in 2014 (pumping bores HU0098 and GW108194 (Wongonbra) with multiple observation piezometers monitored), six long-term pumping tests from private bores in the wider area, 129 estimates of hydraulic conductivity from specific capacity data in government records for private water bores, and laboratory tests on 39 cores of Hawkesbury Sandstone and Farmborough Claystone retrieved from five boreholes. Hydraulic conductivity and storativity decrease with depth. The K field for the Hume area has greater magnitudes than seen elsewhere in the Southern Coalfield, and is believed to result from significant tectonic disturbance and associated intrusive activity.
- An extensive groundwater level and quality monitoring network operated by Hume in the lease area, comprising vibrating wire piezometer (VWP) and standpipe piezometer (SP) installations. The network comprises 46 SPs at 19 locations, 11 VWPs at 3 locations, and 2 private water bores. This provides 59 subsurface measurement points at 24 locations. Monitoring commenced in late 2011 when the first piezometers were installed, and has continued to the present. Useful monitoring information is also available from the Berrima Mine monitoring network (VWPs and bores), and a government monitoring network in the regional area. The combination of highland topography and contrasting outcrop lithologies produces a hydraulic head field which is elevated along the western Hawkesbury Sandstone outcrop and at Wingecaribbee Reservoir to the southeast, and decreases towards the south and northeast. Wingecarribee Reservoir and rainfall recharge at sandstone outcrop areas form the main upper hydraulic controls in the subsurface, for the hydraulic head field. Increased vertical hydraulic head gradients can be identified in proximity to the Berrima mine workings.
- Observations of discharge from the Berrima mine workings, providing vital calibration targets for deep groundwater discharges.

The database also contains large amounts of water quality measurements, bore lithology logs, and other observations (such as stress measurements and mining-related documentation for the Hume area available on the NSW Department of Primary Industries internet data portal).

A hydrogeological conceptual model was developed based on the observations in the database. The presence of a large number of hydraulic conductivity and hydraulic head measurements (including for evolution of drawdown from mining, at the Berrima mine), in conjunction with a large number of baseflow estimates (shallow discharge of groundwater from the system), and observed discharge from the Berrima mine (deep discharge of groundwater from the system) provided a stringent observation dataset for large-scale reliable estimation of Kv down the profile, an important parameter for simulation of deep discharges such as mine inflows. Pumping tests undertaken by Hume at HU0098 and GW108194 provided highly useful independent estimates of large-scale Kv for sandstone, providing strong calibration targets.

The objective of model calibration was to simultaneously replicate the following crucial observation datasets:

- Hydraulic conductivity.
- Hydraulic heads.
- Shallow groundwater discharge (baseflow to streams).
- Deep groundwater discharge (discharge to mine voids).

This is the optimal set of data for calibration of a numerical groundwater flow model, and provided a suitable basis for predictive simulation of the proposed Hume mining operations.

1. Introduction

This is the first of two reports that present the results of a groundwater assessment for the Hume Coal Project. The assessment was undertaken by Coffey Geotechnics Pty Ltd (Coffey) for Hume Coal Pty Limited (Hume). The purpose of the assessment was to assess impacts on the groundwater system and dependent users from proposed mining. Results of the assessment will be used to support an application for development consent.

Approval for the Hume Coal Project is being sought under Part 4, Division 4.1 of the NSW Environmental Planning and Assessment Act 1979 (EP&A Act) and the Commonwealth Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act). An environmental impact statement (EIS) is a requirement of the approval processes. This groundwater assessment forms part of the EIS. It documents the groundwater assessment methods and results, and outlines initiatives built into the project design to avoid and minimise impacts on the groundwater system.

The assessment comprised compilation and analysis of a groundwater database, development of a hydrogeological conceptual model, and development of a groundwater flow numerical model to simulate drawdown of the groundwater system due to mining and any consequent drawdown interference in private bores in the region, and any effects on surface water hydrology. A substantial database of observations was compiled from data provided by Hume, and data obtained from published sources. Database analysis was undertaken to support development of the hydrogeological conceptual model (and subsequent numerical model development and calibration).

This volume presents the results of compilation and analysis of the groundwater database, and development of the hydrogeological conceptual model. Numerical model development, calibration, predictive simulations, and predictive drawdown and inflow assessment, are reported in Volume 2 (Numerical Simulation). This volume should be read in conjunction with Volume 2.

1.1. Background

Hume proposes to develop and operate an underground coal mine and associated mine infrastructure (the Hume Coal Project) in the Southern Coalfield of NSW. Hume is a wholly owned subsidiary of POSCO Australia. Hume holds exploration Authorisation 349 (A349), which covers an area of 89 km^2 to the west of Moss Vale, in the Wingecarribee local government area (LGA). A349 adjoins the southern boundary of the Berrima Colliery lease (CCL748). The underground mine will be developed within A349 and associated surface infrastructure facilities will be developed within and north of A349. The project area and its regional setting are shown in Drawing 1. Drawing 1 shows the interrelationship between A349, the mining lease application area, the proposed workings, and the model domain boundary; the latter two features are further discussed in this report and the numerical simulation report.

The project has been developed following several years of technical investigations to identify and address potential environmental, social and economic constraints. This has allowed for the development of a well-considered, practical and economic project design that will enable effective resource recovery, while minimising adverse impacts to the environment and community.

Hume will undertake a non-caving first workings mining layout and method, which is a low impact method having negligible subsidence effects, and offering a significant amount of protection to overlying hydrostratigraphic media and surface features. The mining target is the Wongawilli Coal Seam of the Permian Illawarra Coal Measures.

Mining is to be carried out in separate compartments known as panels. A panel consists of a number of plunges (parallel tunnels driven into the seam with unmined coal between plunges) connected by gate roads driven along the long dimension of the panel. A panel of the Hume first workings method is dissimilar to a panel in longwall mining with respect to post-mining deformation. All tunnels in a panel occur within the seam. A group of panels forms a mining block, where each panel in the block is connected by a set of main headings that allow access for workers, equipment, and ventilation, and also provide mined coal during their development. The set of headings remains open until mining of the last panel in the block is finished.

Figure 1.1 is a detail of two panels for reference in the following discussion. A mining height of 3.5 m has been adopted. Where the coal seam is thinner than 3.5 m, a cutoff height of 1.8 m has been assumed. All panels are initially developed with gate roads (and associated cut-throughs) that are driven off the main headings in a direction parallel to the panel long dimension. Gate roads are positioned down the centre of the panel. Additional workings comprising plunges (tunnels) are driven off the gate roads. These openings are separated by pillars that are designed not to fail post-mining.

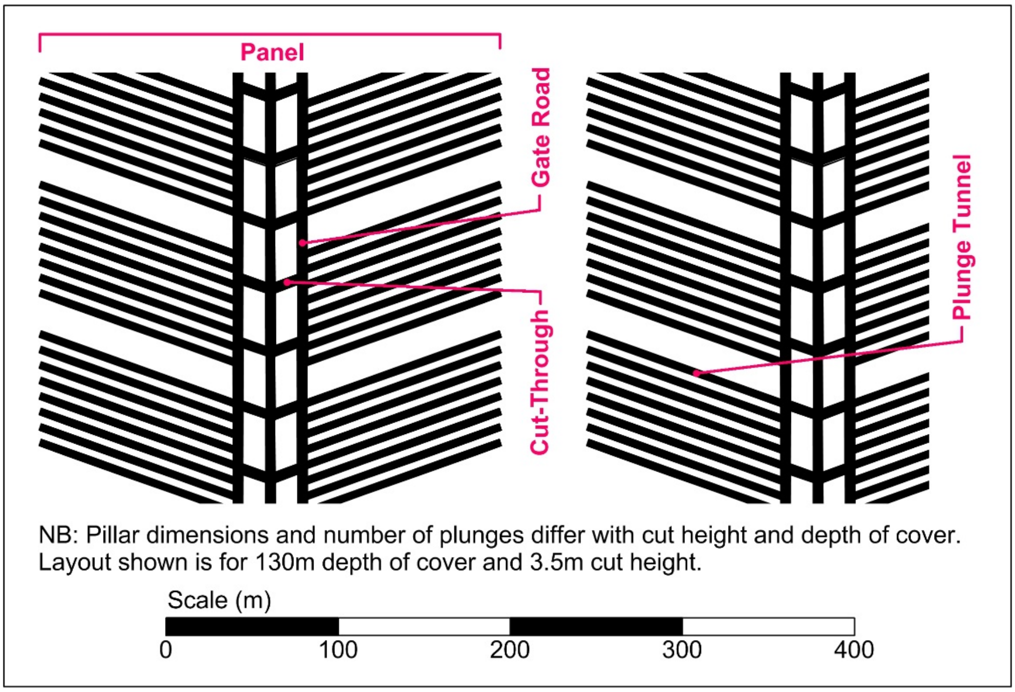


Figure 1.1. Detail of mine openings for the first workings mining method. Black areas indicate removed coal.

The mining method is non-caving, which results in openings remaining open post-mining, without caving (goaf is not created). Overburden deformation would occur as relaxation in the immediate roof over the openings, generally limited to less than 3 m into the overlying roof.

1.1.1. Project description

The project involves developing and operating an underground coal mine and associated infrastructure over a total estimated project life of 23 years. A full description of the project, as assessed in this report, is provided in Chapter 2 of the main EIS (EMM 2016). In summary, the project involves:

- Ongoing resource definition activities, along with geotechnical and engineering testing, and other low impact fieldwork to facilitate detailed design.
- Establishment of a temporary construction accommodation village.

- Development and operation of an underground coal mine, consisting of approximately two years of construction and 19 years of mining, followed by a closure and rehabilitation phase of up to two years, leading to a total project life of 23 years. Some coal extraction will commence during the second year of construction during installation of the drifts, and hence there will be some overlap between the construction and operational phases.
- Extraction of approximately 50 million tonnes (Mt) of run-of-mine (ROM) coal from the Wongawilli Seam, at a rate of up to 3.5 million tonnes per annum (Mtpa). Low impact mining methods will be used, which will have negligible subsidence impacts.
- Following processing of ROM coal in the coal preparation plant (CPP), production of up to 3 Mtpa of metallurgical and thermal coal for sale to international and domestic markets.
- Construction and operation of associated mine infrastructure, mostly on cleared land, including:
  - One personnel and materials drift access and one conveyor drift access from the surface to the coal seam.
  - Ventilation shafts, comprising one upcast ventilation shaft and fans, and up to two downcast shafts installed over the life of the mine, depending on ventilation requirements as the mine progresses.
  - A surface infrastructure area, including administration, bathhouse, washdown and workshop facilities, fuel and lubrication storage, warehouses, laydown areas, and other facilities. The surface infrastructure area will also comprise the CPP and ROM coal, product coal and emergency reject stockpiles.
  - Surface and groundwater management and treatment facilities, including storages, pipelines, pumps and associated infrastructure.
  - Overland conveyors.
  - Rail load-out facilities.
  - Explosives magazine.
  - Ancillary facilities, including fences, access roads, car parking areas, helipad and communications infrastructure.
  - Environmental management and monitoring equipment.
- Establishment of site access from Mereworth Road, and minor internal road modifications and relocation of some existing utilities.
- Coal reject emplacement underground, in the mined-out voids.
- Peak workforces of approximately 414 full-time equivalent employees during construction and approximately 300 full-time equivalent employees during operations.
- Decommissioning of mine infrastructure and rehabilitation of the area once mining is complete, so that it can support land uses similar to current land uses.

The project area, shown in Figure 1.2, is approximately 5,051 hectares (ha). Surface disturbance will mainly be restricted to the surface infrastructure areas shown in Figure 1.3, though will include some other areas above the underground mine, such as drill pads and access tracks. The project area generally comprises direct surface disturbance areas of up to approximately 117 ha, and an underground mining area of approximately 3,472 ha, where negligible subsidence impacts are anticipated.

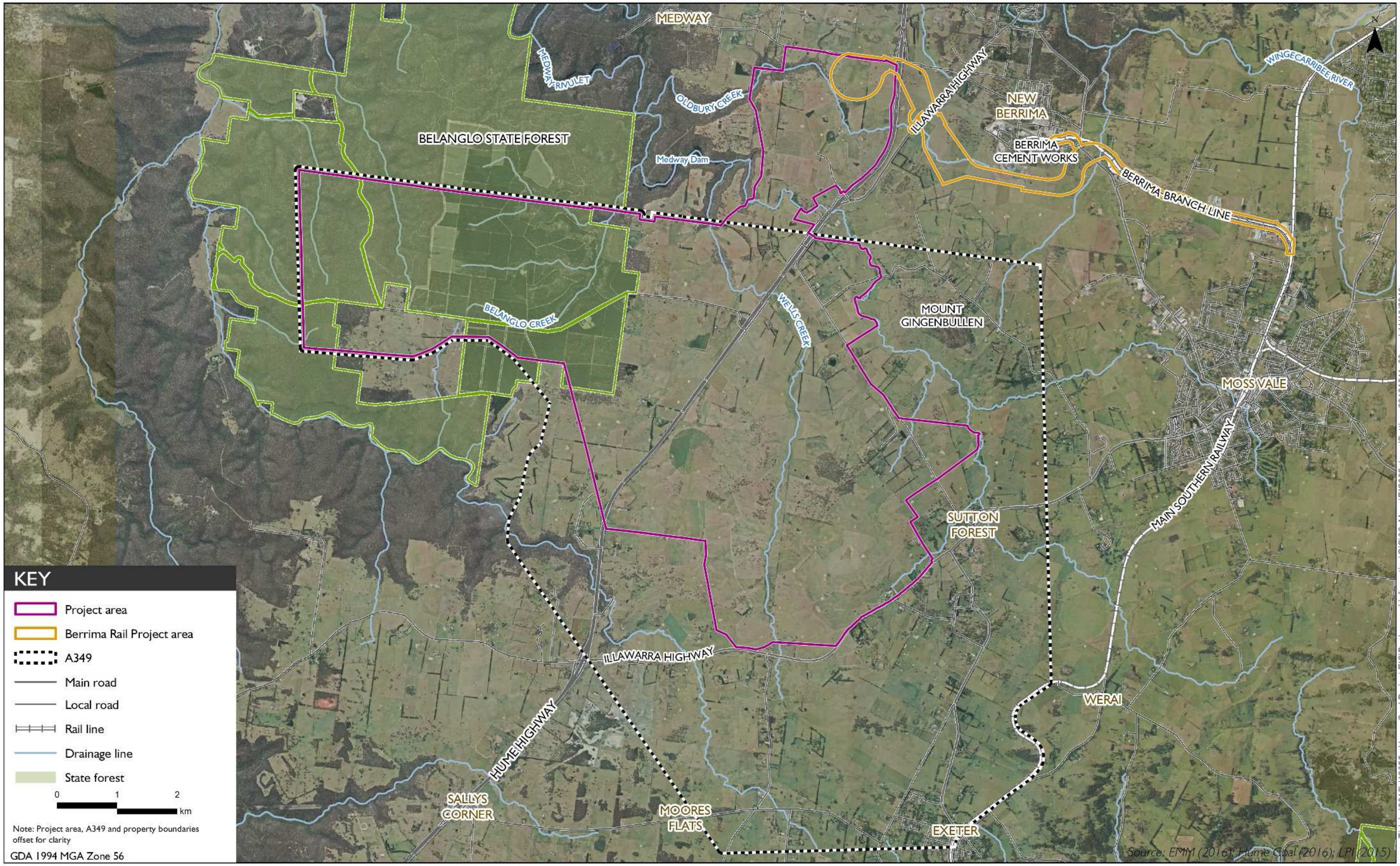


Figure 1.2. Local context

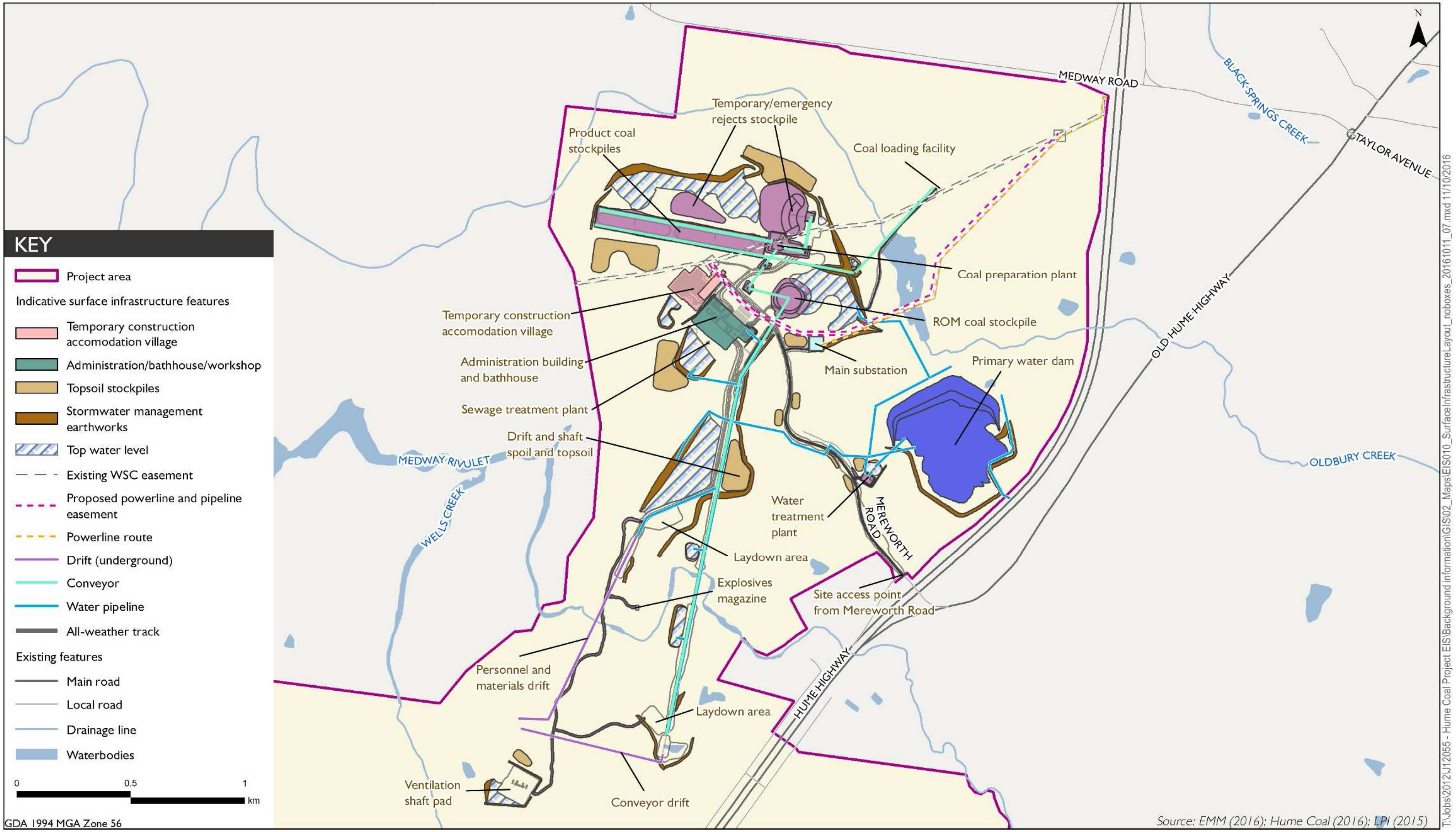


Figure 1.3. Indicative surface infrastructure layout.

A construction buffer zone will be provided around the direct disturbance areas. The buffer zone will provide an area for construction vehicle and equipment movements, minor stockpiling and equipment laydown, as well as allowing for minor realignments of surface infrastructure. Ground disturbance will generally be minor and associated with temporary vehicle tracks and sediment controls as well as minor works such as backfilled trenches associated with realignment of existing services. Notwithstanding, environmental features identified in the relevant technical assessments will be marked as avoidance zones so that activities in this area do not have an environmental impact.

Product coal will be transported by rail, primarily to Port Kembla terminal for the international market, and possibly to the domestic market depending on market demand. Rail works and use are the subject of a separate EIS and State significant development application for the Berrima Rail Project.

General site description

The project area is approximately 100 km southwest of Sydney and 4.5 km west of Moss Vale town centre in the Wingecarribee LGA (refer to Drawing 1 and Figure 1.2). The nearest area of surface disturbance will be associated with the surface infrastructure area, which will be 7.2 km northwest of Moss Vale town centre. It is in the Southern Highlands region of NSW and the Sydney Basin Biogeographic Region.

The project area is in a semi-rural setting, with the wider region characterised by grazing properties, small-scale farm businesses, natural areas, forestry, scattered rural residences, villages and towns, industrial activities such as the Berrima Cement Works and Berrima Feed Mill, and some extractive industry and major transport infrastructure such as the Hume Highway.

Surface infrastructure is proposed to be developed on predominately cleared land owned by Hume Coal or affiliated entities, or for which there are appropriate access agreements in place with the landowner. Over half of the remainder of the project area (principally land above the underground mining area) comprises cleared land that is, and will continue to be, used for livestock grazing and small-scale farm businesses. Belanglo State Forest covers the northwestern portion of the project area and contains introduced pine forest plantations, areas of native vegetation and several creeks that flow through deep sandstone gorges. Native vegetation within the project area is largely restricted to parts of Belanglo State Forest and riparian corridors along some watercourses.

The project area is traversed by several drainage lines including Oldbury Creek, Medway Rivulet, Wells Creek, Wells Creek Tributary, Belanglo Creek and Longacre Creek, all of which ultimately discharge to the Wingecarribee River, at least 5 km downstream of the project area (Figure 1.2). The Wingecarribee River's catchment forms part of the broader Warragamba Dam and Hawkesbury-Nepean catchments. Medway Dam is also adjacent to the northern portion of the project area (Figure 1.2).

Most of the central and eastern parts of the project area have very low rolling hills with occasional elevated ridge lines. However, there are steeper slopes and deep gorges in the west in Belanglo State Forest.

Existing built features across the project area include scattered rural residences and farm improvements such as outbuildings, dams, access tracks, fences, yards and gardens, as well as infrastructure and utilities including roads, electricity lines, communication cables and water and gas pipelines. Key roads that traverse the project area are the Hume Highway and Golden Vale Road. The Illawarra Highway borders the south-east section of the project area.

Industrial and manufacturing facilities adjacent to the project area include the Berrima Cement Works and Berrima Feed Mill on the fringe of New Berrima. Berrima Colliery's mining lease (CCL 748) also adjoins the project area's northern boundary. Berrima colliery is currently not operating with production having ceased in 2013 after almost 100 years of operation. The mine is currently undergoing closure.

1.1.2. Assessment guidelines and requirements

This groundwater assessment has been prepared generally in accordance with the following:

- Barnett B, Townley LR, Post V, Evans RE, Hunt RJ, Peeters L, Richardson S, Werner AD, Knapton A, and Boronkay A. 2012. Australian groundwater modelling guidelines. Waterlines Report Series, Number 82. National Water Commission, Canberra.
- NSW Department of Primary Industries (Office of Water). 2012. NSW Aquifer Interference Policy: NSW Government policy for the licensing and assessment of aquifer interference activities. September.

1.2. Previous mining

Mining has occurred in the area since the 1800s. All known mines in the area are now abandoned, all believed to be underground, comprising (see Drawing 1):

- Berrima Mine, located to the north of Wingecarribbee River on the Berrima Mine lease. The workings are the most extensive of any mine in the area and comprise 1st workings and pillar extraction in the Wongawilli seam. Mining operations commenced in 1926 and ceased in 2013. Mechanisation (and full extraction) commenced in 1968 (EMGA 2011). Production varied between 0.13 and 0.46 Mt/year and was reported as 0.25 Mt/year in 2009 (EMGA 2011). The workings are currently under care and maintenance, remaining largely empty and draining to the Wingecarribee River. Groundwater drawdown from this mine can be identified in monitoring piezometer hydrographs. The owner is considering sealing the mine to reduce or eliminate drainage to the river. Groundwater and surface water quality, and groundwater levels, around the mine are monitored by Boral.
- The Loch Catherine Mine (abandoned), opened in 1924 with an anticipated maximum possible production of 200 t/day. It is located underneath the current Berrima Colliery stockpile in a localised zone of Hawkesbury Sandstone bounded by Medway Rivulet and the Wingecarribee River. The mine worked the Wongawilli Seam and ceased operation in 1958 (BCSC 1993). It included some mechanised workings utilising shuttle cars. Full extraction is thought to have occurred based on the shape of the mine footprint, and its presence in the Mine Subsidence Compensation Act on the list of compulsory contributors to the compensation fund. The adits are still open, and iron staining is evident in the water pooled at the mine entries.
- Southern Colliery (abandoned), located on Foxgrove Road about 5 km from the Hume lease boundary. Mining appears to have occurred in the Tongarra Seam. This was a small scale mine which ceased operations many years ago.
- Numerous adits at coal seam outcrops along escarpments (see Drawing 1, not all identified) for pre-mechanisation (manual) abandoned workings. Typical examples are Black Bobs, Belanglo (abandoned in the 1950s), Belanglo Extended, and Flying Fox collieries to the west and the north of the Hume lease, and Erith Colliery near Bundanoon. These were likely to be very small operations, probably mining less than 100,000 t in total. Most are not sealed and drain into local watercourses. They typically consist of two headings extending in from outcrop by a few hundred metres. Belanglo was a small operation along Black Bobs Creek, presumed to be on the southern side of the creek, to the west of the Hume Highway. Murrimba Colliery was on the eastern side of Black Bobs Creek in approximately the same location and was abandoned after hitting a full face of stone a few hundred metres from the creek (coincident with a high magnetic anomaly). Belanglo Colliery is located in the Berrima lease in a tributary of Medway Rivulet.

Two adits have also been discovered along Longacre Creek. The workings are of unknown length. They are above one another (in the Tongarra and Wongawilli seams). Historical literature discusses a number of old mines in the area around the Loch Catherine mine, and it is likely that other small scale abandoned mine workings are present along the coal seam outcrop in this area.

2. Climate

The distribution of regional rainfall was assessed from a large number of climate stations whose data are held by the Australian Bureau of Meteorology (ABM). Stations which had more than 30 full years of records, with at least 15 years post 1955, were used. The mean and median annual rainfall for these stations are listed in Table 1.

Table 1. Regional rainfall.

Station Name	Station Number	Latitude	Longitude	Mean Annual Rainfall (mm)	Median Annual Rainfall (mm)	Elevation (mAHD)	Opened
Bannaby (Hillasmount)	70002	34.43°	150.00°	791	770	710	1945
Berrima West (Medway (Wombat Creek))	68186	34.48°	150.29°	783	771	655	1970
Brayton (Longreach)	70143	34.64°	149.95°	701	696	610	1959
Bundanoon (Ballymena)	68008	34.65°	150.31°	1158	1093	688	1902
Burragorang	63016	34.20°	150.30°	858	880	Unknown	1942
Burrawang (Range St)	68009	34.60°	150.52°	1374	1304	758	1891
Burruer (Illaroo)	68031	34.87°	150.45°	867	821	Unknown	1902
Buxton (Amaroo)	68166	34.24°	150.52°	856	882	420	1967
High Range (Wanganderry)	68062	34.34°	150.27°	817	797	740	1921
Joadja (Greenwalk)	68089	34.43°	150.24°	785	772	725	1959
Kangaroo Valley (Main Rd)	68036	34.74°	150.53°	1294	1201	85	1914
Mittagong (Alfred St)	68044	34.45°	150.46°	910	902	635	1886
Mittagong (Kia Ora)	68033	34.46°	150.49°	899	902	610	1902
Moss Vale (Hoskins St)	68045	34.54°	150.38°	962	939	675	1870
Moss Vale (Torokina)	68195	34.64°	150.40°	1110	1074	568	1971
Sutton Forest (Eling Forest)	68093	34.57°	150.26°	899	843	658	1945
Wingello State Forest	68067	34.72°	150.20°	1093	1093	640	1940
Wollondilly (Bullio)	68068	34.35°	150.15°	825	785	675	1941
Wombeyan Caves	63093	34.31°	149.97°	833	861	580	1942
Yerrinbool	68071	34.37°	150.55°	901	903	500	1916
Hume AWS (Wongonbra, Mine Lease)	N/A			938*			

* From correlation with Station 68045 (rainfall is 98% of monthly rainfall at Station 68045 over the period April 2012 to January 2015).

Figure 2.1 shows the interpreted distribution of average annual rainfall over the regional area. The mine lease has an area-weighted average annual rainfall of 957 mm. Given the geography of the area and the long-term average at Station 68045 (Moss Vale), that station is useful for comparison to lease rainfall.

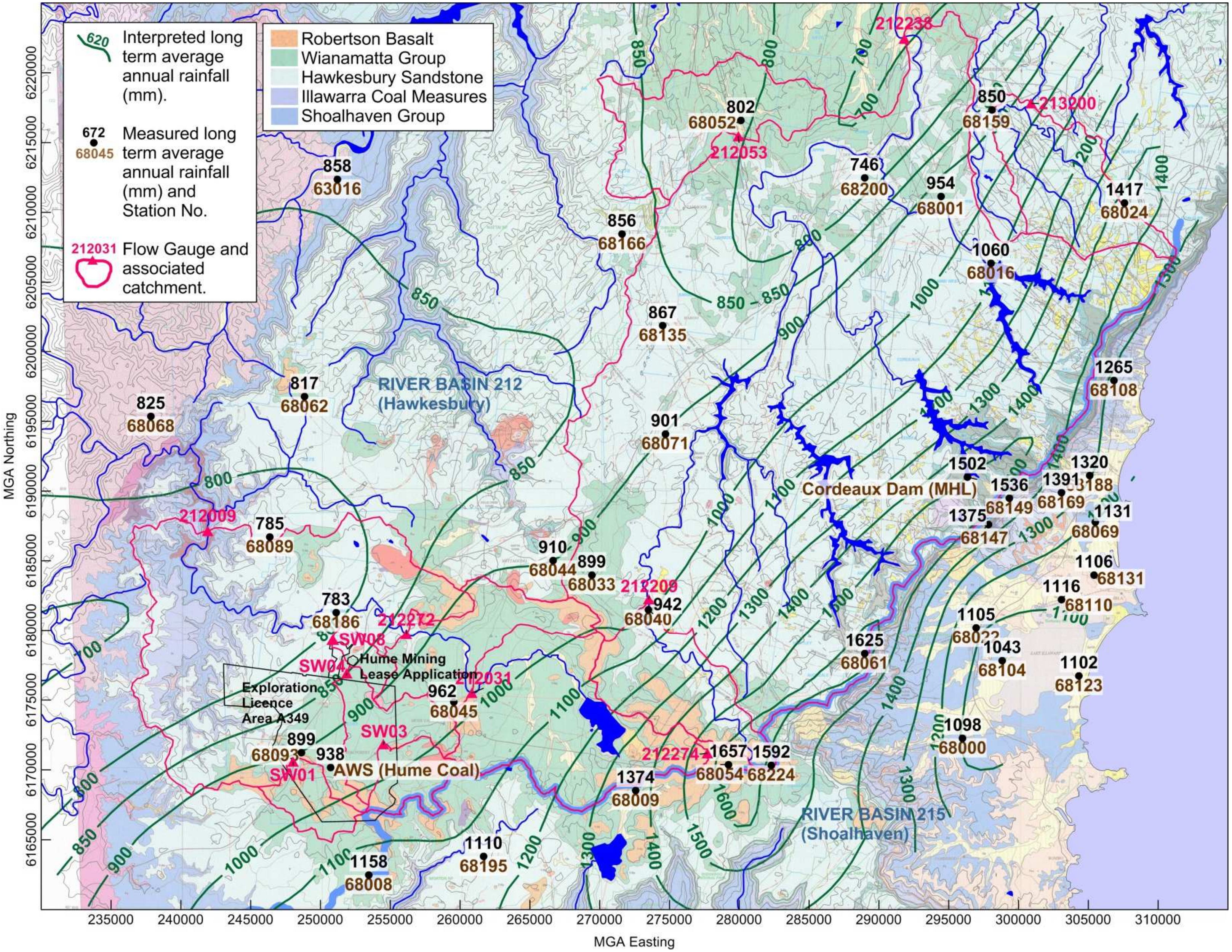


Figure 2.1. Interpreted pattern of average annual rainfall.

Figure 2.2 shows the average monthly rainfall pattern in the vicinity of the mine lease (a combination of monthly averages at Stations 68093 (1945 to 2000) and 68186 (1970 to 2014)), and the average monthly pan evaporation at Goulburn TAFE (Station 70263). Average monthly rainfall ranges between a maximum of 85 mm in February to a minimum of 49 mm in July (the annual average for these stations is 841 mm). Average monthly pan evaporation ranges between a maximum of 198 mm in January to a minimum of 33 mm in June, with an annual average of 1294 mm. A soil moisture deficit is likely to occur between September and April in an average year.

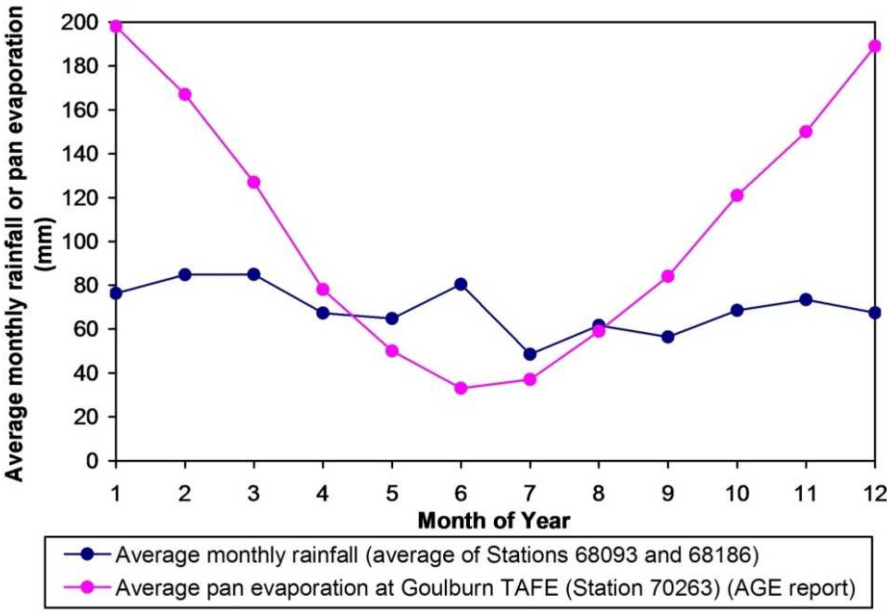


Figure 2.2. Estimated average monthly rainfall in the mine lease and average monthly pan evaporation at Goulburn.

Rainfall has also been measured by Hume at an automatic weather recording station on the mine lease (known as the Wongonbra gauge) from April 2012. Figure 2.3 shows a correlation of monthly rainfall at Wongonbra and Station 68045 for the period April 2012 to January 2015 inclusive. Monthly rainfall for March 2013, June 2013, and July to September 2014 (inclusive) showed poor correlation with their 68045 counterparts, and were removed from the correlation because of known equipment malfunction. The correlation indicates the quality of Wongonbra records appears acceptable.

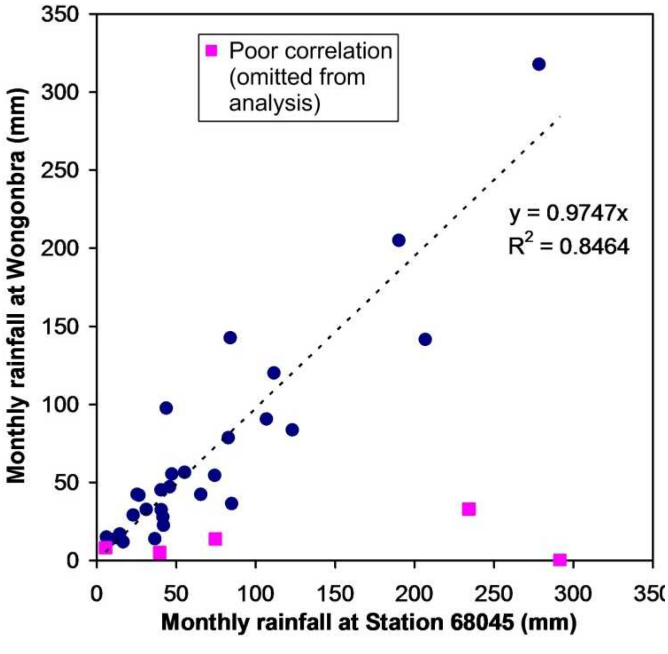


Figure 2.3. Correlation of monthly rainfall between Station 68045 (Moss Vale) and Hume's site gauge at Wongonbra.

3. Surface drainage

The digital topographic elevation dataset used in the current work comprises the 1 arc-second (~30m) gridded smoothed version of the digital elevation model (DEM-S Version 1.0) obtained from the Shuttle Radar Topographic Mission (SRTM) (ANZCW0703013355), available from the Geoscience Australia website.

The mine lease is located on the southern (upstream) limits of the Hawkesbury River Basin (Figure 2.1). This basin is flanked to the south by the Shoalhaven River Basin. Figure 3.1 shows a detail of the surface drainage over the mine lease. Topography in the lease ranges from about 730 m AHD in the southeast to about 660 m AHD in the north. Surface drainage is towards the north/northwest. Beyond the lease, drainage channels become significantly incised where Hawkesbury Sandstone is not overlain by the Wianamatta Group, with elevation of drainage channels falling rapidly near the extremities of the Hawkesbury Sandstone to the northwest.

The main drainage feature is the Wingecarribee River (see Figure 3.1). Wingecarribee River is regulated, mainly by Wingecarribee Reservoir (see Drawing 1), with dam releases common during drought. Its main functions are provision of a potable water supply to the Southern Highlands (approximately 25,000 people), providing a transfer point between the Shoalhaven and Sydney water supply schemes, and maintenance of flows for environmental and Sydney water supply purposes.

Other storages on the Wingecarribee River in the regional area are Medway Dam (on Medway Rivulet; see Figure 3.1) (1300 ML), Bong Bong Weir (500 ML), and Berrima Weir (9000 ML).

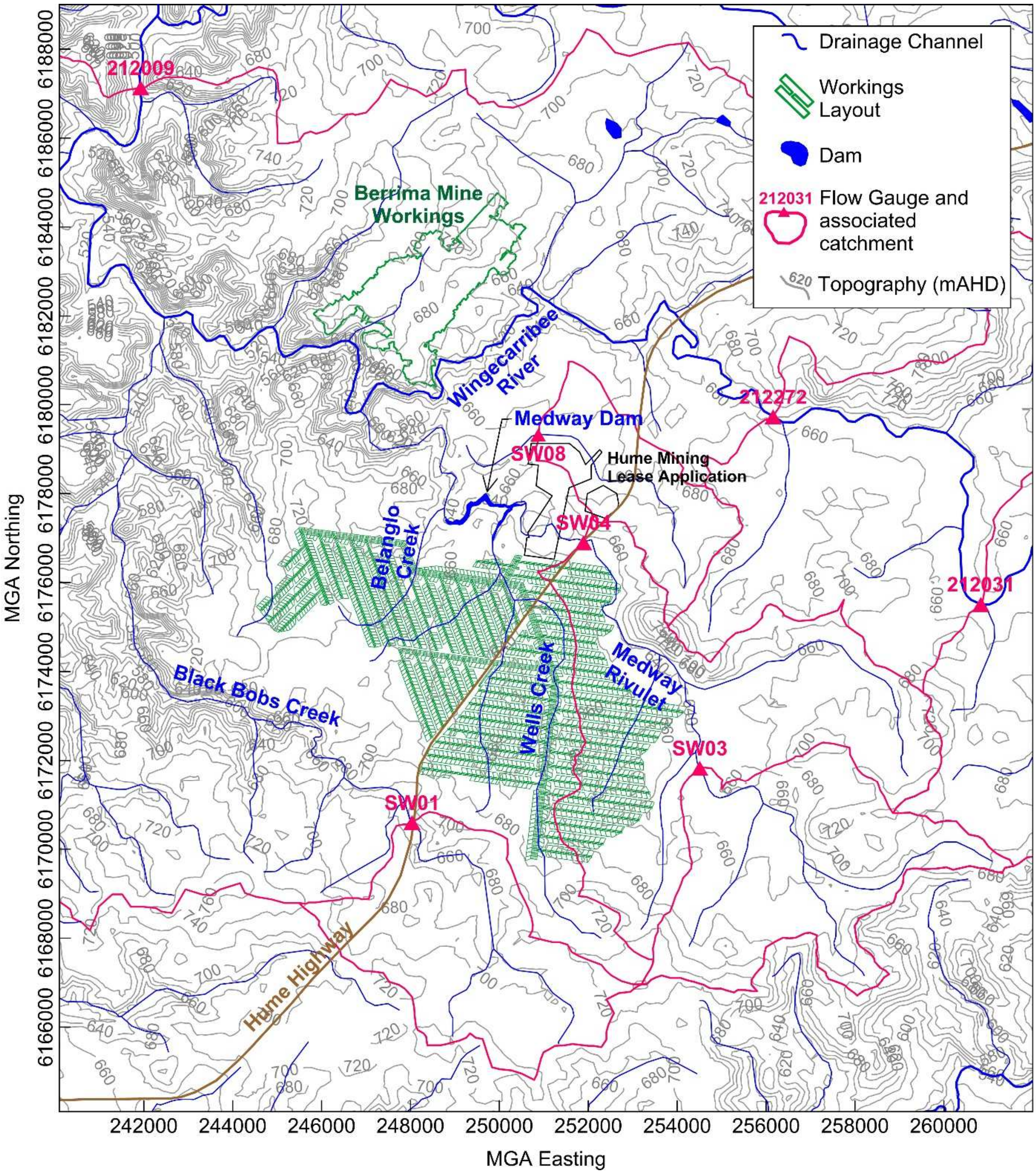


Figure 3.1. Detail of surface drainage over the mine lease.

For the mine lease, stream flow data are available for four gauges monitored by Hume (SW01, SW03, SW04, and SW08, see Figure 3.1) and for three government gauges on the Wingecarribee River (Figure 3.1). Table 2 lists the average daily stream flow measured at these gauges, and the occurrences of nil flow. These flows are resultant flows, after river extraction. Black Bobs Creek and Medway Rivulet are considered ephemeral. Wingecarribee River sustains flow most of the time, assisted by dam regulation in the last few decades, and is considered perennial. The period of monitoring for Oldbury Creek was insufficient to assess its flow sustenance capability.

Table 2. Average daily flow and occurrences of nil flow for streams near the mine lease.

Gauge	Location	Monitoring Period	Monitoring Days	Average Flow (all days) (ML/day)	Nil Flow Days	% of time nil flow
SW01	Black Bobs Creek at the Hume Highway	24 Jan 2012 to 6 Feb 2014	672	19	226	34%
SW03	Medway Rivulet at the Illawarra Highway	23 Jan 2012 to 7 Oct 2015	1354	17.1	315	23%
SW04	Medway Rivulet at the Hume Highway			50.5	371	27%
SW08	Oldbury Creek	15 May 2015 to 8 Oct 2015	147	7.1	0	0%
212031	Wingecarribee River at Bong Bong Weir	1 Jan 1990 to 31 Dec 2002	4748	79	379	8%
212272	Wingecarribee River at Berrima			108	464	10%
212009	Wingecarribee River at Greenstead			185	39	1%

3.1. Rainfall recharge to the water table

Rainfall recharge to the water table was analysed by assessing water level rises in shallow piezometers from rainfall events, using a simple one-dimensional model.

Figure 3.2 shows the interpreted annual recharge to the water table in Hawkesbury Sandstone overlain by residual soil, at five locations in the Southern Highlands, assuming a refillable void space in the short to medium term (days to months) of 0.0125 (based on Tammetta and Hewitt 2004). Of the Hume monitoring network, only H44XB had a combination of a sufficient amount of data and a reasonably shallow screen to allow this type of analysis, and is shown. Vibrating wire piezometer (VWP) response has greater uncertainty than conventional piezometer response. Piezometer screen bases vary from 5 m to 10 m below ground.

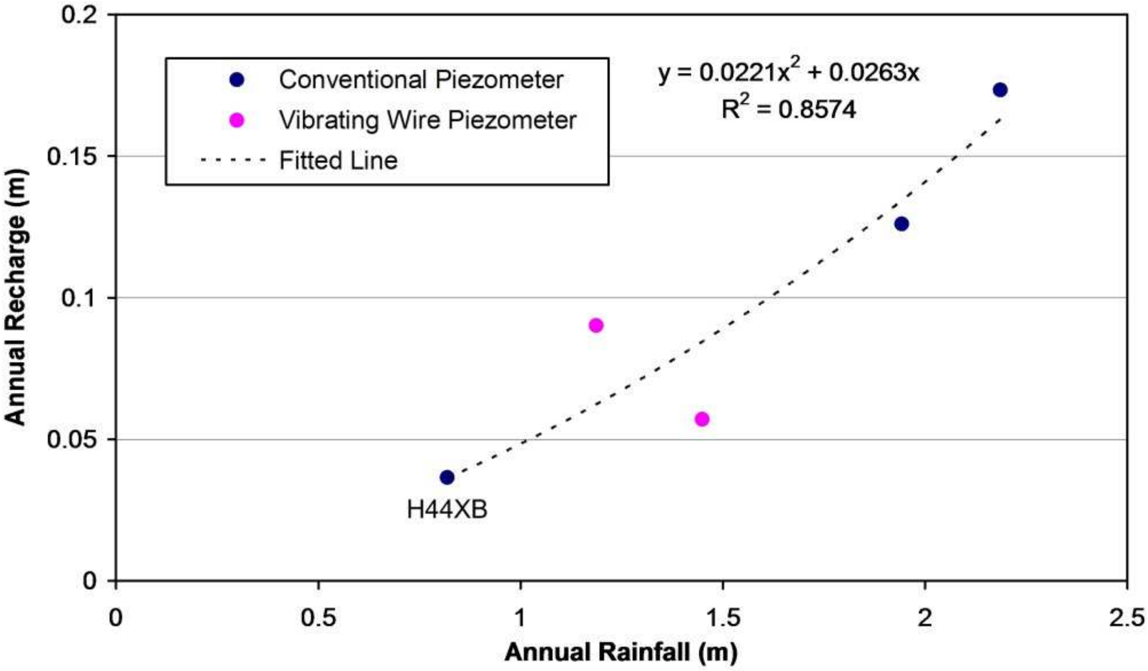


Figure 3.2. Interpreted recharge to the water table for Hawkesbury Sandstone overlain by residual soil, in the Southern Highlands.

Figure 3.3 shows the response at H44XB to rainfall, compared to the daily cumulative rainfall deficit, and indicates that the one-dimensional analytical model is valid, with rise in groundwater levels occurring rapidly following rainfall.

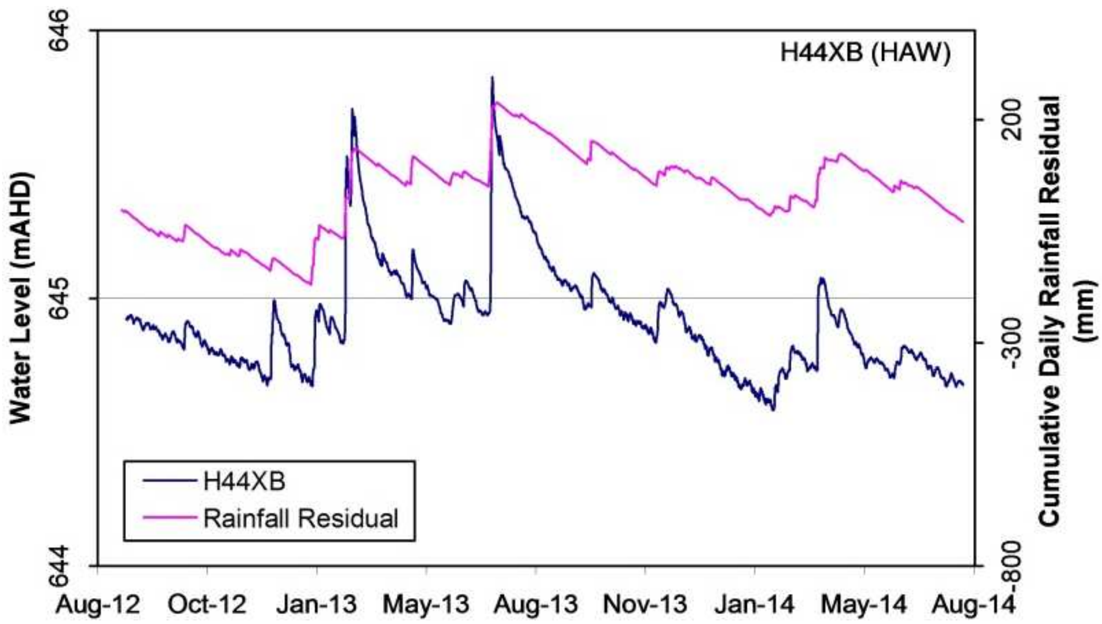


Figure 3.3. Response to rainfall at Hume Monitoring Piezometer H44XB.

No data were available for the Wianamatta Group, however analysis of a piezometer in the Sydney outer metropolitan area, for Ashfield Shale covered by residual soil, returned a recharge rate to the water table of about 1.5% to 2.0% of annual rainfall, assuming a short to medium term refillable void space of 0.01. Recharge to basalt water tables has been observed at greater than 10% in rural areas.

3.2. Stream flow

Stream flow data were obtained for a number of flow gauges in the Hume project area and from the wider Southern Highlands to compare catchments of different outcrop lithologies. Comparison for basalt-dominant catchments was assisted using observations from a basalt catchment in northern coastal NSW. Gauge locations (except for gauge 203012, Byron Creek at Binna Burra, in northern NSW) are shown in Figure 2.1. An analysis of stream baseflow was undertaken for these gauges. Gauging by Hume at SW03 and SW04 provided several years of daily flow observations.

For the Hume Coal Project, baseflow analysis has been undertaken using the local minimum method, implemented using the program BFI and the procedure of Wahl and Wahl (1995). Appendix A provides a discussion of the comparison between baseflow analysis methods, and the method used in this work.

The Nepean and Wingecarribee Rivers are regulated. This has been taken into account in the baseflow analysis (see Appendix A). The baseflow analysis also incorporates removal of river flow through licensed river extraction, using the catchment for gauge 212238 as a guide, in conjunction with licensing information for the Hume area. The analysis also accounts for evaporation from major dams (Wingecarribee Reservoir for gauges 212009, 212031, and 212272), and changes in dam storage.

Results

Catchment 203012 is dominated by basalt and is used for comparison to the Caalang Creek catchment (gauge 212274, located at the head of the Wingecarribee River catchment), also dominated by basalt. Both are microcatchments. Baseflow results are area-averages (for an entire catchment). For large catchments, the effect of flow path length (to a drainage channel) on changes in catchment area is small. The influence of flow path length (and larger hydraulic gradients for basalt systems) is accentuated in micro-catchments.

Baseflow analysis results are listed in Table 3. Baseflow appears highly sensitive to the proportion of basalt terrain (interpreted from results for gauges 212209, 212031, and the basalt microcatchments). Baseflows calculated for gauge 212209 (30% basalt terrain) were conspicuously higher than other gauges. Basalt has significantly enhanced baseflow capability compared to typical sedimentary media.

For Hawkesbury Sandstone terrain, baseflow is about 3% of annual rainfall. For Wianamatta Group terrain, baseflow is about 1% to 1.5%.

The catchment over the lease has about 15% basalt terrain (see Drawing 1 and Figure 2.1). The average baseflow for average rainfall conditions for the Hume mine lease and surrounding area is estimated to be about 1.5% of annual rainfall. This takes into account the contribution from basalt.

Table 3. Results of baseflow analysis.

Gauge	Catchment Area (km²)	Time Period		Average flows over period (ML/day)		Average annual rainfall over period (mm)	Average flows as a proportion of rainfall	
		From	To	Baseflow	Total Flow		Baseflow	Total Flow
SW03 (Medway Rivulet at the Illawarra Highway)	24.3	1-Mar-12	11-Sep-15	0.4	17.8	1053	0.002	0.100
SW04 (Medway Rivulet at the Hume Highway)	61.7	1-Mar-12	11-Sep-15	3.3	51.8	1053	0.019	0.291
212009 (Wingecarribee River at Greenstead)	599.0	1-Jan-90	31-Dec-02	25.2	139.2	710	0.021	0.113
212031 (Wingecarribee River at Bong Bong Weir)	136.9	1-Jan-90	31-Dec-02	11.5	73.5	874	0.033	0.213
212272 (Wingecarribee River at Berrima)	200.6	1-Jan-90	31-Dec-02	12.4	95.9	831	0.026	0.199
212274 (Caalang Creek)	6.1	1-Jan-88	31-Dec-02	8.1	14.2	1476	0.328	0.571
212238 (Nepean River at Menangle Weir)	1311.5	1-Jan-91	31-Dec-06	30.0	341.0	864	0.010	0.110
213200 (O'Hares Creek at Wedderburn)	73.1	1-Jan-62	31-Dec-01	7.0	81.1	1269	0.028	0.319
212209 (Nepean River at Maguires Crossing)	69.3	1-Jan-72	31-Dec-01	28.5	110.1	1552	0.097	0.374
212053 (Stonequarry Creek at Picton)	87.9	1-Jan-91	31-Dec-01	1.1	14.9	754	0.006	0.082
203012 (Byron Creek at Binna Burra)	39	1-Jan-53	31-Dec-02	37.6	114.3	1870	0.188	0.572

Gauge	Dominant Lithologies					
	Alluvium	Basalt	WG	HAW	Permian	Lake
SW03 (Medway Rivulet at the Illawarra Highway)	0.0%	15.0%	85.0%	0.0%	0.0%	0.0%
SW04 (Medway Rivulet at the Hume Highway)	0.0%	16.7%	83.3%	0.0%	0.0%	0.0%
212009 (Wingecarribee River at Greenstead)	2.4%	12.1%	42.1%	28.8%	13.6%	1.0%
212031 (Wingecarribee River at Bong Bong Weir)	9.5%	19.4%	66.8%	0.0%	0.0%	4.3%
212272 (Wingecarribee River at Berrima)	7.2%	19.1%	68.7%	2.0%	0.0%	2.9%
212274 (Caalang Creek)	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%
212238 (Nepean River at Menangle Weir)	1.3%	1.7%	17.2%	72.7%	4.7%	2.4%
213200 (O'Hares Creek at Wedderburn)	4.1%	0.0%	0.0%	95.9%	0.0%	0.0%
212209 (Nepean River at Maguires Crossing)	2.2%	28.4%	29.1%	40.3%	0.0%	0.0%
212053 (Stonequarry Creek at Picton)	4.5%	0.0%	57.6%	37.9%	0.0%	0.0%
203012 (Byron Creek at Binna Burra)	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%

NB: WG denotes Wianamatta Group, HAW denotes Hawkesbury Sandstone.

Figure 3.4 shows the results of the baseflow analysis as baseflow height (baseflow volume divided by catchment area) versus annual catchment rainfall. Appendix A shows these results separately.

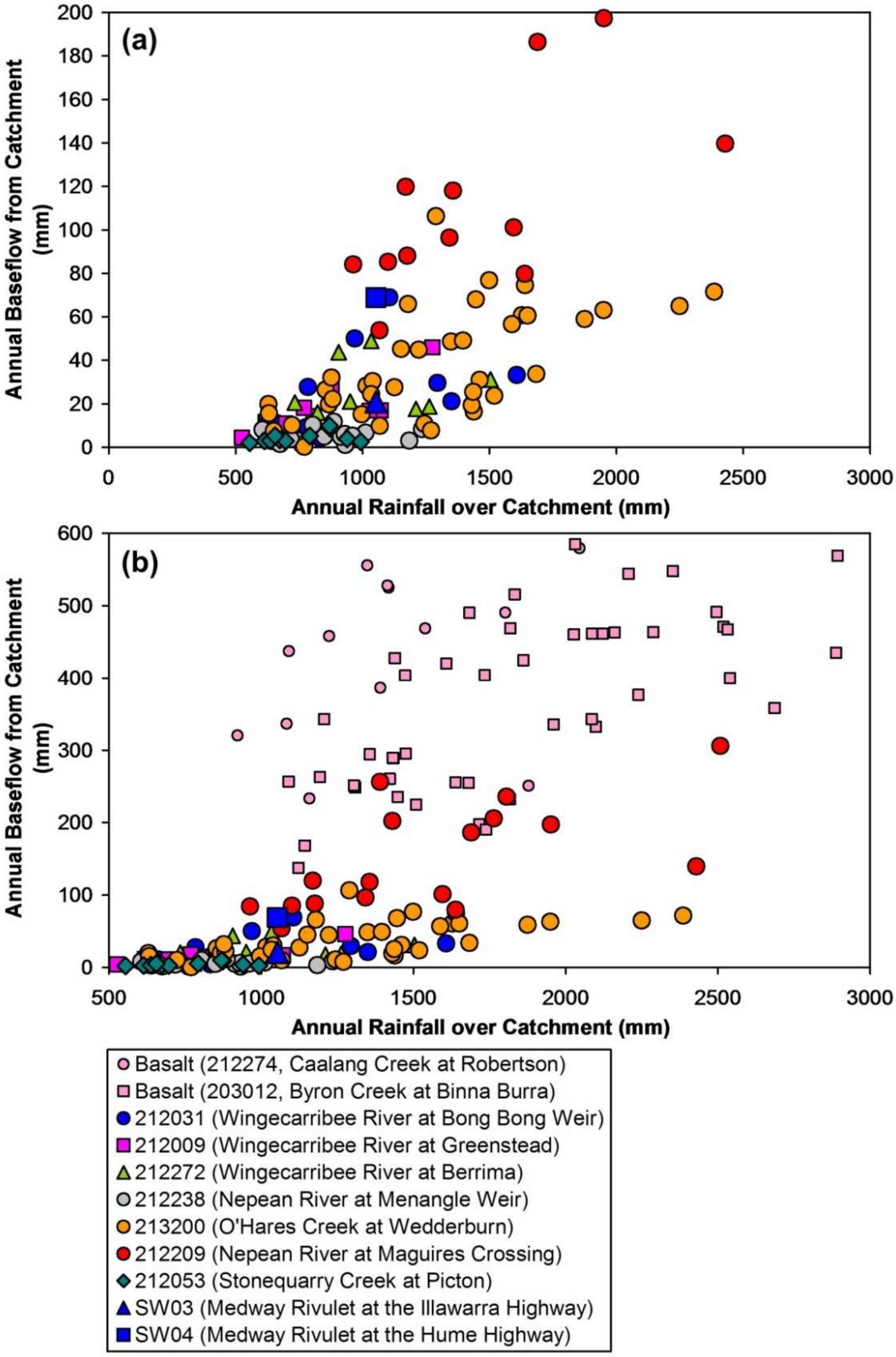


Figure 3.4. Annual estimated baseflow for (a) catchments not dominated by basalt, and (b) all analysed catchments.

According to the published geology map, alluvium occurs only along the upper reach of the Wingecarribee River (see Drawing 1). Its extent is limited to close proximity to the river channel, and is a small proportion of the total recharge area encompassed by the mine capture zone. While it may afford greater rainfall recharge, most of the recharge is considered to be in intimate connection with the river channel. Its extent is considered minor. Borehole logs identifying the strata between the alluvium and rock were unavailable. However, alluvial sequences such as this one commonly overlie a layer of residual soil, present at the start of the depositional phase, which may compact with increasing alluvial thickness. For this case, any compacted residual soil would be of Wianamatta Group origin and be clay-dominant. On an area basis, recharge to underlying fractured media from the alluvium is considered a negligible component of the total recharge to these media.

4. Geology

4.1. Stratigraphy

The Hume Coal exploration area is located on the southwest margin of the Sydney Basin. The geological sequence in this area is shown in Drawing 1 and Figure 2.1. The sequence is (in stratigraphic order of increasing age):

- Robertson Basalt (Tertiary basalt, dolerite and volcanic breccia).
- Wianamatta Group (Bringelly Shale, Minchinbury Sandstone, and Ashfield Shale) and Mittagong Formation (Triassic).
- Hawkesbury Sandstone (Triassic).
- Narrabeen Group (present only in parts) (Triassic).
- Illawarra Coal Measures (Permian).
- Shoalhaven Group (Permian)

Minor alluvium is present along the upstream reach of the Wingecarribee River.

Bulletin 26 issued by the Geological Survey of NSW (1980) provides detailed geological descriptions of the fractured media lithologies. The regional occurrence of these lithologies (Drawing 1 and Figure 2.1) is taken from the 1:100,000 Southern Coalfield geology map and the 1:100,000 Wollongong/Port Hacking and Kiama geology maps, with further descriptions of the lithologies given in the notes that accompany these maps.

The Triassic Wianamatta Group (WG) comprises black shale interbedded with lithic sandstones. The shale consists mainly of sulphide-rich claystones and siltstones containing abundant plant debris and some lenses of coal. The Minchinbury Sandstone is a persistent sandstone horizon which separates the Ashfield and Bringelly Shales of the WG.

The Triassic Hawkesbury Sandstone is a quartz arenite, containing grains of sub-angular quartz and graphite, with a smaller proportion of feldspar, clay, and iron compounds such as siderite. It ranges in thickness from less than 100 m on the southwest edge of the Sydney Basin to around 250 m in the Sydney metropolitan area. In the Hume area it is around 120 m thick where fully developed. It is composed of the following three facies:

- Sheet facies (cross-bedded strata bounded by planar sub-horizontal surfaces).
- Massive facies (nearly, but not wholly, structureless poorly sorted sandstone, containing higher proportions of clay and less chemical cement and quartz overgrowth than the sheet facies).
- Claystone facies (thin dark grey to black mudstone units with a characteristic thickness of between 0.3 m and 3 m).

The Narrabeen Group has been almost completely eroded in the south western marginal zone of the Sydney Basin. It is absent over a large part of the study area, reaching a maximum thickness of around 6 m in the Berrima mine area, north of A349. Where it is not present, the Hawkesbury Sandstone unconformably overlies the Illawarra Coal Measures (ICM).

The ICM are a freshwater sequence comprising alternating layers of conglomerate, quartz-lithic sandstone, grey shale, carbonaceous shale and coal seams. These rock types occur in a cyclic pattern up the profile, with each cycle consisting of a basal sandstone layer overlain by shale or mudstone (seat soil), then by a coal seam. The ICM host the Wongawilli Seam (the mining target), located at the top of the ICM in the Hume area. Their thickness ranges from about 50 m in the Southern Highlands to more than 250 m near Wollongong.

The ICM are underlain by the Shoalhaven Group, which comprises sandstones deposited under marine conditions interbedded with latite flows (intermediate potassic volcanic extrusives). In the project area the Group unconformably overlies the strongly folded Palaeozoic basement.

Figure 4.1 shows the stratigraphy for bore HU0016CH (located in the southern part of the exploration lease), typical for the lease area, showing downhole density measurements and gamma ray emissions recorded during the geophysical survey. Figure 4.1 also shows a detail of the Wongawilli Seam using average thicknesses calculated from logs within the Hume lease.

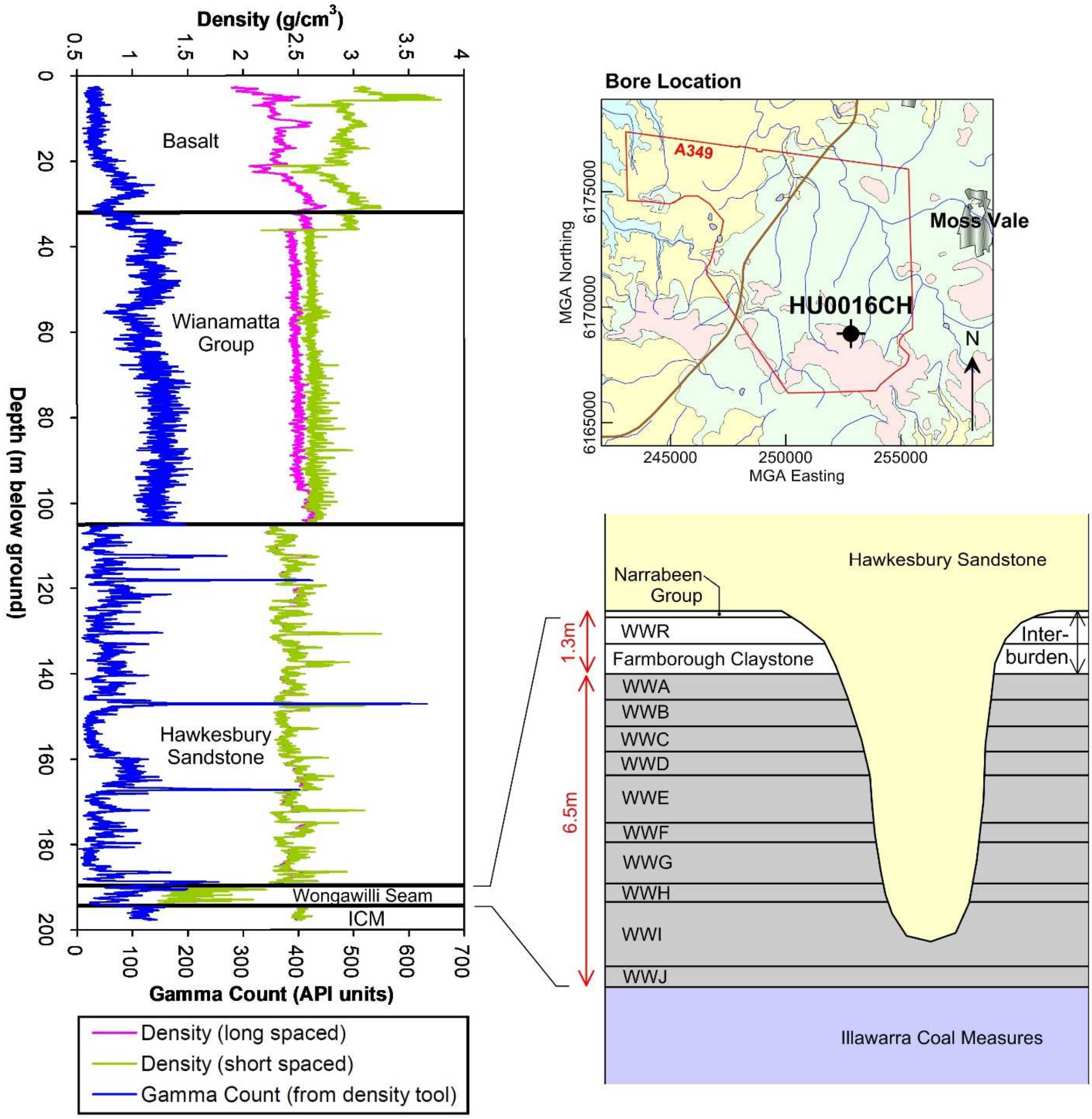


Figure 4.1. Stratigraphy and geophysical measurements for bore HU0016CH (left). The seam detail is shown to the right (colouring denotes adopted hydrostratigraphic subdivisons). Thicknesses are averages over the mine lease.

Geophysical results indicate higher clay mineral content in the WG compared to the overlying basalt and the Hawkesbury sandstone. The Wongawilli Coal seam comprises plies WWR to WWJ. The WWR ply is a carbonaceous claystone. The Farmborough Claystone Member is a tuffaceous claystone (Bamberry 1991). The Narrabeen Group, WWR ply, and Farmborough Claystone are combined into a single, sediment-dominant unit (referred to as the interburden). It has contrasting hydraulic properties to the underlying remainder of the Wongawilli seam (low density, coal-dominated), and overlying Hawkesbury Sandstone (medium to fine quartz arenite). The interburden is not present over part of the lease (see Figure 4.3). The Wongawilli Seam can be incised by the Hawkesbury Sandstone down as far as the WWI ply.

4.2. Structure contours

Structure contours for the most critical geological horizons in the Hume and Berrima leases were compiled from data provided by Hume. These data were complemented with information in Bamberry (1991), McElroy Brian and Associates (MBA) (1980), and the Government Southern Coalfield Geology map to obtain structure contours covering the larger model domain, for six fundamental surfaces. These were the base elevations of the Tertiary Basalt, Wianamatta Group, Hawkesbury Sandstone, Wongawilli Seam, Illawarra Coal Measures, and Shoalhaven Group. For the purpose of modelling, other surfaces (for example, subdivision of the Hawkesbury Sandstone) were developed from these six fundamental surfaces using constant offsets or proportioned thicknesses.

Figure 4.2 shows the structure contour surface for the base of the Wongawilli seam. In A349 the general dip of the seam (and most other strata) is easterly. A conspicuous large-scale palaeochannel is present east of A349, suggesting palaeodrainage to the northeast. Figure 4.2 also shows faults interpreted by others to be present in the area.

Figure 4.3 shows the interburden thickness. The interburden is largely absent over the southwestern half of the A349, but thickens to the north. The interburden forms an important sequence with respect to relaxation above the seam following mining.

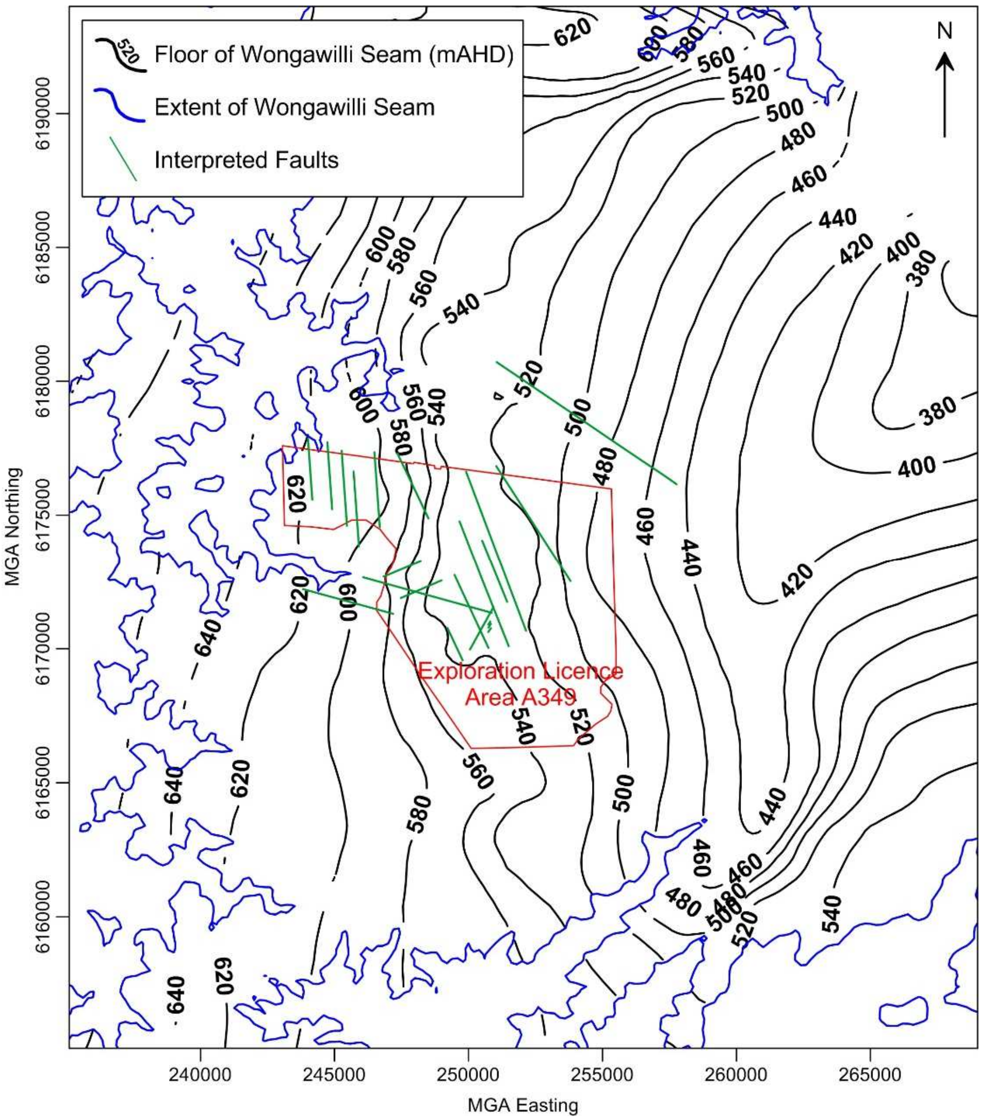


Figure 4.2 (left). Structure contours for the base of the Wongawilli Seam, and interpreted faults.

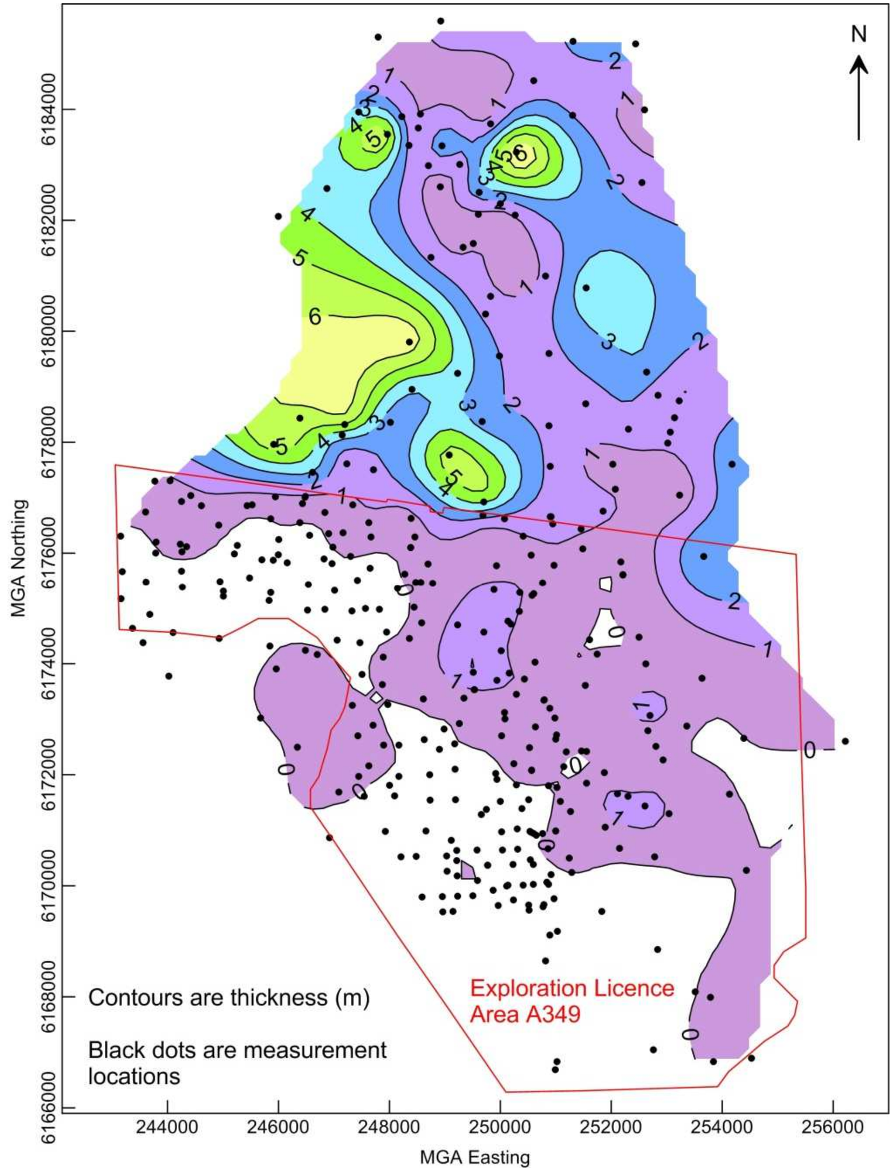


Figure 4.3 (right). Interburden thickness.

During quality control of surfaces, the Narrabeen Group thickness (Figure 4.4) was found to change markedly when traversing the Mount Murray Monocline. The thickness is relatively constant in the Hume area (southwest of the Mount Murray Monocline) but increases considerably northeast of the monocline, moving towards the Sydney urban area. This relationship coincides with the predominance of intrusive activity southwest of the monocline, and the pattern of registered bore airlift yields (where higher yields are generally recorded in areas of greater intrusive activity; see the discussion on media hydraulic properties below).

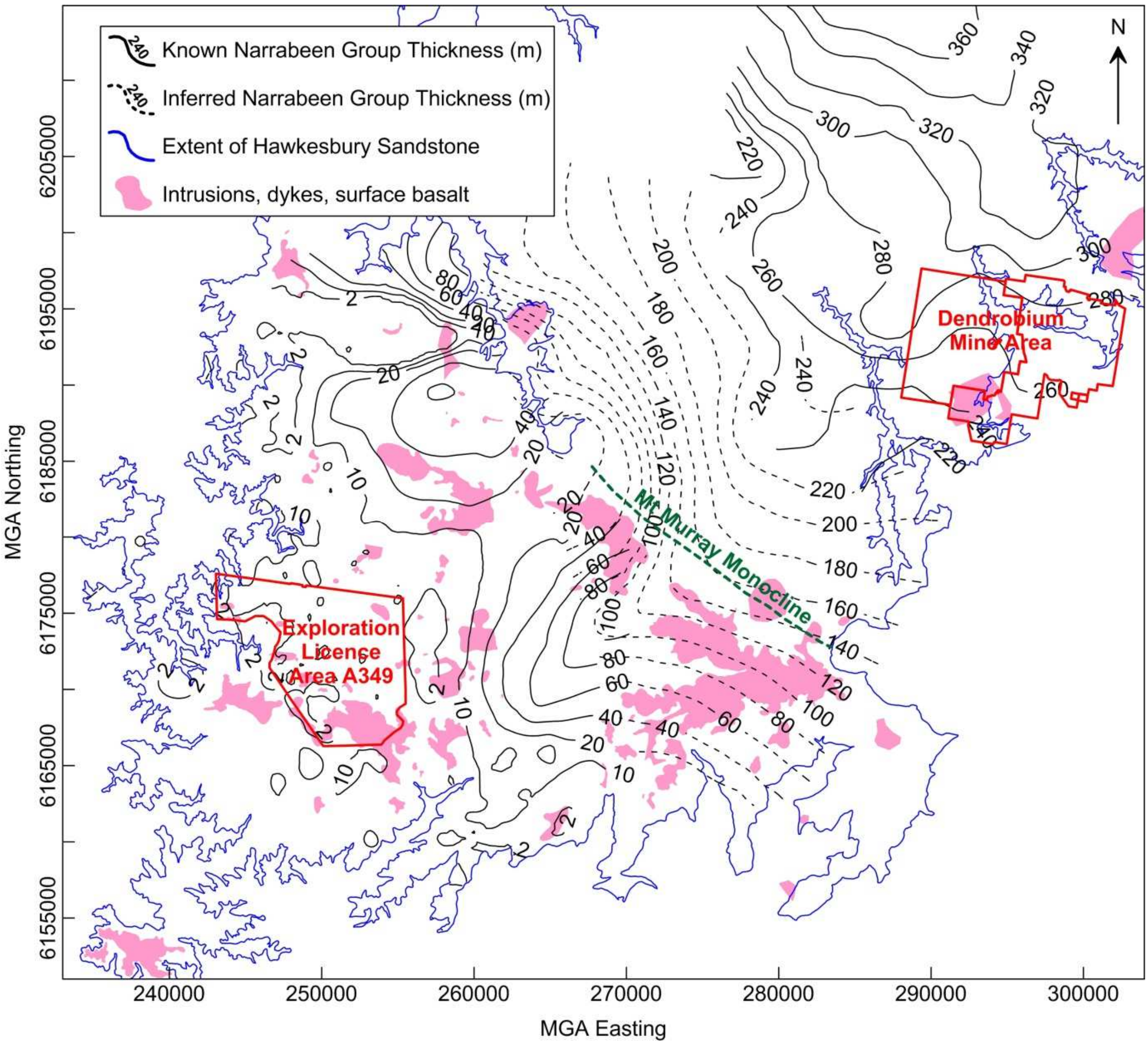


Figure 4.4. Interpreted regional thickness of the Narrabeen Group, from the quality control assessment.

4.3. Faults and Intrusions

Blue Circle Southern Cement (BCSC) (1993) identified two main structural features in the area:

- The Cement Works Fault (Figure 4.5), located southeast of the Wingecarribee River, with an estimated displacement of 65 m near the Berrima Cement Works. The fault strikes approximately WNW-ESE. The degree of displacement diminishes moving westwards towards the Wingecarribee River. It is thought that a number of volcanic intrusions may be associated with this fault. Anecdotal information from more recent years indicates displacement from this fault was not explicitly identified at Berrima colliery. International Environmental Consultants (IEC) (2008) reports that borehole information and surface inspection of the (Wingecarribee) riverbed suggested that the fault displacement probably reduced to nil before reaching (that is, to the east of) the river. The fault has not been mapped beyond the Wingecarribee River.
- A major dome structure located near Berrima township. Its presence was interpreted from aeromagnetic survey data, coal seam floor structure contours, and a dolerite sill intersected by boreholes (see Figure 4.6), thought to be a southwesterly manifestation of the dome.

Figure 4.5 shows the Cement Works Fault and faults in the Hume mining area interpreted by Hume. Also shown are subsurface barriers to groundwater flow that were required to achieve a reasonable model calibration to observed hydraulic heads. These barriers are discussed in greater detail in Volume 2.

The large change in displacement of the Cement Works Fault over such a relatively small distance would suggest the fault plane is not an extensive subvertical plane with consistent displacement. Figure 4.6 shows magnetic field intensity over the area. Also shown are four diatremes (D1 to D4) interpreted by BCSC (1993); these are discussed further below. East of the Hume Highway, a magnetic anomaly is associated with the fault where the fault's displacement is largest. The anomaly indicates a linear igneous media feature associated with the fault damage zone, or remagnetisation of the fault zone from severe movement or thermal change. The absence of an anomaly associated with the fault west of the Hume Highway, and the limited strike of the published fault, suggest the width of the fault zone is smaller there, possibly associated with a smaller displacement. Paul et al (2009) provide results from various authors indicating a direct relationship between fault strike length and fault damage zone width. Three parallel lineaments in the NNE-SSW direction are qualitatively interpreted as part of the current work. These lineaments support the interpreted trend in the K field (see Section 5).

Exploration efforts in the Berrima lease also identified a large syenite plug formed as a result of Tertiary Period volcanic activity, located at Mt Misery, northwest of Berrima township. Seam floor contours indicate that this structure has had a significant impact on the coal seam in its vicinity. However, the structure is distant from the Hume mining area.

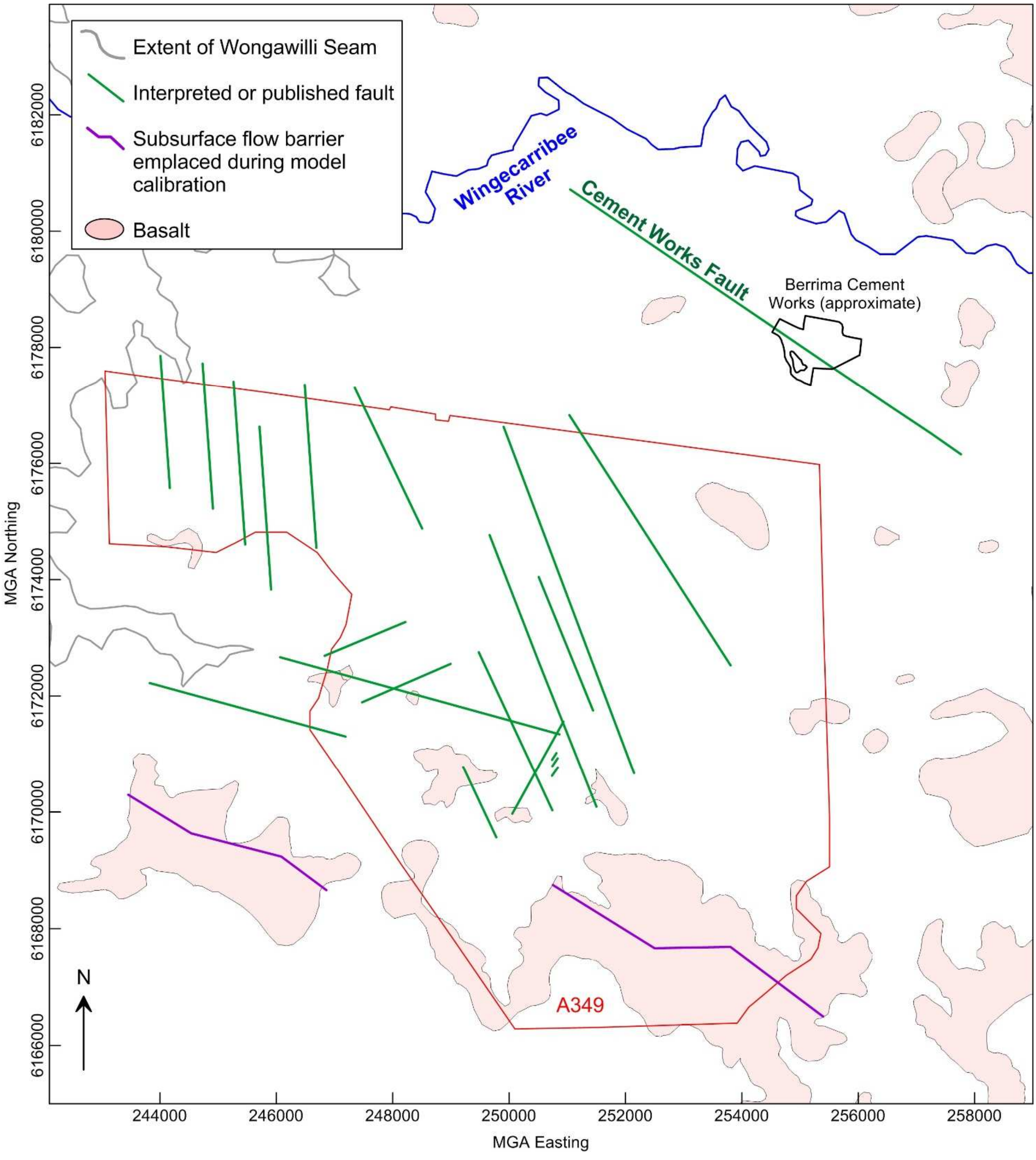


Figure 4.5. Interpreted and published faults in the Hume area, and subsurface barriers to groundwater flow interpreted during model calibration.

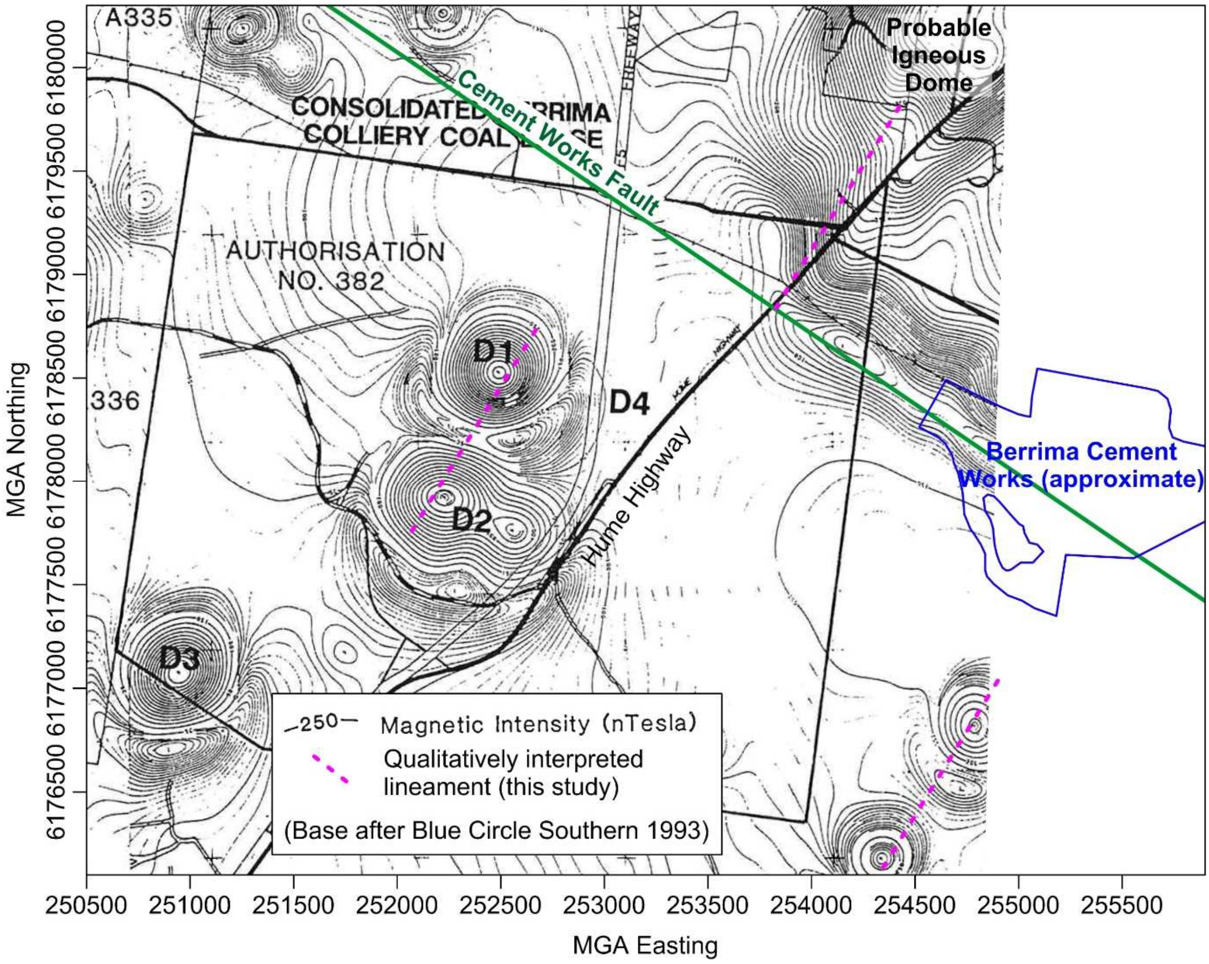


Figure 4.6. Magnetic field intensity compared to the Cement Works Fault (base after BCSC 1993).

The regional area has a higher density of igneous intrusions than elsewhere in the Sydney Basin (refer to the discussion on sub-surface hydraulic properties below). The closest known intrusions to the proposed Hume mine workings layout are shown in Figure 4.7 (after BCSC 1993), comprising intrusions D1 to D4 (interpreted in BCSC 1993) and the Mount Gingenbullen intrusion.

BCSC (1993) undertook a detailed interpretation of intrusions D1 to D4 using borehole logs, aeromagnetic survey data, and ground-based magnetic survey data. These intrusions were classified as diatremes, generally consisting of analcime or olivine basalt, or basalt breccia. Each plug is encircled by a disturbed zone of sedimentary and volcanic breccia. Disturbed zones vary in thickness between 20 m and 60 m. Plug boundaries were reported to be mapped with an accuracy of 5 m while the disturbed zone to an accuracy of 10 m. For mining purposes, BCSC (1993) made allowance for a 20 m safety zone around diatreme boundaries. Observations made at Ulan coal mine, where numerous igneous plugs and sills are present, indicate that increases in inflows to the workings generally occur within about 100 m, or less, of the edge of such a feature (after intersection of the disturbed zone). At Ulan mine, wherever mining has occurred in proximity to, but outside, the disturbed zone, the effects of the intrusive feature on the observed hydraulic head field, and on inflows at the working face, appear to have been absent. Perturbation in the hydraulic head field due to the properties of the feature is thus assessed as being likely to occur only with intersection of the disturbed zone.

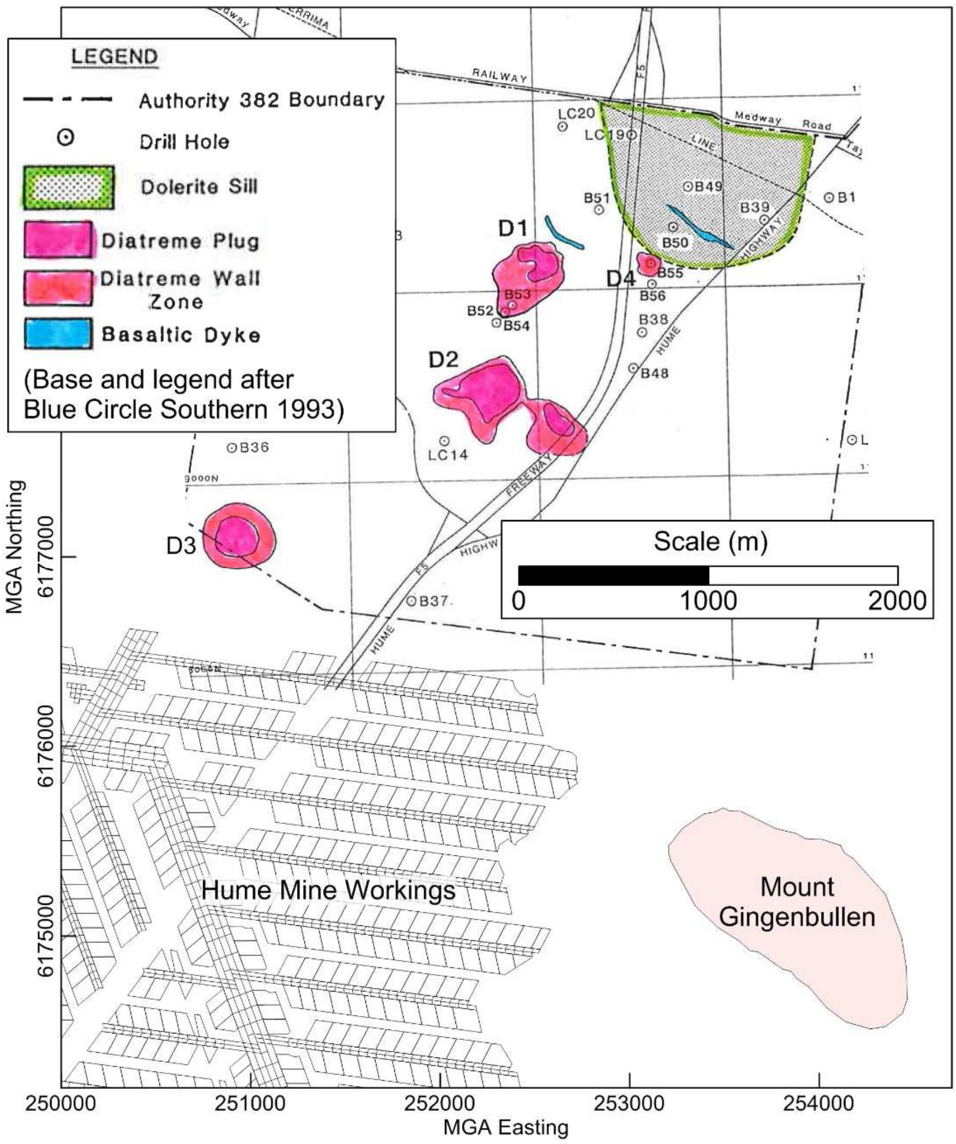


Figure 4.7. Known intrusions close to the proposed Hume mine workings (base and legend after BCSC 1993).

4.3.1. Mount Gingenbullen

The Mount Gingenbullen intrusion (see Drawing 1) is located in the northeastern corner of A349, forming a steep hill. Thomas et al (2000) describe the intrusion as a horizontal sill 80 m thick and composed of crudely columnar quartz dolerite that intruded the Wianamatta Group shales and sandstones. Its overburden has been removed by weathering. In surface expression the intrusion is approximately 1200 m long and an average of about 350 m wide. The published extent of the intrusion (see Figure 4.7 and Drawing 1) is a minimum of 600 m from the proposed workings. Figure 4.8 shows the intrusion as a shadow image using topographic elevations obtained from LIDAR (Laser Imaging Detection and Ranging) surveying undertaken by Hume. A quarry was worked on the north eastern flank of the intrusion but is now abandoned. Sedimentary media surrounding the intrusion can be identified on the southern slope of the mountain. The interpreted extent from LIDAR surveying is similar to the published extent.

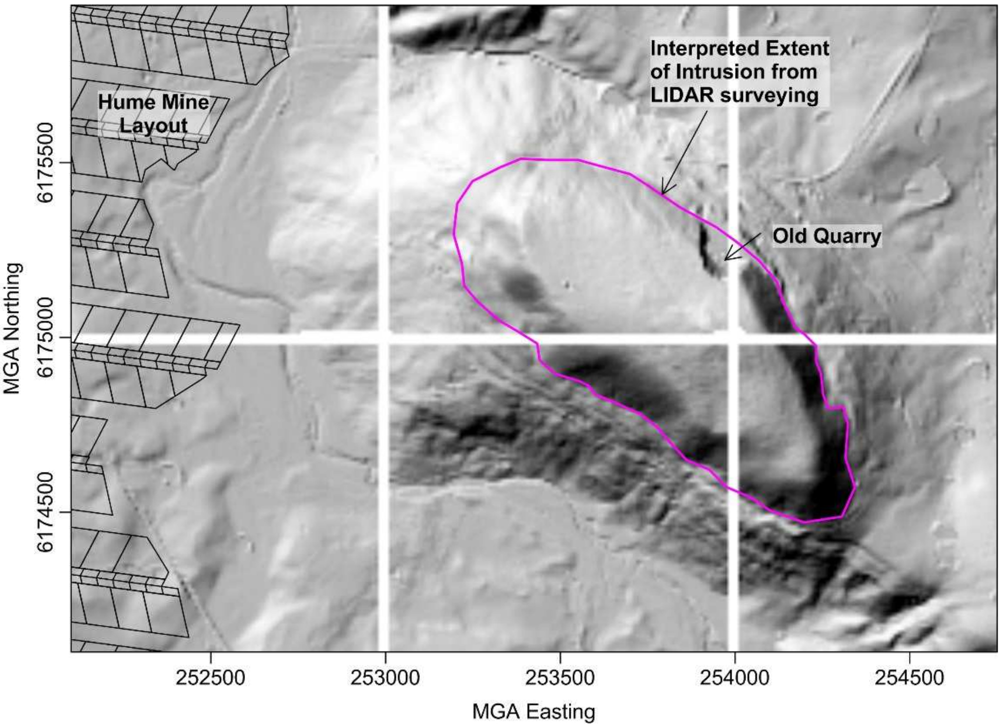


Figure 4.8. The Mt Gingenbullen intrusion as revealed by LIDAR topographic survey.

Allowing for a disturbed zone of 100 m thickness (based on preceding observations and interpretations), it is estimated that at least 500 m of sedimentary media separate the Hume workings from the intrusion. This is supported by drilling information from an exploration bore drilled about 400 m to the north of the intrusion, where a full sequence of the Wongawilli seam was present. Due to its isolated circular nature, the presence of the intrusion is therefore expected to have minimal impact on the evolution of the hydraulic head field during Hume mining operations. Thomas et al (2000) report that the intrusion is a sill, in which case the access gallery for the intrusion (the space defined by the pathway linking the source to the point of intrusion), at the level of the workings, may be smaller in lateral extent than the sill, and the thickness of sedimentary media (between it and the mine) greater.

Intrusions of this type usually locally warp the stress field, and, together with their usually different hydraulic characteristics, may show a contrast in groundwater response (compared to their host rock) when the disturbed zone is intersected. When intersected, groundwater impacts mainly take the form of short-term increased inflows while the storage of the intrusion is depleted, and localised drawdown at the intrusion. After this, impacts mitigate significantly. At reasonable distances these bodies provide imperceptible perturbation to the flow field and groundwater retained in storage by them remains unchanged. For this reason the intrusion is not explicitly modelled.

4.3.2. Berrima Mine

A series of dykes was intersected in the Berrima underground workings. They occur mainly as sub-vertical sheet-like single features and as sub-parallel swarms, generally trending west-northwest, and appear to have intruded minor faulting and joints. They vary in thickness between 0.2 m and 10 m at seam level. They are altered, highly weathered, and relatively soft, with cindered zones on each side. Dyke swarms are generally spaced an average of 400 m apart, ranging from 150 m to 620 m. Some mining panels in the 10 years before the end of mining were truncated to avoid known zones of significant igneous intrusions. The reported average distance between dyke swarms compares favourably with the orthogonal distance between the qualitatively interpreted lineaments in Figure 4.6.

5. Subsurface hydraulic properties

5.1. Hydraulic conductivity

A large database has been compiled of K measurements from insitu hydraulic testing (Parsons Brinckerhoff 2015). The database consists of the following:

- 28 packer tests on the Hume lease.
- Two long-term pumping tests undertaken by Hume on the lease in 2014 (pumping bores HU0098 and GW108194 (Wongonbra) with multiple observation piezometers monitored).
- Six long-term pumping tests from private bores in the area.
- 129 estimates of hydraulic conductivity from specific capacity data in government records for private water bores, for basalt, WG, Hawkesbury Sandstone, and the ICM. Appendix B shows the method used to obtain K from specific capacity.
- Laboratory tests on 39 cores of Hawkesbury Sandstone and Farmborough Claystone, retrieved from five boreholes.

Figure 5.1 shows the K database developed from these measurements. Results indicate decreasing K with depth, but elevated magnitudes in comparison to other areas in the Southern Coalfield. Laboratory results for cores have been approximately corrected for gas slippage but not for overburden pressure; no correction for overburden pressure will bias the results toward higher values.

Figure 5.2 shows packer test results for the regional Southern Coalfield and for the Dendrobium mine leases (all northeast of the mount Murray Monocline; see Figure 4.4), with Hume packer tests (to maintain comparison between consistent observation scales). Salient features of this figure are:

- The Dendrobium area K distribution is similar to the regional Southern Coalfield K distribution.
- The Hume area K distribution is laterally offset from the Southern Coalfield K distribution by about one decade (towards higher values), but has approximately the same rate of decrease with depth.

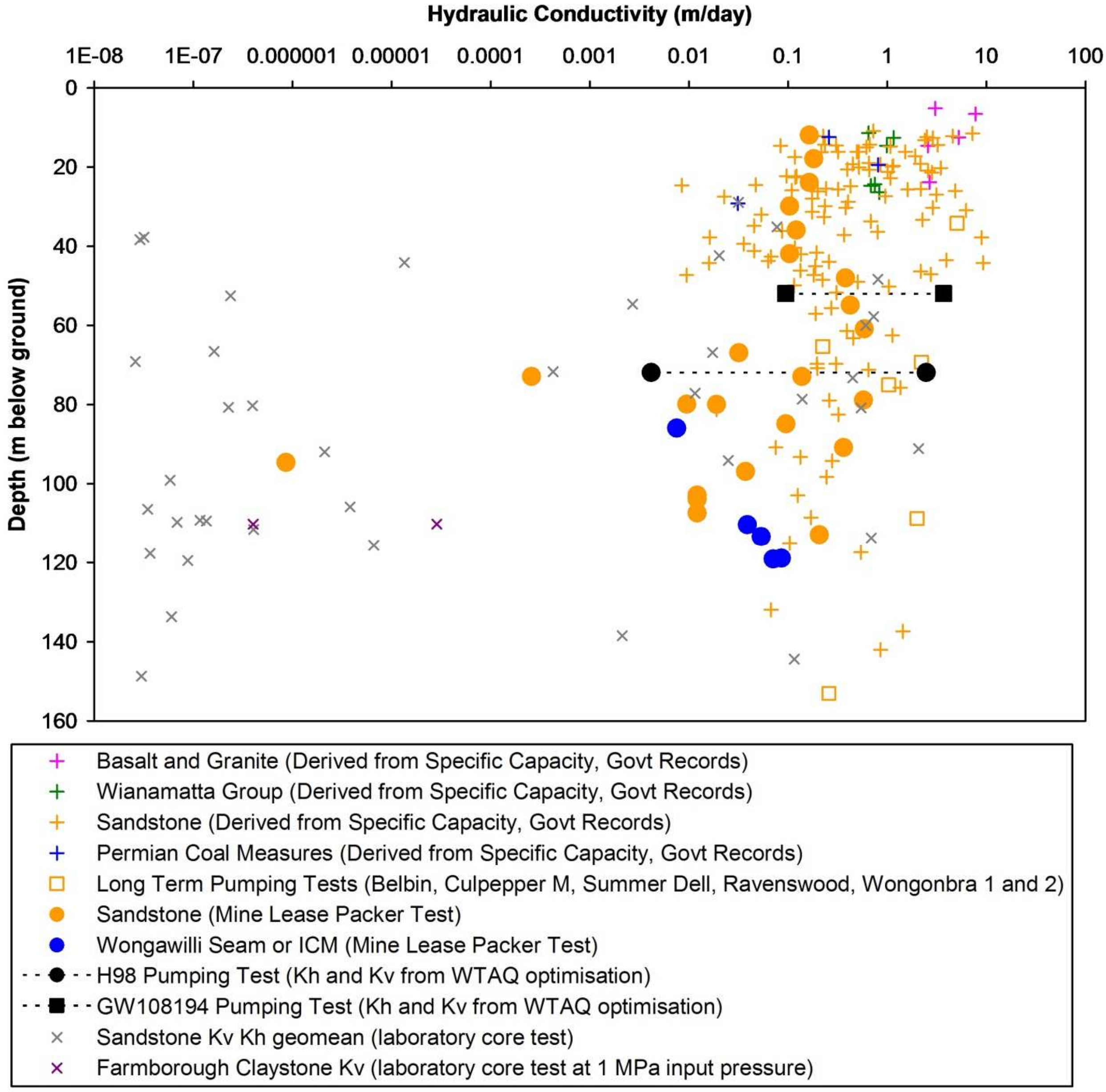


Figure 5.1. K database for the Hume area.

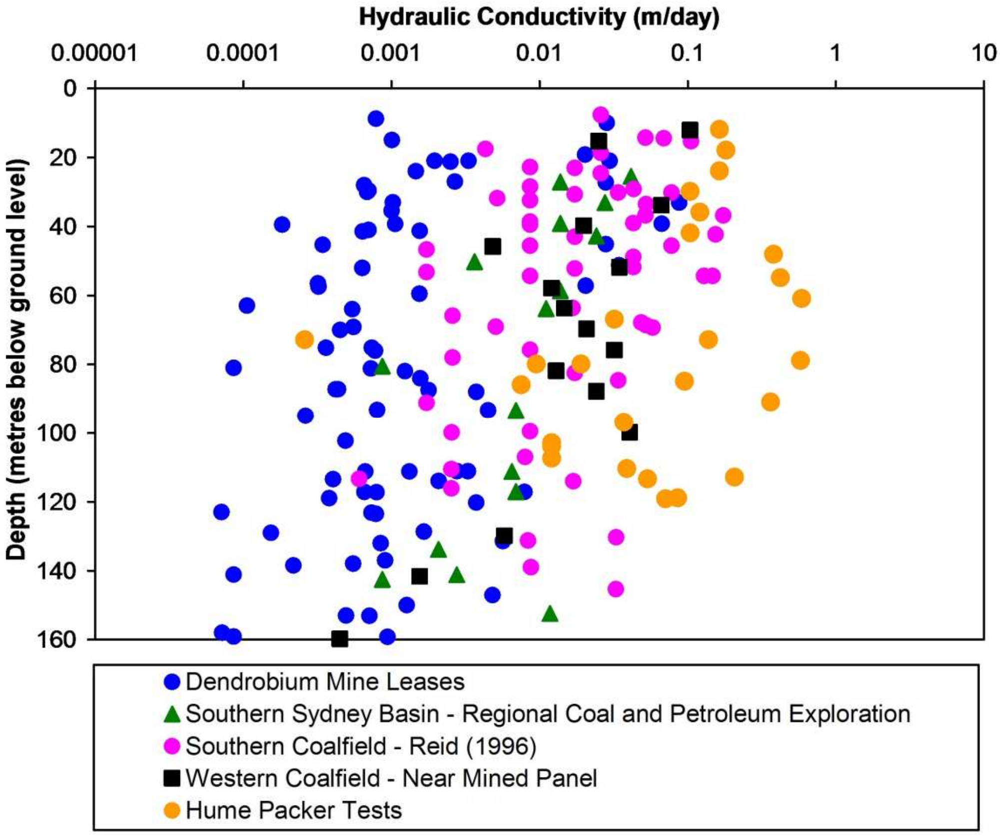


Figure 5.2. Packer test K distributions for the regional Southern Coalfield and the Dendrobium mine leases, compared to Hume area packer tests.

Figure C1 in Appendix C shows the data of Figure 5.2 (without the Hume packer tests, for improved clarity) to greater depths, illustrating measurements obtained in coal seams where natural K has increased due to shrinkage from degasification and reduction in coal seam stresses from proximal full extraction mining and associated caving. These measurements are used as a guide for the Hume area.

Russell (2007) analysed airlift yields in Hawkesbury Sandstone over the Sydney Basin from government records of registered bores and identified lower yields at greater burial depths underneath shale in the Cumberland Basin and higher yields in the southern areas (Figure 5.3). He interpreted the higher yields to the south as being influenced by stress relief, tectonic uplift, and possible solution enhancement of defect and matrix voids. The region southwest of the Mount Murray monocline has also undergone prolific igneous activity. Intrusions are known to permanently alter the natural stress field, due to their emplacement as fluids. The results of Russell (2007) indicate the conspicuous nature of the K field southwest of the monocline. These support the contrast in Narrabeen Group thickness (Figure 4.4).

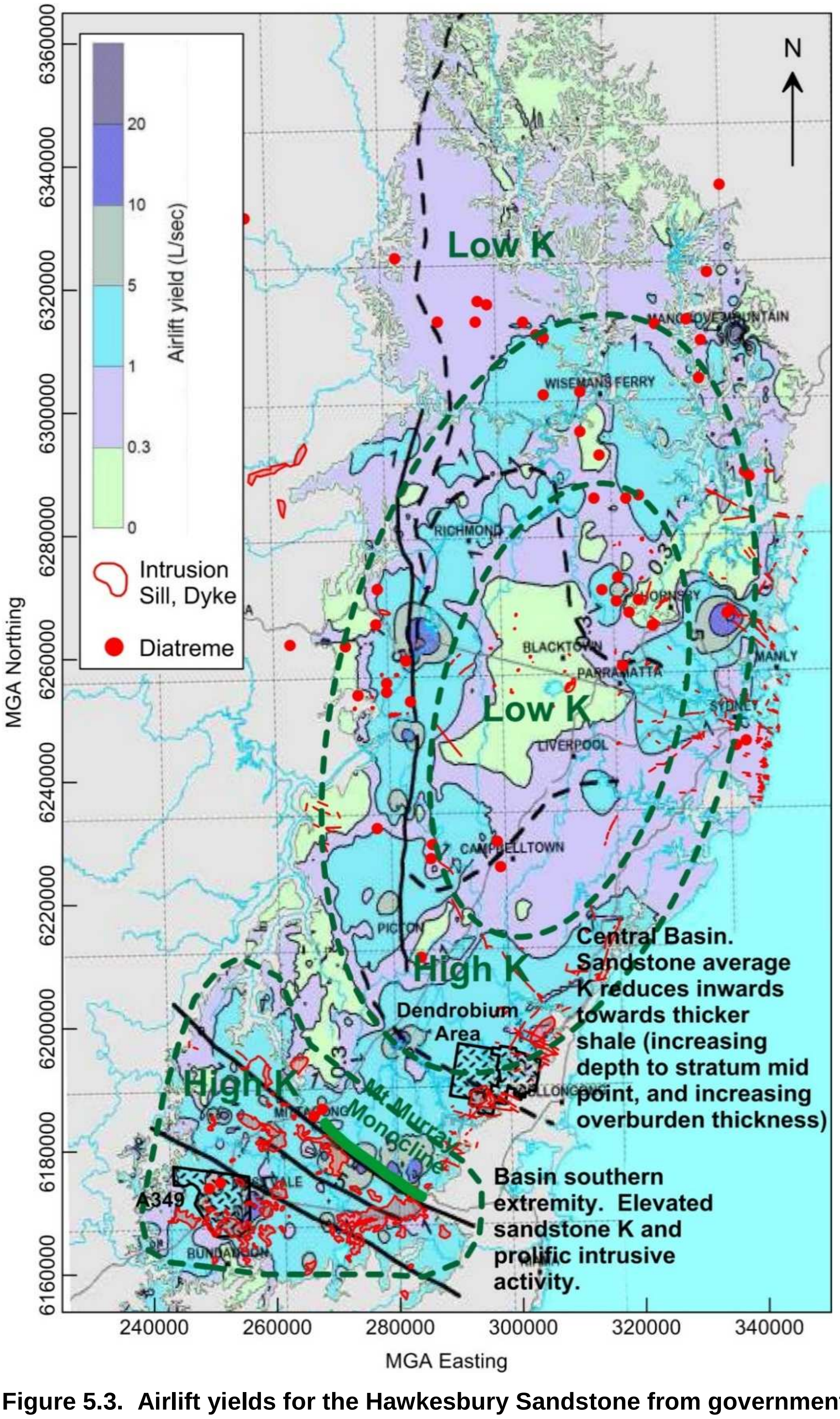
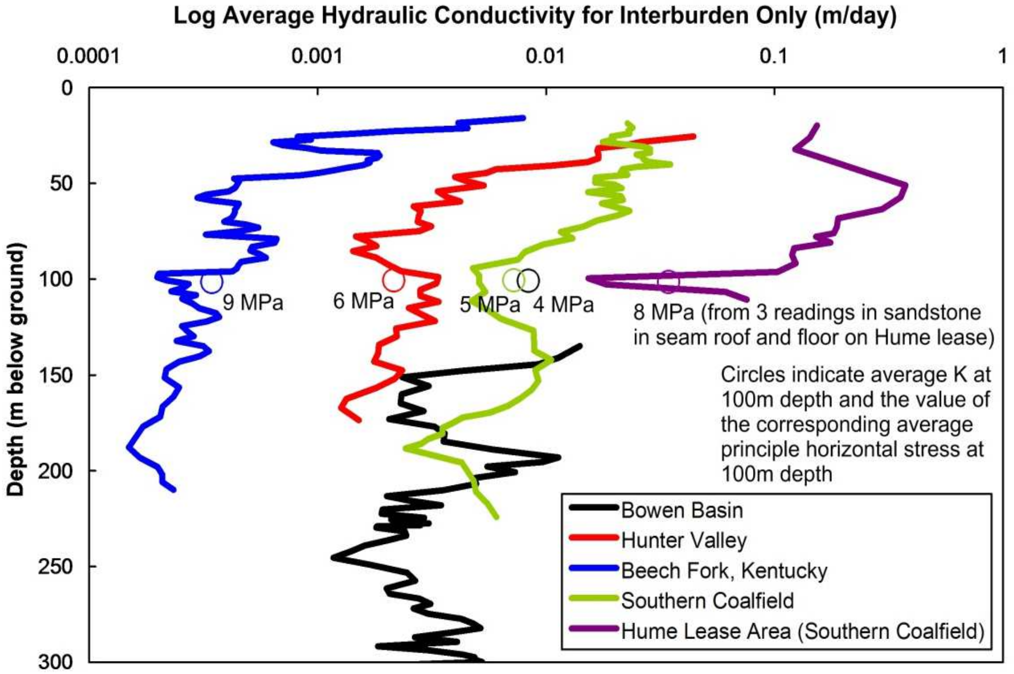


Figure 5.3. Airlift yields for the Hawkesbury Sandstone from government records (after Russell 2007), overlain with igneous structures, mine leases, and interpreted regional trends.

The relationship between the K field and principal horizontal stress magnitude was explored by considering only the stiffer media within the profile. This included general interburden (mostly sandstone) only, and excludes coal seams. Figure 5.4 shows the running 10-point log-average K down the depth profile for Permian Coal Measures (excluding coal seams) at a site in Kentucky (Hutcheson et al 2000a, 2000b), the Southern Coalfield (Reid 1996), the Hunter Valley, and the Bowen Basin, compared to the Hume area. Figure 5.4 also shows the measured principal horizontal stress in the Southern Sydney Basin (Hillis et al 1999) and three measurements undertaken on the Hume lease. All five datasets identify a reducing K with depth, caused by increasing overburden pressure. Average horizontal stress magnitudes for a depth of 100 m as estimated from field measurements are labelled at the average K for each K distribution.

Each distribution has approximately the same rate of decrease in K with depth, mostly caused by increasing overburden pressure (with media densities being similar between areas). Excluding the Hume area, a clear relationship in lateral position of each K distribution and the magnitude of horizontal stress is also apparent, where increasing horizontal stress displaces the lateral position of a K profile to the left (smaller magnitudes).



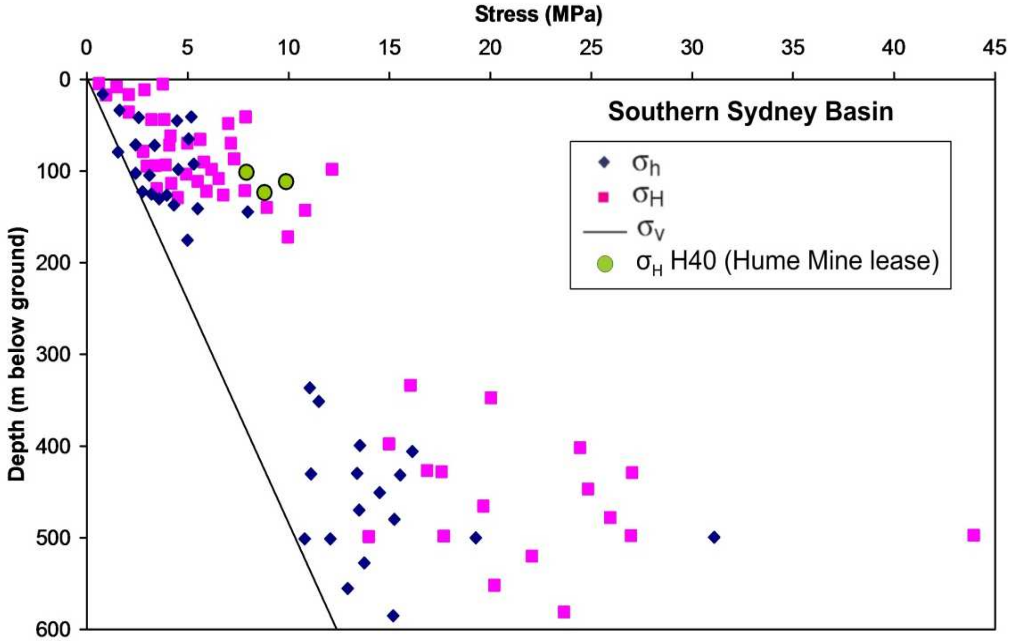


Figure 5.4. Comparison of stress and hydraulic conductivity (K). The upper chart shows K and regional stress magnitude for Permian Coal Measures (excluding coal seams) at four locations in Australia and one in the USA. The lower chart shows actual stress measurements unsegregated by media stiffness, for the southern Sydney Basin (base from Hillis et al 1999). σ_H and σ_h are the maximum and minimum horizontal stresses respectively; σ_v is the vertical stress.

Three stress measurements were undertaken in the Hume area, in bore HU0040CH (Sigra 2012) in the roof and floor of the Wongawilli Seam. One of the roof measurements was reported as having reduced reliability (Sigra 2012). Field measurements returned a principal horizontal stress ranging between 7.9 and 9.9 MPa, oriented just east of magnetic north. Shallow breakout at HU0031CH indicates the potential for locally elevated horizontal stress, typically associated with faults, dykes, and intrusives (SCT 2014). The tectonic factor (excess tectonic lateral stress normalised to rock stiffness) calculated from the measurements ranges between 0.0003 and 0.0006; results are shown in Figure 5.5 (after Figure 6 from Nemcik et al. 2006), indicating average tectonic conditions compared to other coal mines (other data are from SCT measurements only; Nemcik et al. 2006).

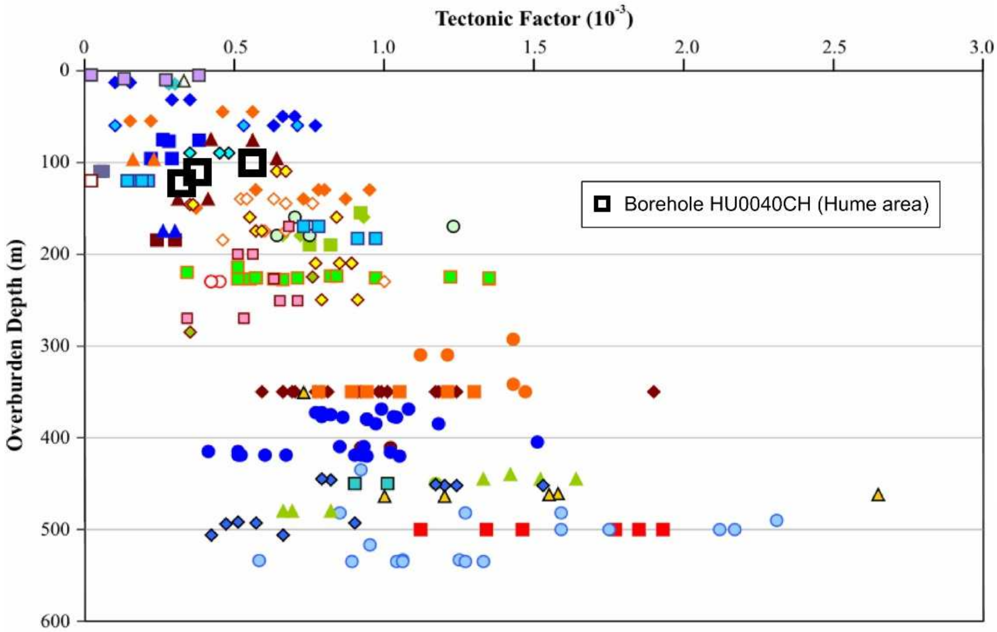


Figure 5.5. Tectonic factor calculated from results from borehole HU0040CH plotted on Figure 6 of Nemcik et al. (2006). Other data (coloured) are from SCT measurements only (Nemcik et al. 2006).

The Hume area is unique amongst the group of areas in Figure 5.4 for the proliferation of igneous activity. Based on the limited stress measurements, it also does not appear to accord with the relationship between K magnitude (at some depth) and magnitude of horizontal stress as seen for the other four areas. Large differences in Young's modulus for the various media may be influencing this. In contrast to the Hume area, the Dendrobium area (also being classified in the Southern Coalfield) has not suffered the same level of igneous activity, and hosts lower K magnitudes. It is believed that the K field in the Hume area results from increased tectonic disturbance and changes induced in the stress field from subsequent intrusive activity.

The large number of K measurements for the Hume lease was used to estimate the spatial variation in K for the Hawkesbury Sandstone for an interval between 14 m and 44 m above its base, with a minimum overburden thickness of 40 m (Figure 5.6). Despite the northwest/southeast trending structures, the K field appears to align with the major horizontal stress direction (just east of magnetic north), but is perturbed by warping of the stress field by igneous intrusions. Figures C2 to C4 in Appendix C present additional information supporting this conclusion.

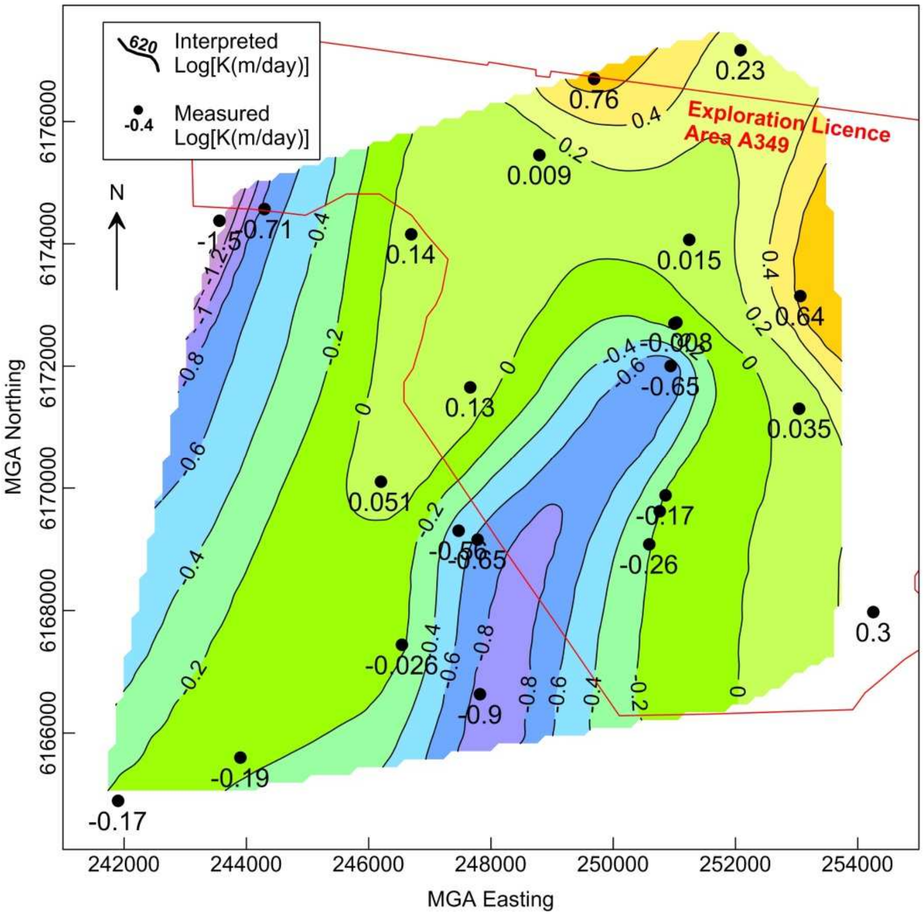


Figure 5.6. Log[K(m/day)] for Hawkesbury Sandstone between 14 m and 44 m above its base.

5.1.1. Pumping tests

Two long-term, single-rate pumping tests were carried out by Hume at bores HU0098 (duration 1 day) and GW108194 (duration 7 days) on the mine lease, with monitoring at multiple observation piezometers for each test (Parsons Brinckerhoff 2015). Pumping bore locations are shown in Figure D1 in Appendix D. Drawdown observations from these tests (observation piezometer nest H96 for pumping at HU0098, and H73 for pumping at GW108194) were subjected to automated parameter estimation using the WTAQ algorithm (Barlow and Moench 1999) for unconfined media, which allows partial penetration and vertical anisotropy. Drawdown records from two monitoring piezometers for each test were simultaneously optimised. The match between calculated and observed drawdowns is shown in Figure 5.7. Optimised K values are shown in Figure 5.1. The optimised average specific yield was 0.015, and specific storage 3×10^{-6} m^{-1}. The ratio of vertical K (Kv) to horizontal K (Kh), Kv/Kh, was 0.0017 and 0.026 for the H98 and GW108194 tests respectively.

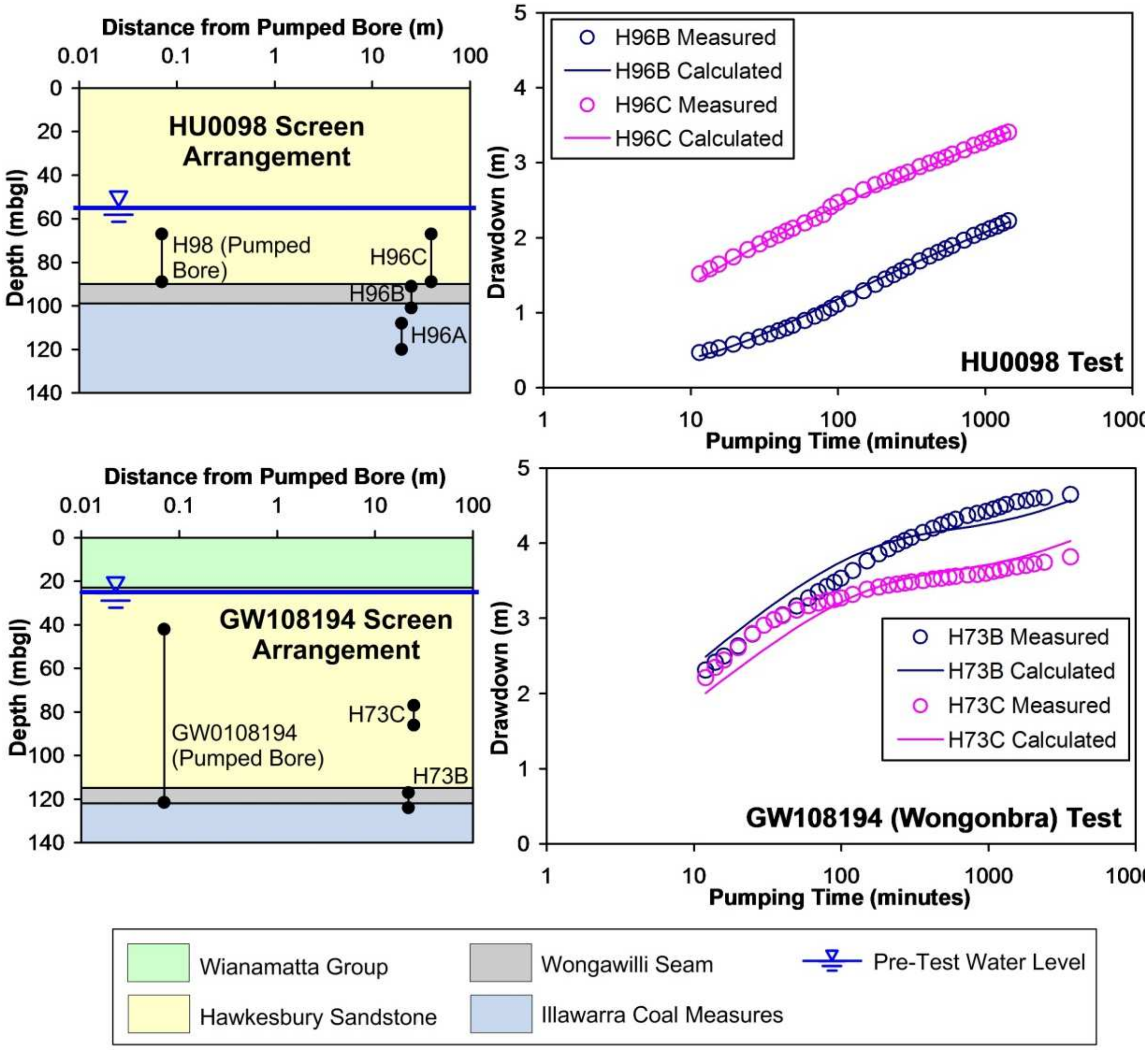


Figure 5.7. Calculated and observed drawdowns using the WTAQ algorithm in an optimisation capacity, for pumping tests at HU0098 and GW108194 on the Hume lease.

5.2. Storativity

5.2.1. Specific yield

Typical coal measures media have a void distribution composed of pores and defects. The pore distribution is created during sedimentation and diagenesis, and individual entities are closely spaced and very small. Defects (existing fractures, joints, and partings, and those introduced by caving) are created during failure of the rock mass (from a changing stress field) and their geometry is completely different to pores. Drainage occurs quickly from defects and slowly from pores. The majority of the total void space is contained in the pores (typically 10% to 20% of the medium) however observations demonstrate that this void space contributes negligibly to specific yield (Sy) in the medium term. This is due to the moisture retention characteristics of the matrix. It can withstand much higher suction (compared to defects) prior to pore drainage. This is amplified by the absence of solar radiation in underground voids.

If the time rate of water table change in defects is rapid compared to matrix K then overall Sy may approach defect Sy. Conversely, where the time rate of water table change is slow compared to matrix K, overall Sy may have a non-negligible matrix component.

Specific yield, void space, and specific storage usually decrease with depth. Sy for coal measures rocks is rarely more than a few percent, ranging from less than 0.01 for claystones to around 0.02 to 0.03 for highly fractured sandstone. Typical published estimates are 0.013 for Devonian siltstone (Risser et al. 2005) and 0.012 for laminated shale (Woods and Wright 2003). Unpublished results from Australia are an Sy of between 0.005 and 0.007 (over 5 years) for Permian coal measures (claystone, sandstone, and interbedded coal) in the Western Coalfield, and an Sy of between 0.004 and 0.008 (over 3 years) for Permian coal measures in the Hunter Coalfield. Studies conducted in the Sydney metropolitan area and elsewhere indicate a specific yield of between 0.01 and 0.02 is reasonable for typical, undeformed Hawkesbury Sandstone (Tammetta and Hewitt 2004). The transient aspect of Sy is important.

5.2.2. Specific storage

The dominant component of specific storage is media compression, mostly via contraction of defect apertures. The specific storage of Hawkesbury Sandstone in the Blue Mountains west of Sydney has been estimated to be about 1×10^{-6} m^{-1} (Kelly et al. 2005) in the upper zones where fracture flow is dominant. Results of long duration pump testing in Hawkesbury Sandstone in western Sydney (Tammetta and Hawkes 2009) indicated an average specific storage of 1.5×10^{-6} m^{-1} for depths between ground surface and 300 m.

Assuming that the total primary and secondary porosity that allows fluid flow ranges between 10% at the surface and 5% at depth, and assuming that the medium is incompressible, then the specific storage ranges between 4.5×10^{-7} m^{-1} at the surface to 2.3×10^{-7} m^{-1} at depth (field measurements of specific storage show its depth variability; see for example Heywood, 1997). Greater media compression is possible at shallower depths, where flow through defects predominates, than at deeper depths.

5.2.3. Defect distributions

A Coffey in-house borehole imaging database for the Hawkesbury Sandstone (from a number of large infrastructure projects in the Sydney metropolitan area) provides 5671 defects in 89 bores which has been analysed to assess defect spacing and aperture (Figure 5.8). Defect spacing is an average of about 1 m to 2 m at depth. Spacing distribution occurs in cycles, with the recurring pattern for a group of defects rarely extending more than 20 m along the profile.

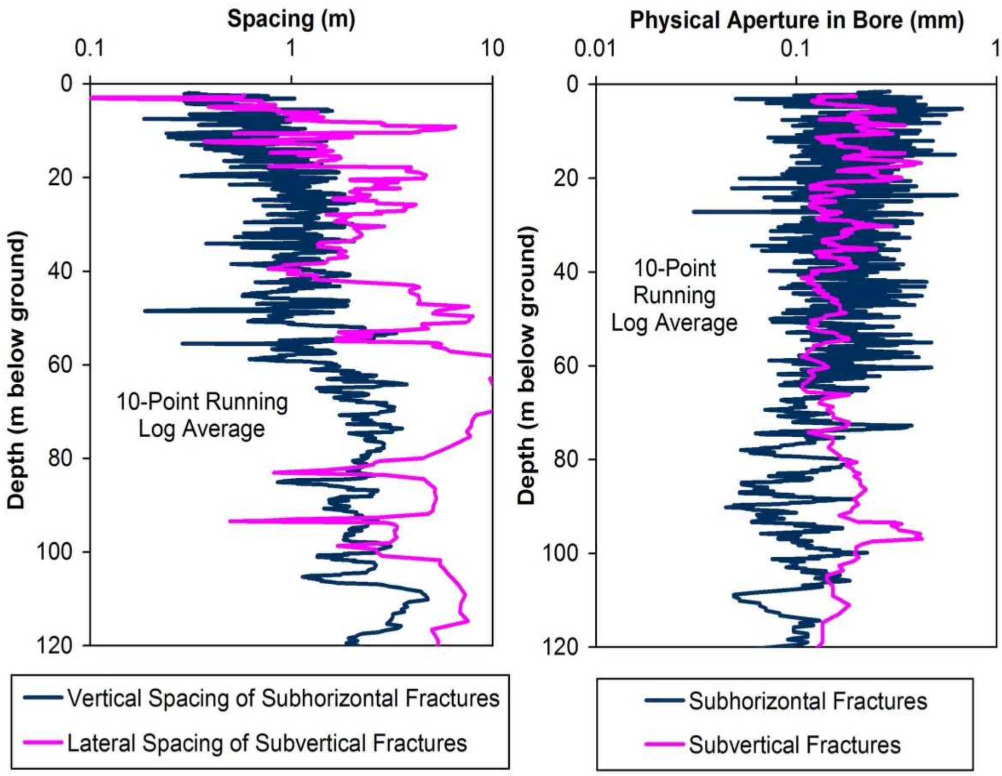


Figure 5.8. Defect spacing and aperture estimated from acoustic imaging of Hawkesbury Sandstone in the Sydney metropolitan area.

For typical claystones, inclined defects of non-zero aperture are recorded at depths up to 500 m (see for example Risser et al 2013). Kv can be controlled by defects and also open boreholes. The Hume area has a high density of such boreholes, mostly in sandstone. Numerical simulation of a regional shale sequence (the Maquoketa Formation) by Hart et al (2006) suggested a large scale Kv of 1.6 x 10^{-6} m/day. Matrix measurements of Kv ranged between 1.6 x 10^{-9} to 3.5 x 10^{-7} m/day. Based on bore logs, erosional windows or high-conductivity zones were considered unlikely. Defects penetrating the entire thickness of shale, spaced 5 km apart with an aperture of 50 microns, were estimated to provide sufficient flow across the sequence to match that provided by an equivalent bulk Kv of 1.6 x 10^{-6} m/day. Alternatively, 50 bores of 0.1 m radius open across the sequence, evenly spaced 10 km apart, could also match the model Kv. This case study illustrates a requirement to characterise large-scale Kv for regional simulation, and the inapplicability of using matrix measurements.

5.3. Summary

Hydraulic conductivity and storativity in the Hume area decrease with depth. The K field for the Hume area has greater magnitudes than seen elsewhere in the Southern Coalfield. This is believed to be the result of significant tectonic disturbance and associated intrusive activity. At the scale of packer tests, Kh ranges from about 1 m/day near the surface to about 0.1 m/day at 100 m depth. For measurements in the same depth interval, the Kh distribution is log-normal, with a standard deviation of between 0.5 and 0.8 decades around the geometric mean.

Kv/Kh is approximately 0.01. Kv has also been enhanced by the large number of open private water bores present in the area. Storativities for the Hawkesbury Sandstone calculated from pumping tests are in agreement with published values.

6. Groundwater levels

Groundwater levels in the Hume area are monitored by Hume using an extensive network of vibrating wire piezometer (VWP) and standpipe piezometer (SP) installations. The network comprises 46 SPs at 19 locations, 11 VWPs at 3 locations, and 2 private water bores. This provides 59 subsurface measurement points at 24 locations. Typically, a monitoring site comprises several SPs in separate boreholes. The Hawkesbury Sandstone and Wongawilli Seam are screened at most of these locations. Several monitoring sites comprise a single borehole with several VWPs fixed at various depths down the borehole in grout. Monitoring commenced in late 2011 when the first piezometers were installed, and has continued to the present. Useful monitoring information is also available from the Berrima Mine monitoring network (VWPs and bores), and a government monitoring network in the regional area.

These data were combined into a database which allows identification of natural and human processes, in preparation for conceptual model development. Appendix D presents a register of monitoring piezometers and bores forming the three monitoring networks, maps showing their locations (the regional area and a detail around the Berrima mine), and water level hydrographs. For numerical simulation, piezometers where no saturation was ever recorded, or where the screen interval is unknown, or where the screen interval or hydraulic interval is excessively large compared to model layer thicknesses, have not been used.

Government records for registered bores indicate that three private bores (GW043849, GW106337, and GW059975) occur over existing Berrima mine workings (see Appendix D). These provide useful historical information regarding impacts from mining.

6.1. Hydrographs

Water levels are relatively stable in the Hume lease area, except for periodic drawdown induced by pumping at private bores close by. Small long-term decreases in hydraulic heads are apparent at some locations; numerical simulation suggests this is depressurisation occurring from private pumping and drainage from existing mines. Significant vertical hydraulic head gradients generated by full extraction mining at Berrima are clearly seen at B62 and B63, which are alongside the last portion of workings (full extraction) to have been undertaken at the mine over the period 2011 to 2013.

Slow recovery from sampling events is seen at sites HU37 and HU38. Periodic drawdown in monitoring piezometers greater than 5 m, interpreted to be caused by periodic groundwater pumping from nearby private bores, is present at HU32LD, HU35, HU88, GW075034, and GW075036. Periodic drawdown smaller than 5 m amplitude, caused by private pumping, is interpreted to be present at HU40, HU72, HU73, GW075032, and GW075033. This provides useful information on the presence of private pumping bores, and is further discussed below. The location of GW075033 is shown in Figure 6.3 below; it is far to the east of the Hume area (near Wingecarribee Swamp) and not considered further, except for hydraulic head surface compilation. Water levels at GW075033 may be partly controlled by variations in the Reservoir water level. Observations made in 2015 at HU118 are to be confirmed. HU136B appears to have failed in late 2014 and Hume is currently in the process of decommissioning it.

Hydraulic head observations in the vicinity of the Berrima mine provide vital calibration targets and conceptual information. Details of the monitoring piezometers and bores around the mine are provided in Appendix D. Monitoring bore C Mon (Culpepper Monitoring) was converted from an old coal exploration bore (believed to be B28). It penetrated the Wongawilli Seam and shows little variation in water level except during approach of the Berrima Mine working area in mid-2012 when the bore failed and was reported blocked at a depth of about 40 m below ground. The water level fell to below the blockage at around the same time. This behaviour was caused by large depressurisation in the Wongawilli seam at the bore location, and penetration of the Wongawilli seam by the bore. Other bores in the vicinity, completed to shallower depths (C Prod and DeBeaujeu), maintained measurable water levels at the same time.

Private bore GW059975 was installed in 1983 over Berrima mine 1st workings that were mined prior to 1982 (and probably prior to 1977). It had a recorded water level of 37 m below ground. The bore was 92 m deep and the top of the Wongawilli seam is at an approximate depth of 125 m at that location. This indicates saturation above 1st workings areas, consistent with Tammetta (2013). Neither the current bore status nor water level is known.

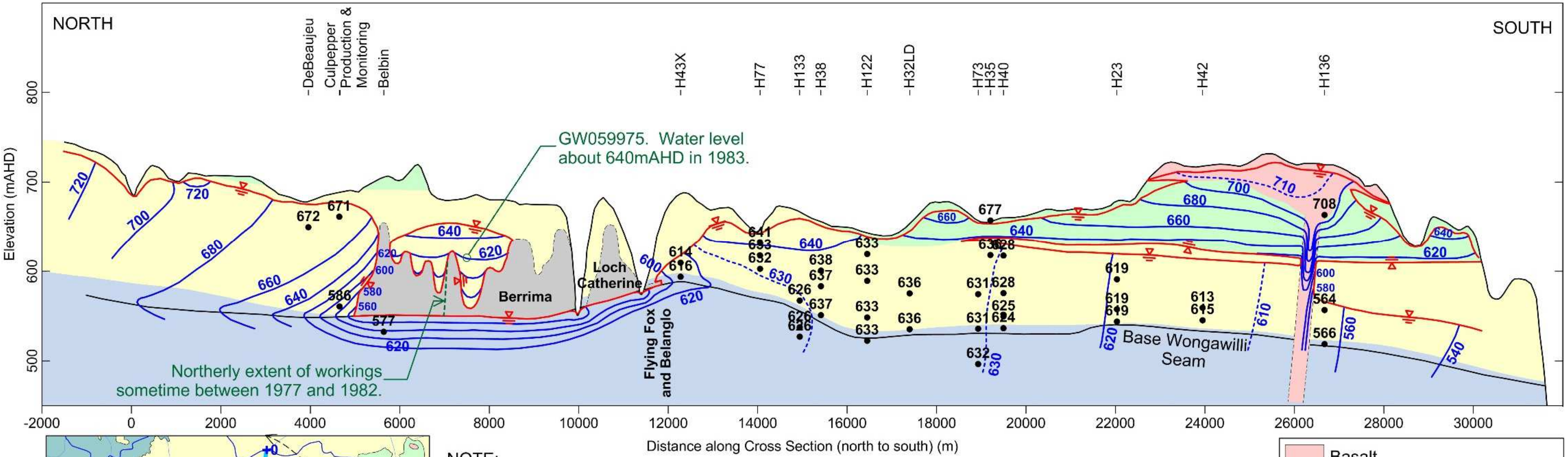
Bore GW106337 was installed in 2002, to a depth of 122 m, probably having intersected the Wongawilli Seam, in another portion of the 1st workings area mined prior to 1982. No measured water level is recorded at its installation, however it appears to have sustained a water level at installation since it was reported as going dry in 2005 and subsequently abandoned. It may have penetrated a pillar instead of a roadway, which probably provided a reasonable seal at the base while hydraulic heads were not drawn down below some threshold (below which pillar drying would occur).

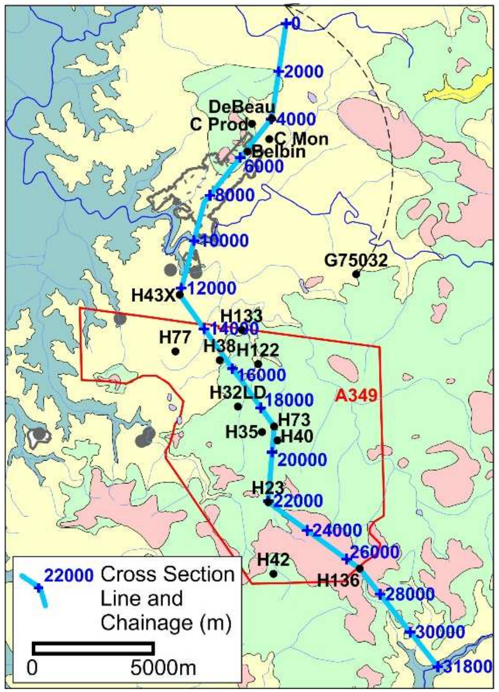
The current Belbin bore is a deeper replacement for a previous bore in the same location (overlying full extraction workings) which went dry after undermining. The previous bore was drilled in May 2004 to 115 m depth; it dried up and the replacement bore was drilled in April 2008 to 186 m depth. The replacement bore was screened in saturated media below the mined seam, harnessing the pressures and reasonable water quality present there. The C Prod (Culpepper Production) and DeBeajeu bores show drawdown accompanying the approach of the full extraction working area in the northern part of the Berrima mine.

6.2. Vertical hydraulic head gradients

To assess the hydraulic head field in three dimensions, hydraulic heads were first assessed by developing a hydraulic head cross-section for late 2013 / early 2014 through the mine lease (Figure 6.1). Results suggest a high probability of a desaturated zone beneath the shale in the southern part of the lease. Other salient features are:

- Hydraulic heads in the sandstone near the Berrima and Loch Catherine mines are largely controlled by the Wongawilli seam deformation processes resulting from full extraction, creating moderate to strong vertical gradients. The effect from Berrima has migrated northwards in a normal way, but has only migrated slightly to the south, influenced by barriers caused by incision of the sandstone by drainage courses.
- Vertical hydraulic head gradients are very small in the central area over the lease (overlain by WG), due to its distance from mining and escarpments. This suggests minimal recharge from above. On approach to escarpments, vertical gradients are generated by the discharge (and associated decrease in hydraulic head) at escarpment seepage faces (usually consumed by vegetation), and rainfall recharge vertically above (direct to the sandstone).
- Hydraulic heads and structure contour surfaces taken in tandem indicate a very high probability of a major sub-vertical structural feature present in the southern part of the lease, running approximately ENE-WSW, underneath the basalt body. The structure was likely an access gallery for the basalt extrusion, and appears to exhibit the classical behaviour of increased K along its plane, but decreased K in a direction normal to its plane.
- The hydraulic effect of the small bord and pillar operations in the escarpments (Flying Fox and Belanglo on the section) is to contract the water table further in towards the main body, and main recharge area, of the hydrostratigraphic unit.





NOTE:

1. The vertical hydraulic head gradient at chainage -1000 was estimated using the gradient at GW075032, since the radial depressurisation, and topography, are similar at both locations. This nest indicates a a hydraulic head difference of 16m between 147m and 110m above the base of the Hawkesbury Sandstone.
2. Zones in the southern (old) part of the Berrima Colliery workings where the extraction type is unknown are assumed to have undergone full extraction.
3. Flying Fox and Belanglo Collieries are assumed to have undergone 1st workings only.
4. The estimated height of desaturation over existing workings is calculated using Tammetta (2013). The height is representative for the plane of the cross-section, and is not necessarily the maximum height.
5. The position of the water table was estimated using the hydraulic head, pressure head, and pressure head gradient.
6. The hydraulic head for the Culpepper Monitoring bore is taken as midway between the reported blockage in 2012 (40m below ground), and the base of the bore (143m below ground).
7. The hydraulic head in the Wianamatta Group at H35 does not correlate with the section because there is a 15m difference in topography between it and the section. It demonstrates the curvature of the water table and the vertical gradients that are typically present in the Wianamatta Group, there being a difference of about 15m between H35 and the section line, in a direction normal to the section line (about the same difference as the fall in ground level). H35 Wianamatta Group has a pressure head of 20m at 24.5m below ground level.

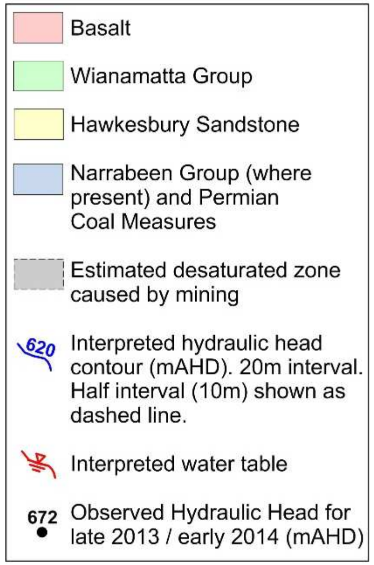


Figure 6.1. Interpreted hydraulic head cross-section for late 2013 / early 2014 through the Berrima and Hume mine leases.