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10 July 2018

David Kitto
Resource Assessment
Department of Planning & Environment
320 Pitt Street
Sydney NSW 2000

Re: Response to Independent Expert Report - Groundwater Modelling Review

Dear Mr Kitto,

Following the public exhibition of the *Hume Coal Project Environment Impact Statement* (EIS), the NSW Department of Planning and Environment (DPE) engaged Hugh Middlemis of Hydrogeologic Pty Ltd to conduct an Independent Expert Review of the Hume Coal Project EIS Groundwater Model and related modelling elements (Coffey 2016a,b). A draft copy of Hydrogeologic's *Hume Coal Project EIS Independent Expert Review Groundwater Modelling* was issued to Hume Coal in December 2017 (Attachment A).

In response to the Hydrogeologic report and submissions received during the exhibition period, Hume Coal engaged HydroSimulations to review the Hume Coal EIS Groundwater Model and update where required to address issues raised. The results of the HydroSimulations modelling work are presented in *Hume Coal Project Revised Groundwater Modelling for Response to Submissions* (HydroSimulations 2018) (Attachment B).

A summary of nine key issues raised by Hydrogeologic and the Hume Coal responses are provided below, in no particular order. Other minor issues raised by Hydrogeologic are addressed in HydroSimulations (2018).

1 Response to key issues

1.1 Water Balance

1.1.1 Independent Expert Review

Hydrogeologic (2017) states that the approximate 5% discrepancy term within the water balance tables was not sufficiently clarified and had the potential to be misinterpreted by readers as indicative of a poor model solution relative to the national guideline set criterion of less than 1% discrepancy at any stress period (Barnett et al. 2012). However, Hydrogeologic notes that the water balance data presented were reported as the "average flow budget" over a range of stress periods and are consistent with aquifer storage depletion due to mine dewatering, so the discrepancy is understandable.

Further, Hydrogeologic states 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.

1.1.2 Hume Coal response

Hume Coal agrees with Hydrogeologic that the water balance tables required clarification and explanation. The language and terminology have been reworded in HydroSimulations (2018) for clarity and transparency.

With respect to model performance HydroSimulations (2018) clarified that with the rerun of the EIS model using MODFLOW SURFACT V4, which applied more sophisticated solver software, a mass balance error of less than 0.2% was achieved. This mass balance discrepancy indicates good model performance and is below the 1% criterion set in the national guidelines (Barnett et al. 2012).

1.2 Calibration

1.2.1 Independent Expert Review

Hydrogeologic (2017) refutes claims made in submissions that the EIS model is a Class 1 model due to an scaled root mean squared (SRMS) statistic of 11.9%. Although Hydrogeologic does agree that an SRMS of greater than 10% is a Class 1 model indicator, it is noted that there are few other characteristics within the EIS groundwater model indicative of a Class 1 model, and many more of Class 2. Hydrogeologic states the Class 1 classification given to the model within submissions is a misrepresentation (quoting the term 'cherry picking') of the national modelling guidelines commentary (Barnett et al. 2012) and assesses the model to be of a Class 2.

1.2.2 Hume Coal response

Hume Coal agrees with Hydrogeologic that the Hume Coal Groundwater Model is of at least Class 2 and is therefore fit for the use as an assessment tool. To reinforce this, the model SRMS was reduced down to 10.76%, and approximately 30% of the uncertainty realisations achieved less than 10% root mean squared error (RMS), following model revisions and the upgrade to MODFLOW USG software.

1.3 Modelling of the interburden

1.3.1 Independent Expert Review

Hydrogeologic (2017) states that the description of the interburden between the Hawkesbury Sandstone and the working section of the Wongawilli coal seam is unclear, and needs to be considered and then clarified in the report.

1.3.2 Hume Coal response

HydroSimulations' (2018) review agreed reporting was not always clear and therefore investigated this in detail in the model. HydroSimulations (2018) found that the interburden thickness (or absence) is correctly represented in the EIS groundwater model and did not require any change as part of the model revisions, and this was then clarified and explained more clearly in the updated report.

1.4 Representation of the height of relaxation

1.4.1 Independent Expert Review

Hydrogeologic (2017) identified inconsistencies within the EIS groundwater model report (Coffey 2016b) in relation to the implementation of the relaxation zone simulated above the Hume Coal Project mine footprint. Hydrogeologic noted that Figure 5.2 of the EIS groundwater model report (Coffey 2016b) indicates the relaxation zone above the Hume Coal mine area extends into the lower Hawkesbury Sandstone and is not consistent with the text in the report.

1.4.2 Hume Coal response

The HydroSimulations (2018) review found that drain cells had been used to simulate the 2 m high relaxation zone in layer 10 only; however, in some areas Layer 10 does not include 2 m of thickness. This was identified following the investigation of layer thickness across the model domain. Subsequent model revisions made have corrected the model to extend the relaxation zone to 2 m 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.

1.5 Drain cell conductance for mining

1.5.1 Independent Expert Review

Hydrogeologic (2017) noted that the calibration of drain conductance to mine inflow and groundwater level data at Berrima mine, as done in the EIS groundwater model (Coffey 2016b), is a good example of a best practice method. The adjustments made to the drain conductance parameter for the Hume Coal Project (comparing differing cell size between the Hume site and Berrima mine) were considered appropriate.

Hydrogeologic also referred to (and disputed) submissions that suggested the conductance value used in the EIS model was incorrectly calculated and too low. Hydrogeologic stated that 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” is incorrect. Hydrogeologic stated that the methods described in some submissions were inapplicable for this project, and therefore inferior to the best practice history match calibration methods which were applied to the EIS groundwater model.

1.5.2 Hume Coal response

HydroSimulations (2018) did not alter the drain conductance value within model revisions as it was confirmed that the original values adopted in the EIS were appropriate. However, sensitivity analysis on drain conductance was undertaken using values an order of magnitude (10 times) higher than that used in the EIS model. The order of magnitude increase only increased mine inflow by a comparatively small volume, and was therefore considered insensitive. The order of magnitude higher conductance did not calibrate with actual known data (ie Berrima mine inflow), and therefore the original EIS values are most appropriate and considered accurate. The results of the sensitivity analysis can be found in Section 8.2 of HydroSimulations (2018).

1.6 Hawkesbury Sandstone hydraulic conductivity parameters

1.6.1 Independent Expert Review

Hydrogeologic (2017) stated that the modelled hydraulic conductivity values applied to the Hawkesbury Sandstone were reasonable in the EIS groundwater model. 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. However, Hydrogeologic recommended uncertainty analysis on horizontal hydraulic conductivity (Kh) of the Hawkesbury Sandstone be undertaken.

1.6.2 Hume Coal response

HydroSimulations (2018) 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 realisations were simulated, and that results are reliable. The uncertainty analysis on hydraulic conductivity is reported in Section 7 of HydroSimulations (2018).

1.7 Rainfall recharge and evapotranspiration rates

1.7.1 Independent Expert Review

Hydrogeologic (2017) noted 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.

1.7.2 Hume Coal response

HydroSimulations (2018) 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 model demonstrates that mine-related impacts on the groundwater system are largely insensitive to climate. The climate scenario analysis is presented in Section 6 of HydroSimulations (2018).

1.8 Storage values

1.8.1 Independent Expert Review

Hydrogeologic (2017) agrees with concerns raised in some interest group submissions regarding the specific storage (Ss) values used within the EIS model being very low. However, as the confined storativity parameter (a product of Ss and the layer thickness) is utilised by MODFLOW, Hydrogeologic finds these values to be valid and acceptable.

1.8.2 Hume Coal response

During model revisions, HydroSimulations (2018) increased the specific storage values marginally in the model to align more closely with the values gained from site specific pumping tests as presented in the EIS (Coffey 2016a). The updated specific storage values are detailed in Section 5.1 of HydroSimulations (2018).

1.9 Model confidence

1.9.1 Independent Expert Review

Hydrogeologic (2017) 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 Guidelines (Barnett et al. 2012). The review found the EIS model to be of dominantly Class 2 weighting.

1.9.2 Hume Coal response

HydroSimulations (2018) 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 to 3 confidence. The class assessment is summarised in Table 1 of HydroSimulations (2018).

2 Conclusion

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 remains appropriate.

Following consultation with Hydrogeologic and the presentation of the outcomes from additional groundwater modelling investigations (HydroSimulations 2018), all key matters raised have been satisfactorily addressed.

Please contact me if you require further information.

Yours sincerely

Liz Webb
Principal Hydrogeologist
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Attachments

A *Hume Coal Project EIS Independent Expert Review Groundwater Modelling* (Hydrogeologic 2017)

B *Revised Groundwater Modelling for Response to Submissions* (HydroSimulations 2018)

References

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.

Coffey Geotechnics Pty Ltd 2016a*, Hume Coal Project Groundwater Assessment Volume 1: Data Analysis.* Prepared by Coffey for Hume Coal Pty Ltd.

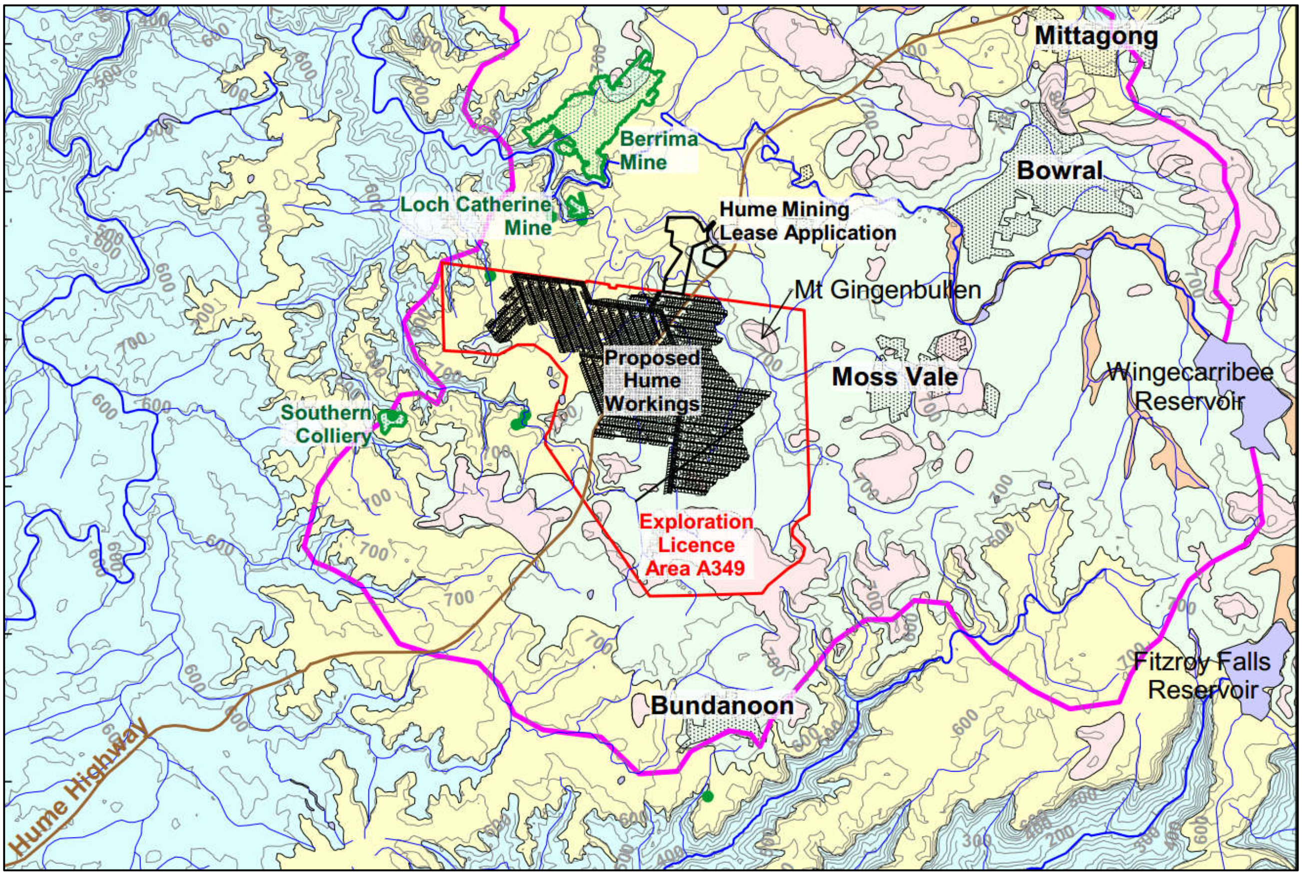
2016b, *Hume Coal Project Groundwater Assessment Volume 2: Numerical Modelling and Impact Assessmen*t. Prepared by Coffey for Hume Coal Pty Ltd.

Hydrogeologic 2017, *Hume Coal Project EIS Independent Expert Review Groundwater Modelling*, prepared for NSW Department of Planning and Environment.

HydroSimulations 2018, *Revised Groundwater Modelling for Response to Submissions*, prepared for Hume Coal Pty Ltd by HydroSimulations.

Hume Coal Project EIS
Independent Expert Review
Groundwater Modelling

Prepared for:	NSW Dept. Planning & Environment	6 Dec. 2017



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Author	Hugh Middlemis	
Version 1	23 Oct. 2017	Draft report for discussion
Version 2	6 Dec. 2017	Updated report, after groundwater experts meeting 16 Nov. 2017

THIS REPORT SHOULD BE CITED/ATTRIBUTED AS:

Middlemis H (2017). Hume Coal Project EIS Independent Expert Review Groundwater Modelling. Prepared by Hydrogeologic for the NSW Department of Planning and Environment. December 6, 2017.

1. Introduction

This report presents the findings of an independent expert review of the groundwater and related modelling elements of the Environmental Impact Statement (EIS) submitted for the Hume Coal Project (SSD 7172) near Moss Vale in the southern highlands coalfield of New South Wales. The review was commissioned by the NSW Department of Environment and Planning (DPE) and was carried out consistent with the peer review elements of the established best practice groundwater modelling guidelines (Barnett et al. 2012; Middlemis et al. 2001). Some commentary is also provided regarding reports prepared by others in response to the EIS.

A key driver for this review is understood to be the extent and magnitude of groundwater drawdown predicted, in the range of 2 to 80 metres at 93 private bores on 71 properties in and around the project site. A key aim of this peer review is to identify whether the assessments made, or conclusions reached are supported by the evidence presented, and/or whether additional information, monitoring, assessment and/or modelling may be required.

1.1 Review Scope and Evidentiary Basis

The Department of Planning and Environment has requested expert advice on the groundwater-related impact assessment in general, and on some issues in particular, including:

- the groundwater model, and whether its assumptions and resulting predictions are reasonable, especially in terms of dewatering volumes and drawdown extent/magnitude;
- the proposal to re-inject mine water back into the workings and cement seal the voids, and the potential effect of these activities on groundwater quality;
- the potential effect of underground bulkhead failure on dewatering volumes and drawdown impacts (putting aside risk of occurrence of inrush and safety issues);
- the suitability of the make good provisions the mining company has proposed to mitigate groundwater impacts to private bores.

The main evidentiary basis for the expert review comprised several report volumes (components of the Hume Coal EIS), with the following reports as the main targets:

- EMM (2017). Hume Coal Project Environmental Impact Statement Main Report. Prepared for Hume Coal Pty Limited, March 2017.
- Coffey (2016a) Groundwater Assessment Volume 1: Data Analysis. Prepared for Hume Coal Pty Limited, 17 November 2016.
- Coffey (2016b) Groundwater Assessment Volume 2: Numerical Modelling and Impact Assessment. Prepared for Hume Coal Pty Limited, 17 November 2016.

In addition, some other reports were considered, and some commentary is provided, notably:

- Department of Primary Industries (2017). Hume Coal Project (SSD 7172) and related Berrima Rail Project (SSD 7171). Comment on the Environmental Impact Statement (EIS). 16 July 2017.
- Pells, S. (2017) Groundwater Modelling of the Hume Coal Project. Prepared by Pells Consulting for the Coal Free Southern Highlands. 22 June 2017.
- Anderson, D. (2017). Hume Coal Project SSD 15_7172. Peer Review of Conceptual and Numerical Groundwater Modelling that predicted likely groundwater impacts. Prepared by the Water Research Laboratory, University of NSW, for the Coal Free Southern Highlands. Submitted online to the Dept of Planning and Environment via the Major Projects Portal. 23 June 2017.
- Lee, J (2017). Hume Coal Project SSD 15_7172: Southern Highlands NSW – Objection to Project Approval. Prepared by Hydroilex for Coal Free Southern Highlands. 30 June 2017.

1.2 Review Process, Issues Log and Status

The expert review process on the Hume Coal Project groundwater issues has comprised:

- a desktop review of key reports, leading to preparation of an issues log (11th August), which was discussed briefly with DPE staff via telephone on 13th August;
- clarification of various technical issues via telephone discussions between Mr Middlemis and key members of the Hume Coal groundwater assessment team:
  - Mr Paul Tammetta (Coffey) on 24th and 25th August; and
  - Dr Noel Merrick (HydroSimulations) on 24th August and 7th and 9th September;
- receipt of a response to the issues log from the Hume Coal groundwater assessment team (understood to have been prepared by Dr Merrick) on 5th October;
- a face-to-face meeting between Mr Middlemis and Dr Merrick on 9th October 2017 at the DPE office to discuss the model refinements and additional scenarios in progress;
- update to the issues log on 11th October with this reviewer's responses (see Appendix A);
- groundwater experts meeting at DPE on 16 November (see agenda and attendee list in Appendix B);
- preparation and updating of this review report.

While this review finds that the Hume Coal model itself is suitable for the mining impact assessment purpose (Class 2 confidence level), the EIS documentation does not meet best practice modelling standards. Some model improvements are warranted, notably to investigate uncertainty issues, but the EIS presents reasonable predictions of dewatering volumes and drawdown extent/magnitude. The review status is currently on hold, awaiting the results from a range of model refinements and additional scenarios in progress by HydroSimulations.

2. Model Refinements and Performance

The model refinements in progress by HydroSimulations (Dr Merrick, pers.comm.) are designed mainly to address issues identified via a model audit by Dr Merrick, and to address certain items in the issues log identified by this expert review (see Appendix A). The following points summarise the refinements in progress that were identified by Dr Merrick, and are endorsed as warranted by this review:

- improving model performance generally via trimming inactive grid cells, improving the solver settings, replacing Modflow-Surfact with Modflow-USG which allows the time-varying materials function to be used, as well as an improved pseudo-soil function; all of which has reduced the water balance discrepancy term to less than 0.5% and reduced the SRMS statistic to <10% (both within guideline criteria), and achieved faster run times;
- revising the relaxation zone above the Hume workings to account for where (thin) dummy layer thicknesses apply where lithological units pinch out;
- deactivating drain cells once a mined section is sealed, and directly injecting mine water from active dewatering into sealed sections if required for excess water management, and revising the water balance analyses.

The issues log (Appendix A) outlines a range of issues where this review has found that the EIS report documentation does not provide sufficient clarity, leading to potential misinterpretations of the model setup and/or performance.

A notable example relates to the water balance tables in the EIS report, which indicate a discrepancy term (difference between inputs and outputs) in the order of 5%. It is easy to misinterpret those tables as indicative of a poor model solution, given that the guidelines set a criterion of less than 1% discrepancy at any stress period during the simulation. However, the water balances are reported (somewhat confusingly) as the "average flow budget" over a range of stress periods (e.g. calculated as a cumulative volume over 22 years of mining, divided by the 22 years; Paul Tammetta, pers.comm.). Although this is a little unusual (water balances are typically presented for specific stress periods), the water balance data presented are consistent with aquifer storage depletion due to mine dewatering (at Berrima and/or Hume), so it is understandable that there is a significant average "discrepancy" shown over the mining period.

The reported water balance "discrepancy" is not indicative of fundamental flaws in the Hume Coal model, contrary to review comments from DPI Water (2017) and Anderson (2017), and hence their downgrading to a Class 1 model confidence level 1 is invalid. Accordingly, any criticisms based on this invalid premise are also not necessarily valid.

This review has found that most of the items raised in the issues log (Appendix A) arise from the less than transparently clear reporting (Coffey, 2016b). Most items have been clarified via technical discussions with the modellers (as suggested by the guidelines). Some residual issues do warrant model revisions (as well as report revisions), but it is understood that most of these model revisions were in progress already, further to the model audit process by Dr Merrick. Some interim results from that process were presented and discussed at the meeting with Dr Merrick on 9th October 2017, confirming that the fundamental model setup and performance are indeed adequate in terms of guideline criteria (statistical and water balance measures).

3. Hume Coal Groundwater Model Review Summary

While we await a revised assessment based on the revised modelling, this report presents a summary of the review findings on the groundwater modelling impact assessment.

3.1 Model Confidence Level

The groundwater assessment report (Coffey, 2016b) claims a model confidence level of Class 2/3, suitable for an impact assessment purpose. This review finds that a Class 2 is justified, based on an independent assessment (Table 1) of the attribute weightings of the Hume Coal model as reported in Coffey (2016b).

Table 1 - Model confidence class characteristics - Hume Coal Project

Class		Data		Calibration		Prediction		Quantitative Indicators
1 (simple)		Not much.		Not possible.		Timeframe >> Calibration		Timeframe >10x
		Sparse coverage.	~	Large error statistic.		Long stress periods.		Stresses >5x
	√	No metered usage.		Inadequate data spread.		Poor/no validation.		Mass balance > 1% (or one-off 5%)
		Low resolution topo DEM.		Targets incompatible with model purpose.		Transient prediction but steady-state calibration.		Properties <> field values.
		Poor aquifer geometry.						No review by Hydro/Modeller.
2 (impact asessment)	√	Some.	√~	Partial performance.	√	Timeframe > Calibration	√	Timeframe = 3-10x
	√	OK coverage.	~	Some long term trends wrong.		Long stress periods.	√	Stresses = 2-5x
	~	Some usage data/low volumes.	~	Short time record.	√	OK validation.	~	Mass balance < 1%
	√	Baseflow estimates. Some K & S measurements.		Weak seasonal match.	√	Transient calibration and prediction.	~	Some properties <> field values. Review by Hydrogeologist.
	√	Some high res. topo DEM &/or some aquifer geometry.		No use of targets compatible with model purpose (heads & fluxes).	√	New stresses not in calibration.		Some coarse discretisation in key areas of grid or at key times.
3 (complex simulator)		Lots, with good coverage.		Good performance stats.		Timeframe ~ Calibration		Timeframe < 3x
		Good metered usage info.	√~	Most long term trends matched.	√	Similar stress periods.		Stresses < 2x
	√	Local climate data.	~	Most seasonal matches OK.		Good validation.	~	Mass balance < 0.5%
	~	Kh, Kv & Sy measurements from range of tests.		Present day data targets.		Calib. & prediction consistent (transient or steady-state).	√~	Properties ~ field measurements.
		High resolution DEM all areas.	√	Head & Flux targets used to constrain calibration.	√~	Similar stresses to those in calibration.	√	No coarse discretisation in key areas (grid or time).
	√	Good aquifer geometry.					√	Review by experienced Modeller.

(after Table 2-1 of Barnett et al (2012) Australian Groundwater Modelling Guideline)

Anderson (2017) disagreed with the groundwater assessment report statement of a Class 2/3 model, suggesting a lower confidence Class 1 level. DPI Water (2017) also suggested Class 1, citing commentary in the modelling guideline (Barnett et al, 2012) that any element of Class 1 renders the entire model Class 1. These assessments were largely based on the relatively poor SRMS statistic of 11.9% reported in the EIS (Figure 4.2 of Coffey, 2016b), and the (misinterpreted) water balance issues, discussed above in section 2. An SRMS of more than 10% is indeed a Class 1 indicator, but there are very few other characteristics of the Hume Coal model that could reasonably be assessed as Class 1.

The model Class is important because DPI Water and Anderson have relied heavily on the demonstrably false premise of a Class 1 model to base their initial claims of inadequate modelling for impact assessment purposes. It is understood that a meeting was held between DPI Water and Dr Merrick when the draft issues log (Appendix A) was discussed, and DPI Water have now agreed that a Class 2 level applies to the Hume Coal model, based on the attribute weighting approach (Table 1) devised by Dr Merrick, although there is no written evidence to that effect.

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 due to misinterpretation of the guideline commentary on the model confidence level classification. That is, the model confidence level classification table in the guidelines is itself not unreasonable (Barnett et al, 2012; Table 2-1), but the related commentary and guidance is poor and self-contradictory. In this case, cherry-picking one guideline comment rather than considering all the attributes suggested in the table does not constitute a valid argument to support the claims by others of poor model performance.

In any event, the stress period water balance discrepancy term has been confirmed as less than 1% and the SRMS has been reduced to less than 10% during the model refinements in progress (see section 2), and the water balance issue has been further clarified by this review, removing most of the grounds for the Class 1 claim by others.

3.2 Model Compliance Checklist - Hume Coal Project

In addition to the model confidence level classification assessment, the guidelines (Barnett et al, 2012) suggest a compliance checklist of 10 key questions to summarise review outcomes, which is presented in Table 2 based on the findings of this expert review.

In summary, it is my professional opinion that the Hume Coal model is fundamentally consistent with best practice, although the EIS report documentation is deficient (not sufficiently clear on some details; see Appendix A). It is fit for mining impact prediction purposes. Certain model performance improvements are warranted, along with uncertainty analyses and updated reporting (it is understood that these are already in progress; see section 2 for details).

Table 2 - Groundwater Model Compliance Checklist: 10-point essential summary

Question	Yes/No	Comments re Hume Coal Project groundwater model
1. Are the model objectives and model confidence level classification clearly stated?	Yes	Mining impact assessment context. Class 2 confidence level (Barnett et al, 2012). Medium complexity model (Middlemis et al, 2001). Clearly described in model reports.
2. Are the objectives satisfied?	Yes	Adequate model calibration performance (latest/improved model shows <10% SRMS, improved from 11.9% in EIS reports). Reasonable time series matches. Impact assessments have been completed diligently, although report documentation is sometimes not crystal clear/transparent.
3. Is the conceptual model consistent with objectives and confidence level classification?	Yes	Conceptualisation is sound. Model design of 50m grid (min.) and 13 active layers represents geological structure, coal seams and interburden. Calibration to existing nearby mining effects (Berrima) and recent climate variability address non-uniqueness issues and support a Class 2 confidence level.

4. Is the conceptual model based on all available data, presented clearly and reviewed by an appropriate reviewer?	Yes	Reports describe previous investigations and data sources, with reviews at many stages, along with reference to relevant papers (e.g. on coal mine subsidence issues). Most assessment reports are very well presented, but the model report (Coffey, 2016b) is deficient in that it is sometimes inconsistent or not crystal clear in describing certain methods or results (e.g. commentary on interburden thickness treatments, water balances, and use of undefined terms such as “active stress period” and “transmissivity-weighted average drawdown”). In-house review by Dr Merrick and Dr Kalf. Dr Merrick completed a detailed model audit, and model refinements are in progress, with improved model performance outcomes (see section 2 for details).
5. Does the model design conform to best practice?	Yes	The model software, design, extent, grid, boundaries and parameters form a good example of best practice in design and execution. The EIS work used Modflow-Surfact and the refinements are using Modflow-USG, both industry-leading software, with USG adding the benefit of time-varying properties for subsidence issues. The western boundary is somewhat close to the Hume and Berrima mine areas, but it is constrained to the up-dip extent of the coal measures, which seems appropriate. Interburden treatments are not well described in the report, and refinements are in progress by Dr Merrick (see section 2).
6. Is the model calibration satisfactory?	Yes	Acceptable model calibration performance and good time series matches at most bores (except 2 of 6 VWPs, which is not unreasonable). EIS report states 11.9% SRMS, exceeding 10% criterion, but refinements have reduced SRMS to <10%, and water balance error terms to <0.5% (see section 2 and Appendix A), which is satisfactory. Calibration of aquifer property values (Kh, Kv, S, Sy) has been well constrained by pumping test estimates of property values, and by simultaneously honouring observed groundwater levels, along with the measured Berrima mine inflow (deep system) and inferred stream baseflows (shallow system). This is a best practice approach that reduces model non-uniqueness problems (that many different sets of model inputs can produce nearly identical aquifer head distributions). Uncertainties remain, and as the evapotranspiration discharge (a riparian zone flux) is unconstrained by measurement or estimates, sensitivity testing is warranted on the maximum ET rate and extinction depth (especially in high relief areas, including parts of the riparian zone).
7. Are the calibrated parameter values and estimated fluxes plausible?	Yes	Appropriate level of complexity in parameter distributions has been applied to achieve good calibration performance, including to effects of underground mining at Berrima. Parameter values and fluxes are plausible and consistent with site-specific testing and literature values (e.g. relaxation heights; Tammetta, 2013, 2015). The EIS report claim of two “long term pumping tests” is exaggerated; a one-day test is not “long term” and the other test was only 7 days duration. However, the tests did give some information on the key/sensitive property value for vertical hydraulic conductivity (Kv). Specific storage (Ss) is set at 5.10^{-7} m^{-1}. This is very low (almost at the physical limit for the compressibility of water). However, the confined storativity parameter (product of Ss and thickness) that is actually used in model calculations is reasonable (around 10^{-4} for the full thickness of Hawkesbury Sandstone). Sensitivity testing is warranted (but results are probably not highly sensitive to Ss). Model refinements in progress by Dr Merrick (section 2) have applied higher Ss values, which will change the inflow volumes and drawdown effects.

8. Do the model predictions conform to best practice?	Yes	Prediction results are credible in terms of water volumes and drawdowns, but water balance descriptions are not presented clearly in the report. Awaiting further results from current model refinement and scenario analysis program (see section 2). Method applied in groundwater assessment EIS of leaving drain cells on (after mining and sealing panels) until residual void behind bulkheads is filled provides a prediction of the effect of bulkhead failure in terms of water take and drawdown. Latest model refinements (see section 2) of turning off drains when mined areas are sealed is more realistic. This work may require direct injection of mine water behind bulkheads (for mine water circuit management/balancing). Comparison of the EIS and latest results would allow “unpacking” of bulkhead failure effects, but a sensitivity-style run of the refined model to emulate the previous method is recommended.
9. Is the uncertainty associated with the predictions reported?	No/Yes (in progress)	No comprehensive uncertainty assessment was done for the EIS groundwater assessment. A sensitivity analysis was done on the identified sensitive parameters of relaxation height, mine drain conductance parameter and Hawkesbury Sandstone Kv (Coffey, 2016b). Uncertainty analysis is recommended, with minimum requirements being a composite sensitivity analysis and then selected uncertainty scenarios, preferably including horizontal hydraulic conductivity. A Monte-Carlo constrained calibration uncertainty assessment is reportedly in progress, which should largely address parameter uncertainty issues. DPI Water has also requested scenario analysis of 108 climate datasets (consistent with surface water assessments), and consideration of mine water management (e.g. to confirm low risk of excess water discharge), which should address other uncertainty issues. EIS claimed that a well-constrained calibration to groundwater levels and to shallow and deep fluxes (Berrima inflows and stream baseflows) reduces uncertainty. While this is true, it does not eliminate uncertainty. It is noted that the recharge rates are relatively low (perhaps by a factor of 2) and the ET rates are not constrained, which means there is scope to further test uncertainty via an alternative model with higher recharge. An alternative model (e.g. with higher recharge and other changes) would form a best practice method to address structural model uncertainty (Barnett et al, 2012), even if that is done as a sensitivity test. It is understood that such tests may be in progress; further comment must await the results.
10. Is the model fit for purpose?	Yes	My professional opinion is that the Hume Coal model is fundamentally a good example of best practice in design and execution (let down by unclear report documentation). It is fit for mining project impact prediction purposes and the results presented are reasonable in terms of inflows and drawdown predictions. Refinements in progress (see section 2) are improving its performance, and uncertainty assessments are also in progress. Further comment must await the results.

4. Impact Assessment Issues

The following points are provided in response to requests for information from the DPE and/or to summarise clarifications provided by Mr Middlemis at the independent expert meeting on 16 November (Appendix B).

4.1 Interburden Layer Representation in Hume Coal Model

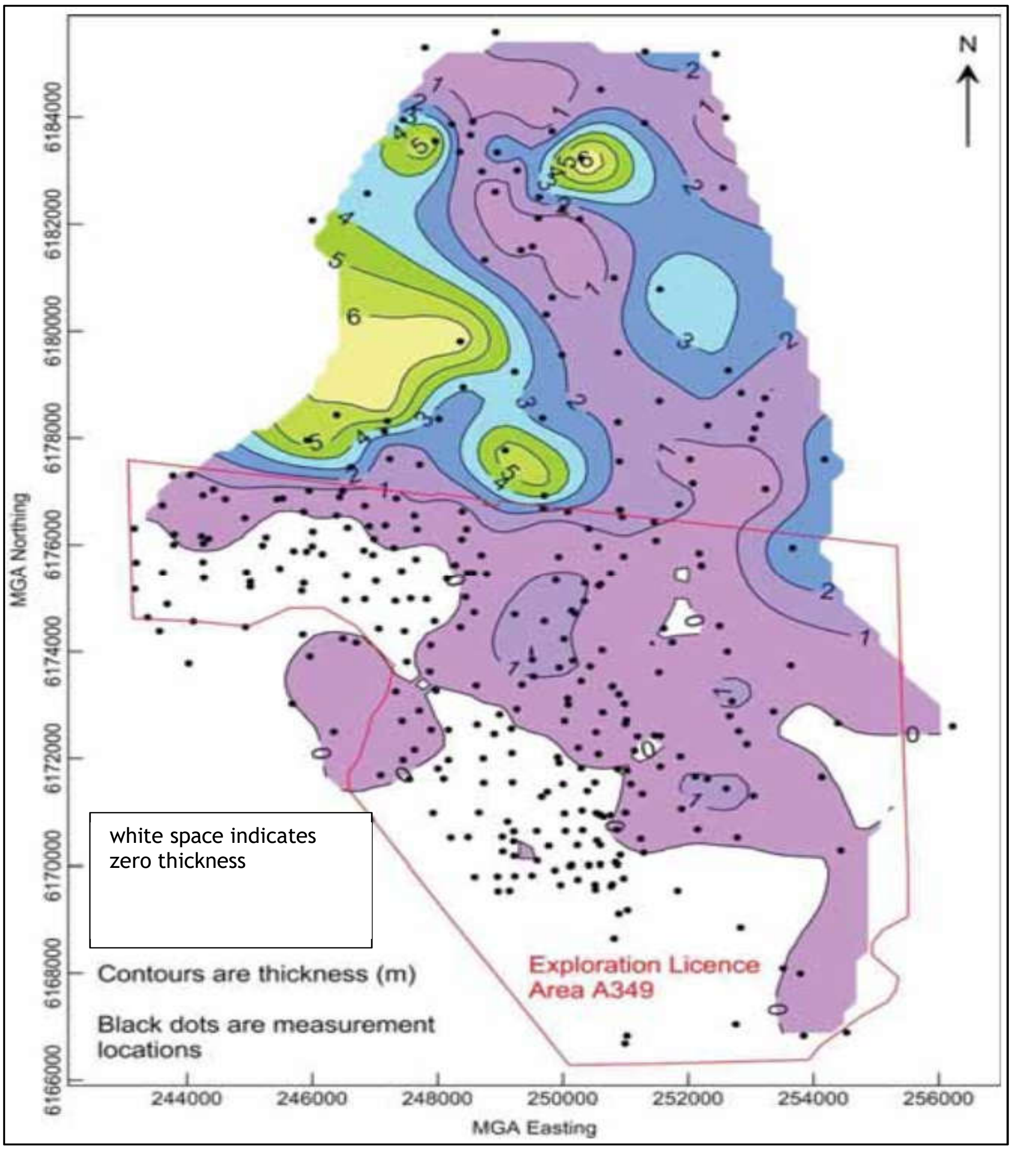
This review finds the reporting on this key topic is very unclear, confused, self-contradictory and sub-standard. Pells (2017) and Anderson (2017) also raised questions about the interburden implementation, and this was discussed further at the meeting on 16 November (Appendix B).

Dr Merrick indicated during review discussions (see Issues Log item 3 in Appendix A) that his internal review of the model identified issues with the implementation of the interburden (layer 8, comprising the combined Narrabeen Group, Wongawilli Ply and Farmborough Claystone) that warranted corrective action in terms of extending the relaxation zone up into layers 6 and 7 in some areas of interburden absence (Figure 1).

Dr Merrick confirmed that the interburden thickness (or absence in extensive areas) is represented properly in the model, and indicated (see Appendix A for details) that:

- a minimum thickness of 0.4m is applied to layer 8 (interburden) in areas where the interburden is absent (Figure 1), but in those areas, the parameters applied are the same as those for the Wongawilli mined seam;
- a minimum thickness of 0.29m is applied to the underlying layers 9 and 10 (the Permian units between the interburden and the mined seam);
- thus, a combined minimum thickness of 0.99m applies to layers 8 to 10, between the roof of the mined coal seam (top of layer 11) and the base of the Hawkesbury Sandstone, and all these layers have the same parameters as the mined seam.

Figure 1 - Interburden thickness (after Coffey 2016a, Figure 4.3)



The report (Coffey, 2016b) confusingly and erroneously describes the thickness of the layer 8 interburden in various ways: average layer thickness of 4m and minimum thickness of 0.1m.

Similarly, layers 9 and 10 are described as having an average thickness of 2m and a minimum thickness of 0.1m.

It is worth pointing out that layers 6 and 7 (immediately above the interburden layer 8) have a thickness of 2m each. While layers 6 and 7 nominally represent the basal unit of the Hawkesbury Sandstone, their main purpose is to "*accommodate roof relaxation from mining where the interburden or plies above the working section are absent*" (Coffey, 2016b, section 3.1). This means that, where there is no interburden, the Hawkesbury Sandstone directly overlies the mined seam. In the model, that is represented via layers 6 to 10 with a combined minimum thickness of 5m and with parameters applied to match those for the Wongawilli mined seam.

Dr Merrick also identified that corrective action is being taken to refine the model to properly represent the relaxation zone (see Appendix A for details). The relaxation zone is represented by including drain features in layer 11 (the mined seam) and in overlying layers to the height of the relaxation zone (nominally 4m). This means that drain features (see section 4.2) should extend up into layer 6 in some areas of zero interburden thickness. The implication is that inflow volumes may increase, but objective analysis must await the results of the model updates.

In other areas, the known interburden thickness (Figure 1) is applied to layer 8 of the model, and similarly for the layers 9 and 10 thickness. However, the aquifer parameters applied to layers 6 to 11 are representative of the coal measures (Figure 2). This means that low permeability parameters are not applied to the interburden layer in the model, as illustrated in Figure 2 in terms of the model values for the interburden being much higher than most of the test results for the deep units.

The areas of zero interburden thickness (Figure 1) align with areas where the mined coal seam thickness (layer 11) is less than 2.6m. Appendix A of Coffey (2016b) presents a figure showing areas of thin coal seams, such as on the eastern side near panels CE9 & CE10 (mined in 2029-31), and all along the western side of the mined area W18 (mined 2026-28); W12 (mined 2025-2027) and W23 (mined 2031-33). The times when those areas of thin coal seams and absent overburden are mined (mine years 10-16) align with the periods of peak inflow between 2030 to 2036 (Coffey, 2016b, Figure 6.1), as one would expect. Interestingly, the Berrima area does not have these thin/absent interburden areas, illustrating at least one significant difference between some parts of the Hume area and the Berrima area.

In summary, this review has found that the Hume Coal model has been set up with an appropriate representation of the interburden properties (e.g. appropriate thicknesses and no low permeability parameters to limit the potential connection between the coal seams and the Hawkesbury Sandstone). Action is in progress by the Hume Coal Groundwater Assessment Team to improve the implementation of the relaxation zone, and action should also be taken to revise the confusing report documentation.

4.2 Drain Feature (Mine Inflows)

The Hume Coal model applies the "Drain" feature of Modflow to simulate groundwater inflows to the mine workings (a standard methodology); see also Figure 3 (later). The drain feature involves a conductance parameter that acts as a resistance to flow (i.e. lower values of conductance require higher groundwater levels to result in the same amount of inflow).

The Hume Coal model history match calibration involved adjusting the drain conductance parameter to match the mine inflow and groundwater level data at the Berrima mine for a period of significant climate variability in recent years. The approach required simultaneous matches to stream baseflows, and is a good example of a best practice method that minimises non-uniqueness issues and supports a model Class 2 confidence level. The method justifies the drain feature conductance parameters applied to Berrima conditions. The application of the calibrated conductance parameter to Hume conditions involved appropriate adjustments to account for the different model cell size at Hume compared to Berrima.

Pells (2017) and Anderson (2017) contend that the drain conductance parameter value is calculated incorrectly and is very low, with the implication that mine inflows may be under-estimated. The modelling guidelines (Barnett et al. (2012), section 11.3.5) state the following: "*Conductance as a model parameter cannot be measured directly. It is a surrogate for the combination of hydraulic conductivities and geometries that occur in the near field of the water body. A number of analytical solutions give guidance for this kind of conductance, but values are generally either assumed or chosen during model calibration.*" While this statement is made in the usual context of a model drain feature representing a water body, it is also applicable to a mine inflow feature. The analytical solutions mentioned include the methods applied by Pells to incorrectly infer that the mine workings are "sealed or surrounded by a thick layer of compacted clay" with an equivalent hydraulic conductivity of 2×10^{-5} m/d. Such an analogy may be hypothetically valid if one accepts the riverbed conceptualisation, but this review finds that concept is not applicable in this case, and is inferior to the best practice history match calibration methods applied to the Hume Coal model.

4.3 Productive Hawkesbury Sandstone

Pells (2017) contends that the lower horizon of the Hawkesbury Sandstone is a "highly productive" unit (citing Lee, 2017), and should be represented with a high value for hydraulic conductivity, and with more sensitivity testing, than was applied to the Hume Coal model.

The example of the Rosedale bore (GW107535) is given to support the case for a highly productive Hawkesbury Sandstone. However, the Rosedale bore productivity (42 L/s or 3.6 ML/d) is attributed to an open fracture system encountered by the bore (Lee, 2017). This is a local scale effect that is not representative of general conditions (if it were, there should be many more such productive bores), and thus it need not be represented as a key feature in an impact assessment model on this scale.

Interestingly, the Rosedale bore is located about 1400m west of the Wongonbra bore (GW108194), a less productive bore, but still capable of 20 L/s (1.7 ML/d). There is evidence of private pumping effects in the area of the Rosedale and Wongonbra bores of 1.0 to 1.5 ML/d (11 to 17 L/s) over the growing season (120 to 180 ML total volume) (Coffey, 2016a, section 9). Both bores are screened over the full thickness of the Hawkesbury Sandstone (36-122m Wongonbra; and 13-114m Rosedale; Coffey, 2016b, Appendix G, Table 1), and the evidence presented does not robustly justify the deep productive horizon conceptualisation on a general scale.

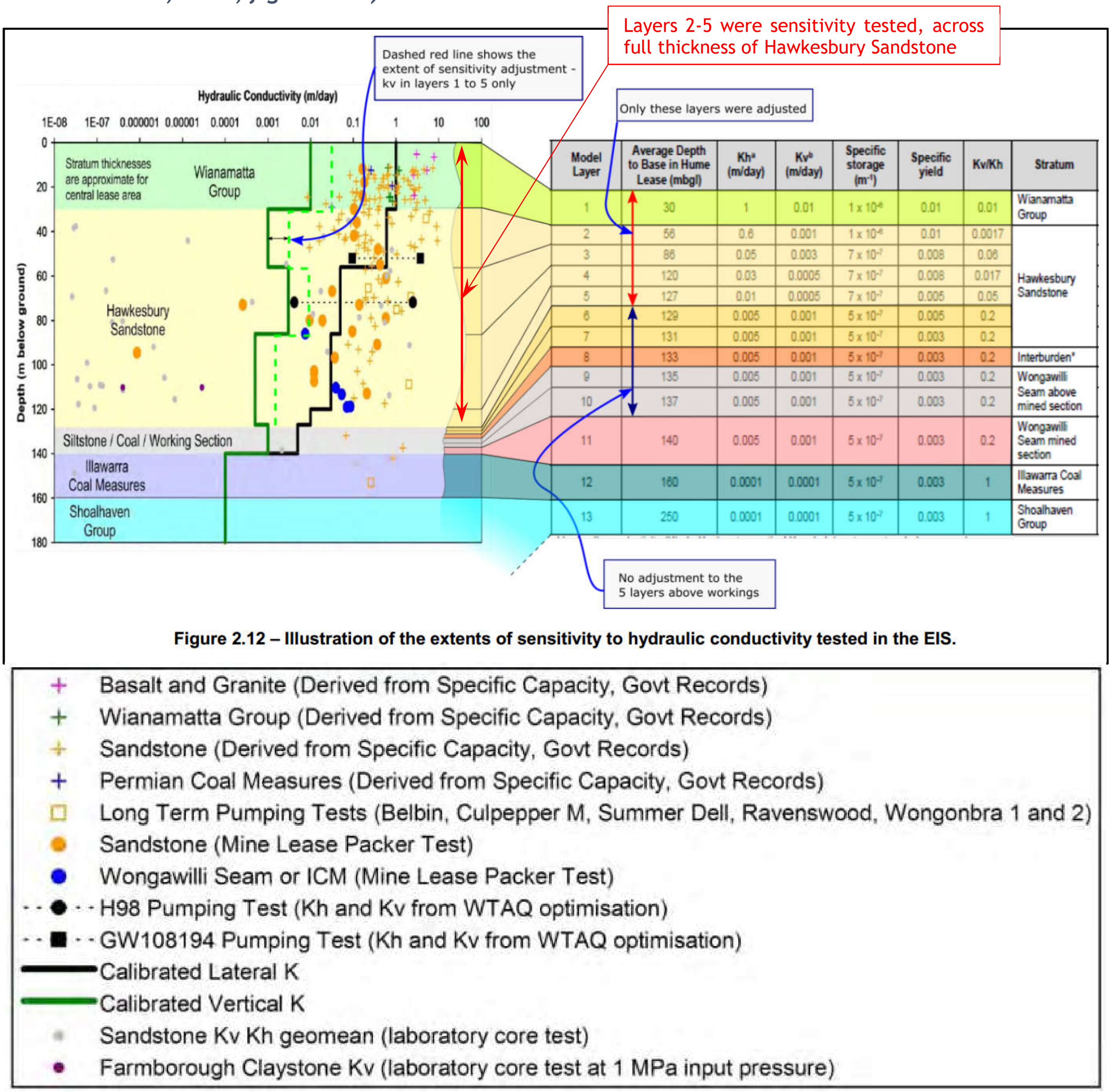
The basal unit of the Hawkesbury Sandstone is Layer 5 in the Hume Coal model, nominally 7m thick and with a horizontal hydraulic conductivity (Kh) value of 0.01 m/d. This is a lower Kh than the overlying bulk thickness of Hawkesbury Sandstone layers 2 to 4 (Kh range from 0.6 to 0.03 m/d; Figure 2), consistent with the conceptualisation of decreasing permeability with depth (justified by information presented in Coffey, 2016a, Appendix C).

The underlying layers 6 & 7 are nominally described as representing Hawkesbury Sandstone (e.g. Table 3 in Coffey, 2016b), but they are only 2m thick (maximum) and are effectively used to represent the complexities in the interburden sequence and relaxation zone between the Hawkesbury Sandstone and the working section mined panels (as discussed in section 4.1 above), rather than the Hawkesbury Sandstone as such.

The modelled Hawkesbury Sandstone Kh values are reasonable in that they lie in the middle of the range of observed values (Figure 2); clearly not at the high end of the range as suggested by Pells (2017), but also not at the low end of values (mainly from core testing, indicated by grey dots in Figure 2). Most of the pumping tests on individual bores (open square symbols in Figure

2) do indicate higher range Kh values, but that is for tests mostly in the higher elevations of the Hawkesbury Sandstone, including the two tests on bores on the Hume lease (H98 and GW108194 indicated by the solid black symbols). Again, the model reflects this effect of higher Kh in shallower units. The exception is the high Kh for the (un-named) bore at about 110m depth.

Figure 2 - observed and modelled hydraulic conductivity (after Coffey, 2016b, figure 4.5 and Pells, 2017, figure 2.12)



Model Layer	Average Depth to Base in Hume Lease (mbgl)	Kh[a] (m/day)	Kv[b] (m/day)	Specific storage (m^{-1})	Specific yield	Kv/Kh	Stratum
1	30	1	0.01	1×10^{-6}	0.01	0.01	Wianamatta Group
2	56	0.6	0.001	1×10^{-6}	0.01	0.0017	Hawkesbury Sandstone
3	86	0.05	0.003	7×10^{-7}	0.008	0.06	
4	120	0.03	0.0005	7×10^{-7}	0.008	0.017	
5	127	0.01	0.0005	7×10^{-7}	0.005	0.05	
6	129	0.005	0.001	5×10^{-7}	0.005	0.2	
7	131	0.005	0.001	5×10^{-7}	0.003	0.2	
8	133	0.005	0.001	5×10^{-7}	0.003	0.2	Interburden*
9	135	0.005	0.001	5×10^{-7}	0.003	0.2	Wongawilli Seam above mined section
10	137	0.005	0.001	5×10^{-7}	0.003	0.2	
11	140	0.005	0.001	5×10^{-7}	0.003	0.2	Wongawilli Seam mined section
12	160	0.0001	0.0001	5×10^{-7}	0.003	1	Illawarra Coal Measures
13	250	0.0001	0.0001	5×10^{-7}	0.003	1	Shoalhaven Group

Figure 2.12 – Illustration of the extents of sensitivity to hydraulic conductivity tested in the EIS.

The model has been tested for sensitivity to Hawkesbury Sandstone vertical hydraulic conductivity (Kv) across the full thickness of the Hawkesbury Sandstone (Figure 2), concluding that the mine inflow predictions are sensitive to Kv, as is often the case in practice. While sensitivity to horizontal hydraulic conductivity was not tested (Coffey, 2016b), it is recommended that uncertainty analysis on horizontal hydraulic conductivity of the Hawkesbury Sandstone should be undertaken (it is understood that this is currently being evaluated as part of the model refinements in progress by Dr Merrick in response to discussions with DPI Water; see section 2).

4.4 Make Good Arrangements

Arrangements have been proposed by Hume Coal for making good on impacts greater than the stated minimal impact criteria (EMM, 2017). The assessment of the third party bores potentially affected by drawdown due to Hume Coal Project dewatering appears to have been undertaken thoroughly and with careful consideration of groundwater engineering principles. The strategies proposed for making good include bore headworks engineering, borehole workovers and/or re-drilling, or providing alternate water supplies or compensation, along with dispute resolution processes. All these arrangements are reasonable in principle, and are consistent with make good arrangement guidelines in Queensland, for example, although those are mostly applicable to CSG projects (DEHP, 2016).

The Hume Coal make good consultation process includes a proposed verification visit to affected properties to obtain specific and objective information on the current bore status. This is a necessary step for an effective make good process, although it does depend on the ability of a proponent to access private properties for that purpose. This review makes no comment regarding NSW government policy or regulations on making good, on access to property, or the acceptability of these arrangements to any party.

This discussion is constrained to technical issues regarding borehole workovers or re-drilling, and whether access to alternative groundwater supplies is feasible. In principle, dewatering of one horizon within the aquifer (e.g. the mined coal seam) does not necessarily preclude the occurrence of saturated aquifer conditions above and/or below that horizon. Further, depressurisation does not dewater an aquifer unit; it simply lowers the groundwater pressure level, which can leave areas of saturated aquifer that can support groundwater pumping (and/or habitat for stygofauna, for example).

Coffey (2016a) present information in section 6.1 on two bores close to the Berrima mine workings, which confirms that good quality groundwater at adequate yields can be obtained above and below mined coal seams. The information presented on the Belbin bore is consistent with my statement to the Land and Environment Court in 2014 on the Berrima Colliery (case number 12/10752). The "Belbin" bore (GW106150) is located on the northern corner of the Berrima mine workings. It was re-drilled in 2008 because the original Hawkesbury Sandstone bore (115 m depth) was impacted by mining (i.e. the groundwater level fell below the base of the bore due to undermining). The re-drilled Belbin bore is 186 metres deep (60 metres below the Wongawilli seam) and it is screened in the Permian Illawarra Coal Measures (132-186 metres). Its groundwater level is around 115 m below ground level, and its salinity is less than 500 mg/L.

Examples such as this do not guarantee that similar results would be obtained everywhere on the Hume Coal lease (although the conditions would suggest that it is likely). However, it does demonstrate that depressurisation and/or dewatering of coal seams does not preclude access to viable aquifer resources via workovers or re-drilling, even within the mine area. Such bores should yield adequate supplies of low salinity water, suitable for stock and domestic purposes at least, and perhaps for low volume irrigation licences, but likely not adequate for high volume irrigation licences.

The Hume modelling study diligently represented the effects of private bore pumping, although some private bores did "go dry" during the simulations due to the combination of mining and private pumping stresses (i.e. water levels drew down below the base of some bores). The associated reduction in private bore pumping amounted to only about 15% (estimated as follows), which should not materially affect the cumulative impact drawdown assessment. Coffey (2016b) state (section 3.2.6) that there are 83 high extraction private bores within the model domain with a combined entitlement of 5300 ML/a (14.5 ML/d). The 299 stock and domestic bores were assumed to pump at 2 ML/a each, giving a combined volume of 598 ML/a (1.6 ML/d). Pumping from private bores was simulated at 14.1 ML/d during the history match calibration, but that decreased during the 22-year mining period to between 11 ML/d (scenario with the Hume mine simulated) and 13 ML/d (null scenario without the Hume mine), or about a 15% reduction (water budget tables 10 & 11; Coffey, 2016b).

Consideration of groundwater engineering factors was applied to the drawdown prediction results to identify make good works that may be required (Coffey, 2016b, section 7 and Appendix G). This is an appropriate assessment at this stage, but further detailed investigations will be required in due course. In addition to the lessons learned from the Belbin bore outlined above, such investigations will need to consider local scale issues, such as:

- increasing the bore yield potential by targeting the full thickness of the Hawkesbury Sandstone (i.e. avoiding the limitations of shallow bores), and by targeting zones more distant from the mined panels if possible (drawdown impacts reduce rapidly with lateral distance from the mine workings);
- the occurrence of open fractures on a local scale that would enhance bore yields if encountered (e.g. the 'Rosedale' bore example outlined in Lee, 2017) but which cannot be adequately characterised in a groundwater model (mainly because there is no information of the distribution of such features).

There is evidence of private pumping effects in the area of the Rosedale and Wongonbra bores (GW107535 and GW108194) of 1.0 to 1.5 ML/d over the growing season (120 to 180 ML total volume) (Coffey, 2016a, section 9). This gives some indication of practical bore and irrigation capacities that may also be relevant to make good considerations.

4.5 Implications arising from Bulkhead Failure

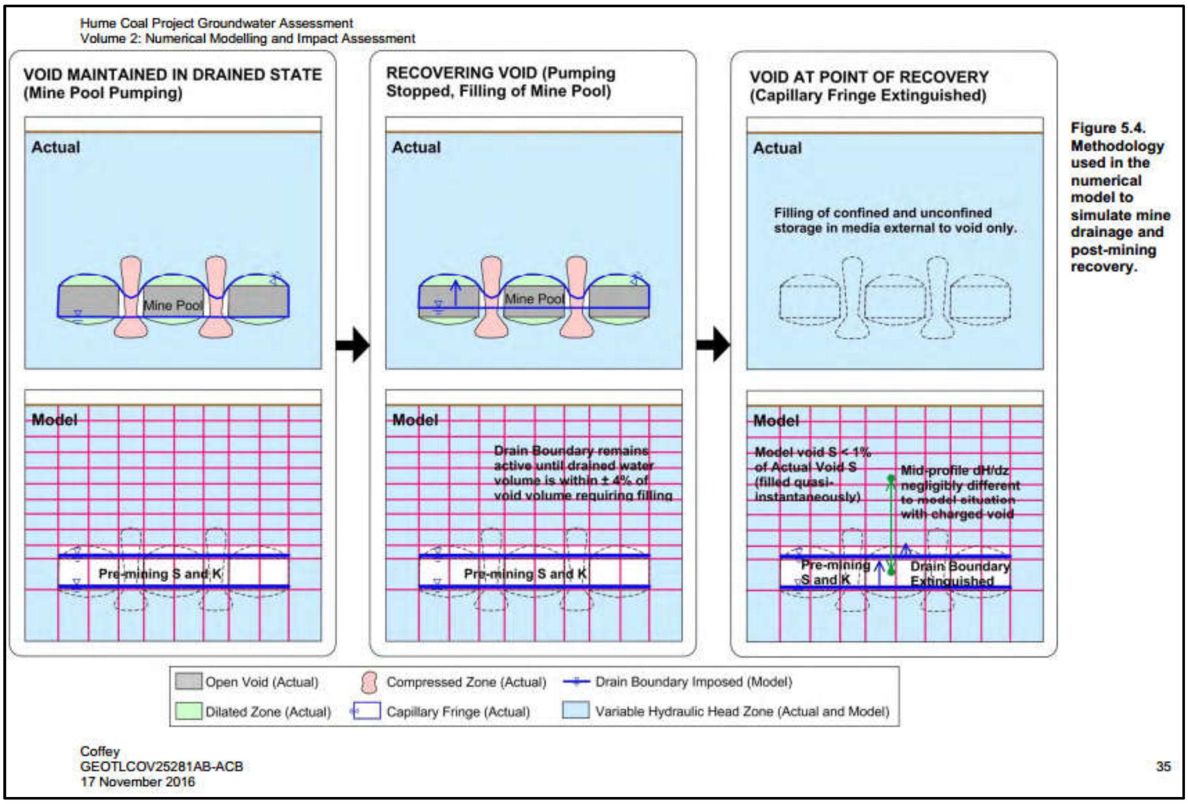
DPE has received expert advice on the potential for bulkhead failure and the subsequent inrush to the workings of water stored behind bulkheads in previously mined panels. This review makes no comment on the probability of such an occurrence, but does point to published reports that provide examples where carefully designed and constructed underground structures have effectively controlled water diversions for many decades (Younger and Wolkersdorfer, 2004).

The groundwater-related effects of potential bulkhead failure were not specifically considered in the EIS, but the results that have been provided can be interpreted to provide some useful information on the issue. The groundwater assessment modelling method included leaving drain cells active after mining until the residual void behind the bulkhead is filled, and then de-activating the drain cells (Figure 3).

This allowed unpacking of the volumes reporting "to void" (which in reality would become part of aquifer storage post-mining) separately from the volumes "to sump" (which are used in the mine water management circuit). The volumes "to void" can be considered to be a prediction of the effect of bulkhead failure in terms of water take and drawdown, because the model is actually removing the "to void" volumes from the model via the drain cells, rather than allowing the volumes to become part of the post-mining aquifer storage (as would happen when the drain cells are turned off). Hence the predicted drawdown using this method actually provides an assessment of the drawdown impacts due to the void volume being removed from the model (i.e. as if a bulkhead failure had occurred; or, more correctly, as if every bulkhead fails in turn).

An alternative modelling method has been applied in the latest refinements (see section 2). The revised method involves turning off model drain cells when the mined areas are sealed. The de-activation of drain cells post-mining is a more realistic method, in that the model allows post-mining inflows to become part of the void element of aquifer storage once a mined panel is sealed.

Figure 3 - mine drainage feature (after Coffey 2016b, Figure 5.4)



Concurrent with the revised drain cell method, the direct injection of mine water to the aquifer may be required to manage mine water balances (this was reportedly not required previously; Coffey, 2016b). If so, it would warrant some form of treatment to reduce any water quality issues (e.g. turbidity, hydrocarbons) arising from contact with mining operations. If, however, the water can be intercepted before such contact, then the direct injection of mine water should not cause groundwater quality issues.

Comparison of the results from Coffey (2016b) and the latest refinements from HydroSimulations would allow assessment of the various effects relating to potential bulkhead failure. However, it is recommended (i.e. it may be simpler) to run a sensitivity-style simulation of the refined model, emulating the previous arrangement of leaving drain cells on post-mining until the voids are filled.

5. Conclusions

The reported water balance "discrepancy" is not indicative of fundamental flaws in the Hume Coal model, contrary to review comments from DPI Water (2017) and Anderson (2017), and hence their downgrading to a Class 1 model confidence level 1 is invalid. Accordingly, any criticisms based on this invalid premise are not necessarily valid.

The groundwater assessment report (Coffey, 2016b) claims a model confidence level of Class 2/3 (30%/70%), suitable for an impact assessment purpose. This review finds that at Class 2 is justified, based on an independent assessment (Table 1) of the attribute weightings of the Hume Coal model as reported in Coffey (2016b).

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; see Appendix A). 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; see section 2 for details).

6. Declaration

For the record, the peer reviewer, Mr Hugh Middlemis, is a civil engineer, hydrogeologist and independent modelling specialist with more than 35 years' experience. Hugh was principal author of the MDBA groundwater modelling guidelines (Middlemis et al. 2001) and was awarded a Churchill Fellowship in 2004 to benchmark groundwater modelling against international best practice.

Mr Middlemis has not undertaken any work at the Hume Coal Project, although he has undertaken investigations nearby at the Berrima Colliery on behalf of Boral Limited, which included an inspection of the underground workings in November 2012 and several site visits to the area. Mr Middlemis appeared as an expert witness to the NSW Land and Environment Court on the Berrima Colliery groundwater issues (case number 12/10752, hearings in 2014).

Mr Middlemis has also completed independent review tasks of investigations by various parties who are now engaged in various roles in relation to the Hume Coal project, including:

- EMM on the Chandler Salt Project in the Northern Territory in 2016.
- Dr Noel Merrick (HydroSimulations) on the Wambo longwall panel 10A expansion in 2015. This also involved discussions with Mr John Williams (NSW Office of Water). Mr Middlemis also completed an independent review of the HydroSimulations report on the Mulgrave River model in June 2016 (the modeller involved was Chris Nicol).
- Joint expert conferencing on the Berrima Colliery case at the NSW Land and Environment Court with Mr John Lee (Hydroilex) in 2014.

Previously, Mr Middlemis has worked with Noel Merrick, notably:

- to write the 2001 guidelines on groundwater modelling and prepare and deliver some related conference papers;
- for a few semesters across about 1996-2005, Mr Middlemis worked as the distance education tutor for Dr Merrick's Groundwater Modelling subject at UTS (i.e. marking assignments and helping students via email and telephone);
- during parts of the period 1986-1989 when Mr Middlemis worked at the Department of Water Resources and he was seconded from the Hydrology unit to work in the Hydrogeology Unit on groundwater modelling projects under Mr Merrick.

Dr Merrick has completed independent reviews of groundwater models developed for catchment and salinity management purposes in South Australia and Victoria by Aquaterra when Mr Middlemis was Technical Director (Adelaide Plains solute transport model (2011); Padthaway solute transport model (2008); Eastern Mallee model EM2.1 (2008) and EM2.3 in 2009).

Having outlined recent experience on projects in the area and with certain parties now engaged in some role with regard to the Hume Coal Project, we assert no conflict of interest in relation to this independent review task.

7. References

Anderson, D. (2017). Hume Coal Project SSD 15_7172. Peer Review of Conceptual and Numerical Groundwater Modelling that predicted likely groundwater impacts. Prepared by the Water Research Laboratory, University of NSW, for the Coal Free Southern Highlands. Submitted online to the Dept of Planning and Environment via the Major Projects Portal. 23 June 2017.

Barnett, B., Townley, L.R., Post, V., Evans, R.E., Hunt, R.J., Peeters, L., Richardson, S., Werner, A.D., Knapton, A. and Boronkay, A. (2012). Australian Groundwater Modelling Guidelines. Waterlines report 82, National Water Commission, Canberra.
http://webarchive.nla.gov.au/gov/20130420190332/http://archive.nwc.gov.au/library/waterlines/82.

Coffey (2016a). Groundwater Assessment Volume 1: Data Analysis. Prepared for Hume Coal Pty Limited, 17 November 2016.

Coffey (2016b). Groundwater Assessment Volume 2: Numerical Modelling and Impact Assessment. Prepared for Hume Coal Pty Limited, 17 November 2016.

Department of Environment and Heritage Protection (2016). Quick Guide. Make Good Obligations. Prepared by Resource Sector Regulation and Support, DEHP, Queensland, version 3, 2 March 2016.

Department of Primary Industries (2017). Hume Coal Project (SSD 7172) and related Berrima Rail Project (SSD 7171). Comment on the Environmental Impact Statement (EIS). 16 July 2017.

EMM (2017). Hume Coal Project Environmental Impact Statement Main Report. Prepared for Hume Coal Pty Limited, March 2017. Includes Appendix O: Drawdown impacts in landholder bores. Proposed 'make good' provisions.

Evans, R., Campbell, L. and McKelvey, P. (2015). Determining realistic specific storage values for input to groundwater flow models. Specific storage – the poor cousin to hydraulic conductivity. 2015 Australian Groundwater Conference, Canberra, November 3-5, 2015.

Lee, J. (2017). Hume Coal Project SSD 15_7172: Southern Highlands NSW – Objection to Project Approval. Prepared by Hydroilex for the Coal Free Southern Highlands. 30 June 2017.

Mackie, C.D. (2009). Hydrogeological characterisation of coal measures and overview of impacts of coal mining on groundwater systems in the upper Hunter Valley of NSW. PhD thesis, Faculty of Science, University of Technology, Sydney, 273 pp. January 2009.

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

Pells, S. (2017). Groundwater Modelling of the Hume Coal Project. Prepared by Pells Consulting for the Coal Free Southern Highlands. 22 June 2017.

Tammetta, P. (2013). Estimation of the height of complete groundwater drainage above mined longwall panels. *Groundwater*. Vol. 51, No. 5, September-October 2013, pp 723-734.

Younger, P.L. and Wolkersdorfer, C. (2004). Mining impacts on the fresh water environment: Technical and Managerial Guidelines for Catchment Management. Prepared by the Environmental Regulation of Mine Waters in the European Union (ERMITE) Consortium, a project of the European Commission's 5th Framework R&D. Journal of Mine Water and the Environment (2004) **23**: pp.S2–S80.

Appendix A

Hume Coal Model Issues Log

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 average "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 plies 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.
5	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 represented 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.

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)
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

Hume Coal Project Independent Expert Roundtable Meeting 16 November 2017

Hume Coal Project – Independent Expert Roundtable Meeting

Thursday 16 November 2017: 11.00am – 2.45 pm (lunch at 1 pm)

Dainun Room, Level 30, 320 Pitt Street Sydney

Attendees:

Facilitator	Anuj Saraogi (DPC)
DPE	Hugh Middlemis (Hydrogeologic)
Community	Dr Stephen Pells (Pells Consulting), John Lee (Hydroilex), Chris Jewell (CM Jewell & Assoc)
Agencies	Alison Collaros (CL&W), Malcolm Hughes (WaterNSW)
Observers	Clay Preshaw (DPE), Paul Freeman (DPE) Peter Martin (CFSH), Alan Lindsay (CFSH)

AGENDA

11 – 11.15	Welcome and Introductions – Tim Kirby
11.15 – 11.45	Briefing on investigations and key findings - Hugh Middlemis
11.45 – 2.30	Key discussion items – All
11.45 – 12.10	a) *Groundwater model* - conceptual geological and hydrogeological model - modelling assumptions based on the conceptual model - class/confidence level - the use of "average flow budget" over a range of stress periods - water balance average discrepancy term of 5% - Scaled Root Mean Squares values greater than 10%
12.10 – 12.35	b) *Dewatering volumes and extent of drawdown* - potential take from aquifers above/below the target coal seam - sensitivity analysis - any additional bores affected – volumes and time periods
12.35 – 1	c) *Technical feasibility of make good for private bores*
1 – 1.30	LUNCH
1.30 – 2.00	d) *Underground bulkheads* - model conceptualisation of aquifer storage in mined voids behind bulkheads - any implications for groundwater model - any further modelling required - potential surface water issues e.g. treatment/discharge
2 – 2.30	Recap of residual issues – All
2.30 – 2.45	Conclusion and key actions – Tim Kirby

Hume Coal Project

Revised Groundwater Modelling for Response to Submissions

FOR

Hume Coal Pty Ltd

BY

NPM Technical Pty Limited

trading as

HydroSimulations

Project number: HUM002

Report: HS2018/02

Date: June 2018

DOCUMENT REGISTER

Revision	Description	Date	Comments
A	First Draft	Insert date	
B	Second draft	16 May 2018	
C	Final Draft	31 May 2018	
D	Final	8 June 2018	

Role	Persons
Authors	Adam Skorulis and Dr Damian Merrick
Contributors	Braiya White, Joel Vernon
Internal Reviewer	Dr Noel Merrick

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ATTACHMENTS

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 5^{th} and 95^{th} 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 (5×10^{-7}/m increased globally to 2×10^{-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)

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

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 $(100 \times p)^{\text{th}}$ 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 – $\text{e.g.}\, c = 3$ 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

10 REFERENCES

Barnett, B, Townley, L.R., Post, V., Evans, R.E., Hunt, R.J., Peeters, L., Richardson, S., Werner, A.D., Knapton, A. and Boronkay, A., 2012. *Australian Groundwater Modelling Guidelines*. Waterlines report 82, National Water Commission, Canberra.

Bureau of Meteorology (BoM), 2017. *http://www.bom.gov.au/climate/data/index.shtml*

Coffey Geotechnics, 2012. *Groundwater Study Area 3B Dendrobium Coal Mine Numerical Modelling*. Report GEOTLCOV24507AA-AB2 for BHP Billiton Limited, 2 October 2012.

Coffey, 2016a. Hume Coal Project Groundwater Assessment Volume 1: Data Analysis. Report GEOTLCOV25281AB-ACA for Hume Coal Pty Ltd. 17 November 2016.

Coffey, 2016b. Hume Coal Project Groundwater Assessment Volume 2: Numerical Modelling and Impact Assessment. Report GEOTLCOV25281AB-ACB for Hume Coal Pty Ltd. 8 August 2016.

Doherty, J., 2015. *Calibration and Uncertainty Analysis for Complex Environmental Models.* Watermark Numerical Computing, Brisbane, Australia. ISBN: 978-0-9943786-0-6.

Doherty, J., 2016. PLPROC: A parameter list processor. Software manual.

Department of Primary Industries (DPI), 2017. *Hume Coal Project (SSD 7172) snd related Berrima Rail Project (SSD 7171) Comment on the Environmental Impact Statement (EIS).* Letter from M.Isaacs to P.Freeman, NSW Department of Planning and Environment. 16 July 2017.

HydroAlgorithmics, 2018. AlgoCompute web site, https://www.algocompute.com/. Accessed 15 March, 2018.

HydroGeoLogic, 2017. *Hume Coal Project EIS Independent Expert Review Groundwater Modelling.* Prepared for NSW Dept. Planning and Environment. 6 Dec 2017.

IPCC, 2013. Climate Change: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press.

Merrick, D. and Merrick, N., 2015. *AlgoMesh: A new software tool for building unstructured grid models*. In Proc. MODFLOW and More, Golden, Colorado.

Merrick, D., 2017. *AlgoCompute: Large-scale calibration and uncertainty analysis made easy in the cloud*. In Proc. MODFLOW and More, Golden, Colorado.

Middlemis, H. & Peeters, L., 2018. *Explanatory Note, Uncertainty Analysis in Groundwater Modelling.* Report prepared for IESC on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment and Energy.

Miller, K.L., Berg, S.J., Davison, J.H., Sudicky, E.A., Forsyth, P.A., 2018. *Efficient uncertainty quantification in fully-integrated surface and subsurface hydrologic simulations.* Advances in Water Resources, Volume 111, pp. 381-394.

Mood, A.M., Graybill, F.A., Boes, D.C., 1974. *Introduction to the Theory of Statistics*, 3rd Edition. Mcgraw-Hill, Inc. ISBN: 978-0-07-042864-5.

NSW Government, 2011. *Water Sharing Plan for the Greater Metropolitan Region Unregulated River Water Sources 2011*. Accessed 12/03/2018. Available at: (https://www.legislation.nsw.gov.au/#/view/regulation/2011/112/id38)

Pells, S.E. and Pells, P.J.N.P., 2012. *Impacts of longwall mining and coal seam gas extraction regimes on groundwater in the Sydney basin. Parts 1 and 2.* Journal of the Australian Geomechanics Society, Vol. 47, No. 3, September 2012.

Pells Consulting, 2017. *Groundwater Modelling of the Hume Coal Project.* Report S025/R1 for Coal Free Southern Highland Inc.

Richardson, S., McMillan, M. and Currie, D., 2017. Communicating uncertainty to decision-makers and stakeholders. Background paper no.5 in Middlemis & Peeters (2018), NCGRT National Groundwater Modelling Uncertainty Workshop, Sydney, 10 July 2017.

USGS, 2018. *https://water.usgs.gov/ogw/modflow/*

UNSW, 2017. *Hume Coal Project SSD 15_7172: Peer Review of Conceptual and Numerical Modelling that Predicted Likely Groundwater Impacts.* Letter report WRL2017018DJA from G.P.Smith to C.Preshaw, NSW Department of Planning and Environment. 23 June 2017.

Vrugt, J.A., ter Braak, C.J.F., Diks, C.G.H., Higdon, D., Robinson, B.A., and Hyman, J.M., 2009. *Accelerating Markov chain Monte Carlo simulation by differential evolution with self-adaptive randomized subspace sampling. International Journal of Nonlinear Sciences and Numerical Simulation,* Volume 10, Issue 3, pp. 273-290.

WSP Parsons Brinckerhoff (WSP PB), 2016. *Hume Coal Project Water Balance Assessmen*t. Prepared by PB for Hume Coal Pty Ltd.

FIGURES

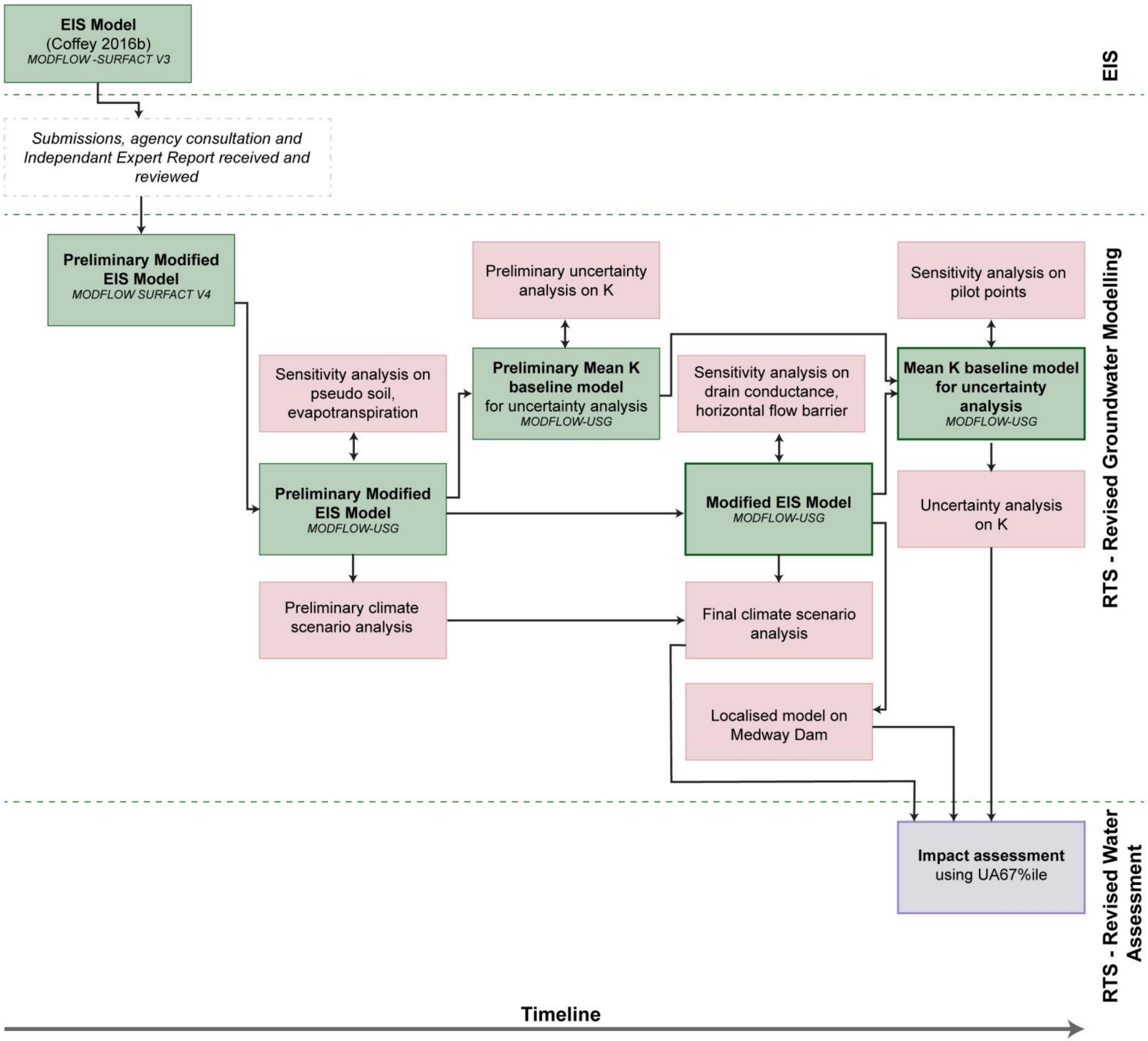


Figure 1 Hume Coal Project numerical groundwater model versions

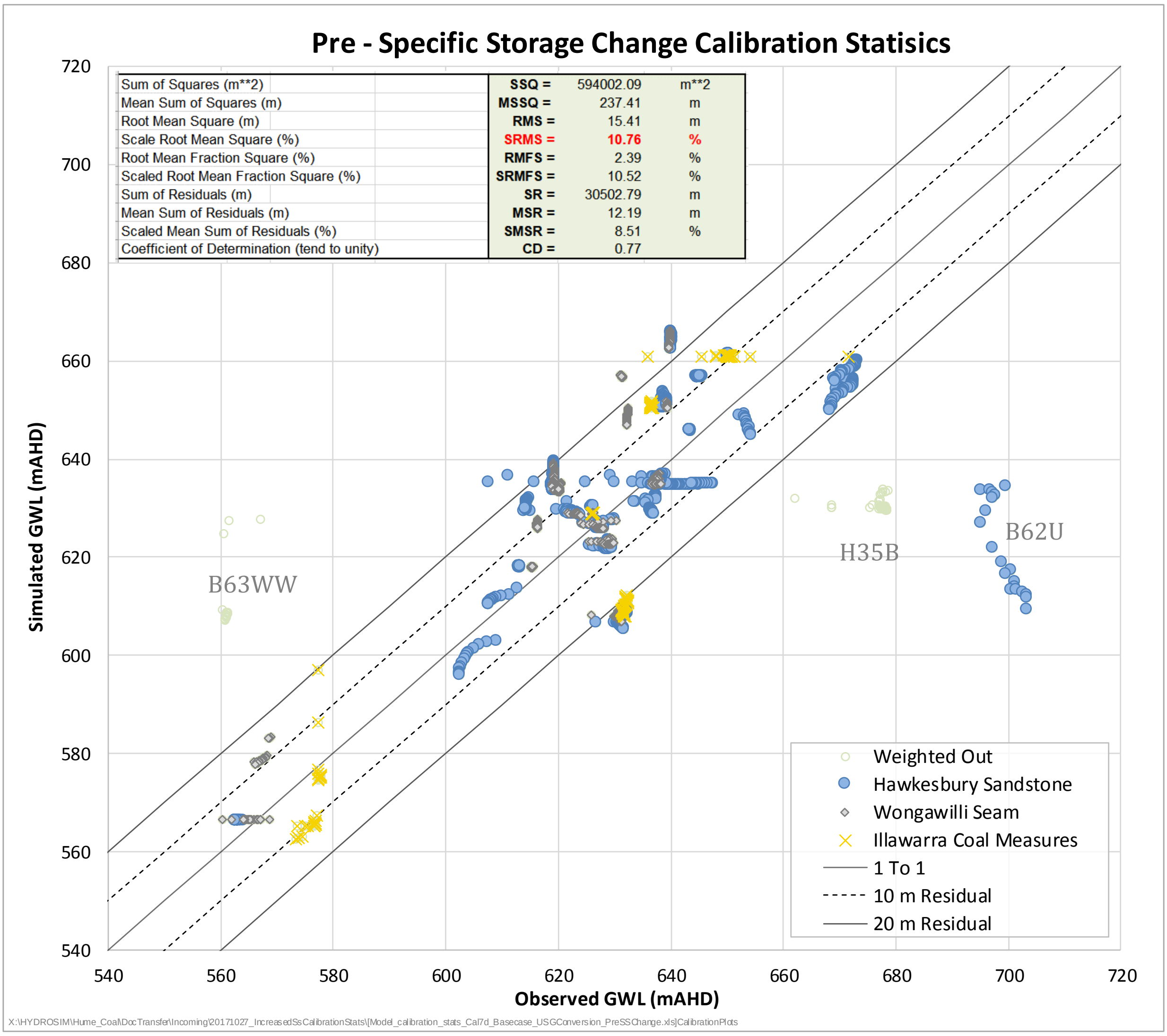


Figure 2 Observed vs modelled groundwater levels for the HydroSimulations revision of the EIS model using MODFLOW USG [Preliminary Modified EIS Model – USG]

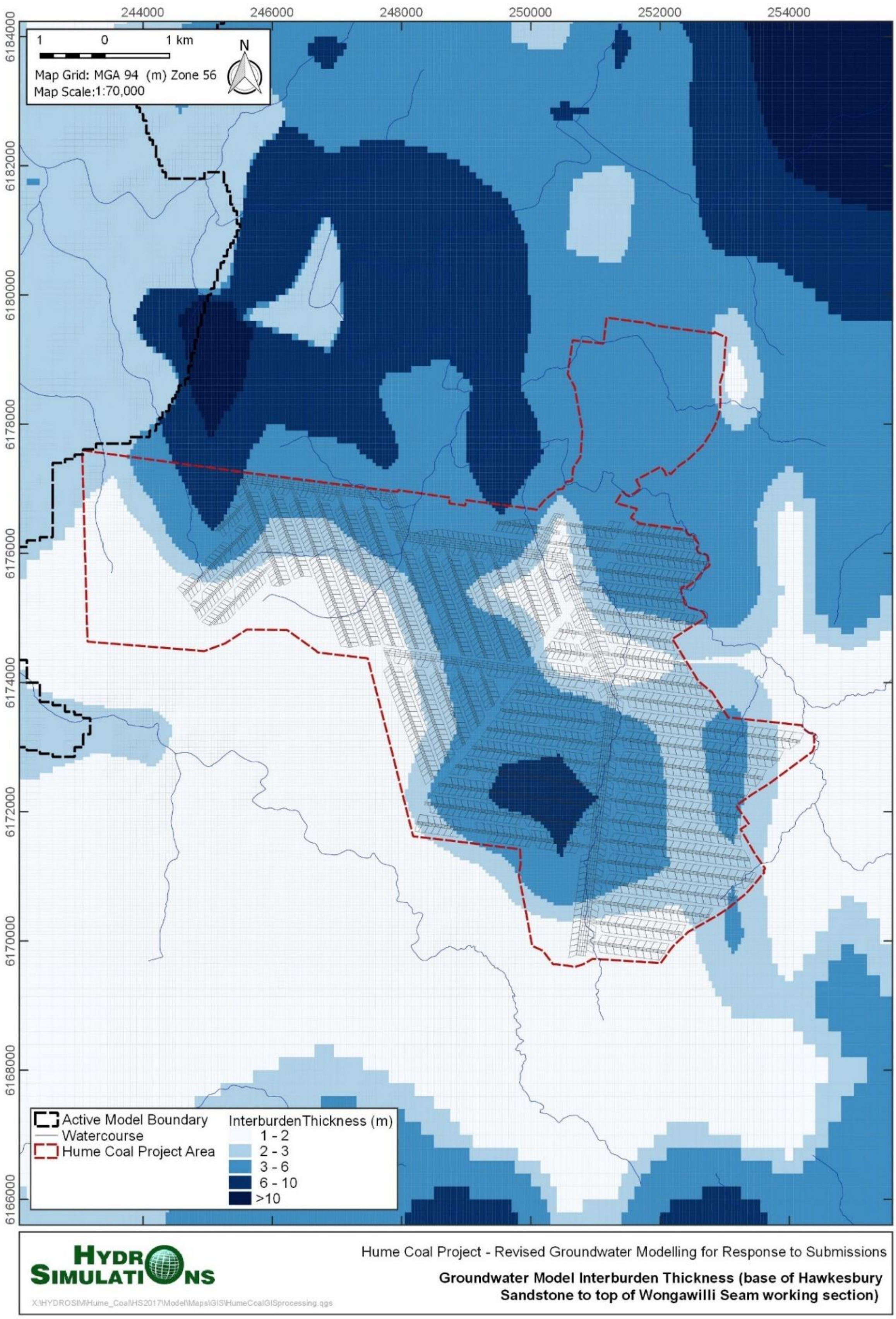


Figure 3 Groundwater model 'interburden' thickness

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

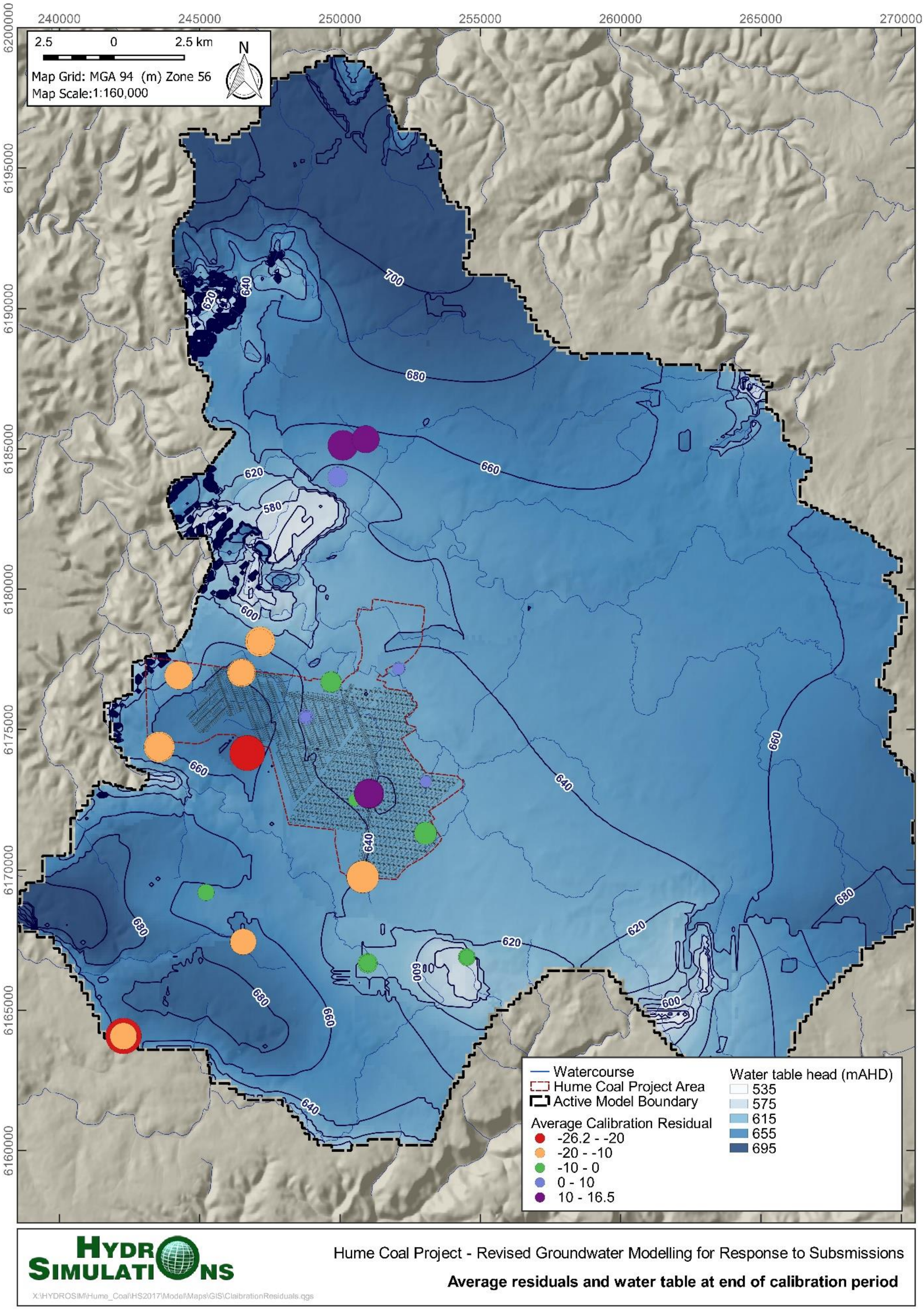
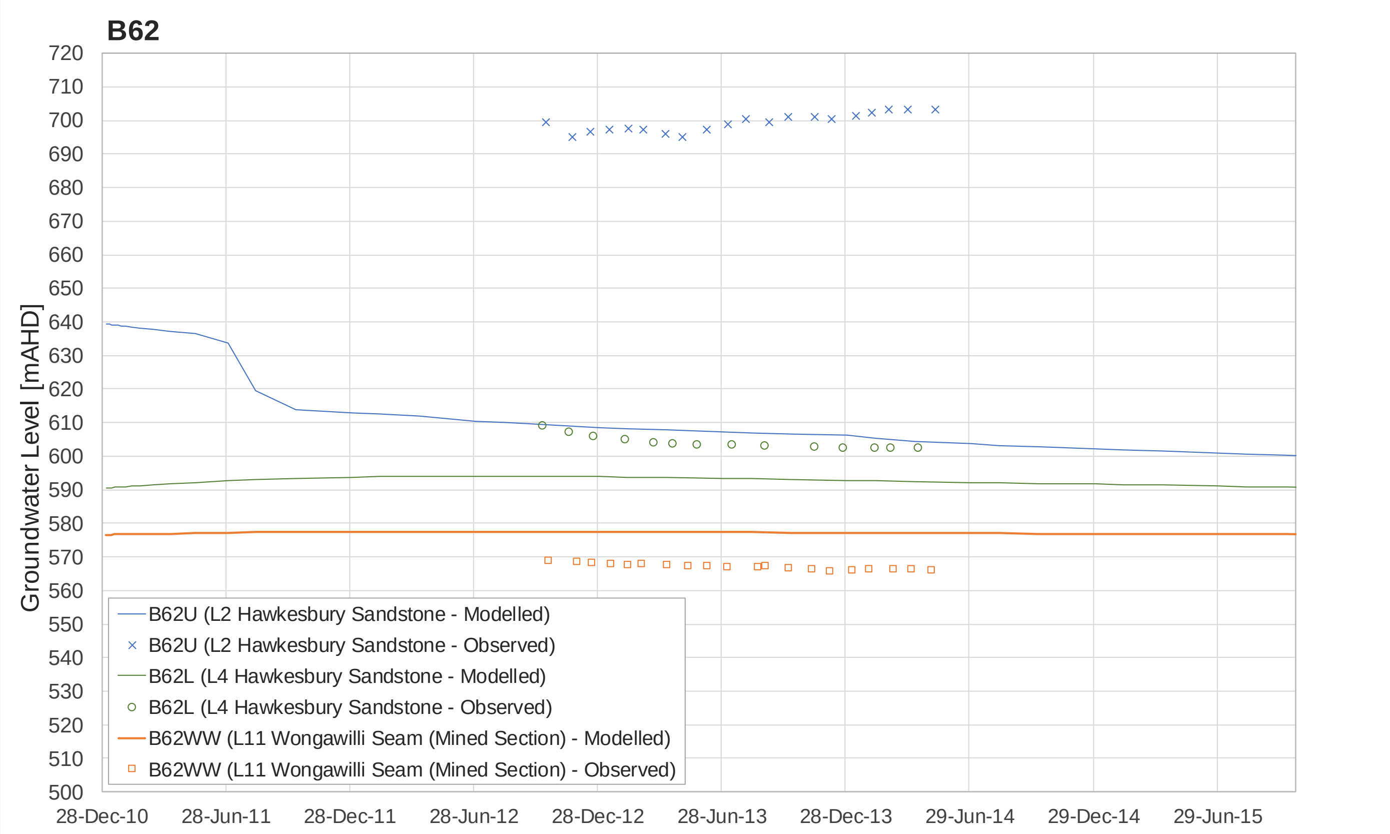


Figure 4 **Average residuals at bores and water table elevation at the end of the calibration period**

[Modified EIS Model – MODFLOW USG]

CALIBRATION HYDROGRAPHS (MODIFIED EIS MODEL – MODFLOW USG)



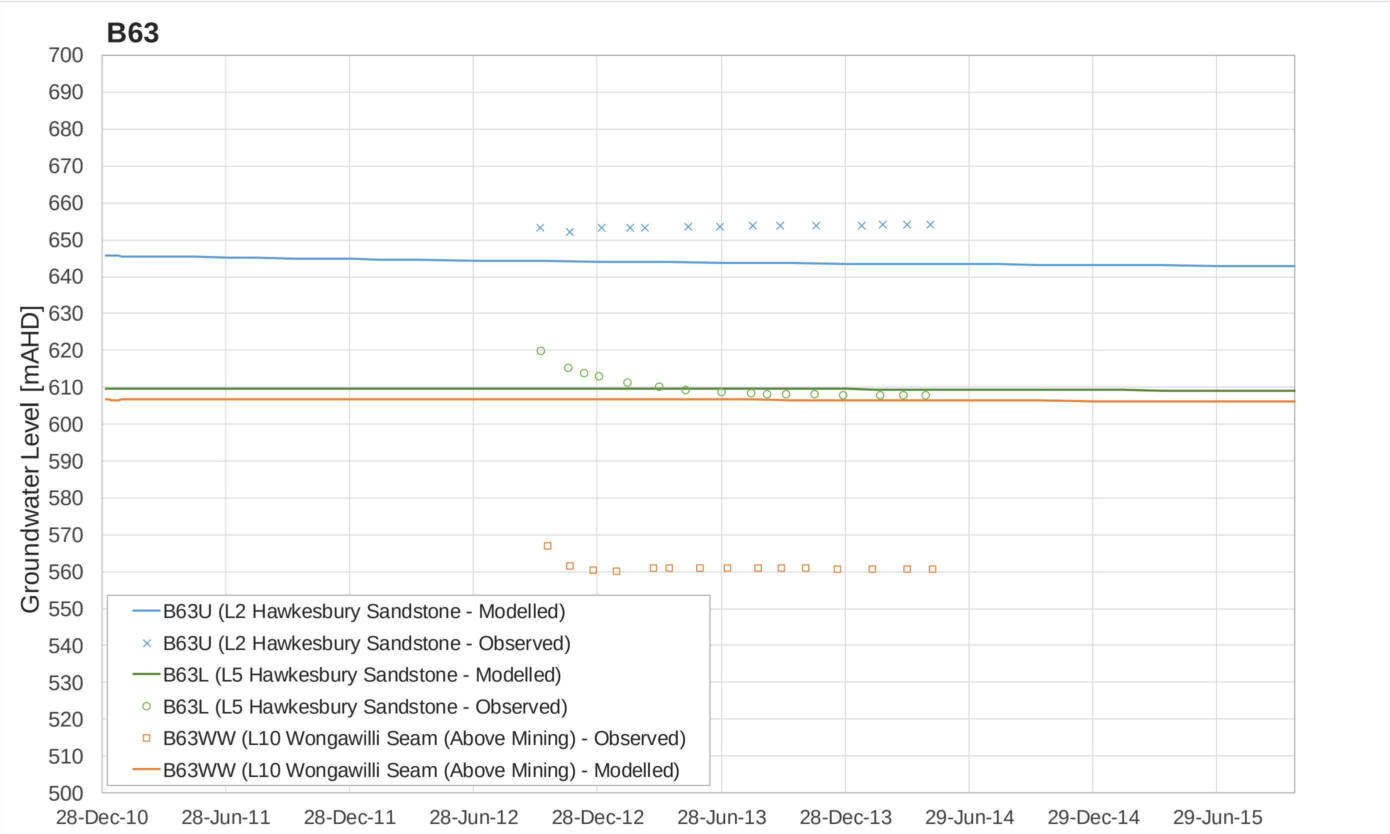
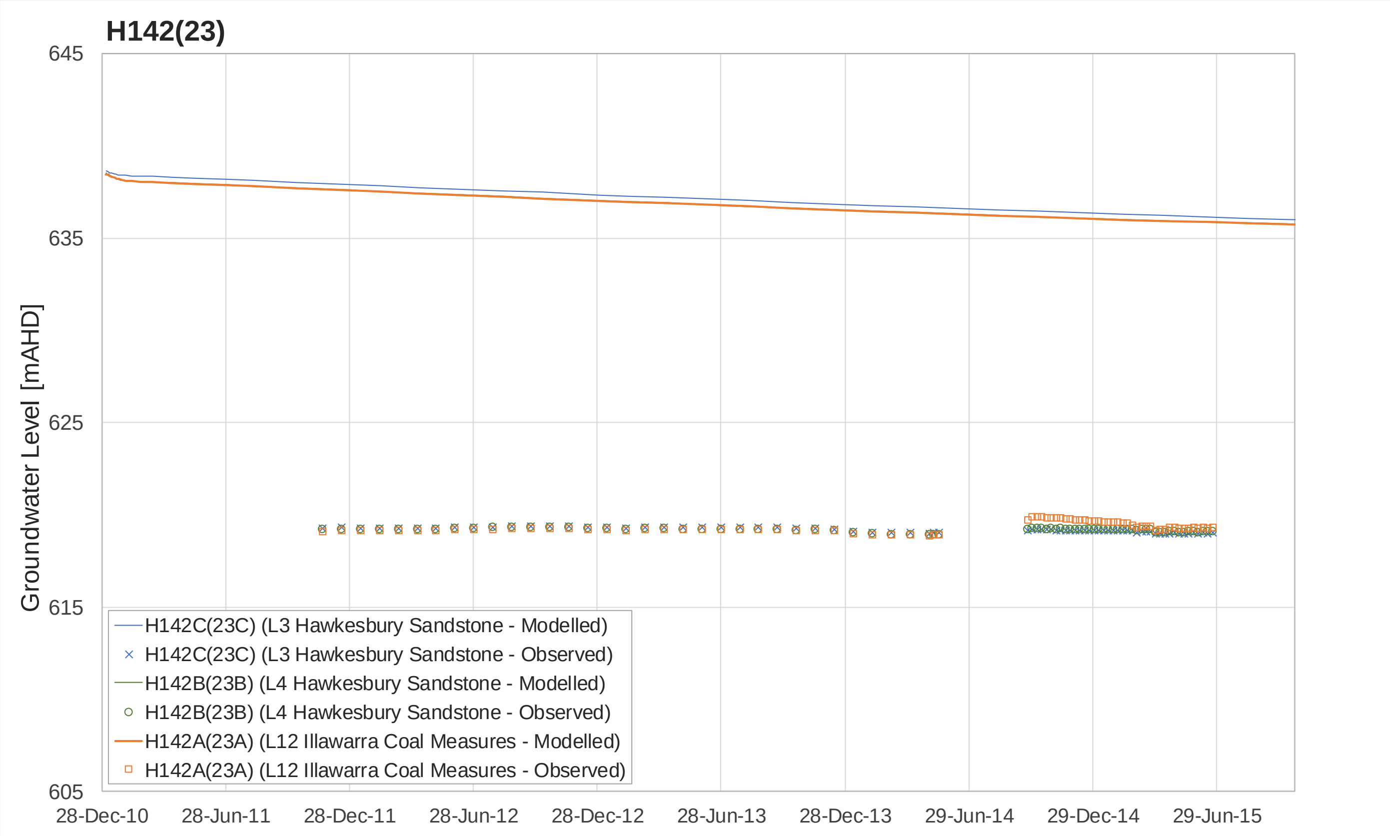


Figure 5 Multi sensor calibration hydrographs for B62 and B63



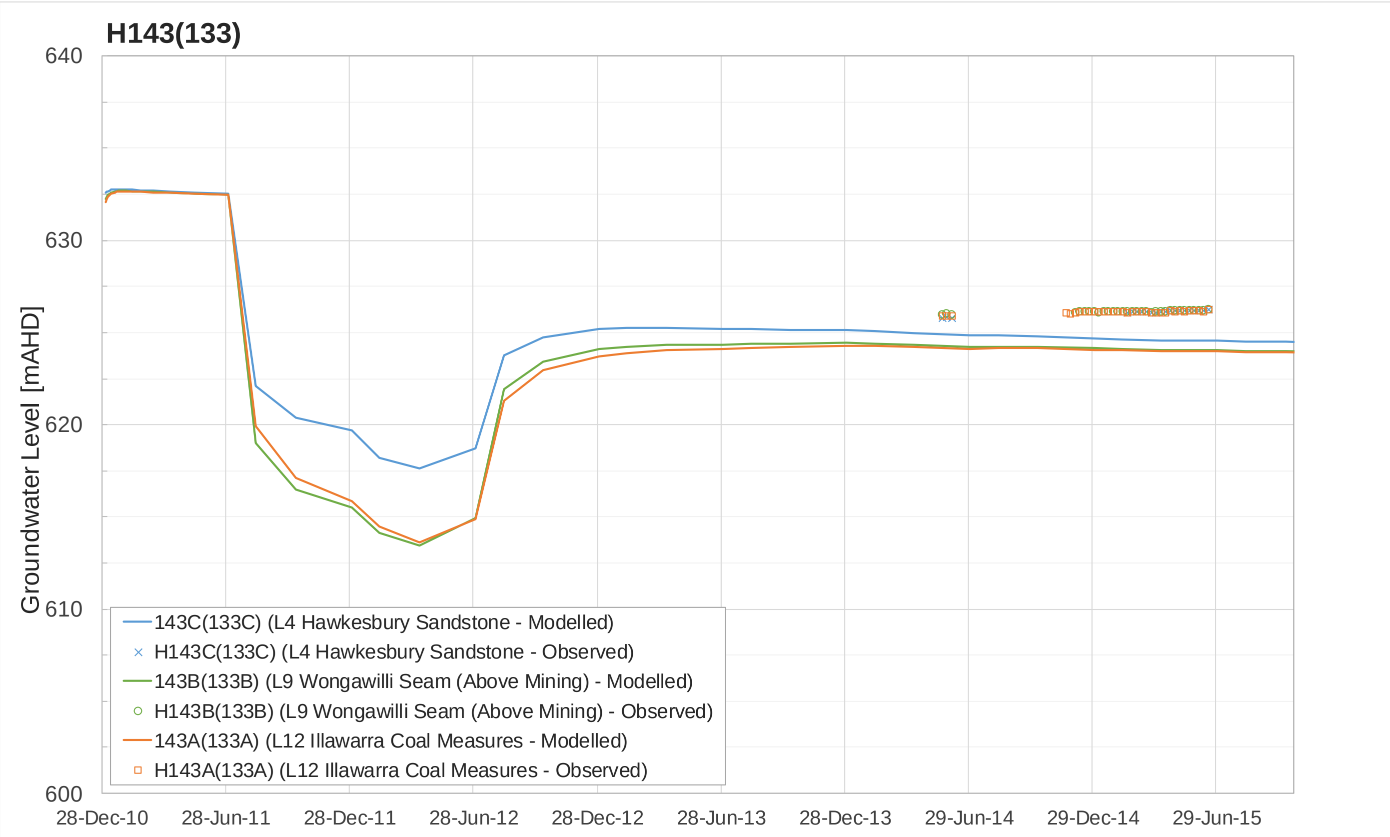
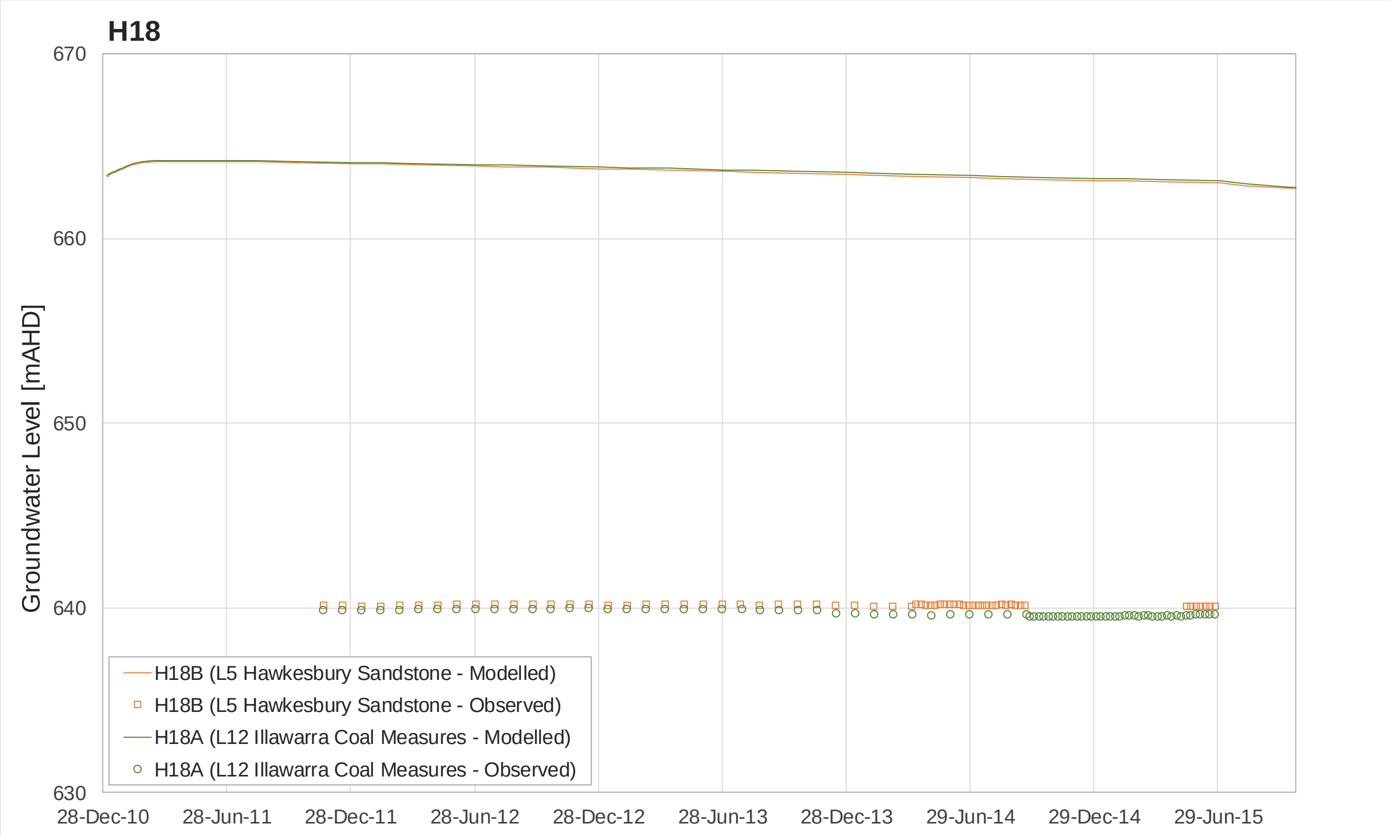


Figure 6 Multi sensor calibration hydrographs for H142(23) and H143(133)



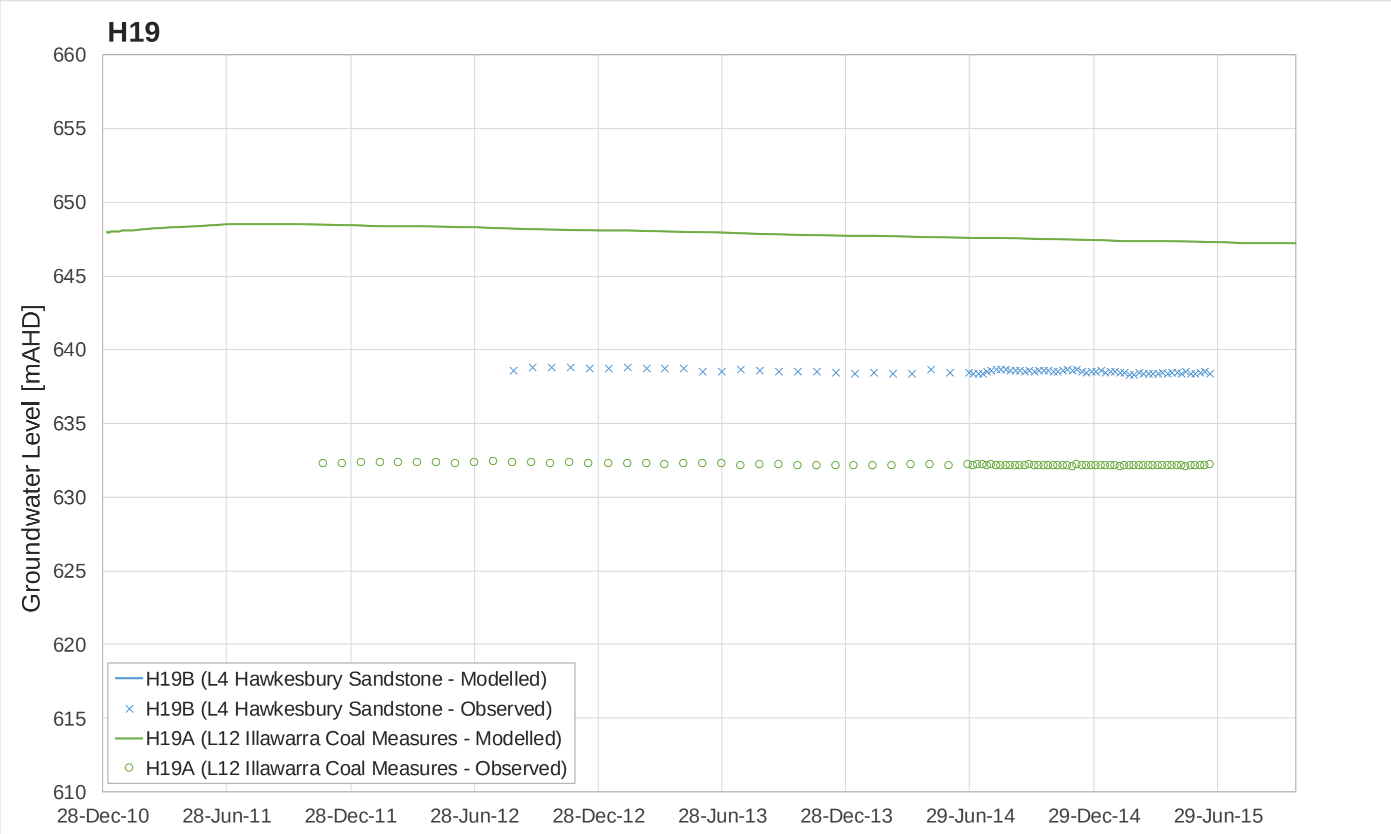
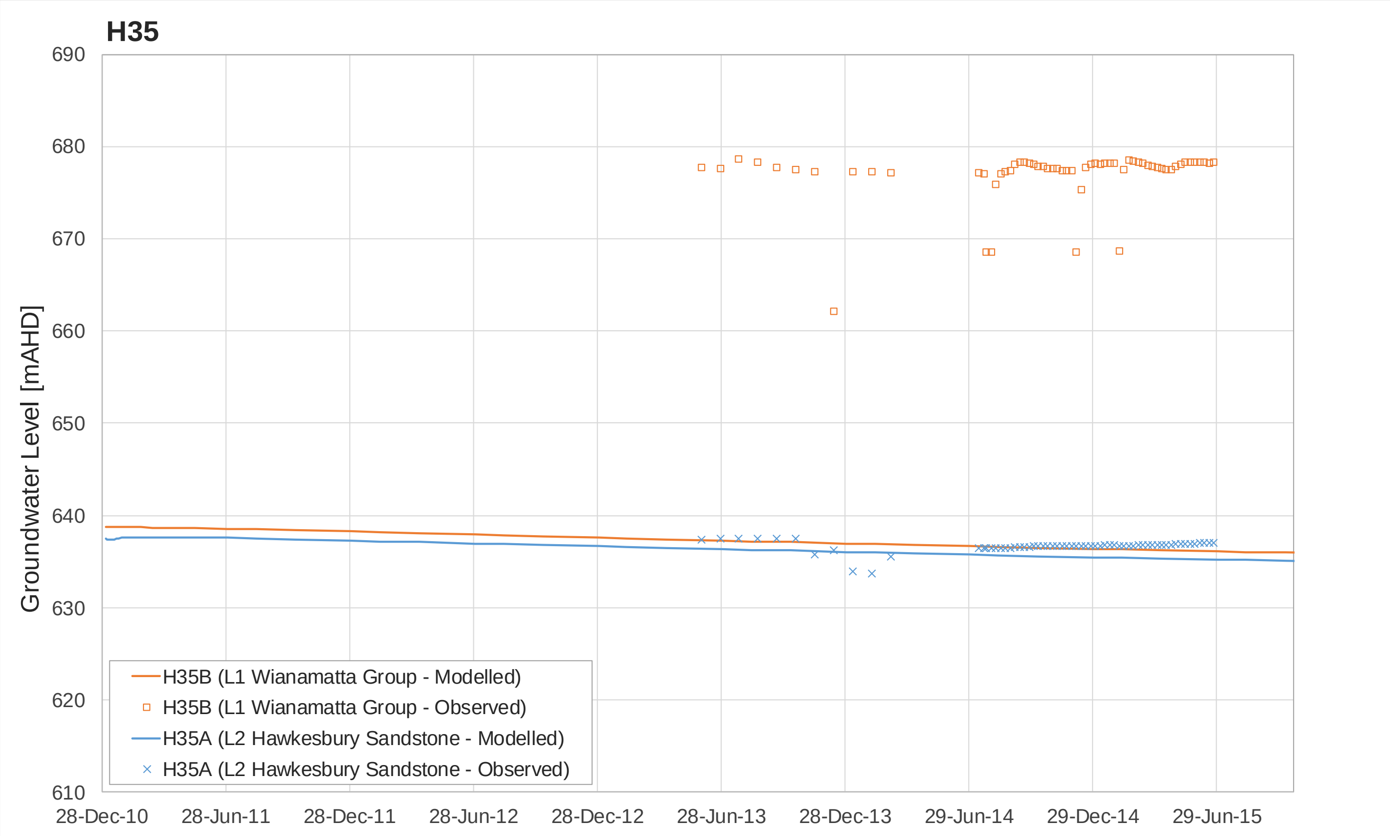


Figure 7 Multi sensor calibration hydrographs for H18 and H19



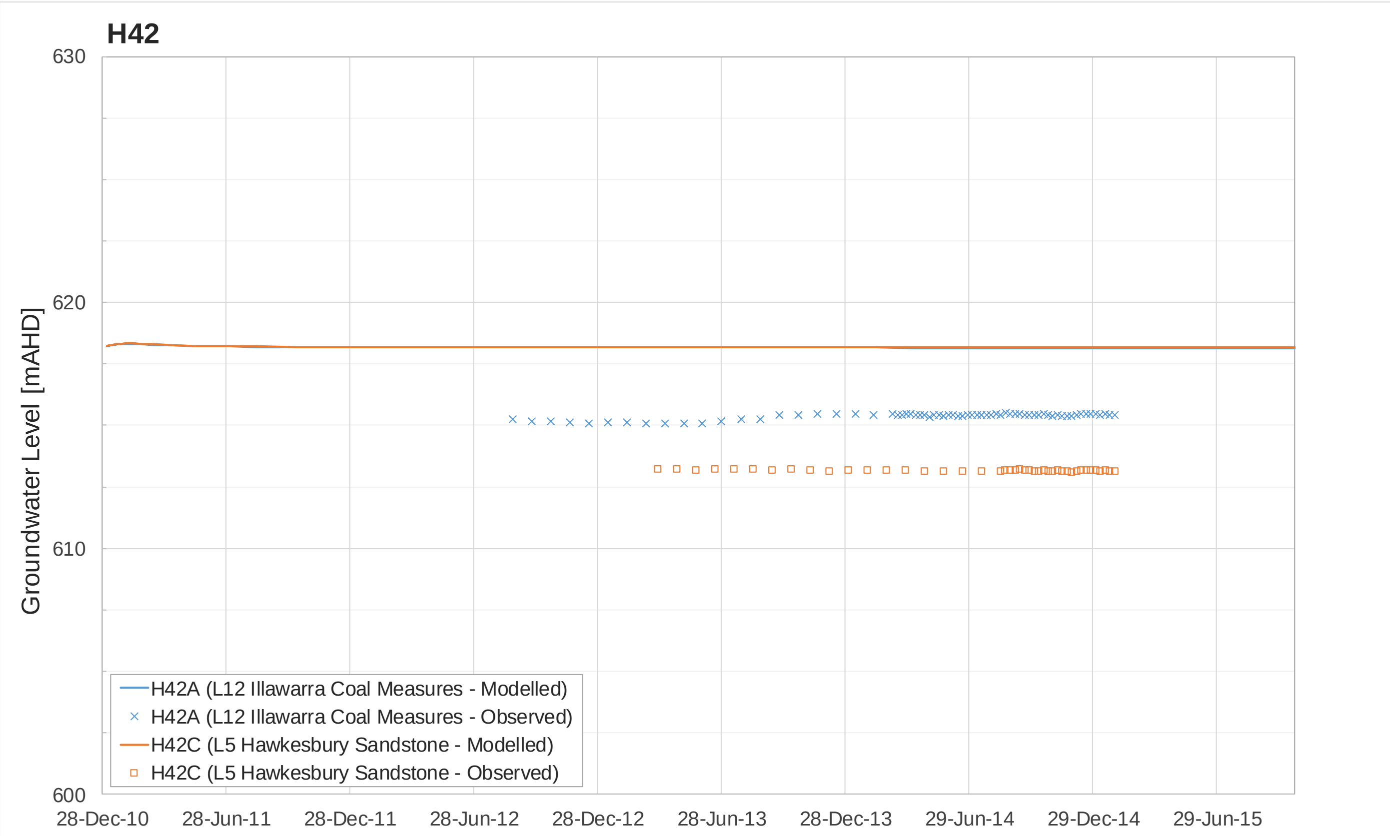
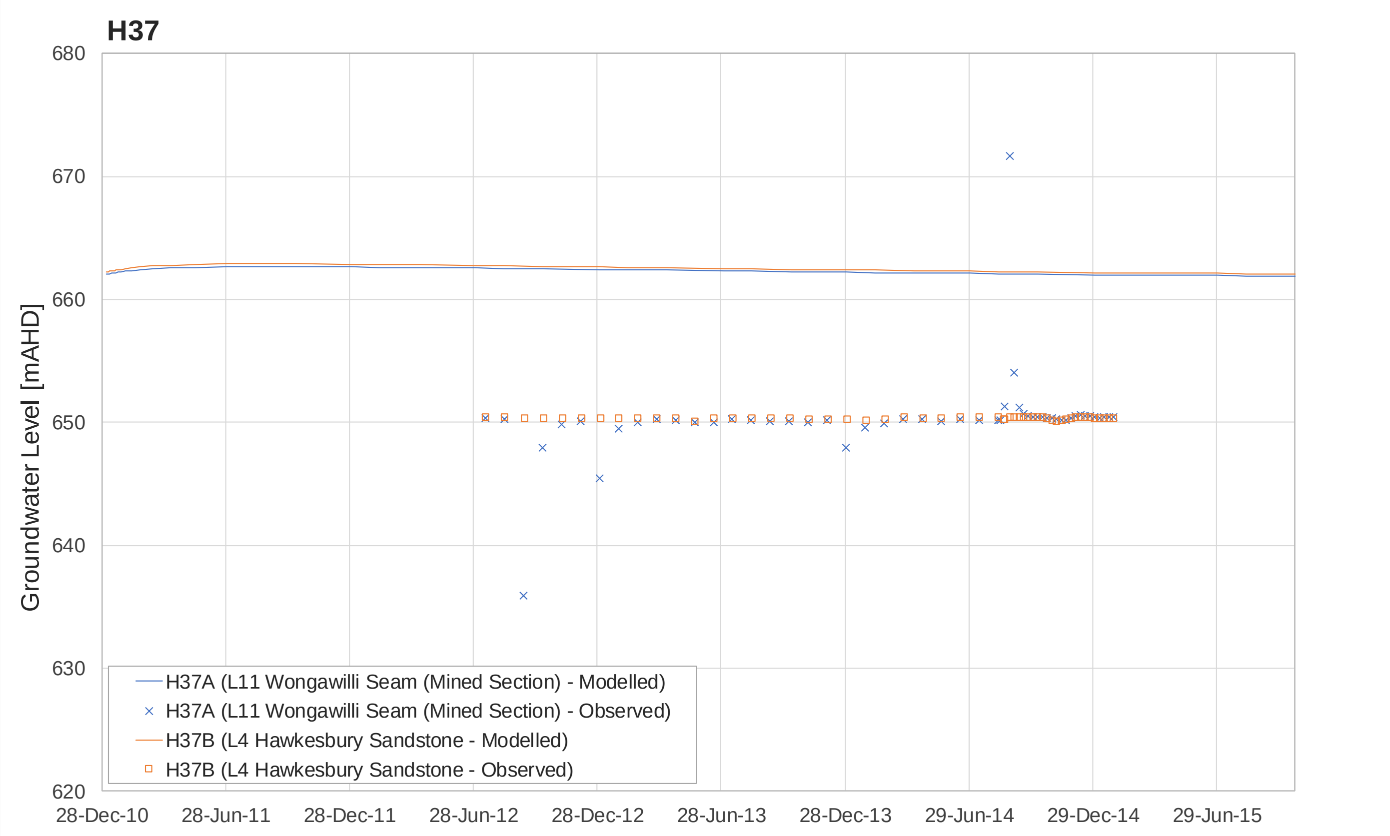


Figure 8 Multi sensor calibration hydrographs for H35 and H42



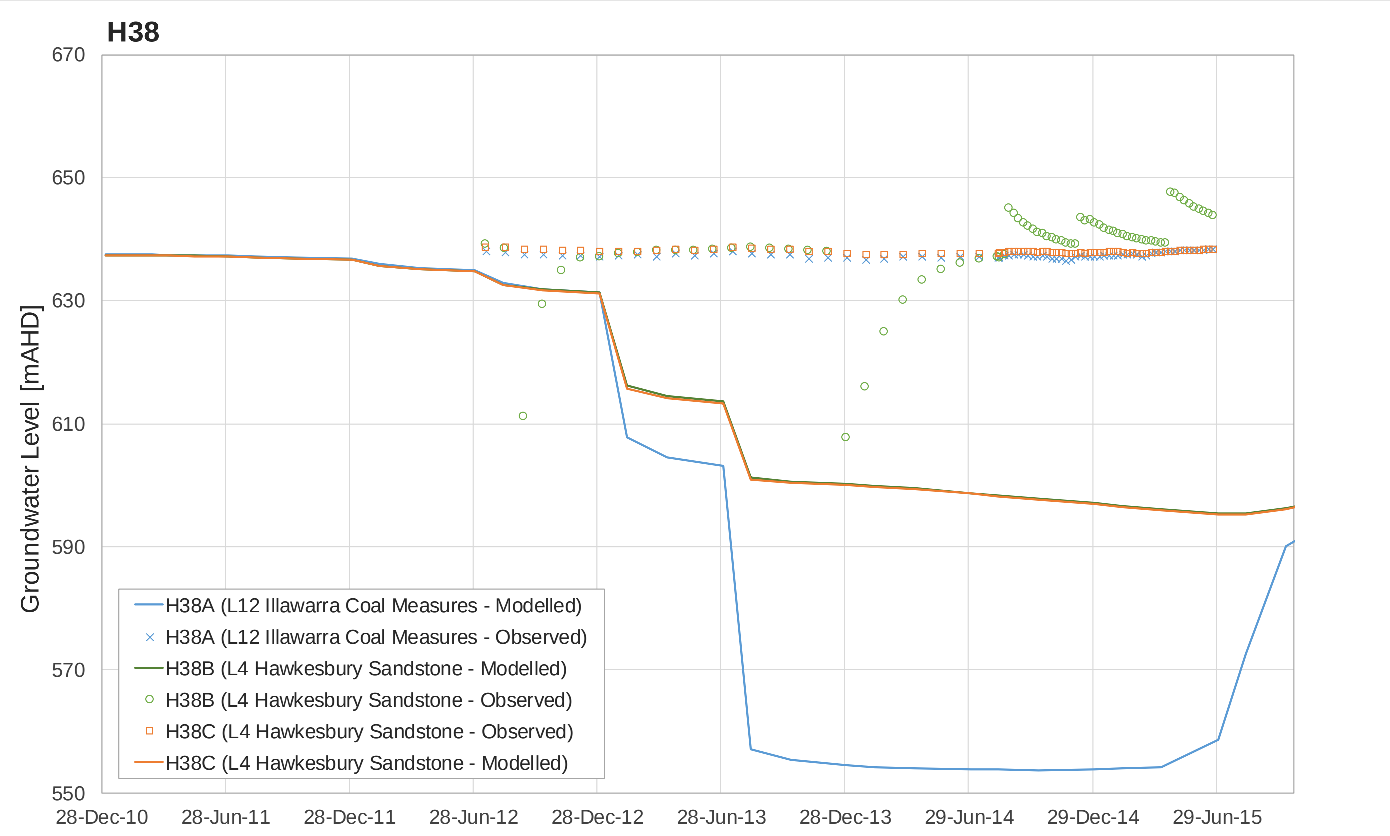


Figure 9 Multi sensor calibration hydrographs for H37 and H38

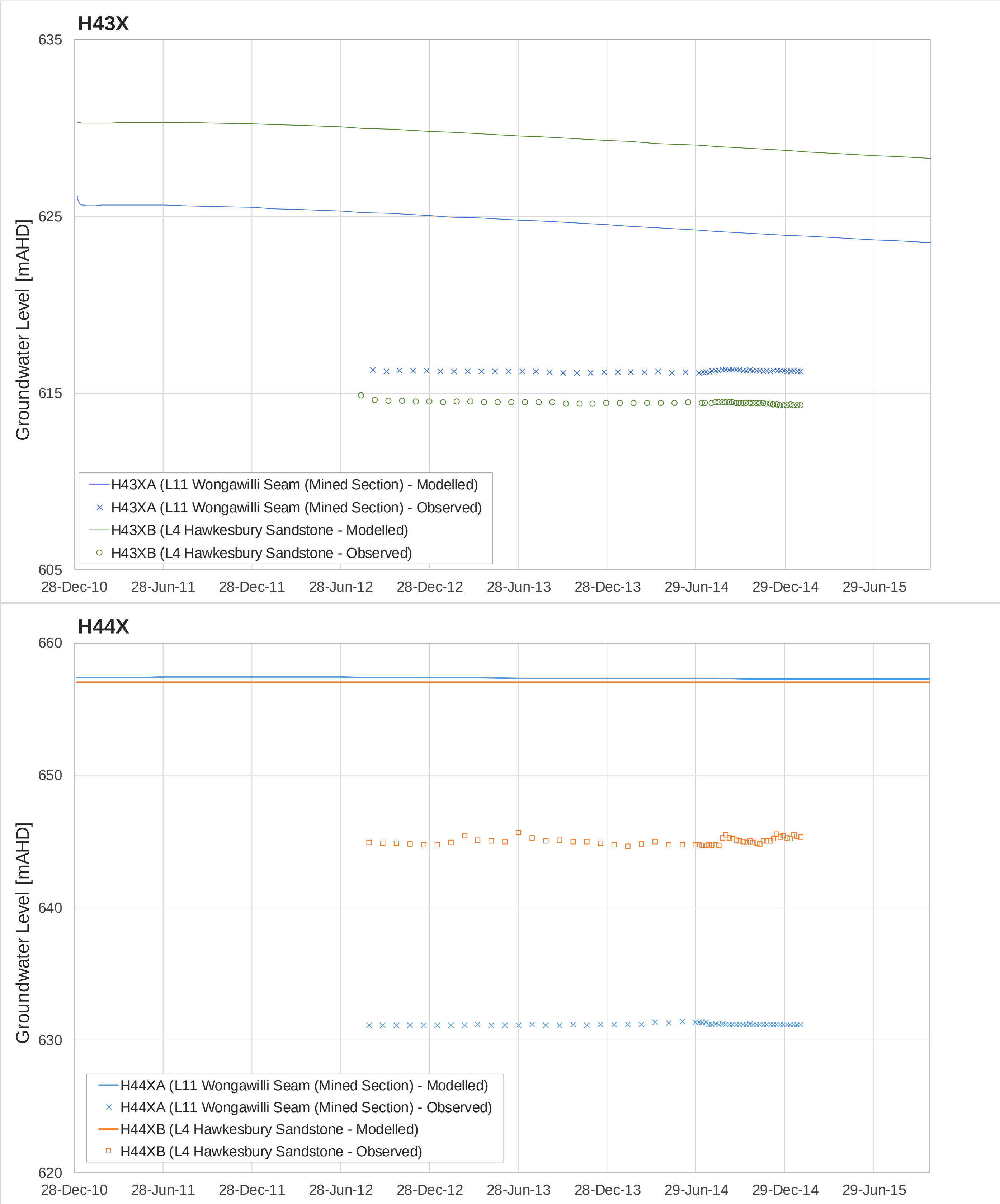
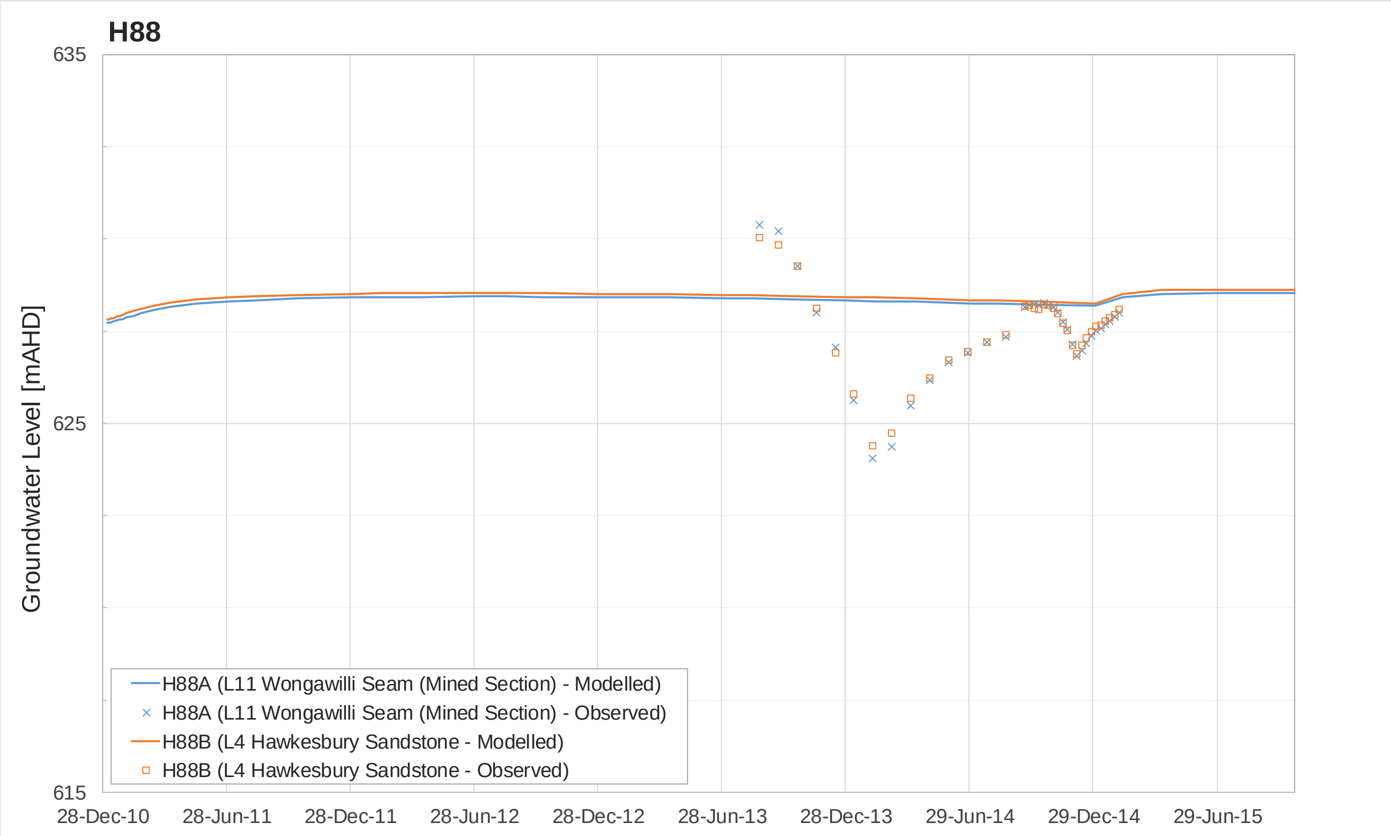


Figure 10 Multi sensor calibration hydrographs for H43X and H44X



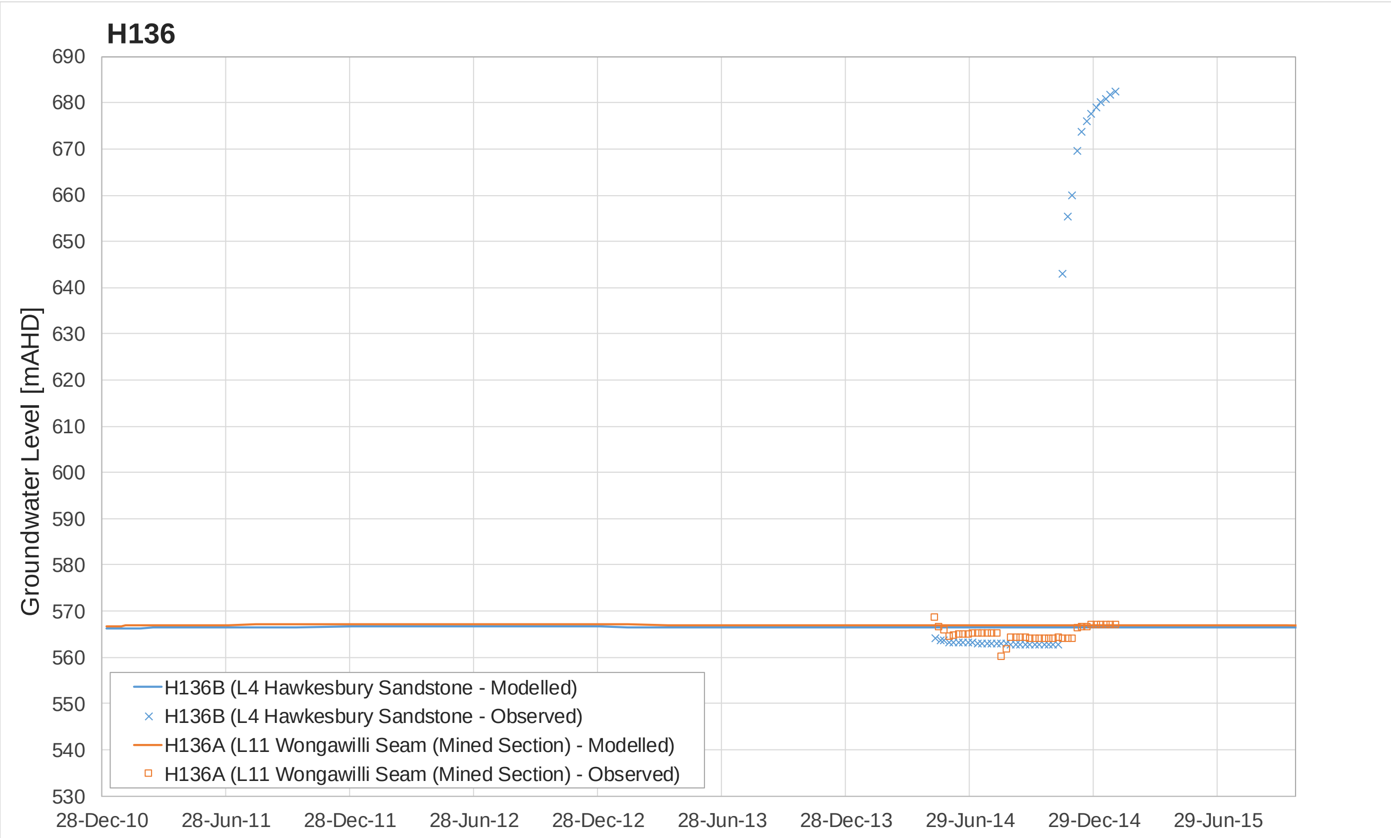
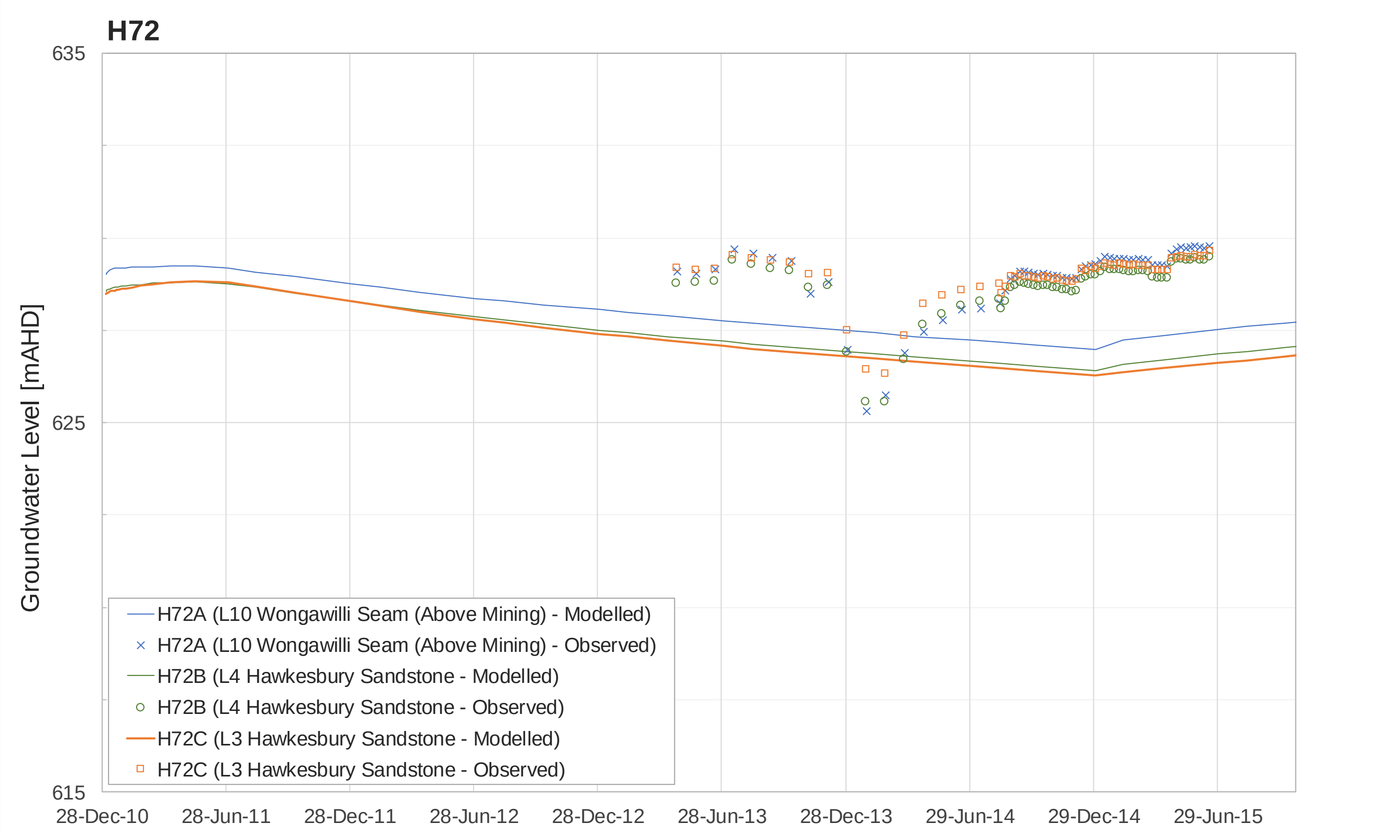


Figure 11 Multi sensor calibration hydrographs for H88 and H136



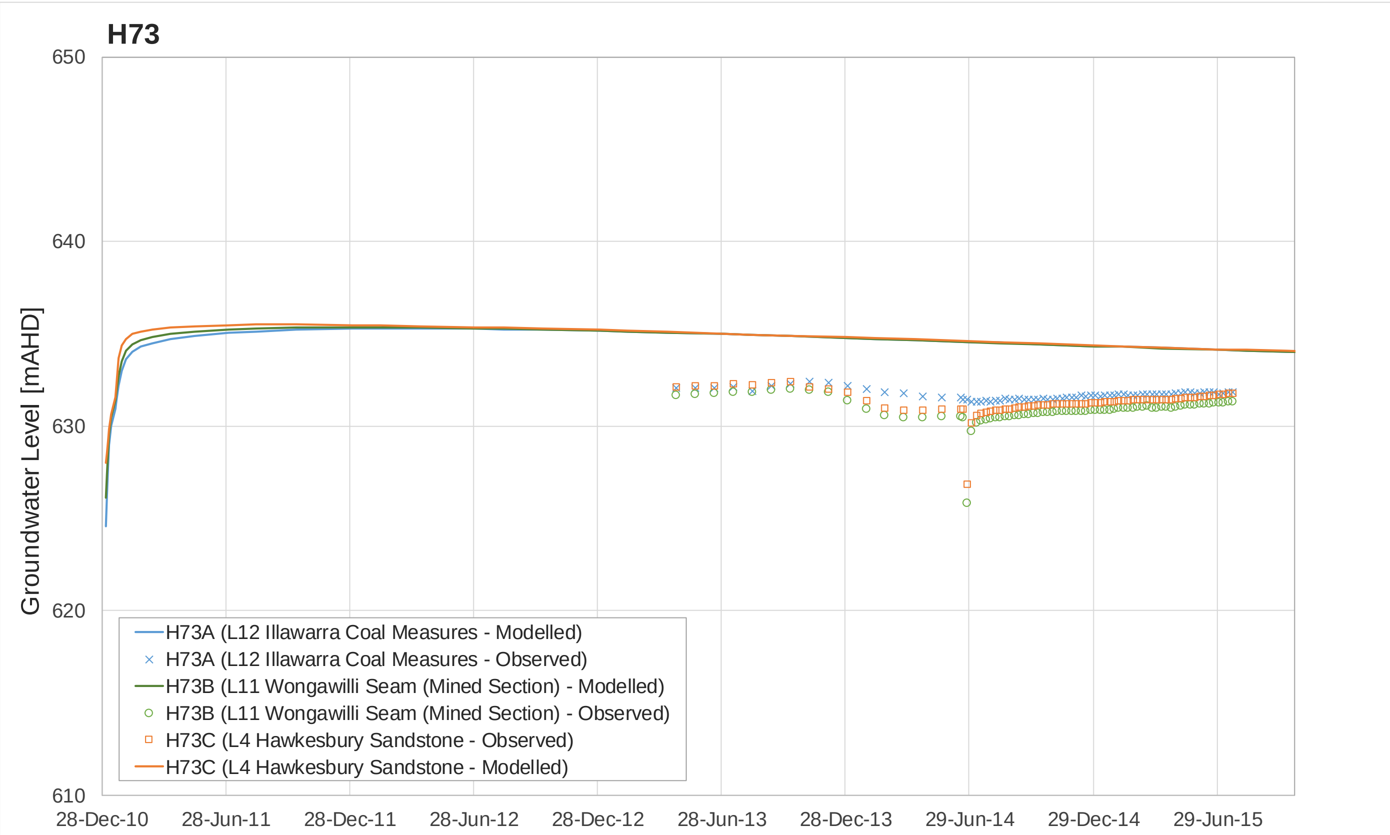


Figure 12 Multi sensor calibration hydrographs for H72 and H73

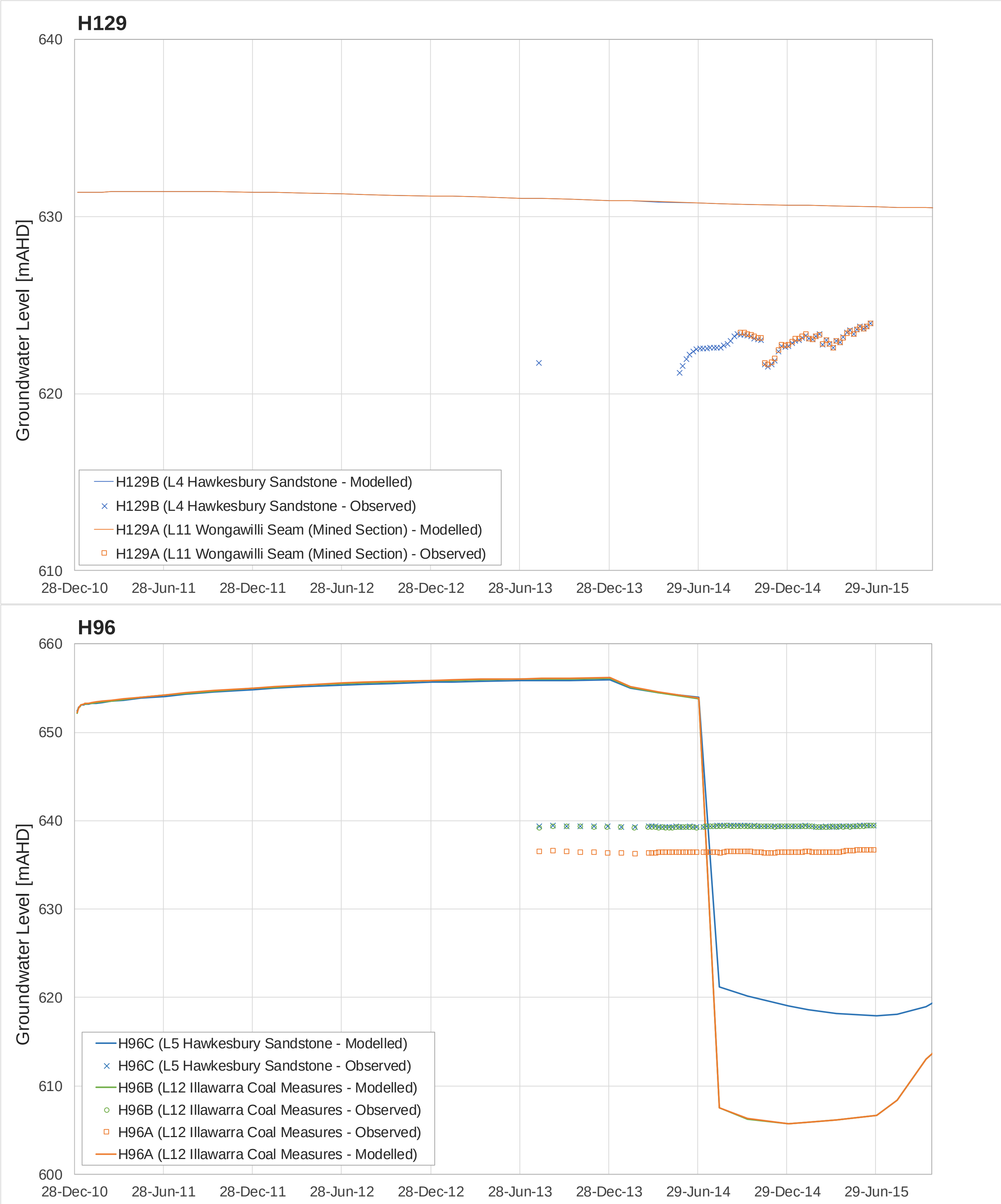


Figure 13 Multi sensor calibration hydrographs for H129 and H96

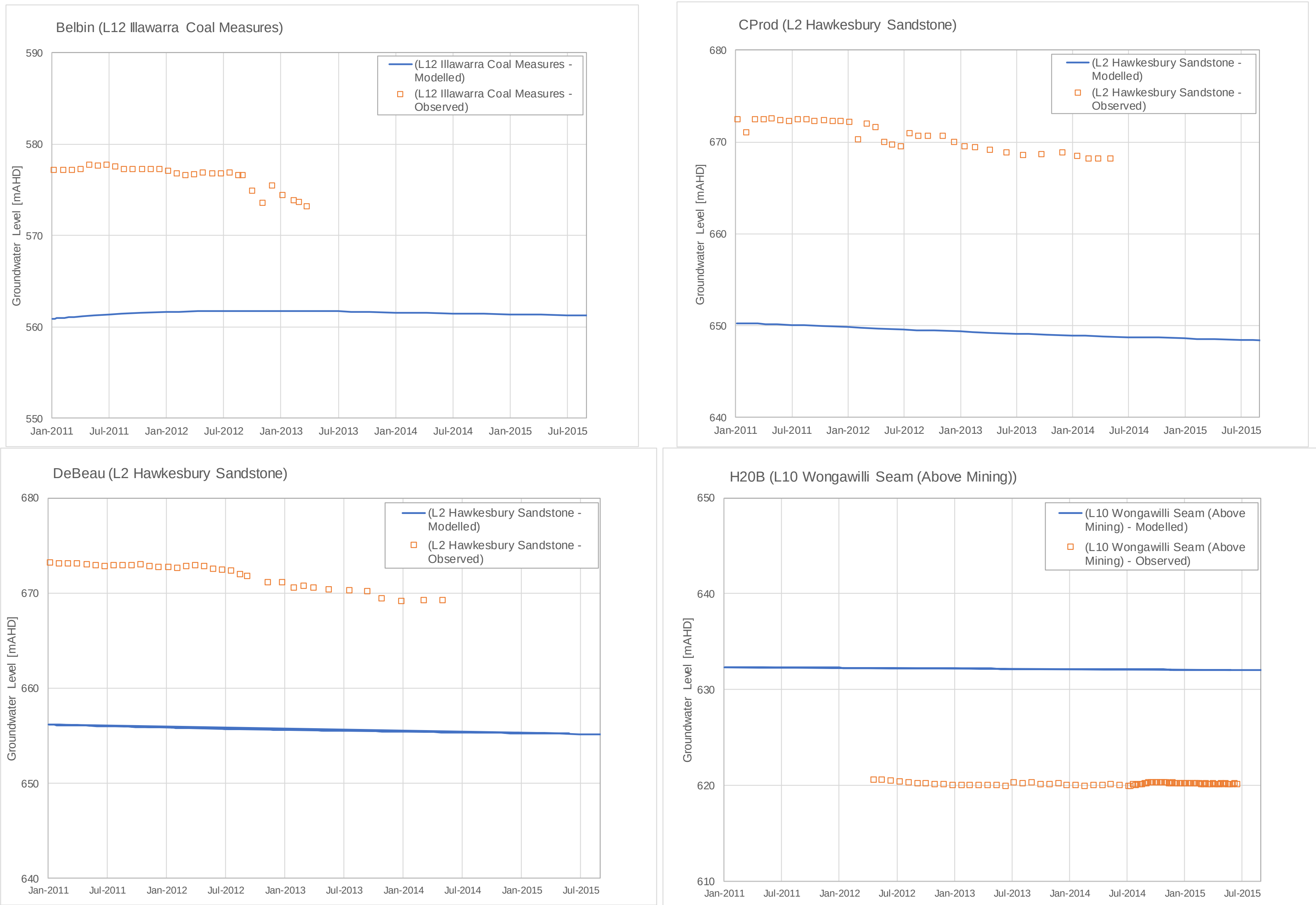


Figure 14 Calibration hydrographs for Belbin, CProd, DeBeau, H20B

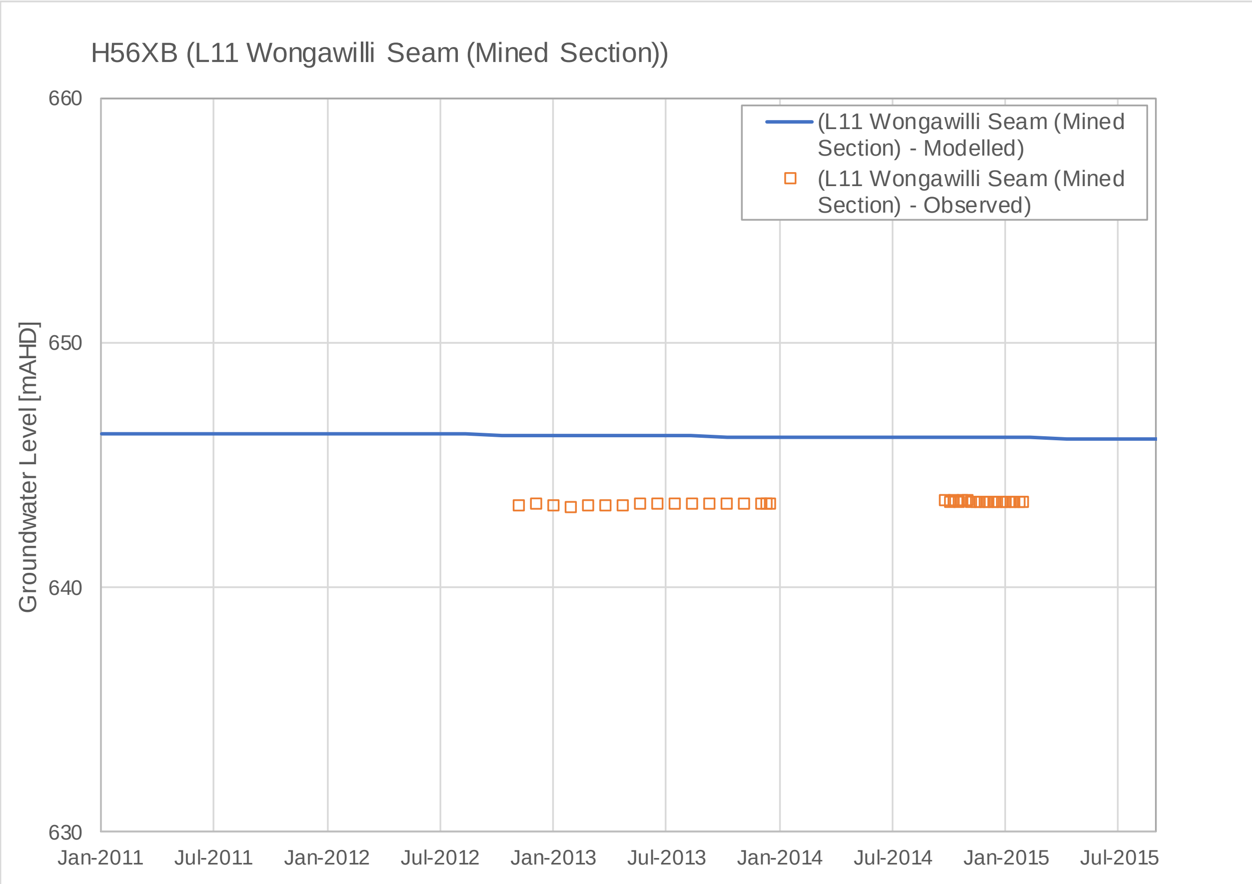


Figure 15 Calibration hydrograph H56XB

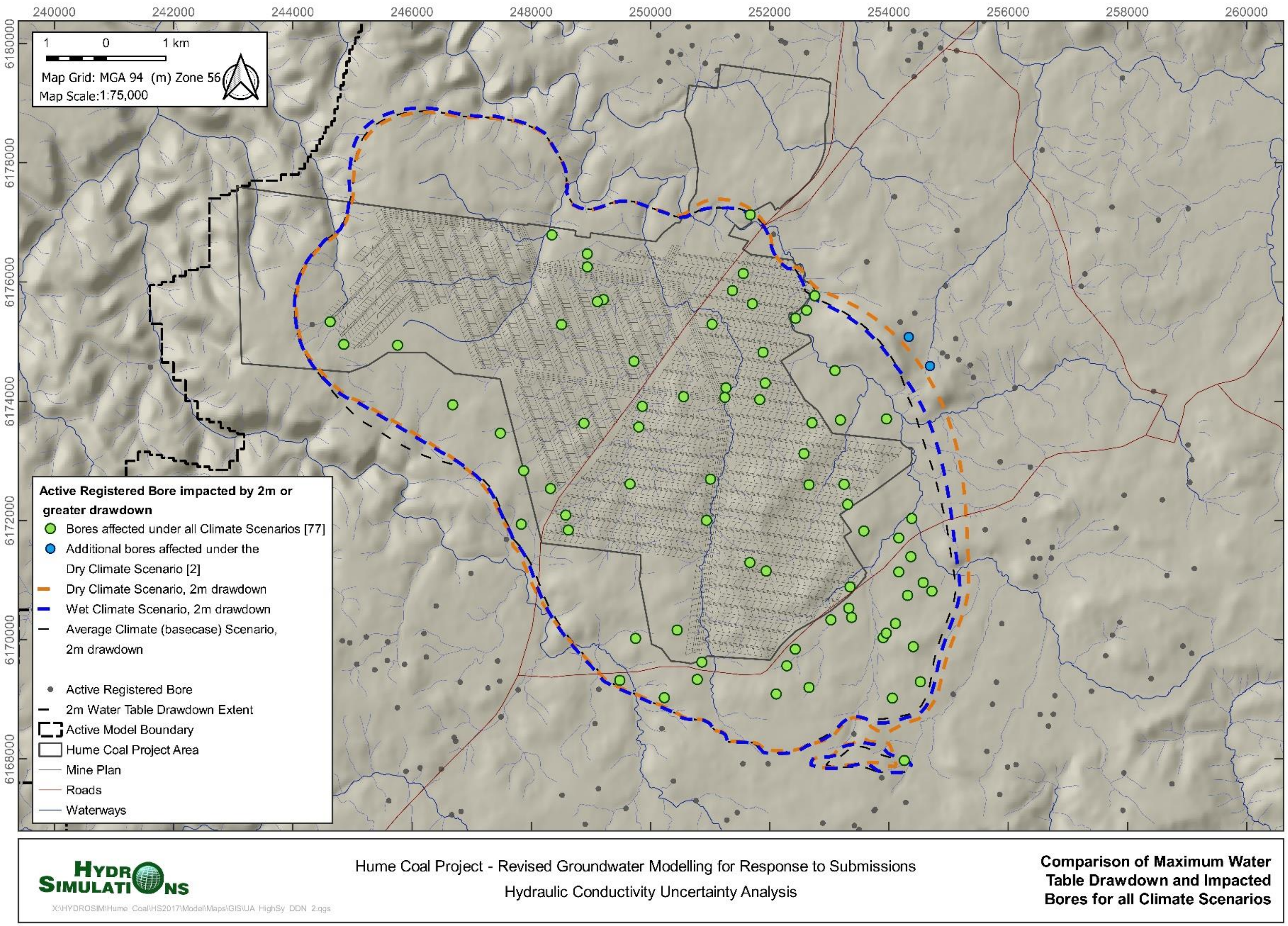


Figure 16 Comparison of water table drawdown and number of impacted bores during mine year 17 for climate scenarios (Modified EIS Model)

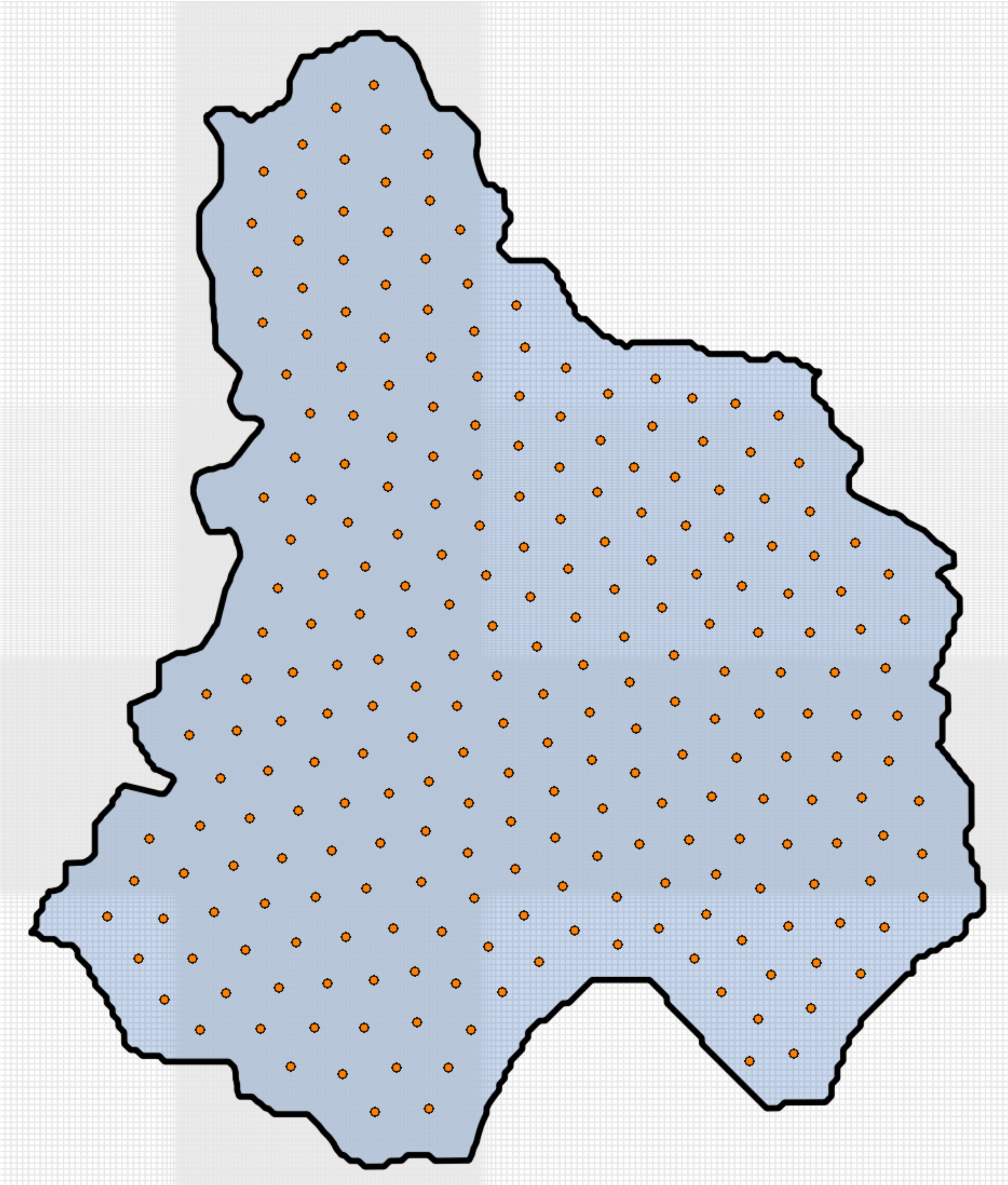


Figure 17 256 pilot point locations used to represent spatially-varying hydraulic conductivity.

UNCERTAINTY ANALYSIS FIGURES

BASELINE MEAN K

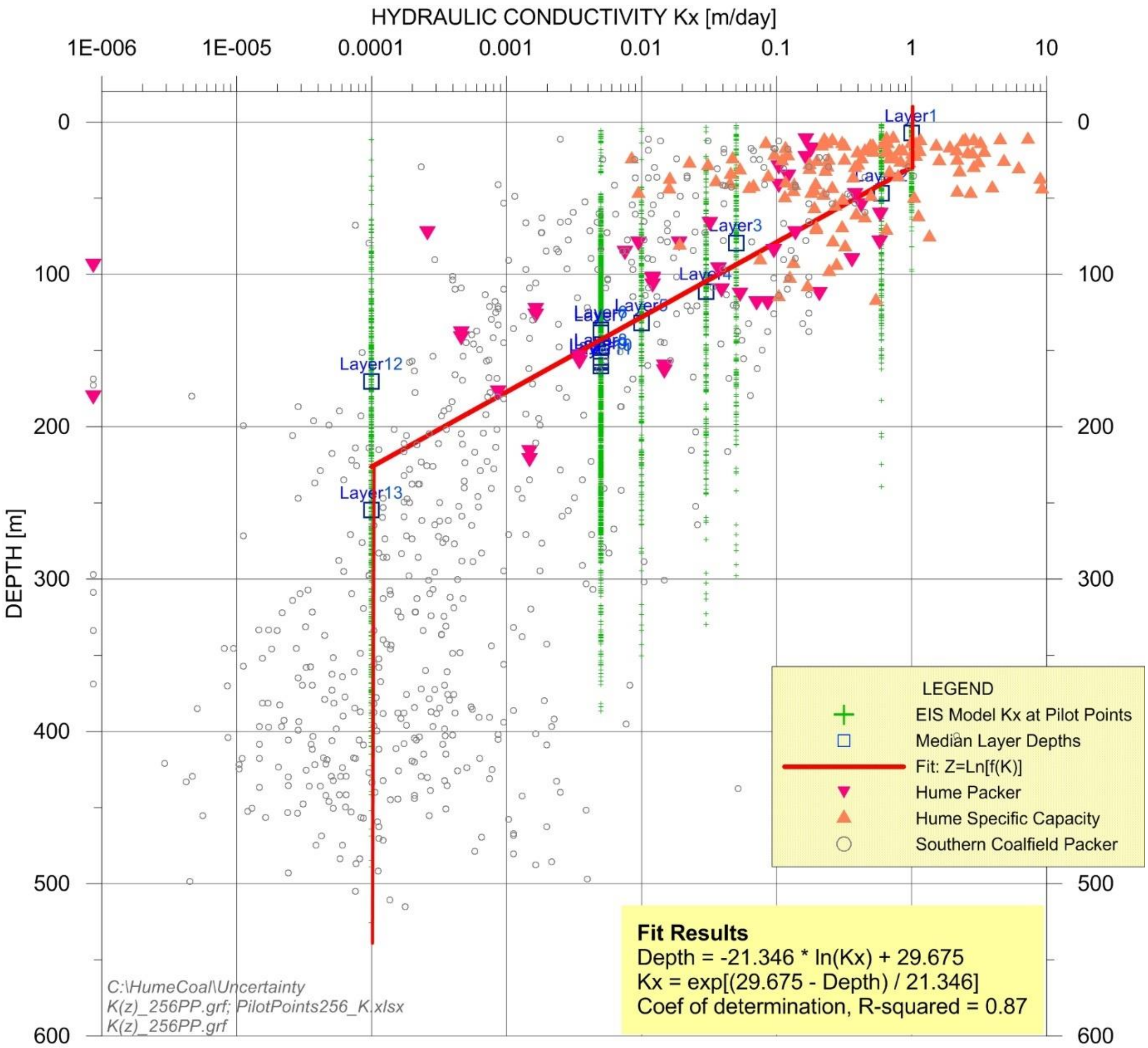


Figure 18 Prior mean Kx versus depth, fit to Hume and surrounding Southern Coalfield data.

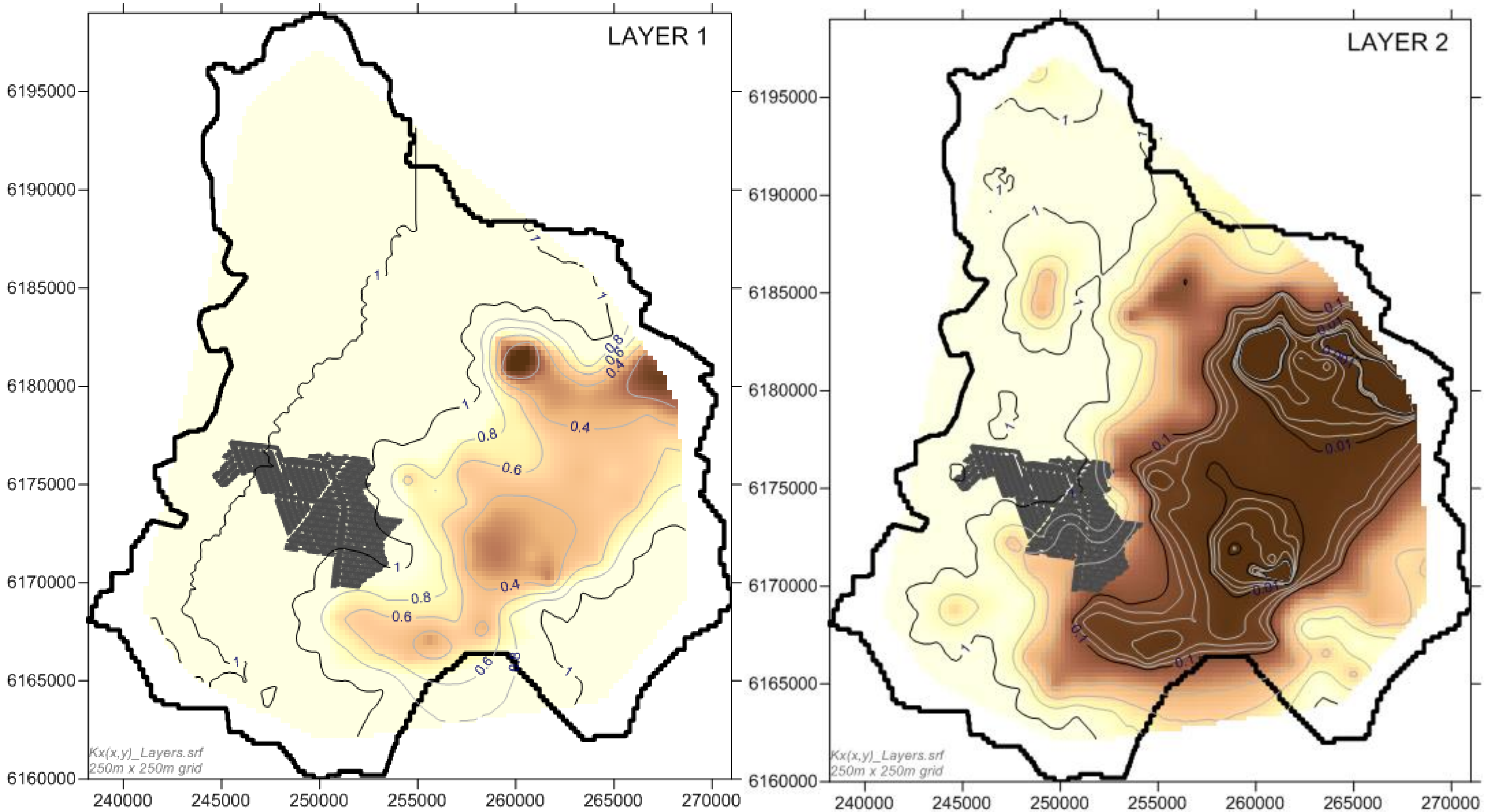


Figure 19 **Spatial Distribution of Hydraulic Conductivity using depth function in Layer 1 and Layer 2**

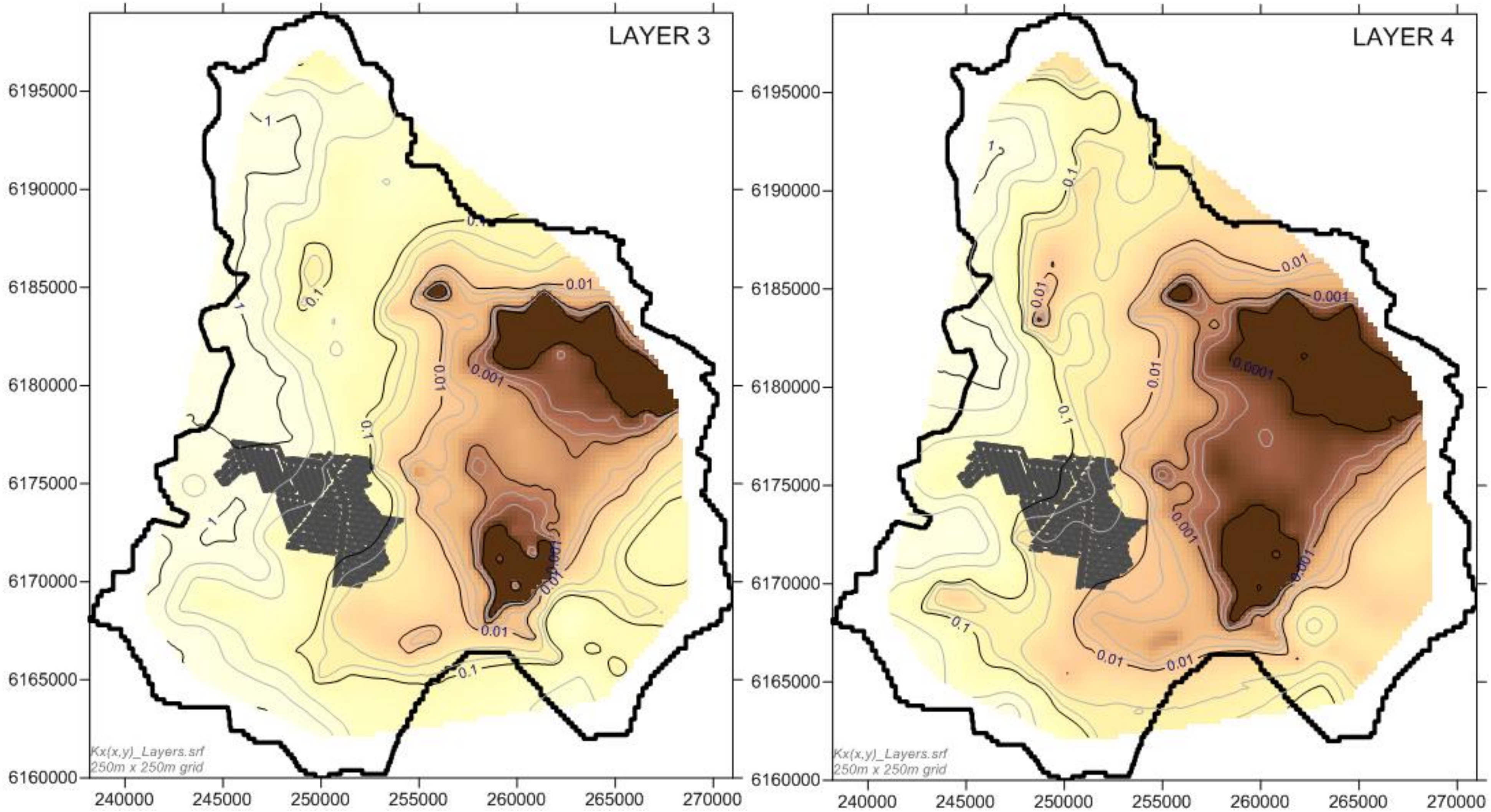


Figure 20 **Spatial Distribution of Hydraulic Conductivity using depth function in Layer 3 and Layer 4.**

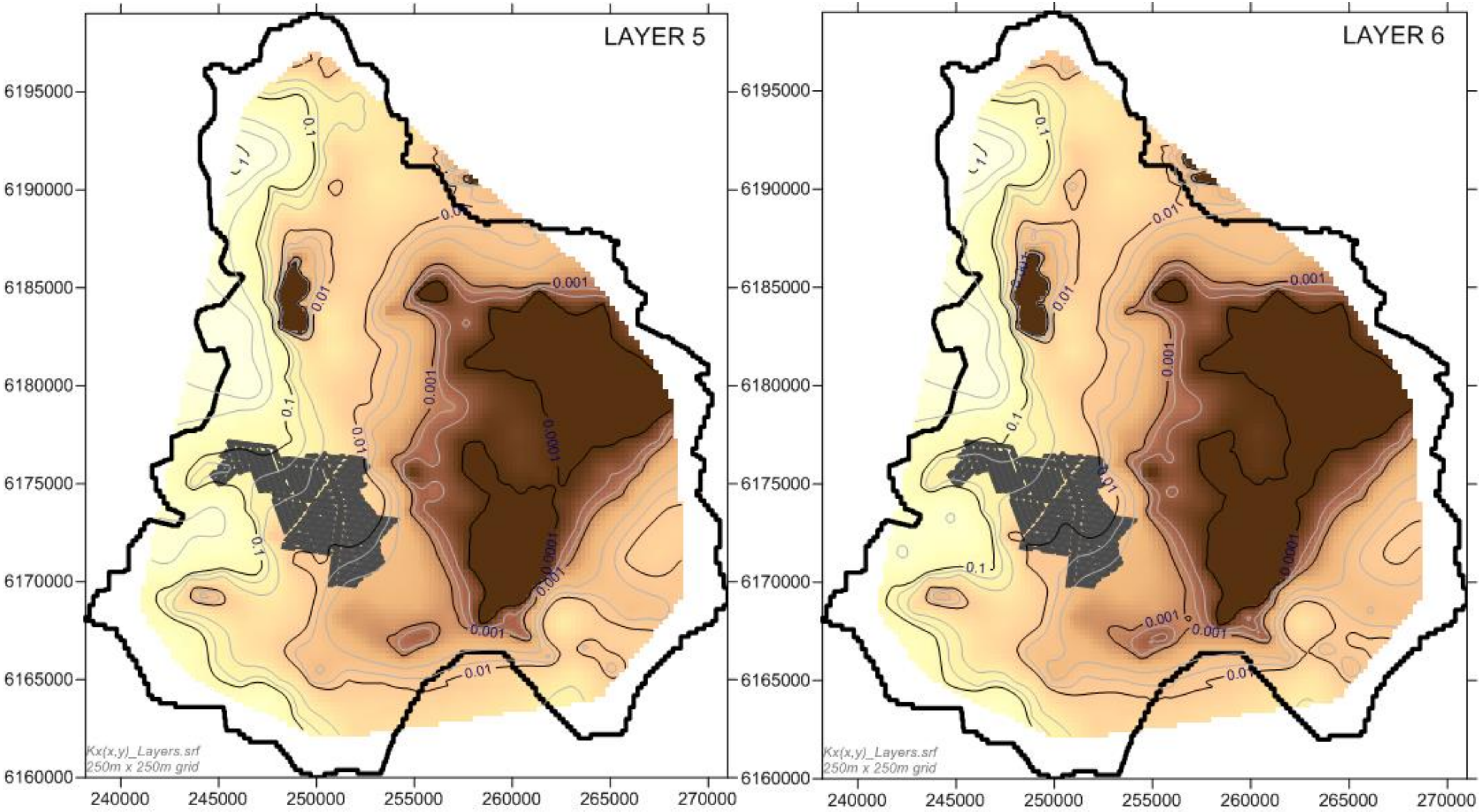


Figure 21 Spatial Distribution of Hydraulic Conductivity using depth function in Layer 5 and Layer 6

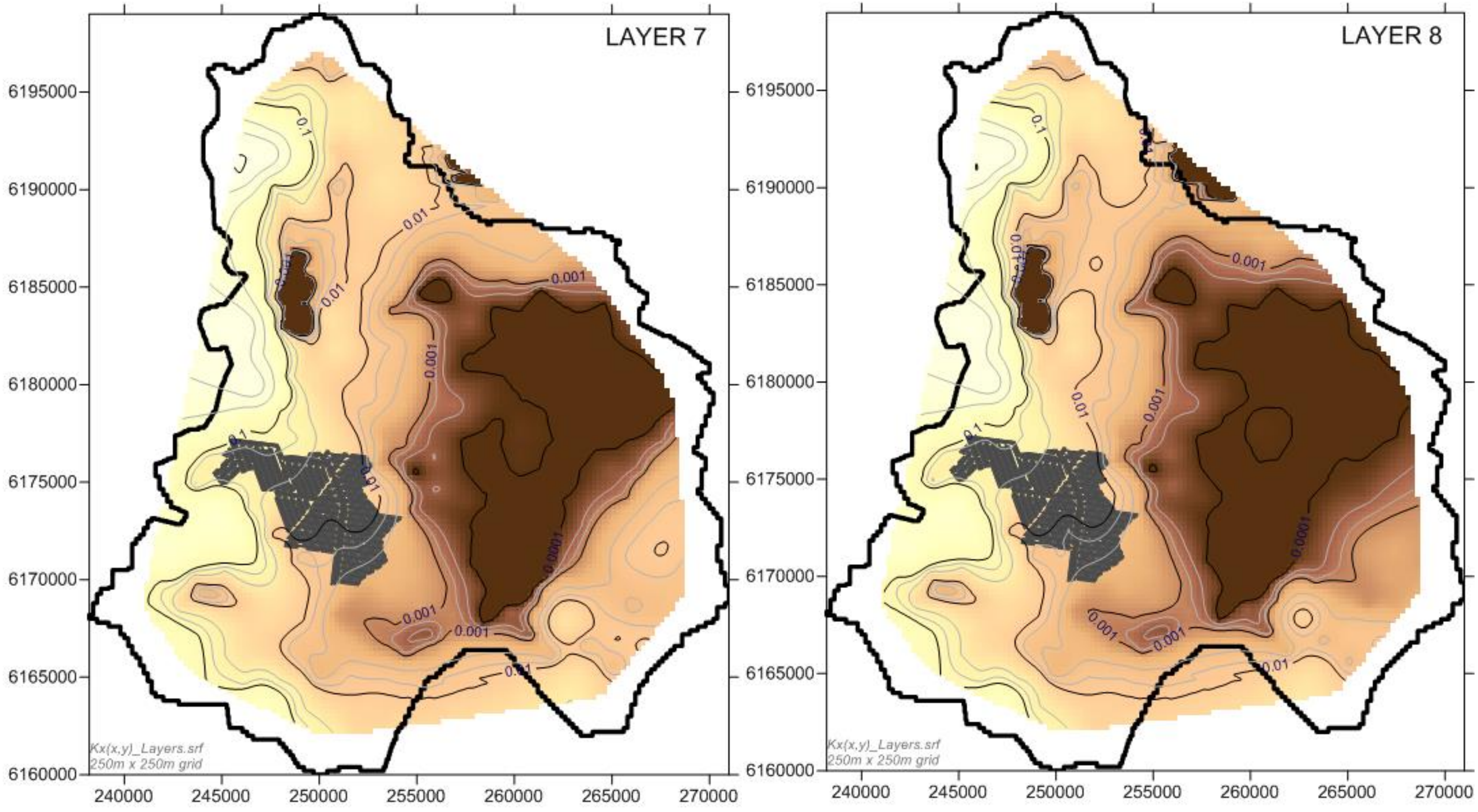


Figure 22 Spatial Distribution of Hydraulic Conductivity using depth function in Layer 7 and Layer 8

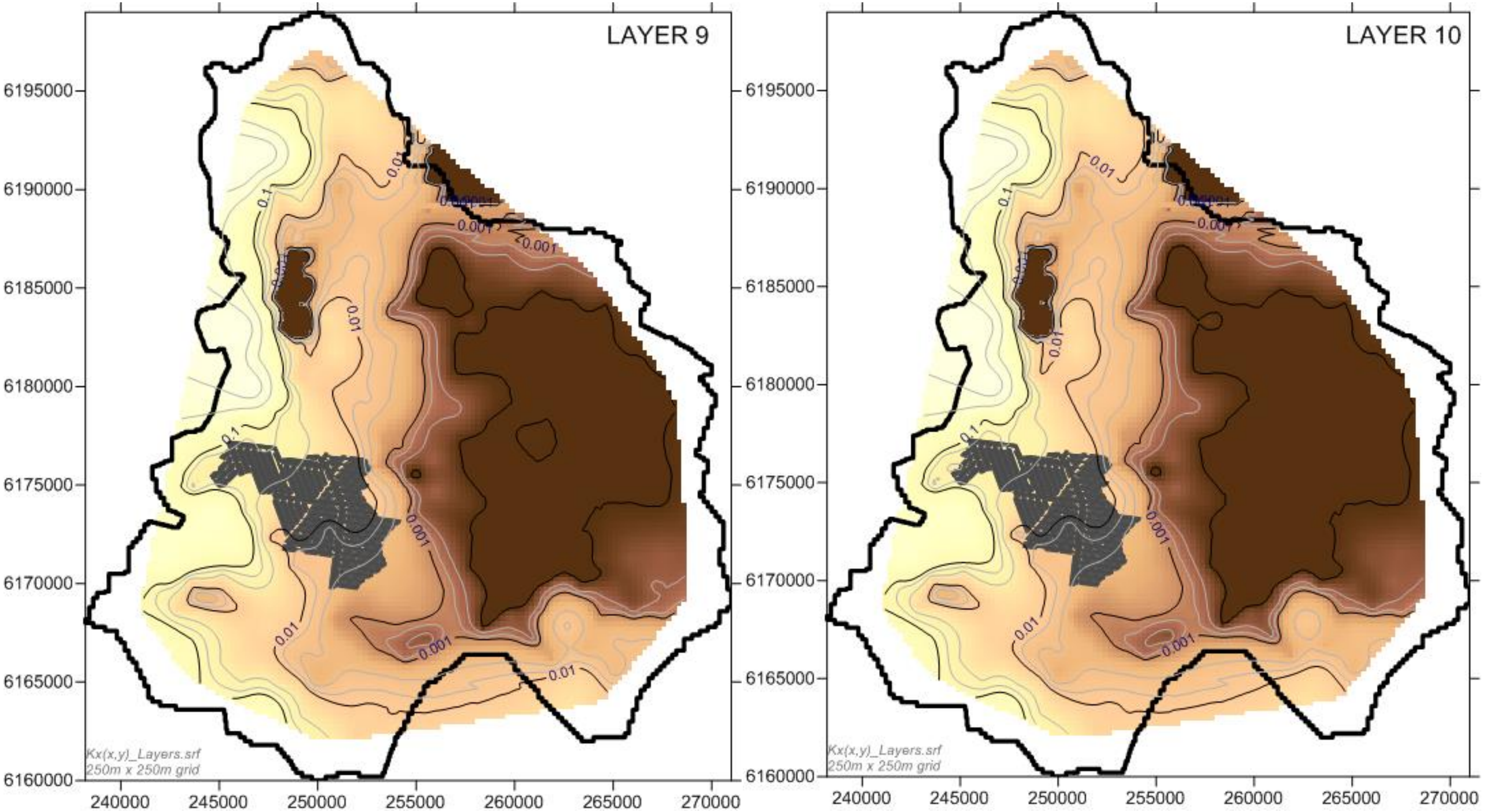


Figure 23 Spatial Distribution of Hydraulic Conductivity using depth function in Layer 9 and Layer 10

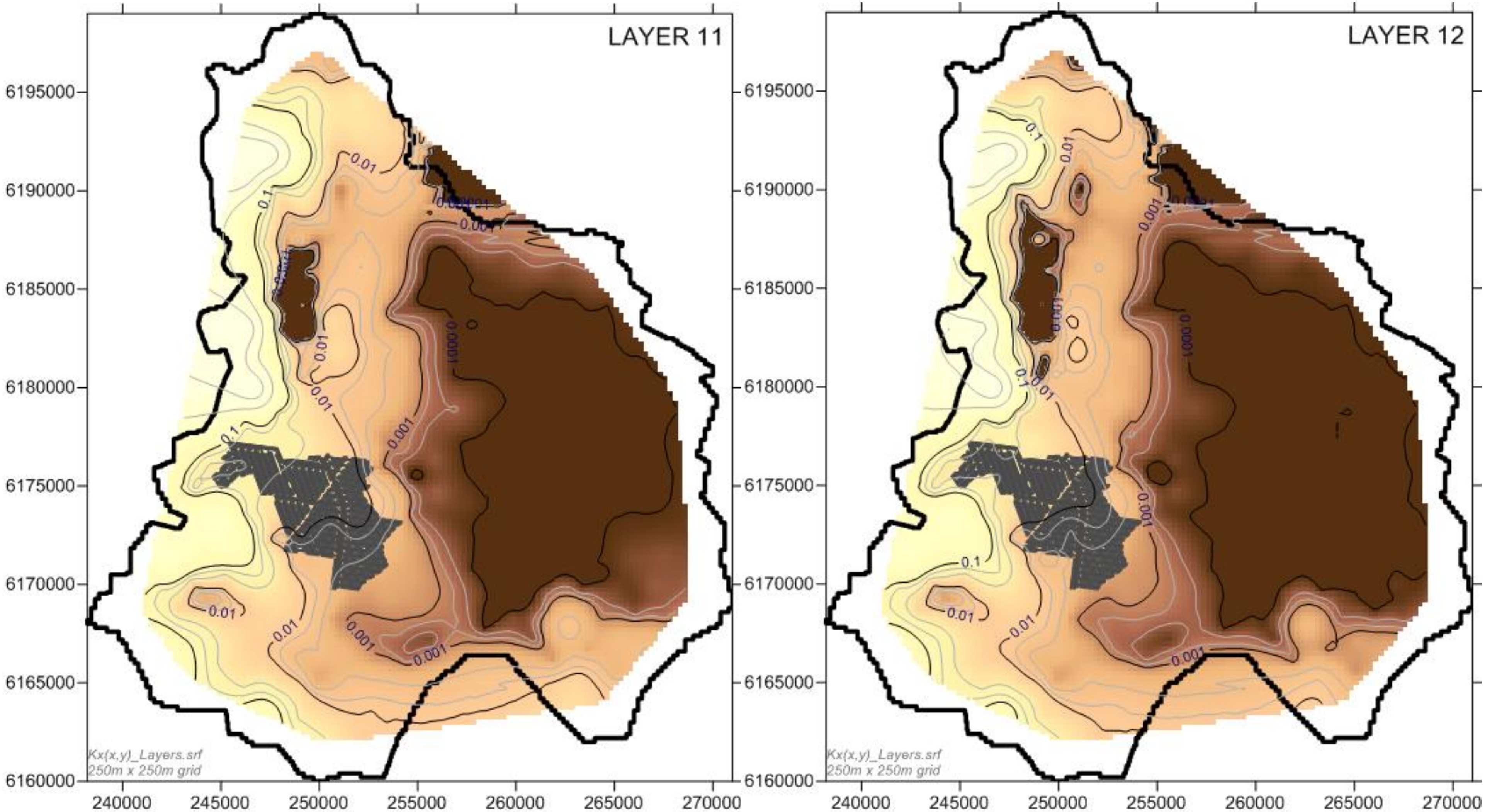


Figure 24 Spatial Distribution of Hydraulic Conductivity using depth function in Layer 11 and Layer 12

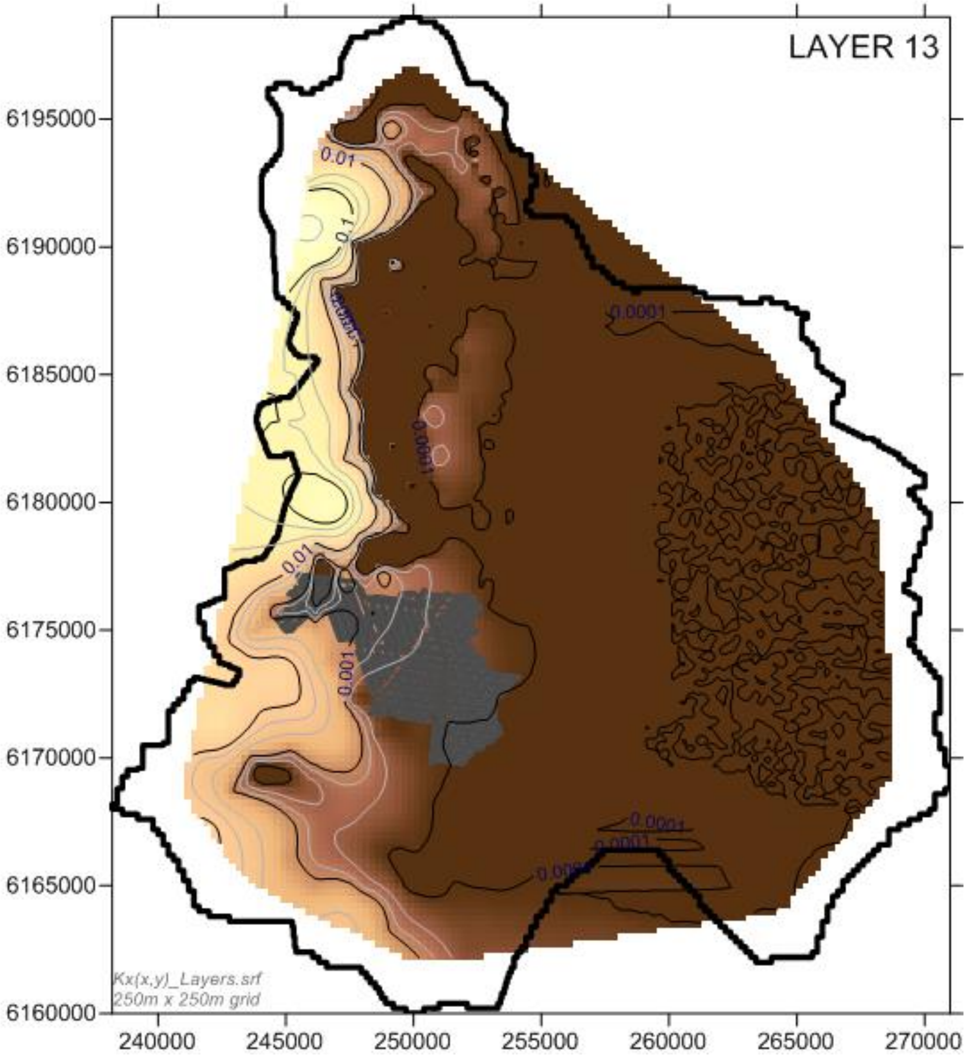


Figure 25 Spatial Distribution of Hydraulic Conductivity using depth function in Layer 13

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.

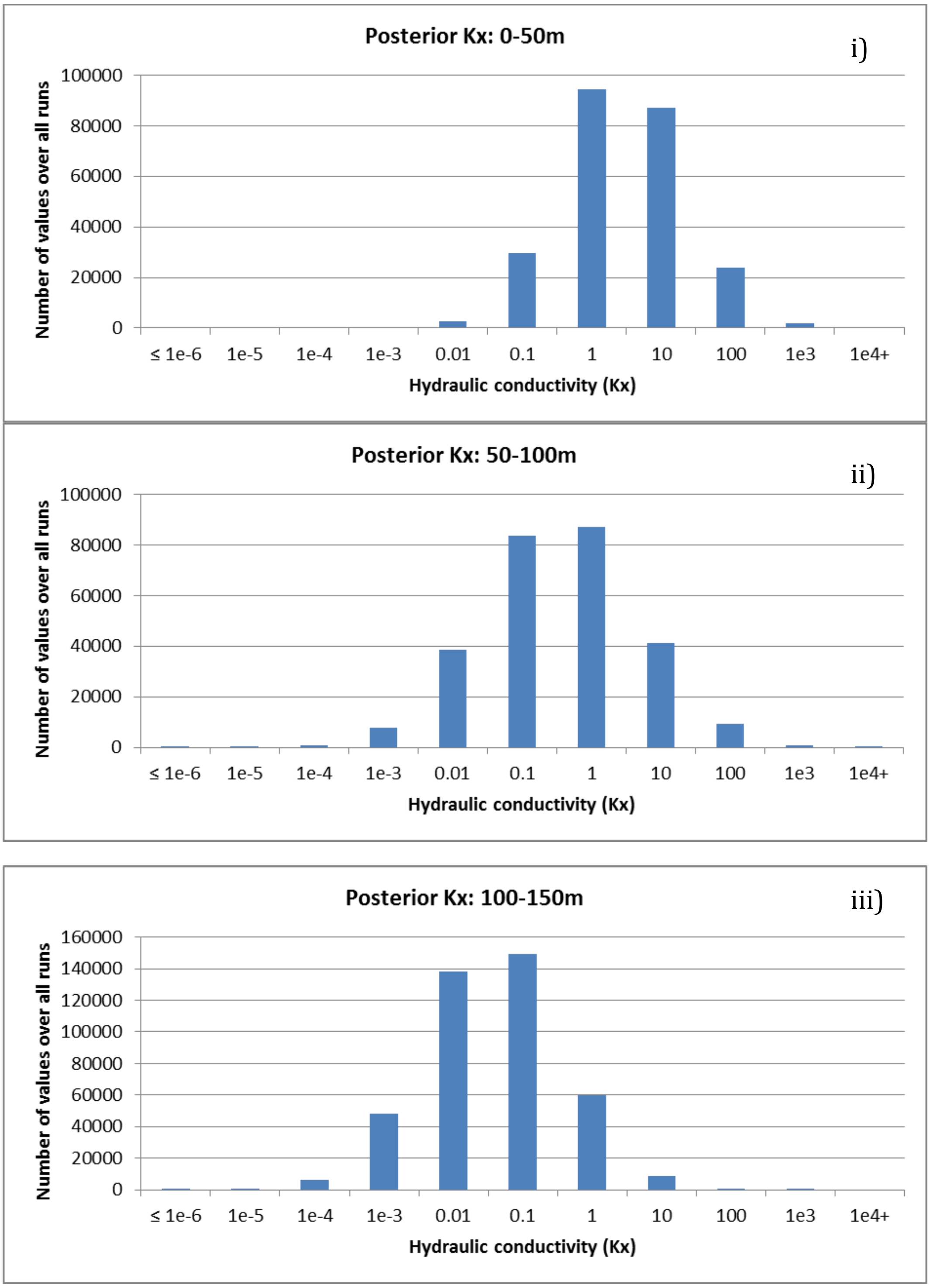


Figure 26 Posterior Kx values for i) 0-50 m; ii) 50 m-100 m; iii) 100 m-150 m.

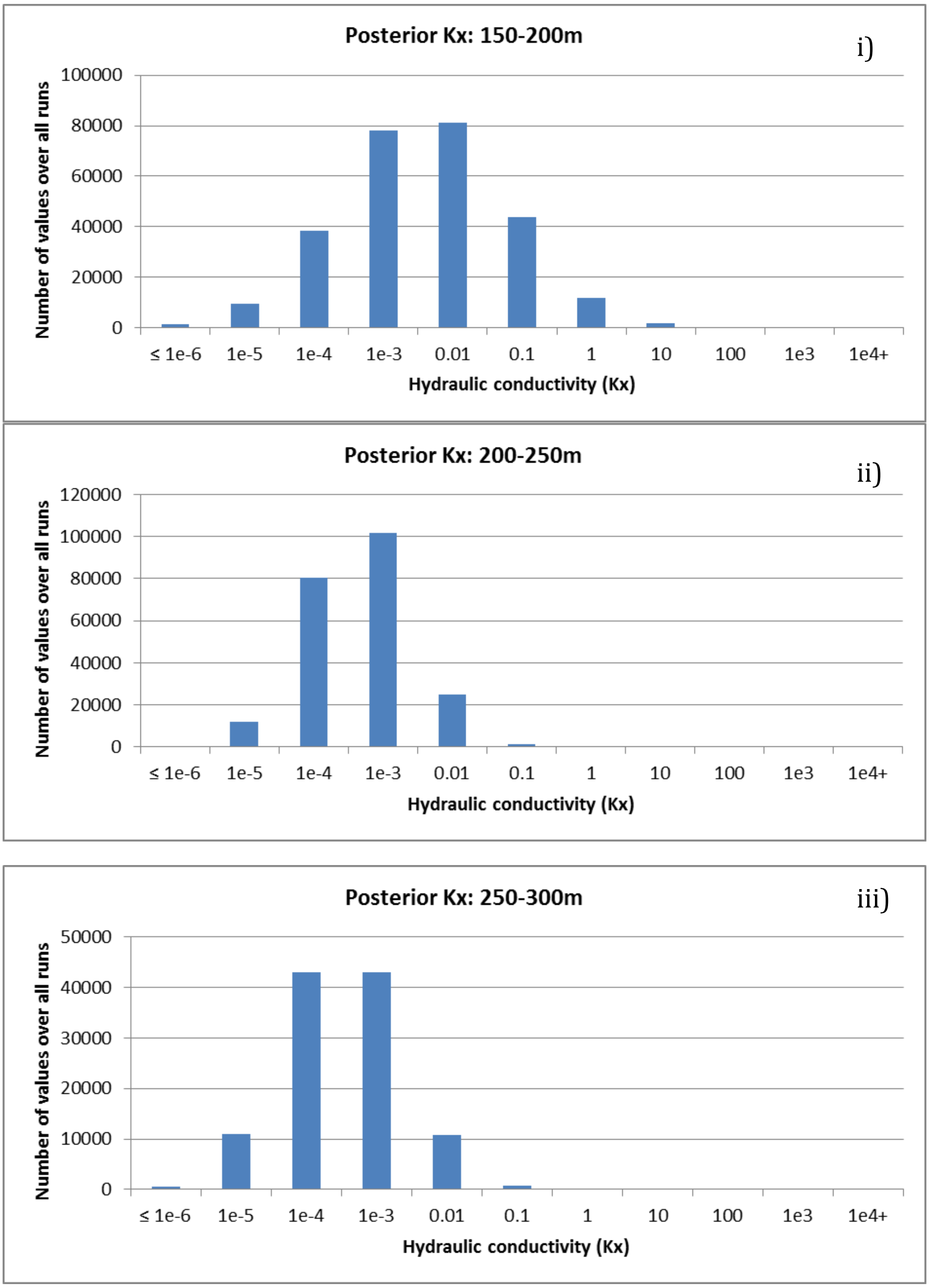


Figure 27 Posterior Kx values for i) 150-200 m; ii) 200 m-250 m; iii) 250 m-300 m.

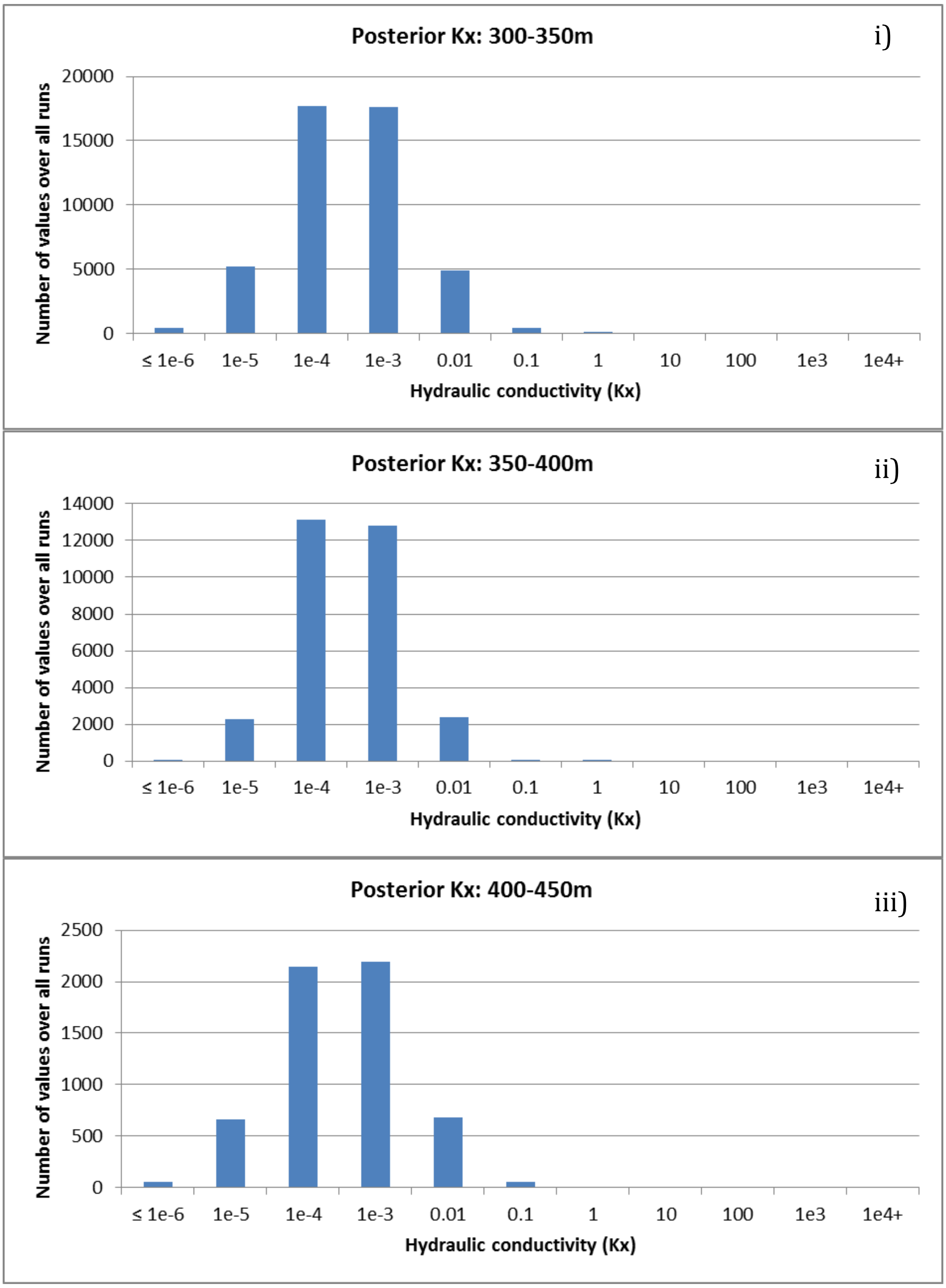


Figure 28 Posterior Kx values for i) 300-350 m; ii) 350 m-400 m; iii) 400 m-450 m.

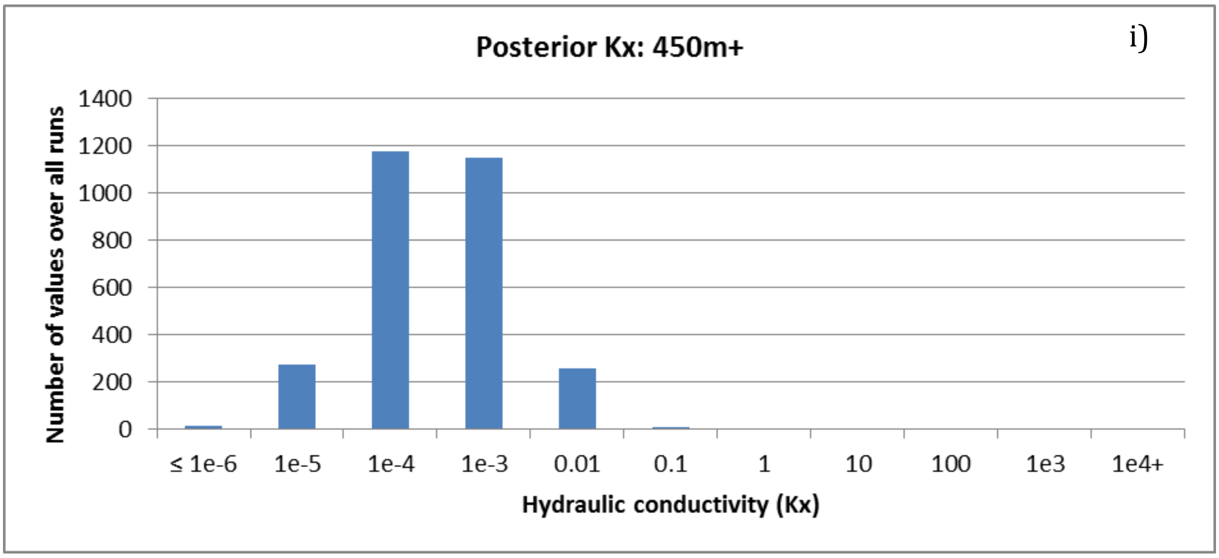


Figure 29 Posterior Kx values for i) 450 m and greater.

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.

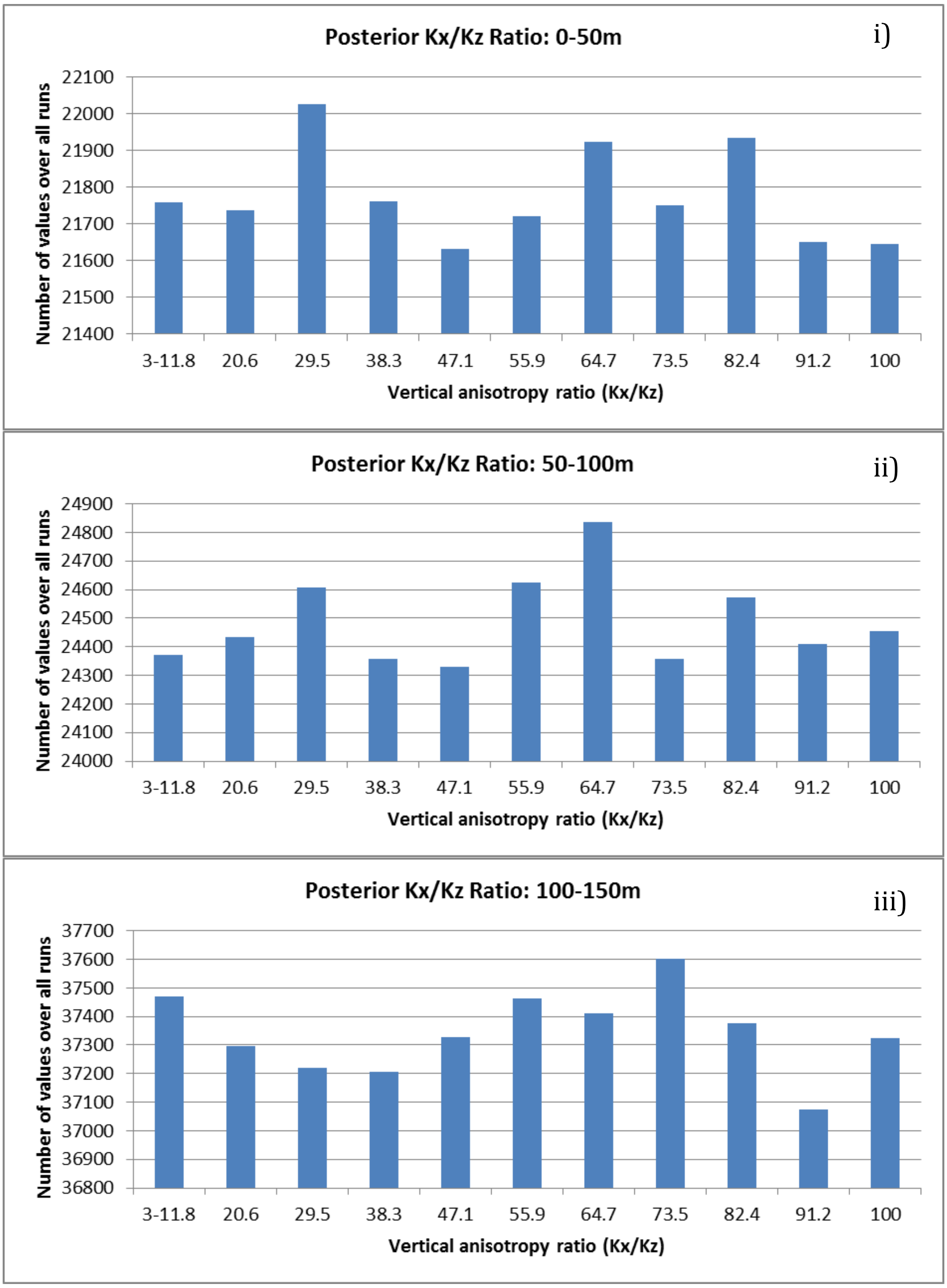


Figure 30 Posterior Kx/Kz ratio for i) 0-50 m; ii) 50 m-100 m; iii) 100 m-150 m.

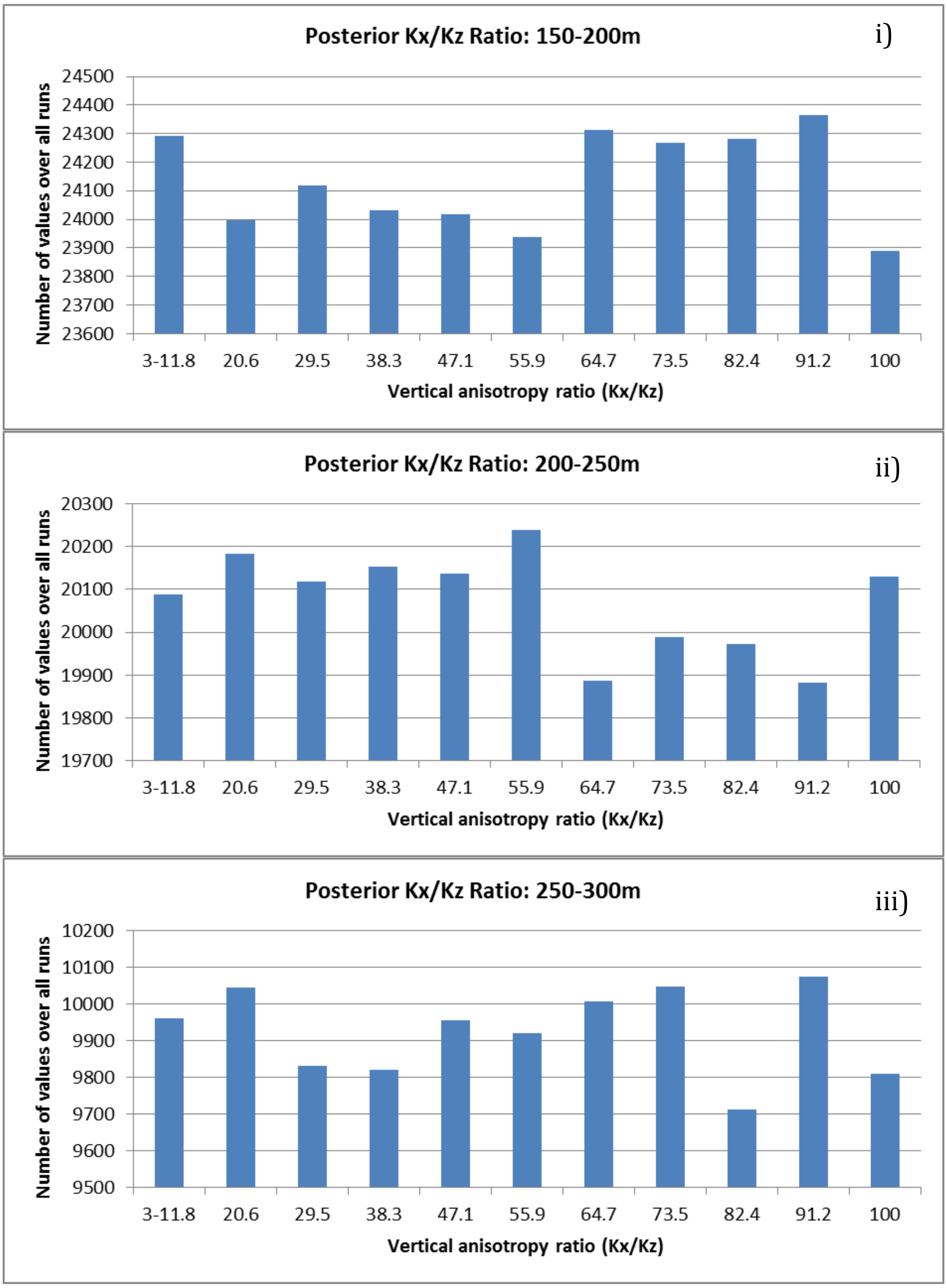


Figure 31 Posterior Kx/Kz ratio for i) 150-200 m; ii) 200 m-250 m; iii) 250 m-300 m.

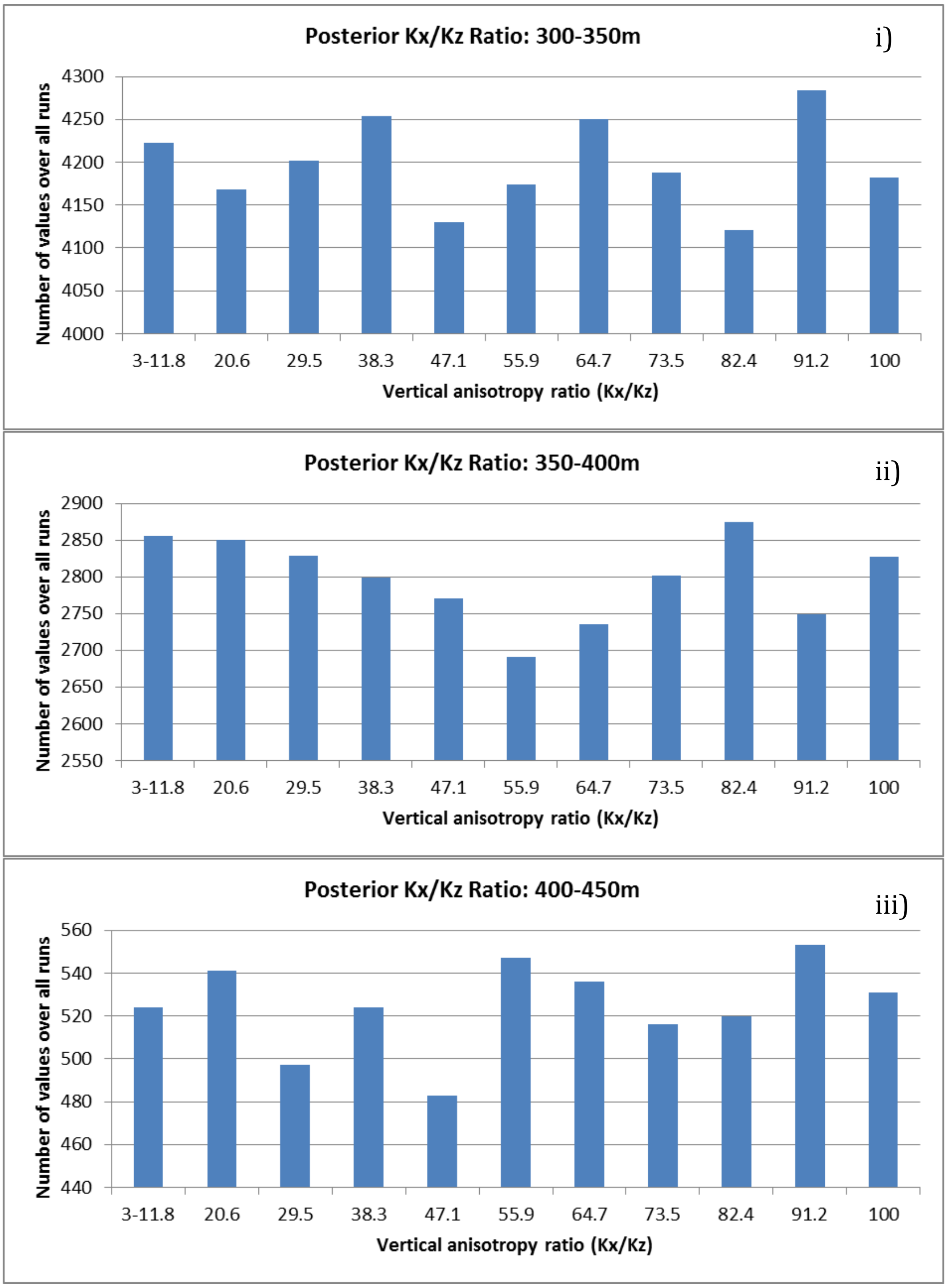


Figure 32 Posterior Kx/Kz ratio for i) 300-350 m; ii) 350 m-400 m; iii) 400 m-450 m.

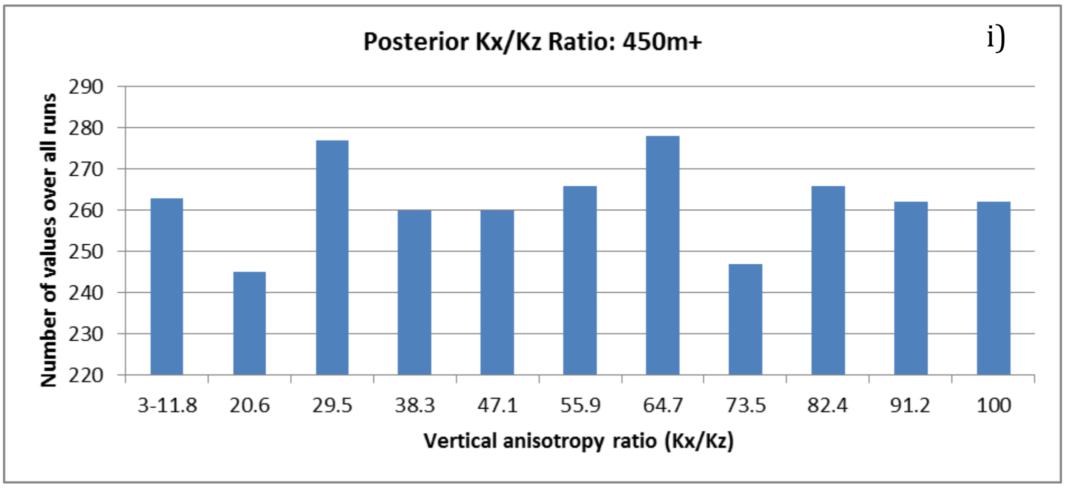


Figure 33 Posterior Kx/Kz ratio for i) 450 m and greater.

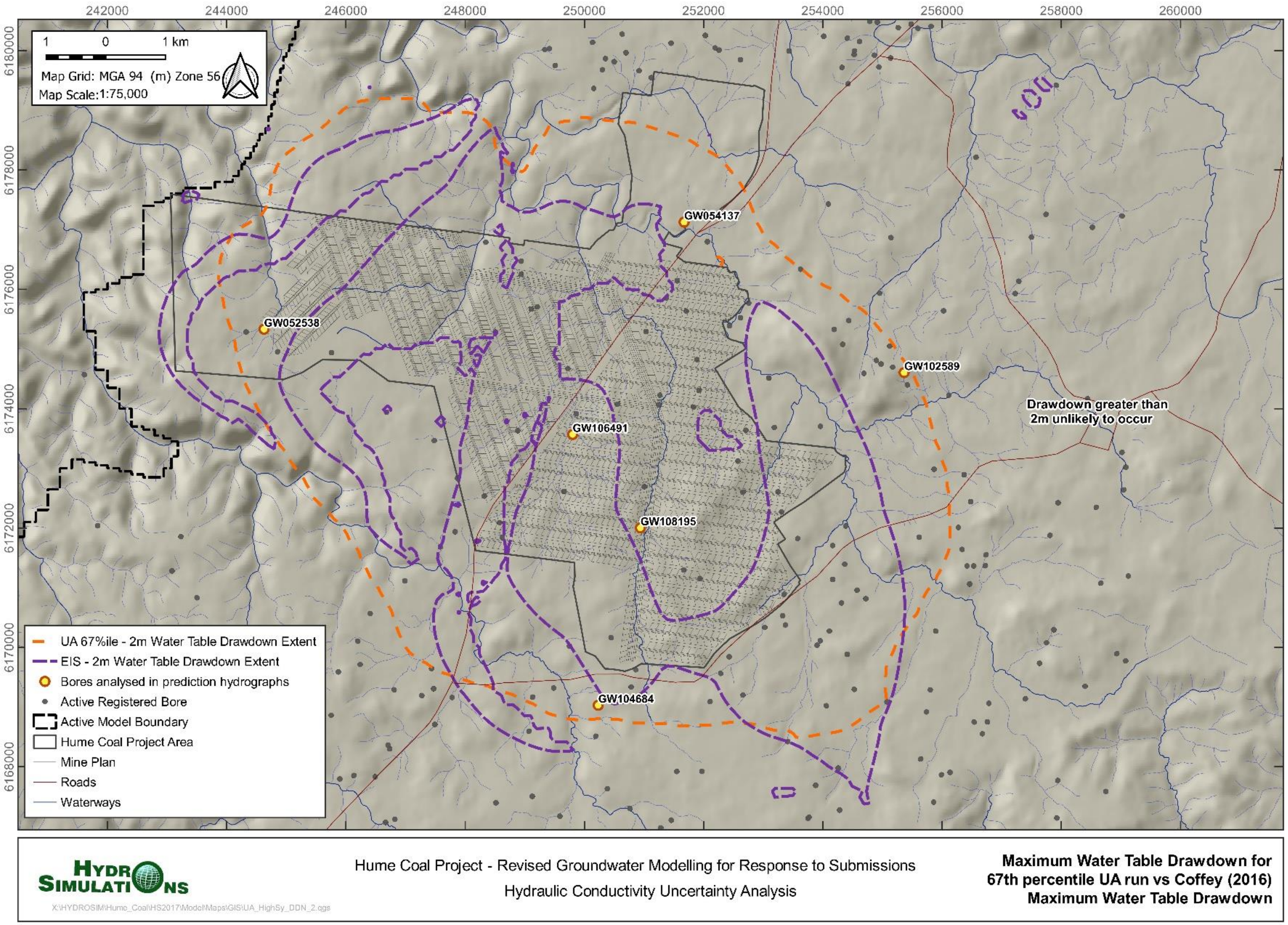


Figure 34 Maximum water-table drawdown for 67th percentile vs EIS Model (Coffey, 2016b) Wongawilli Seam 2m drawdown during mine year 17

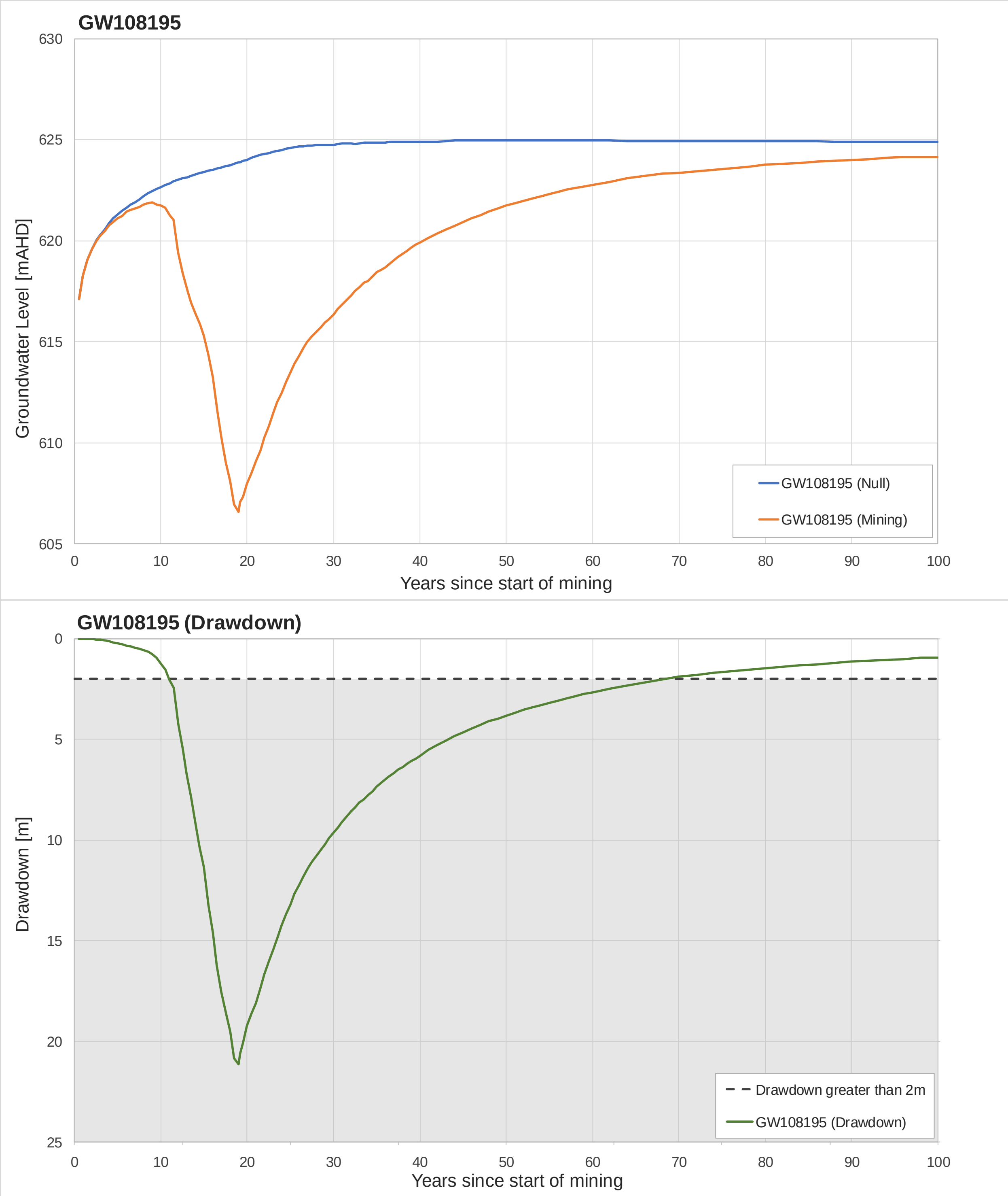


Figure 35 Modelled groundwater level and drawdown at GW108195 from 67%ile aggregate data

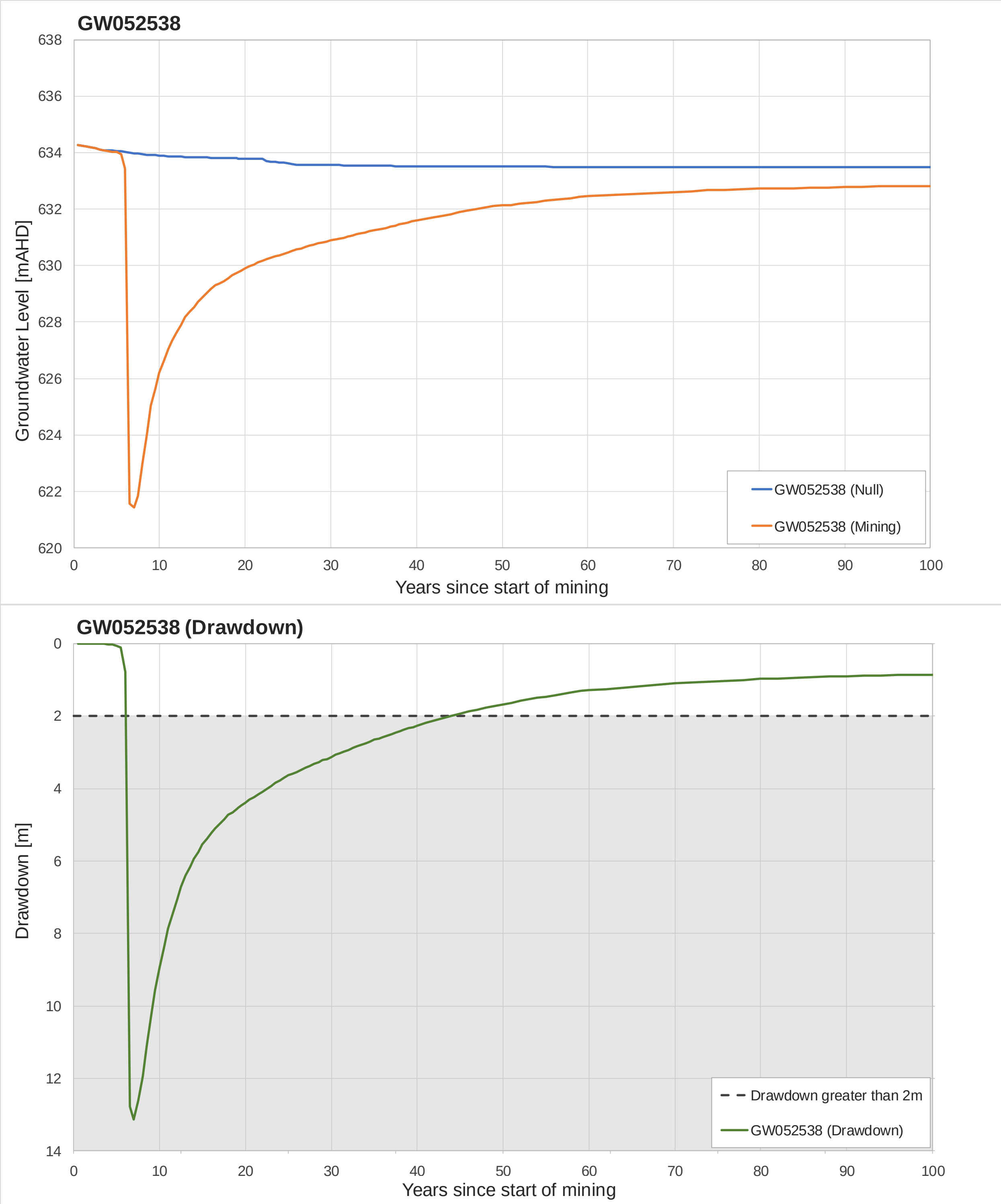


Figure 36 Modelled groundwater level and drawdown at GW052538 from 67%ile aggregate data

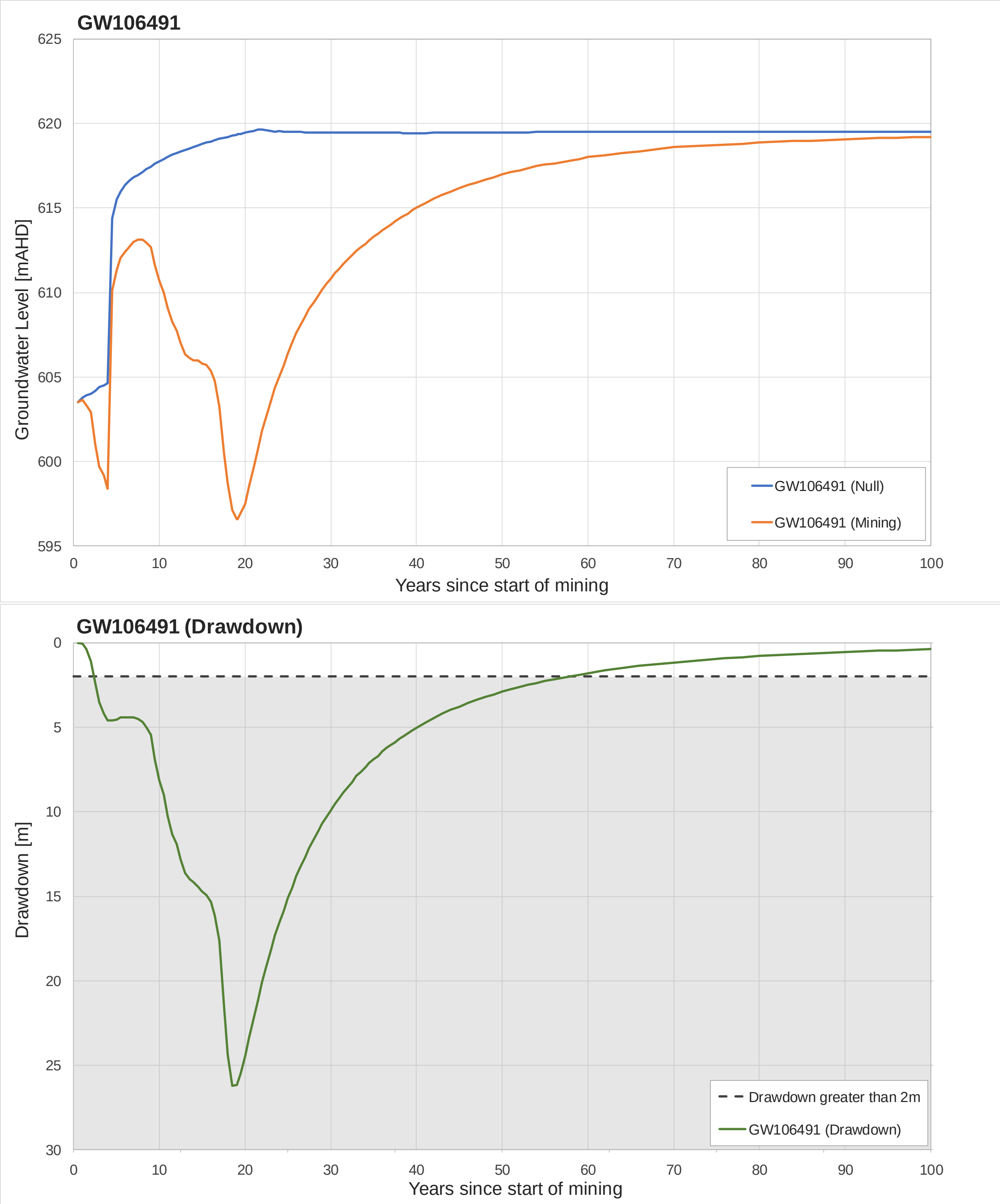


Figure 37 Modelled groundwater level and drawdown at GW106491 from 67%ile aggregate data

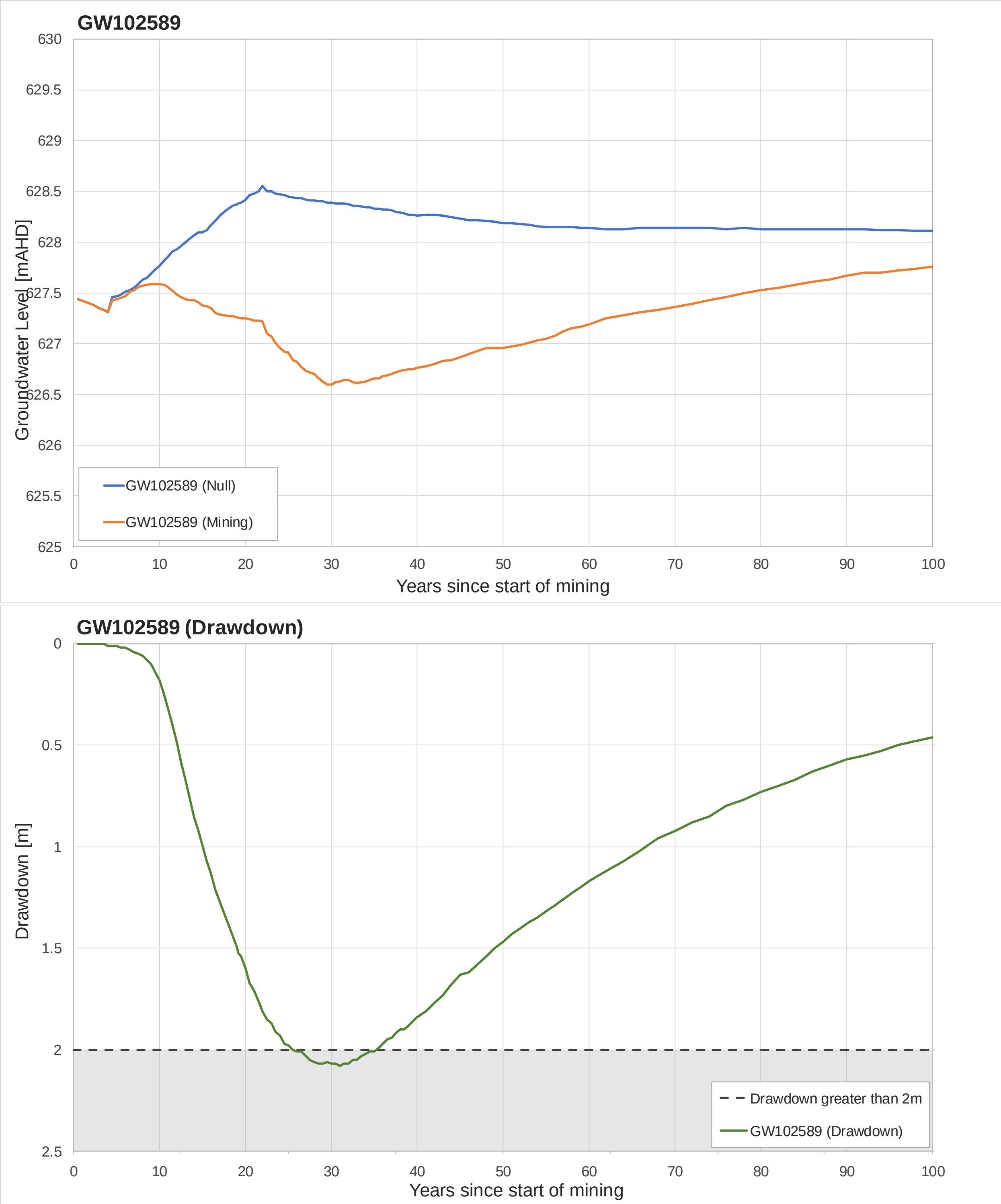


Figure 38 **Modelled groundwater level and drawdown at GW102589 from 67%ile aggregate data**

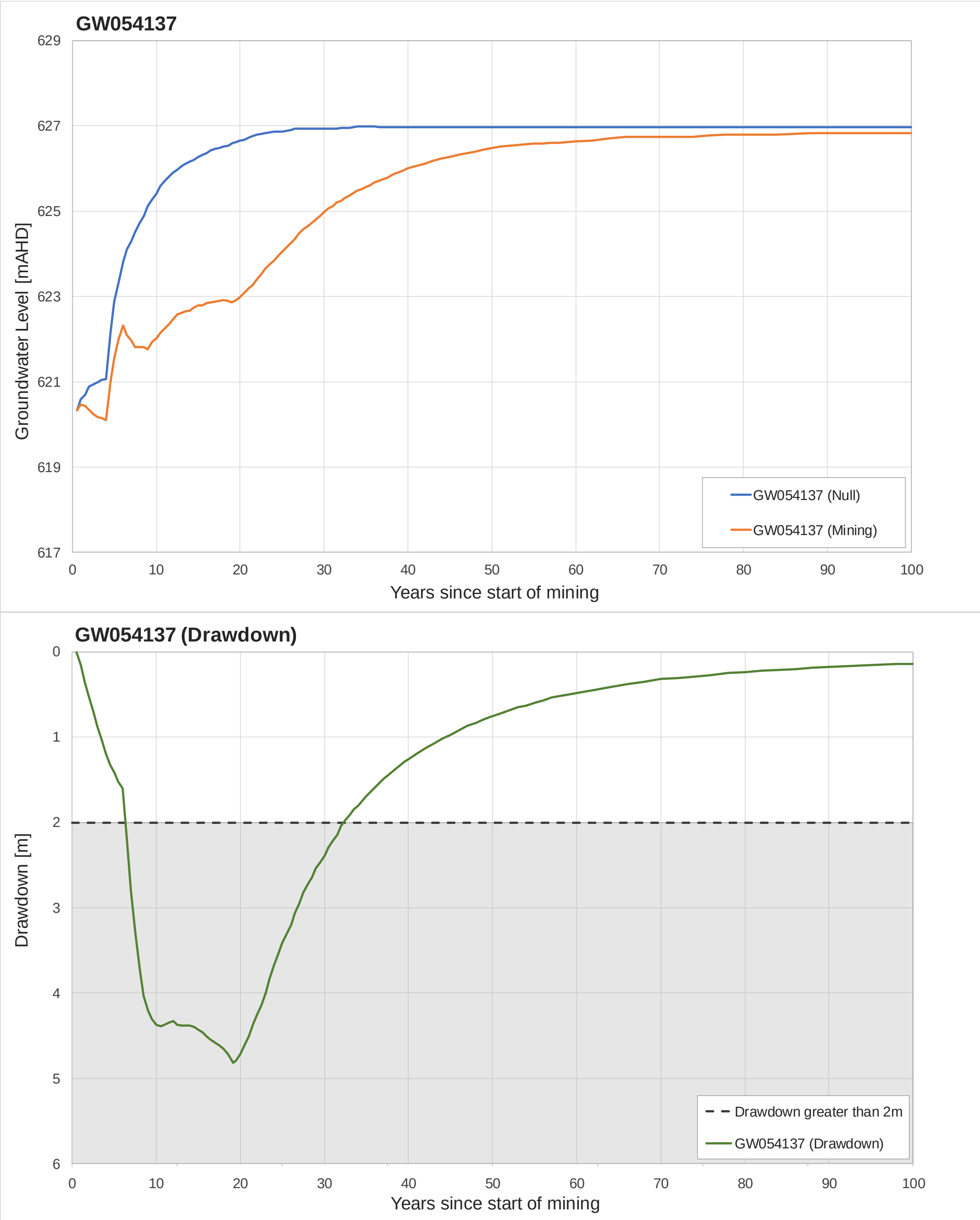


Figure 39 Modelled groundwater level and drawdown at GW054137 from 67%ile aggregate data

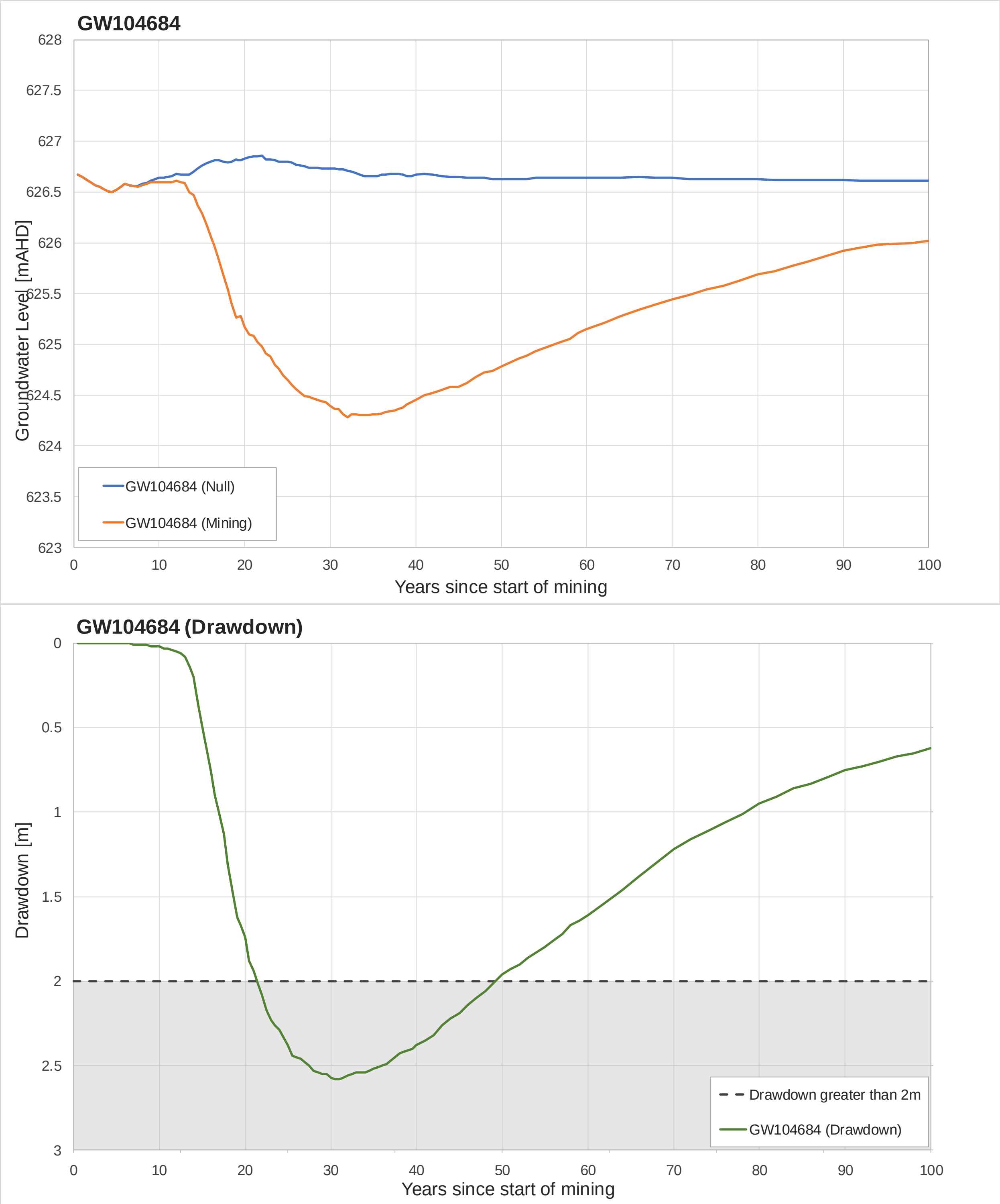


Figure 40 Modelled groundwater level and drawdown at GW104684 from 67%ile aggregate data

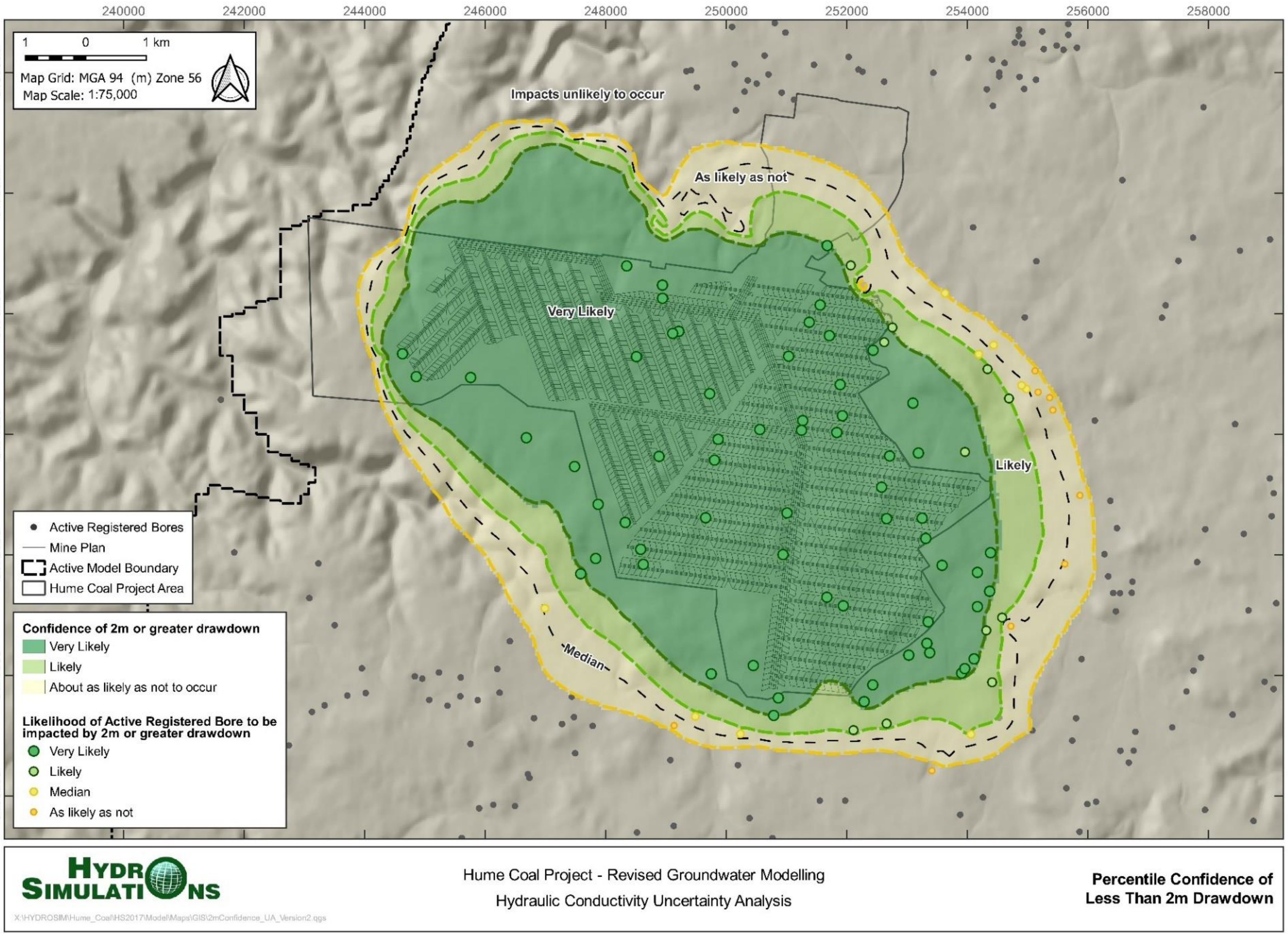


Figure 41 Percentile confidence of less than 2m drawdown at water table and bores

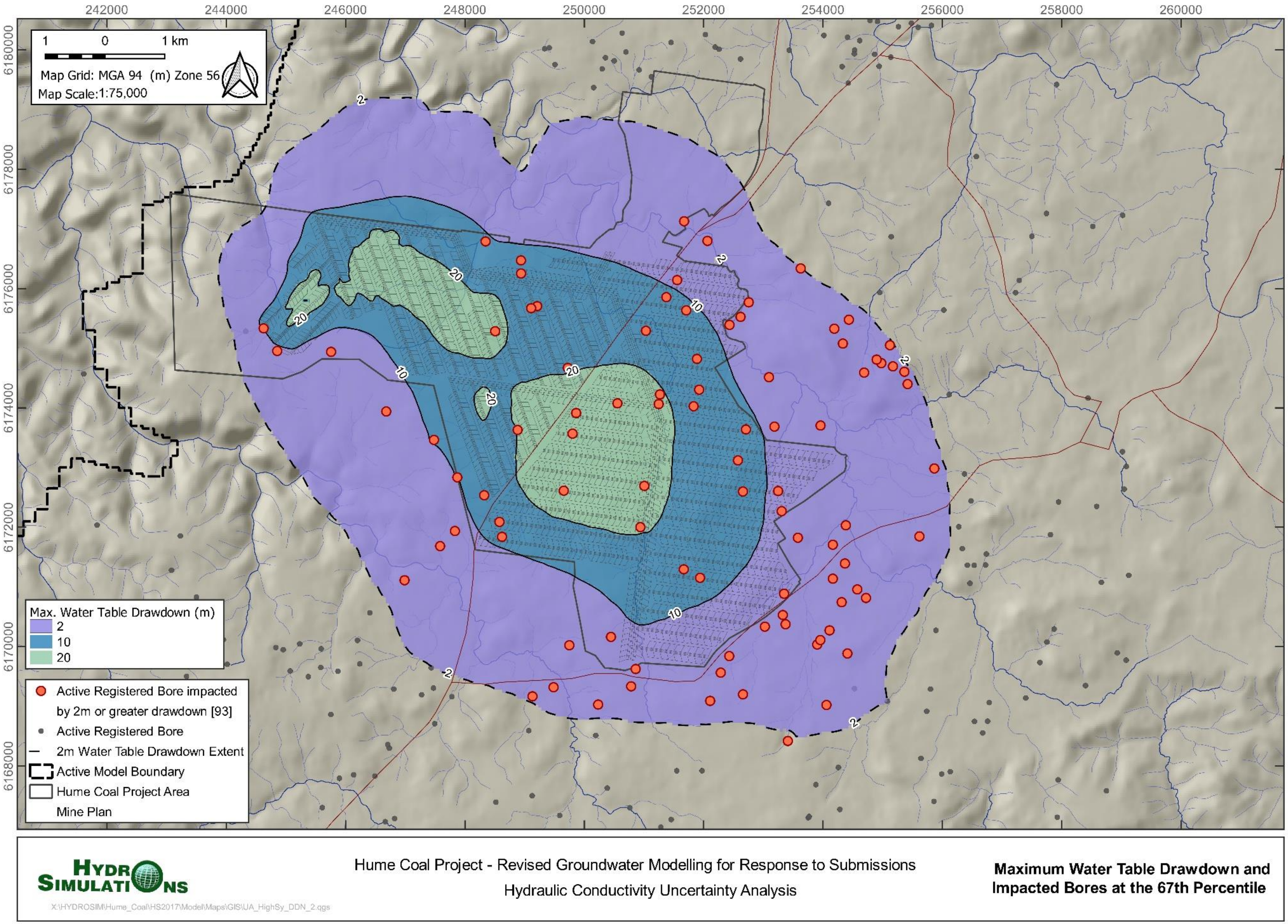


Figure 42 Maximum drawdown and number of impacted bores at the 67th percentile

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.

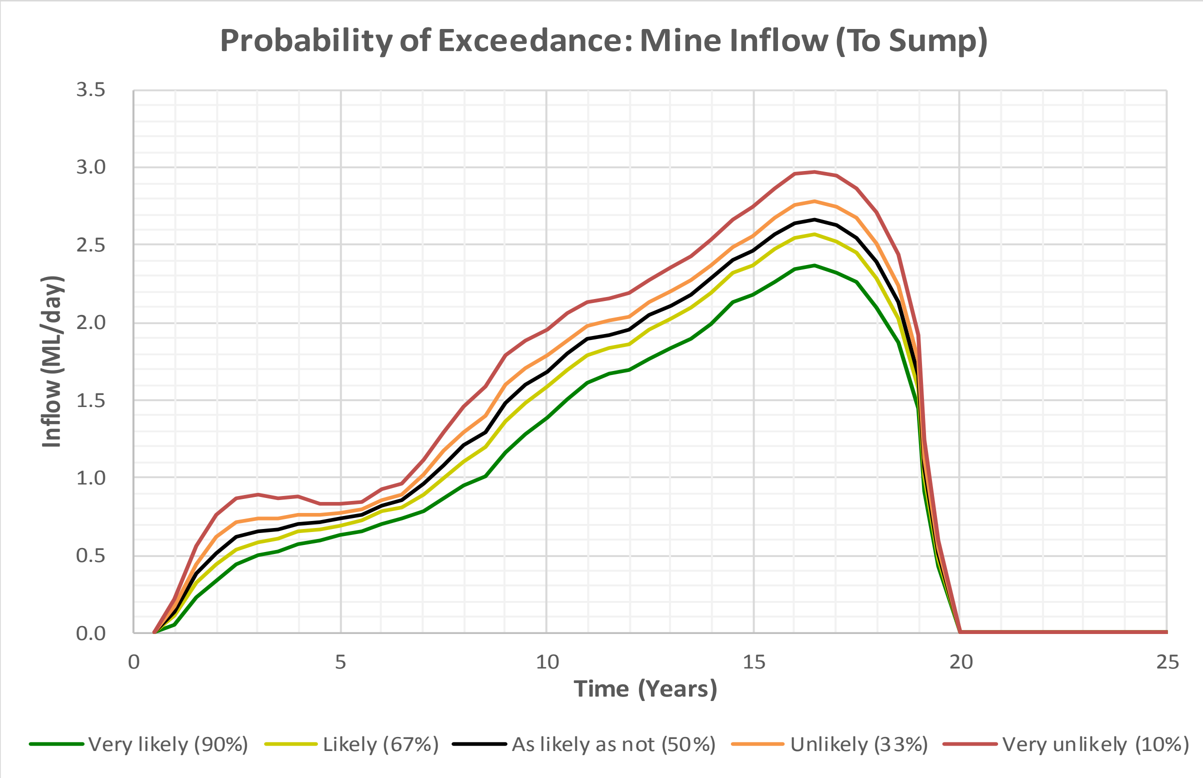


Figure 43 Uncertainty Analysis – Mine inflow (to sump)

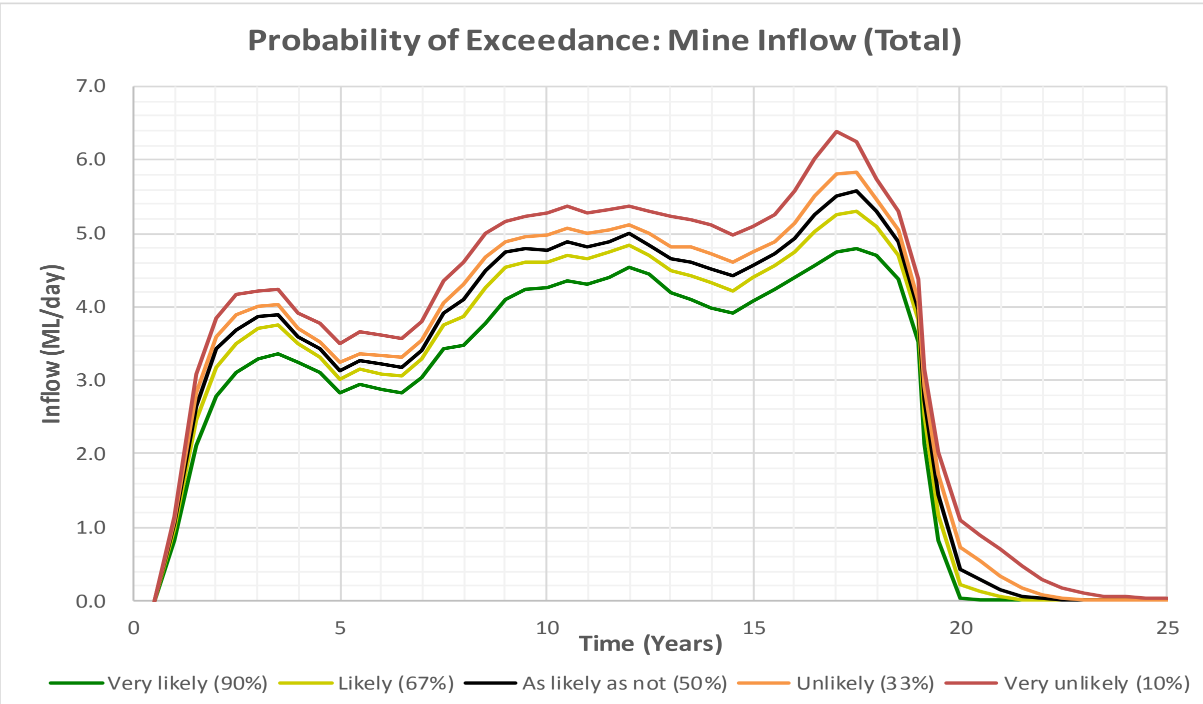


Figure 44 Uncertainty Analysis – Mine inflow (total)

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).

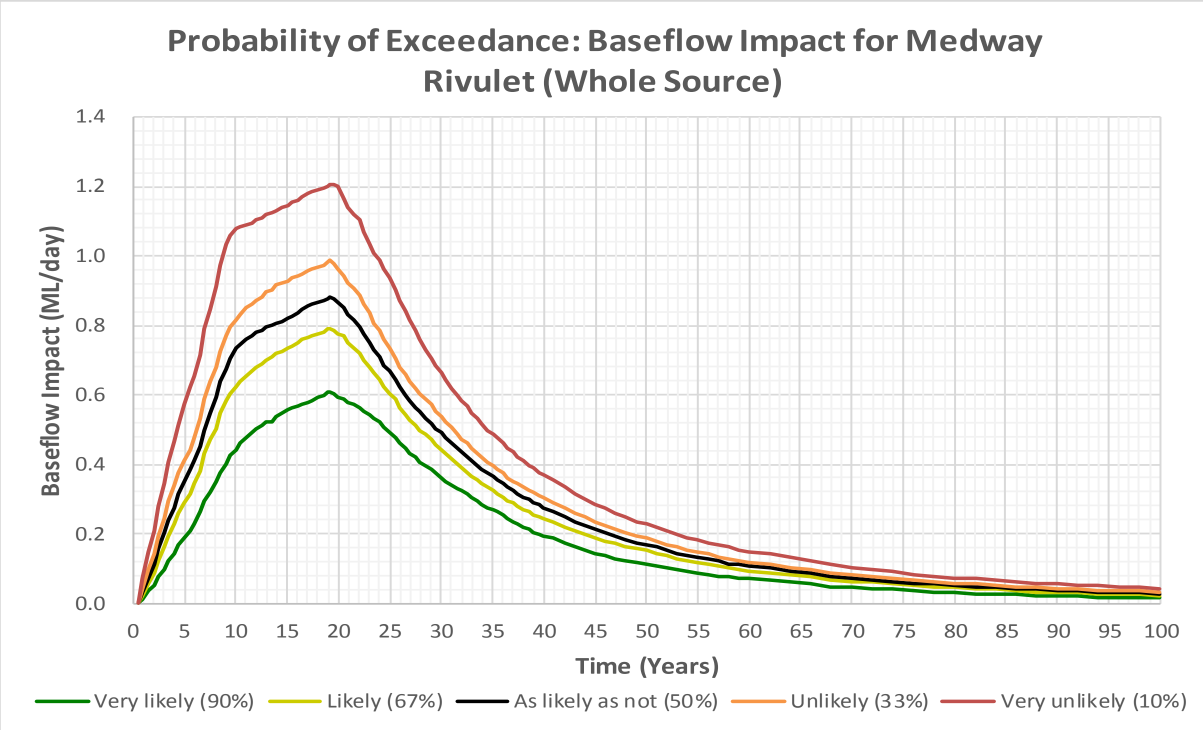


Figure 45 Uncertainty Analysis – Baseflow impact for Medway Rivulet

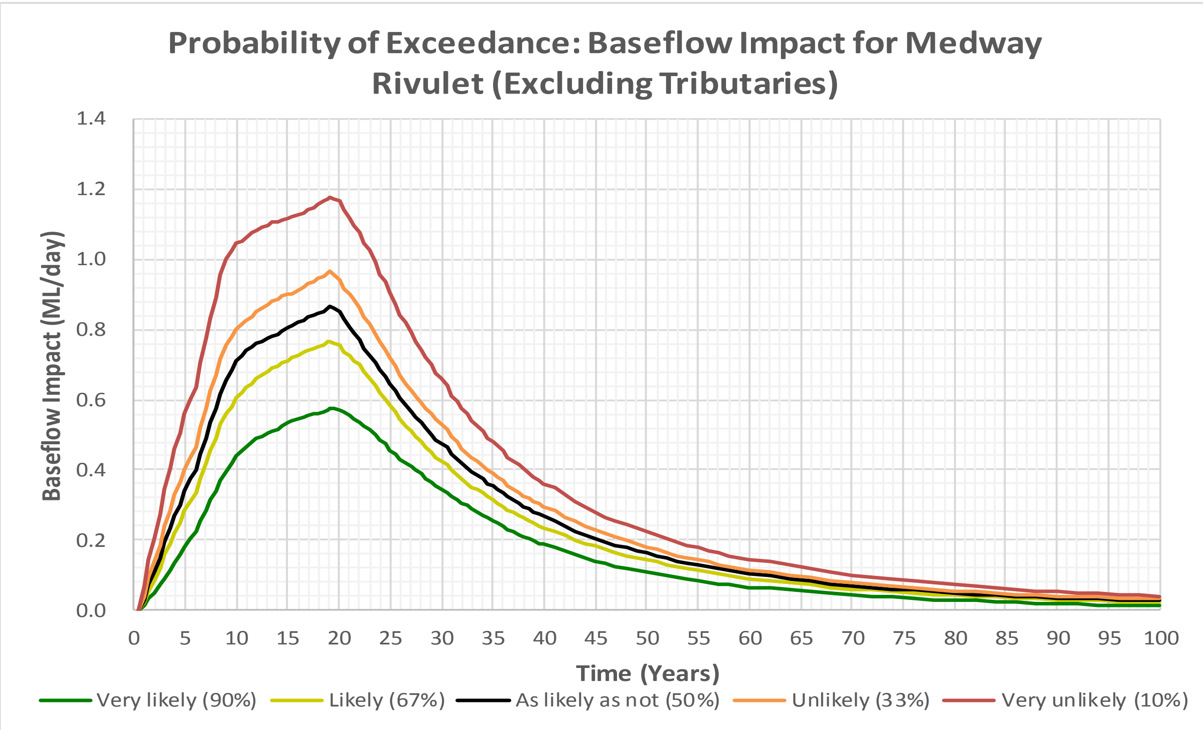


Figure 46 Uncertainty Analysis – Baseflow impact for Medway Rivulet (Excluding Tributaries)

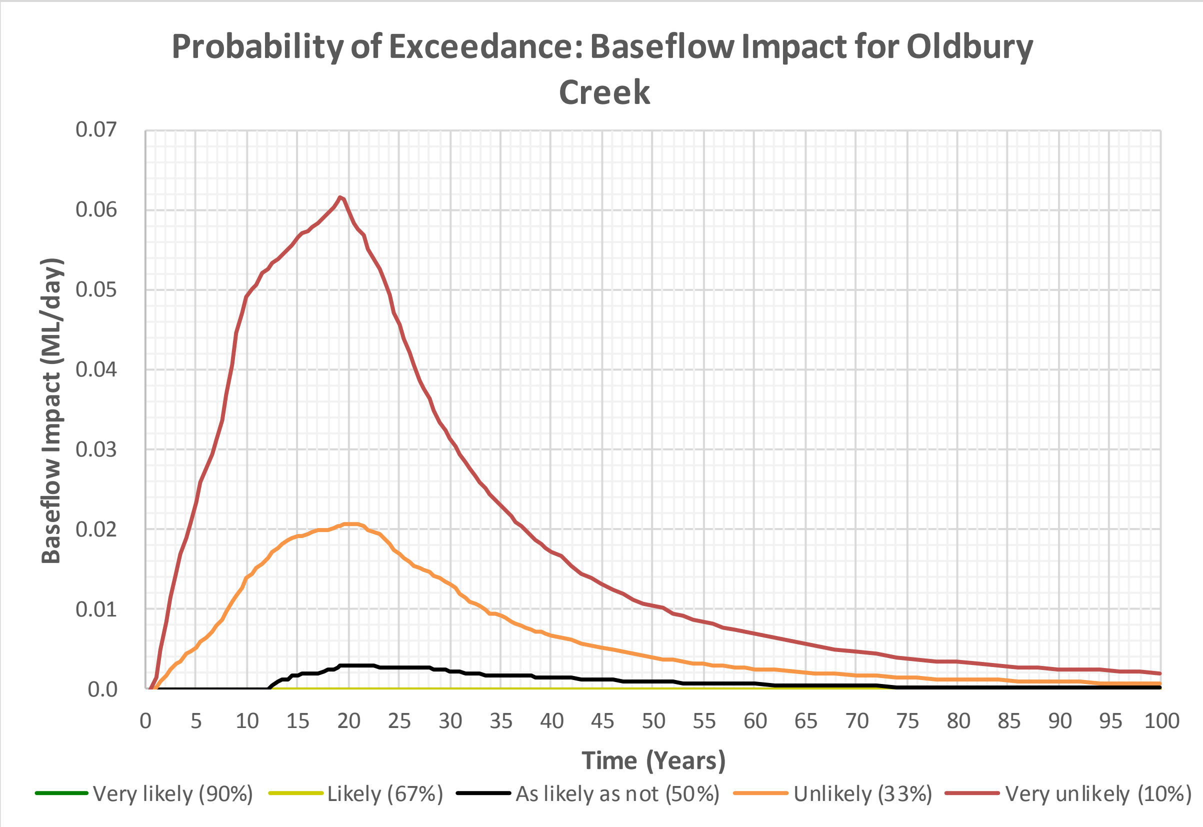


Figure 47 Uncertainty Analysis – Baseflow impact for Oldbury Creek

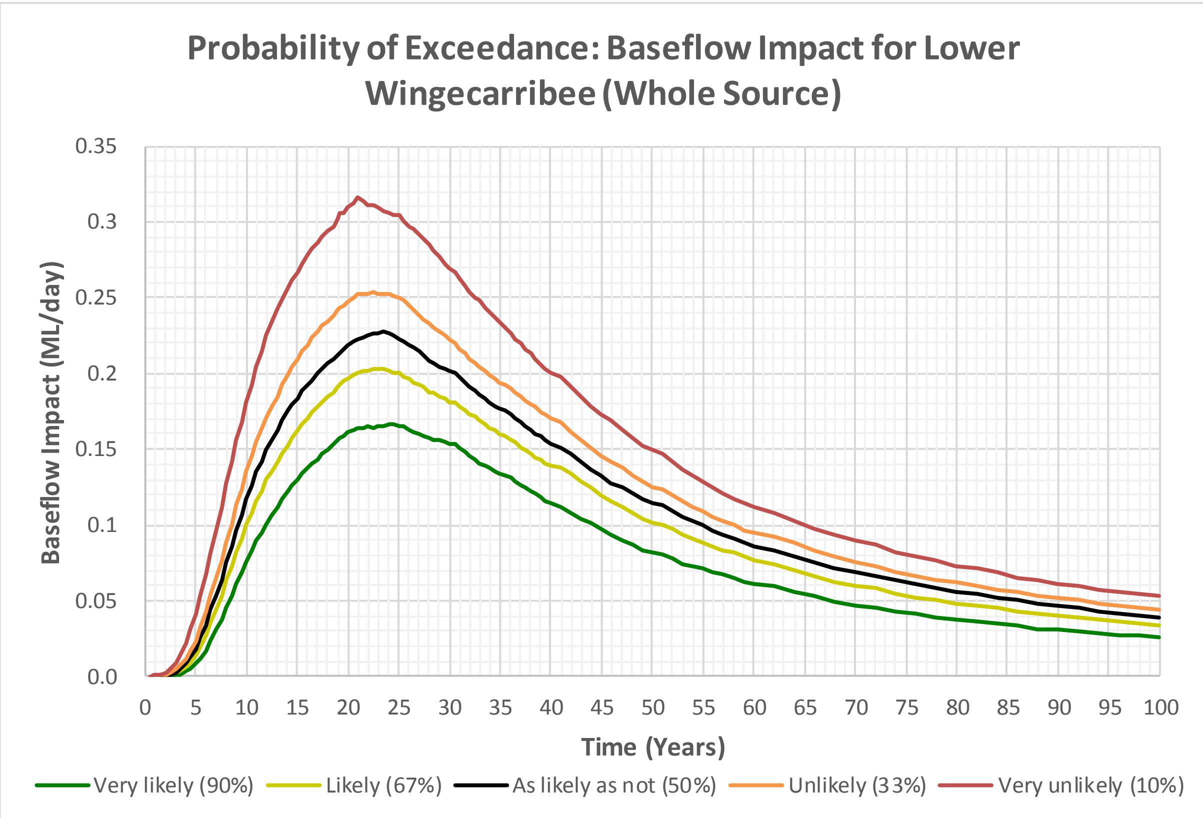


Figure 48 Uncertainty Analysis – Baseflow impact for Lower Wingecarribee

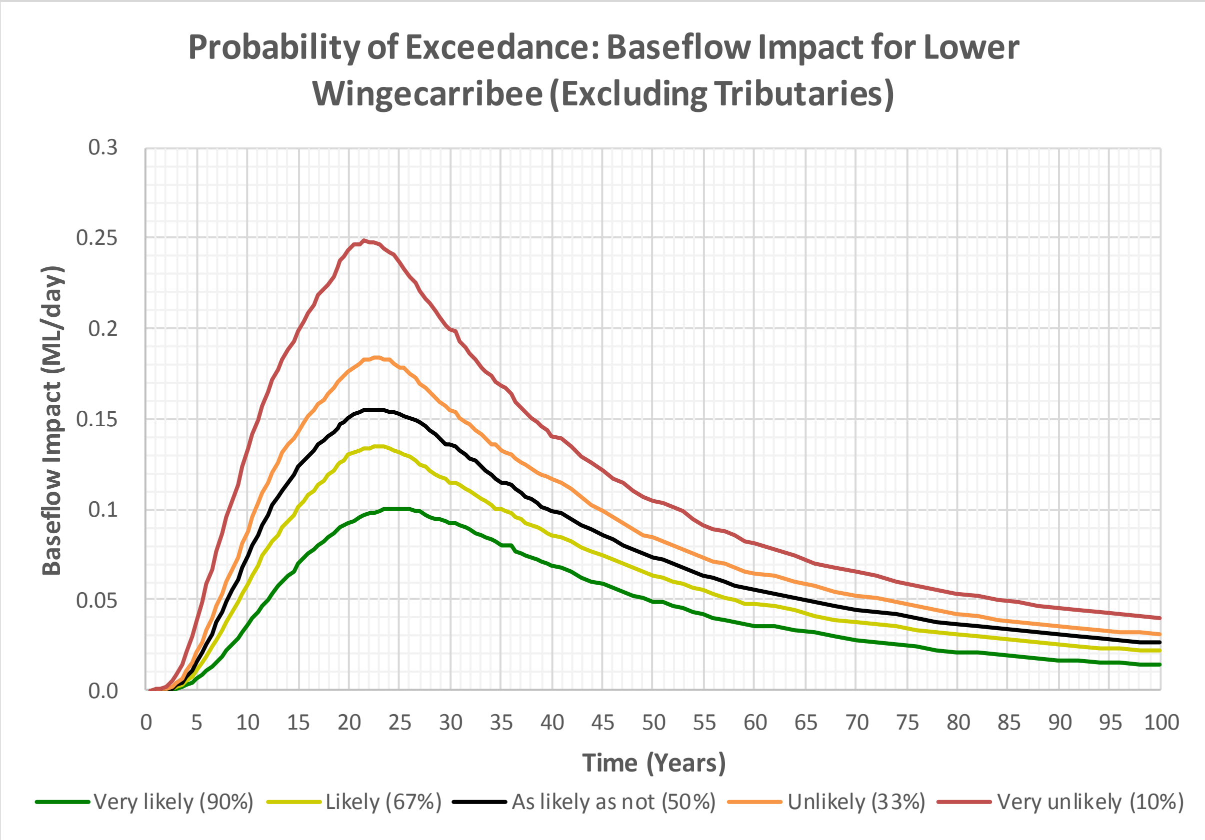


Figure 49 Uncertainty Analysis – Baseflow impact for Lower Wingecarribee (excluding tributaries)

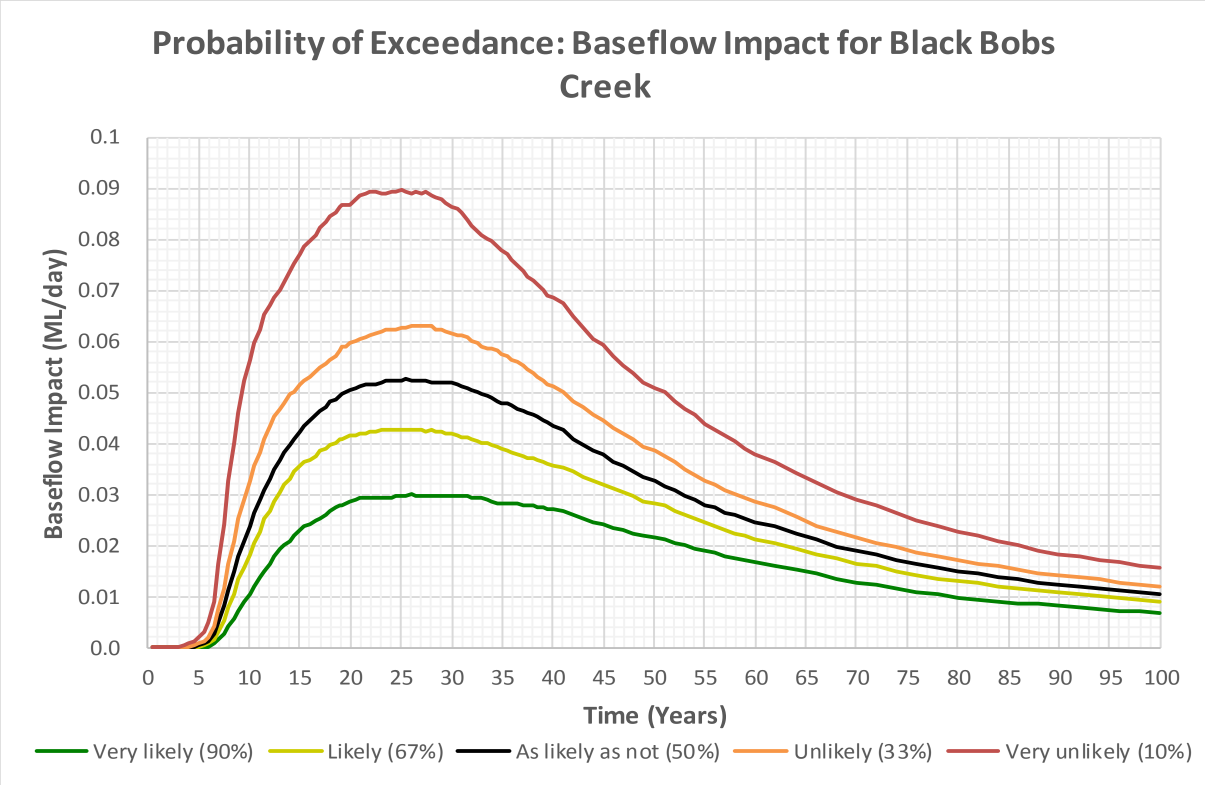


Figure 50 Uncertainty Analysis – Baseflow impact for Black Bobs Creek

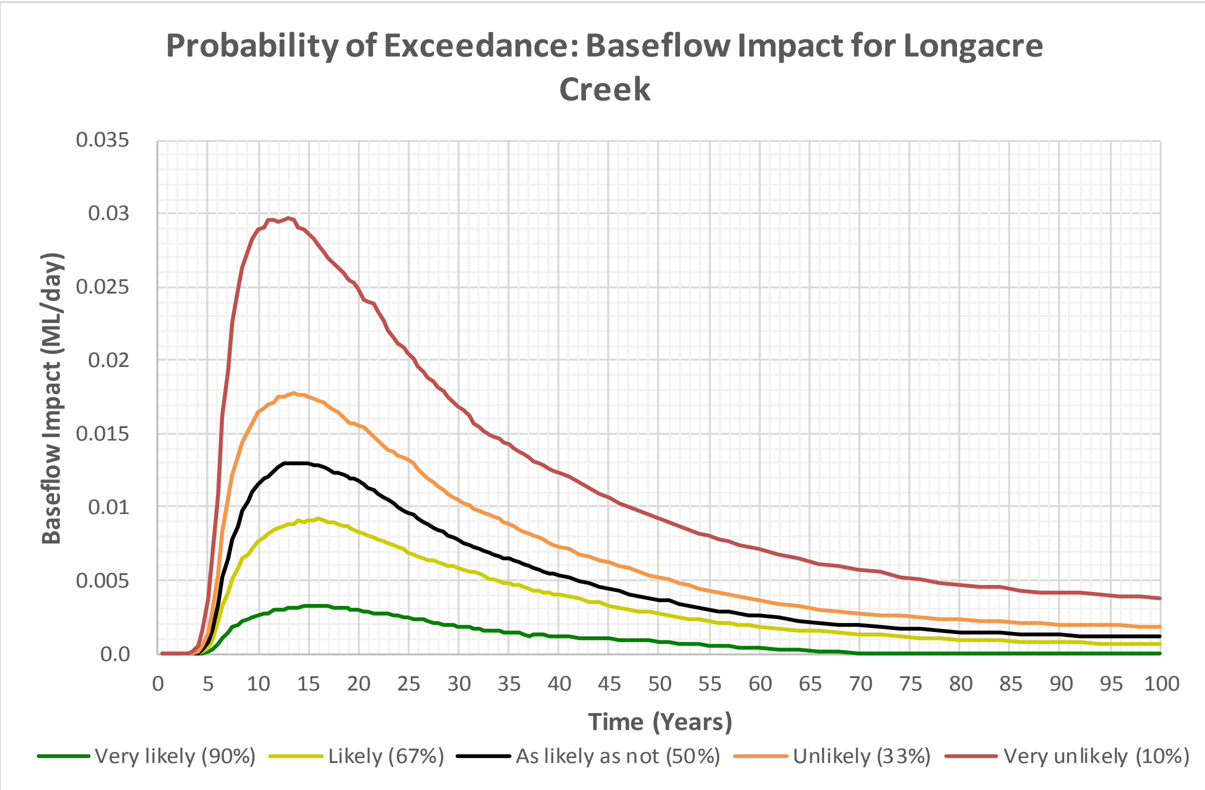


Figure 51 Uncertainty Analysis – Baseflow impact for Longacre Creek

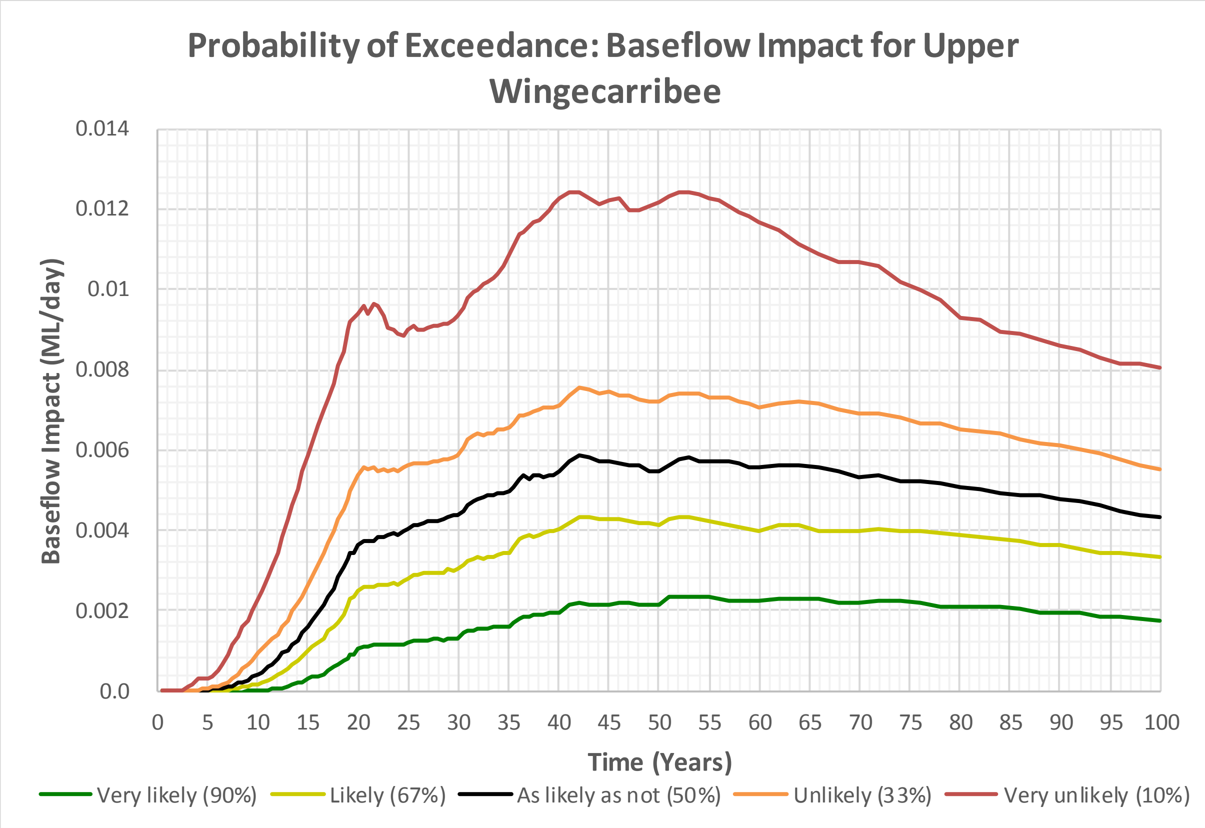


Figure 52 Uncertainty Analysis – Baseflow impact for Upper Wingecarribee River

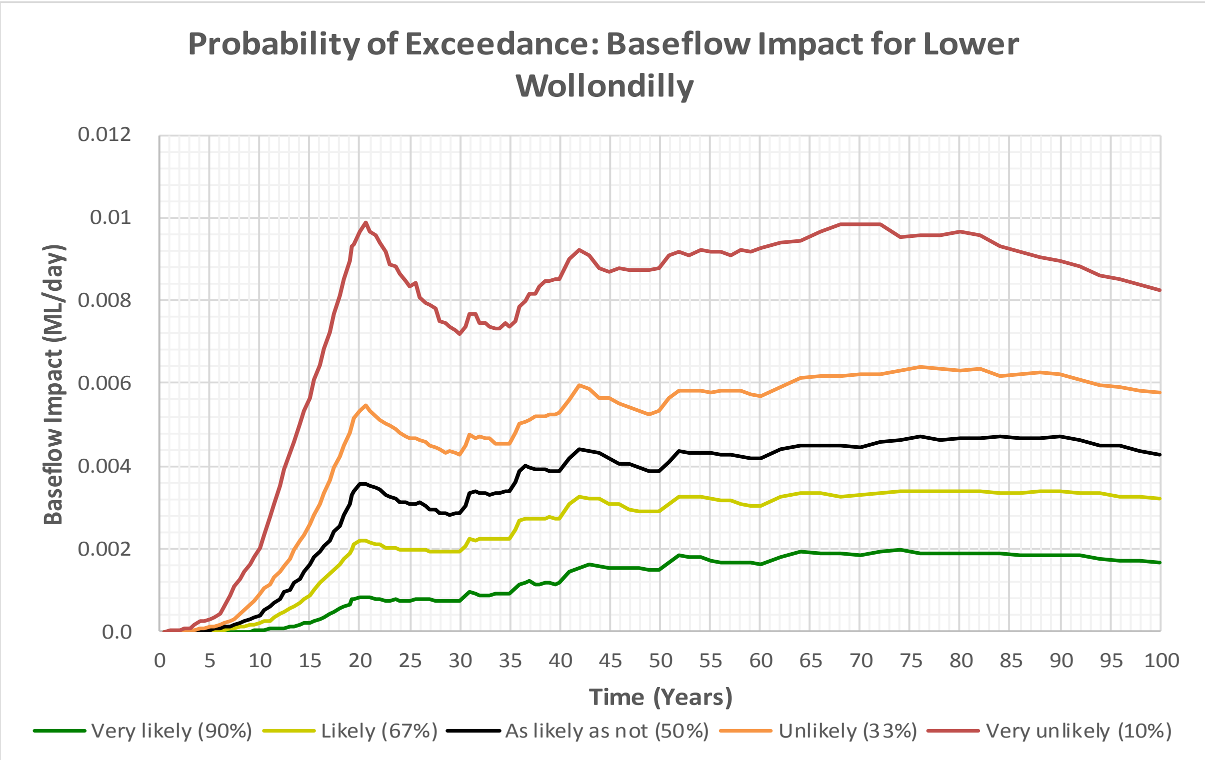


Figure 53 Uncertainty Analysis – Baseflow impact for Lower Wollondilly

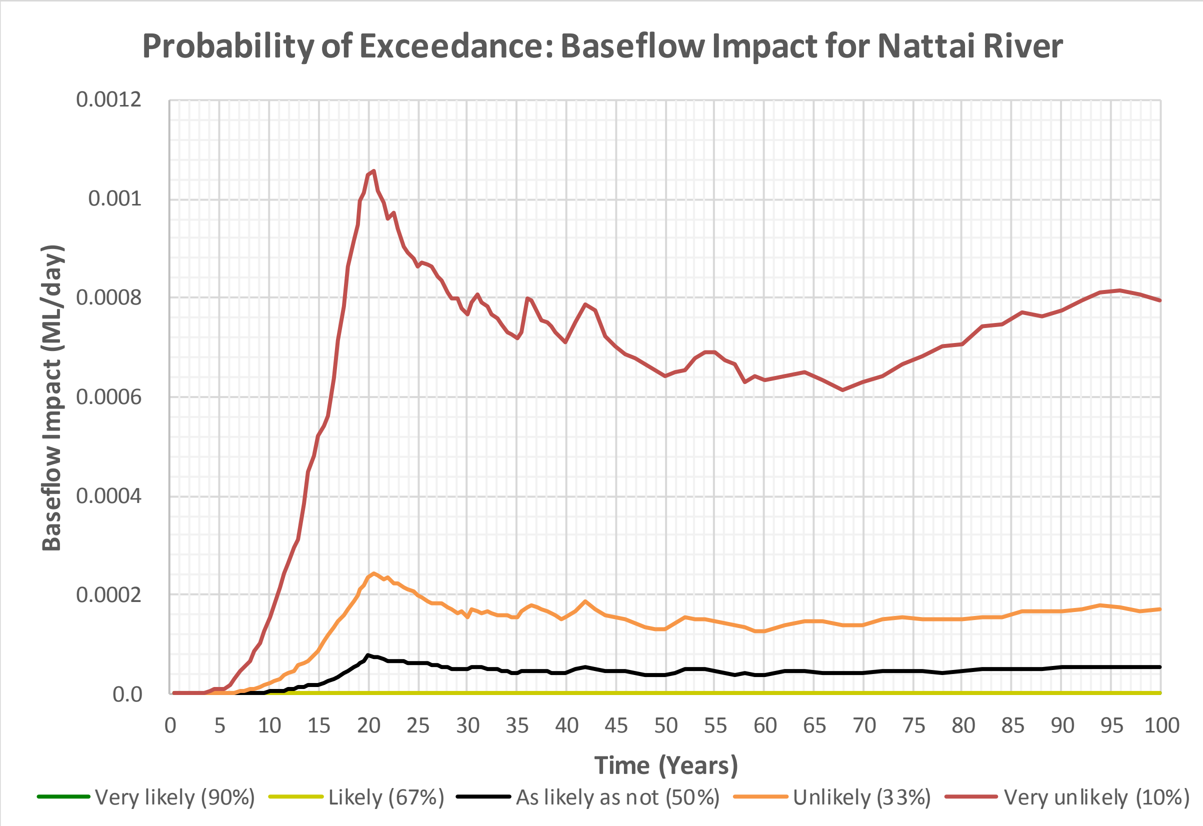


Figure 54 Uncertainty Analysis – Baseflow impact for Nattai River

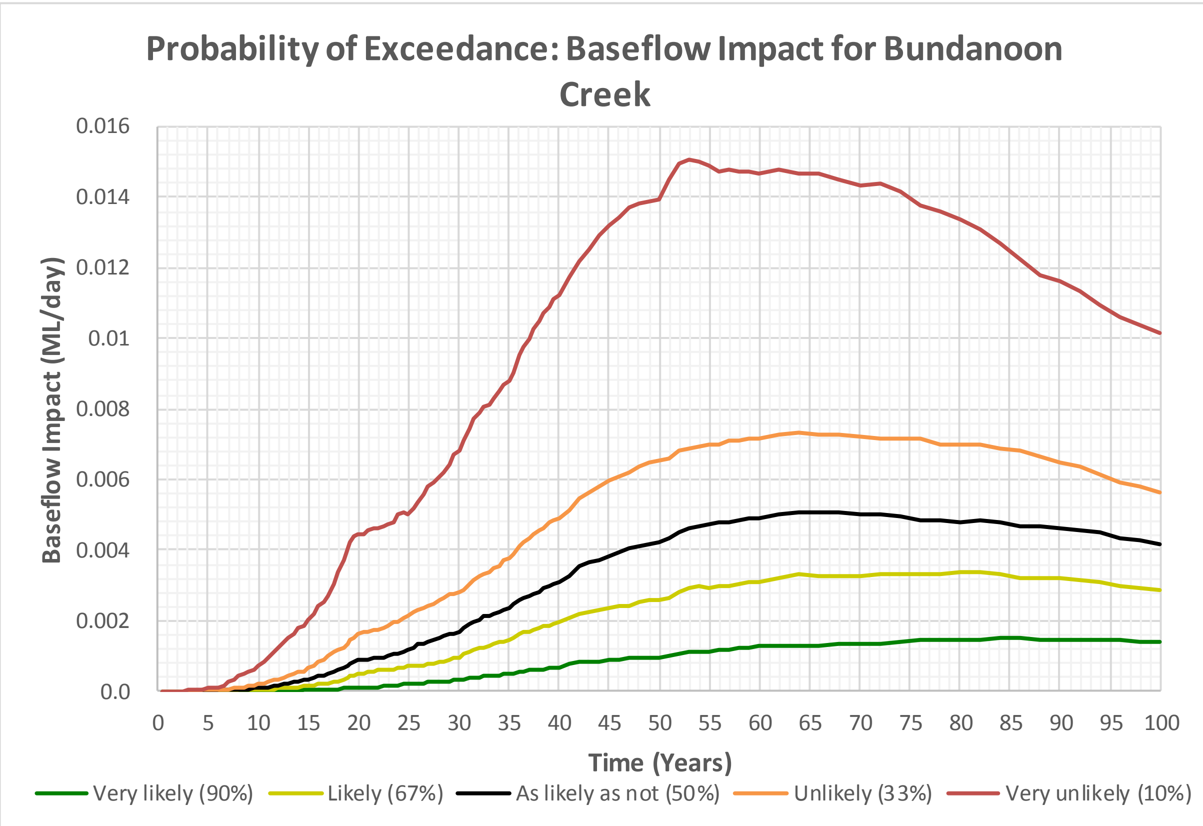


Figure 55 Uncertainty Analysis – Baseflow impact for Bundanoon Creek

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.

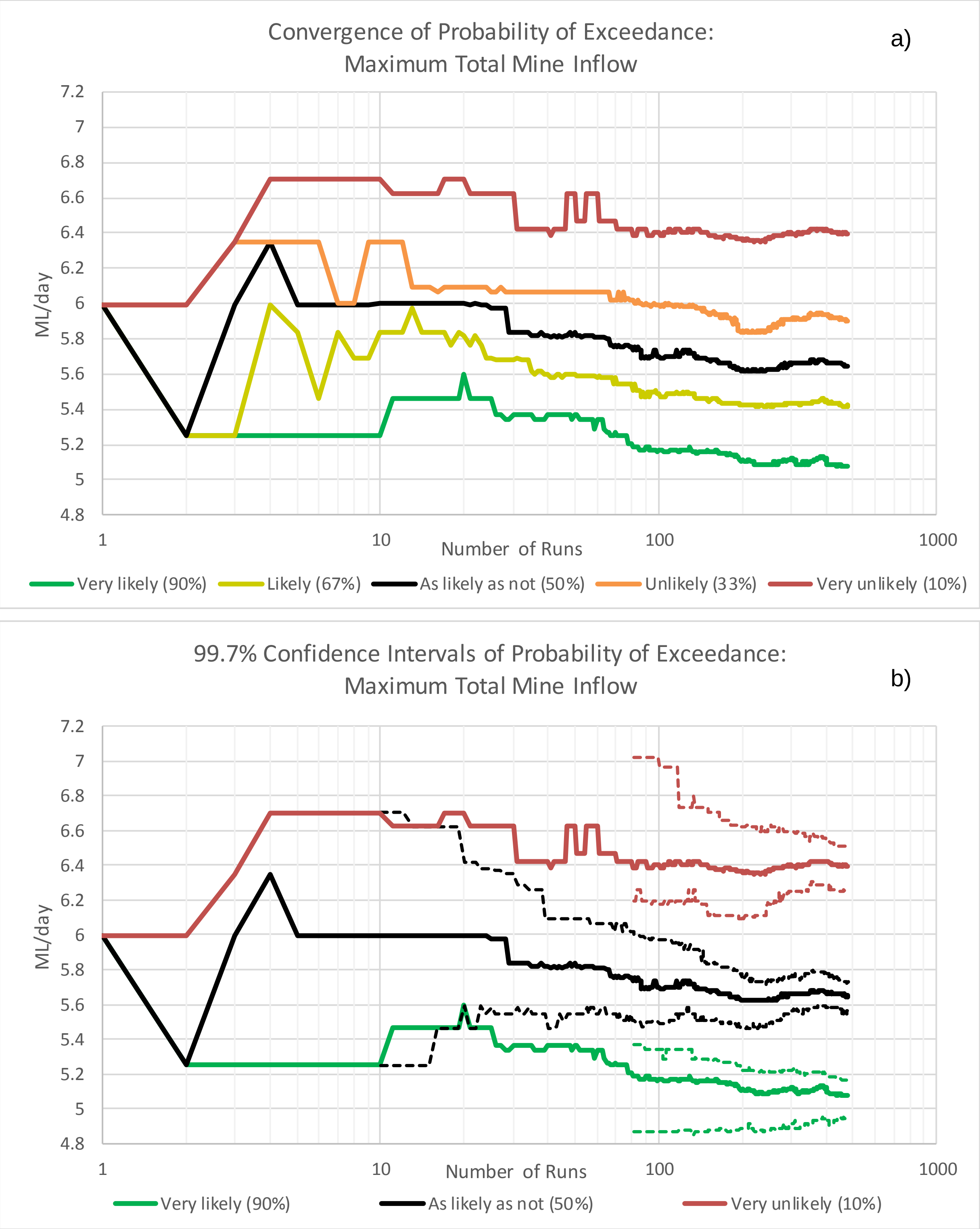


Figure 56 Convergence chart (a) and confidence interval (b) for number of impacted bores

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.

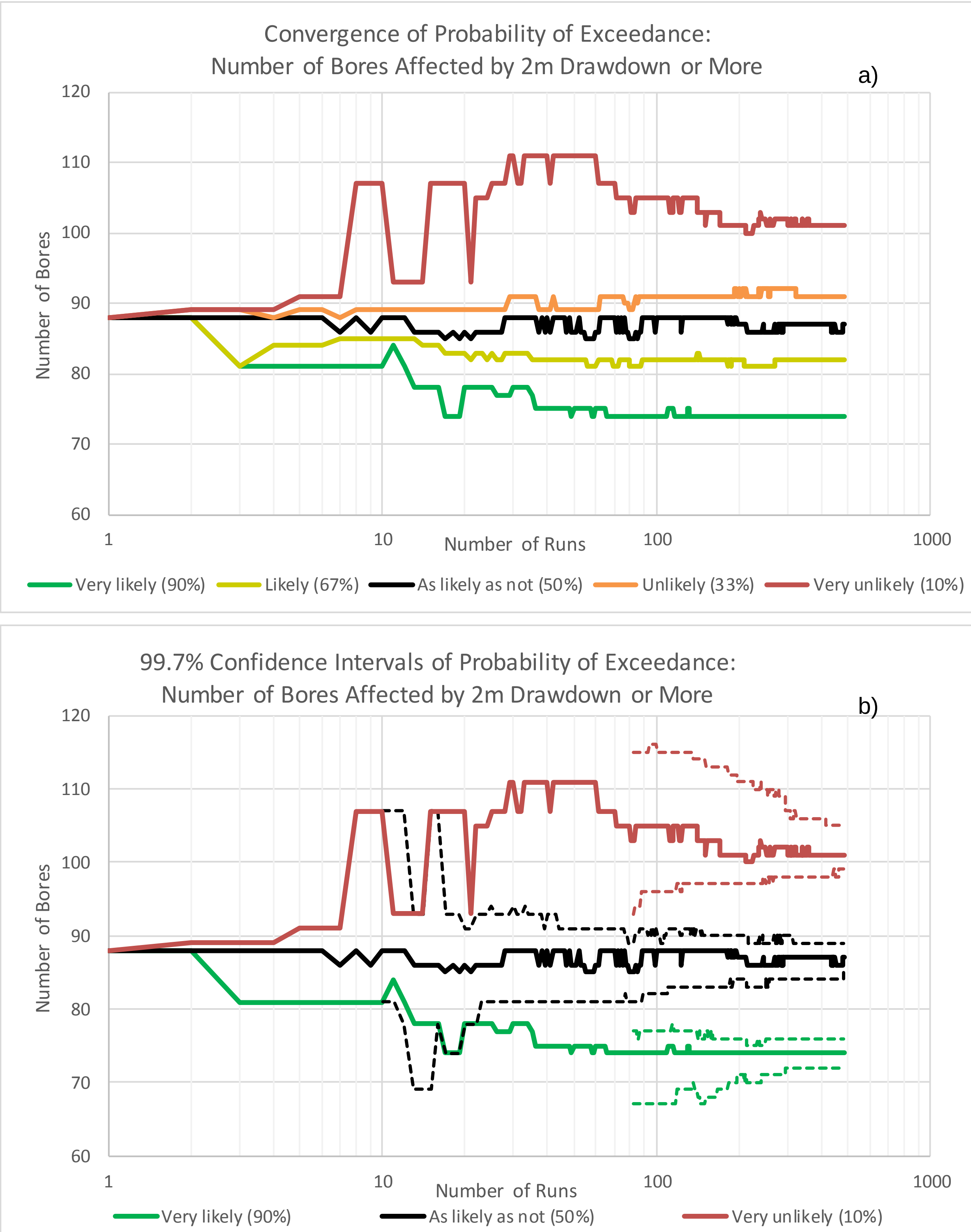


Figure 57 Convergence chart (a) and confidence interval (b) for 'Total' mine inflow.

SENSITIVITY ANALYSIS FIGURES

PILOT POINTS

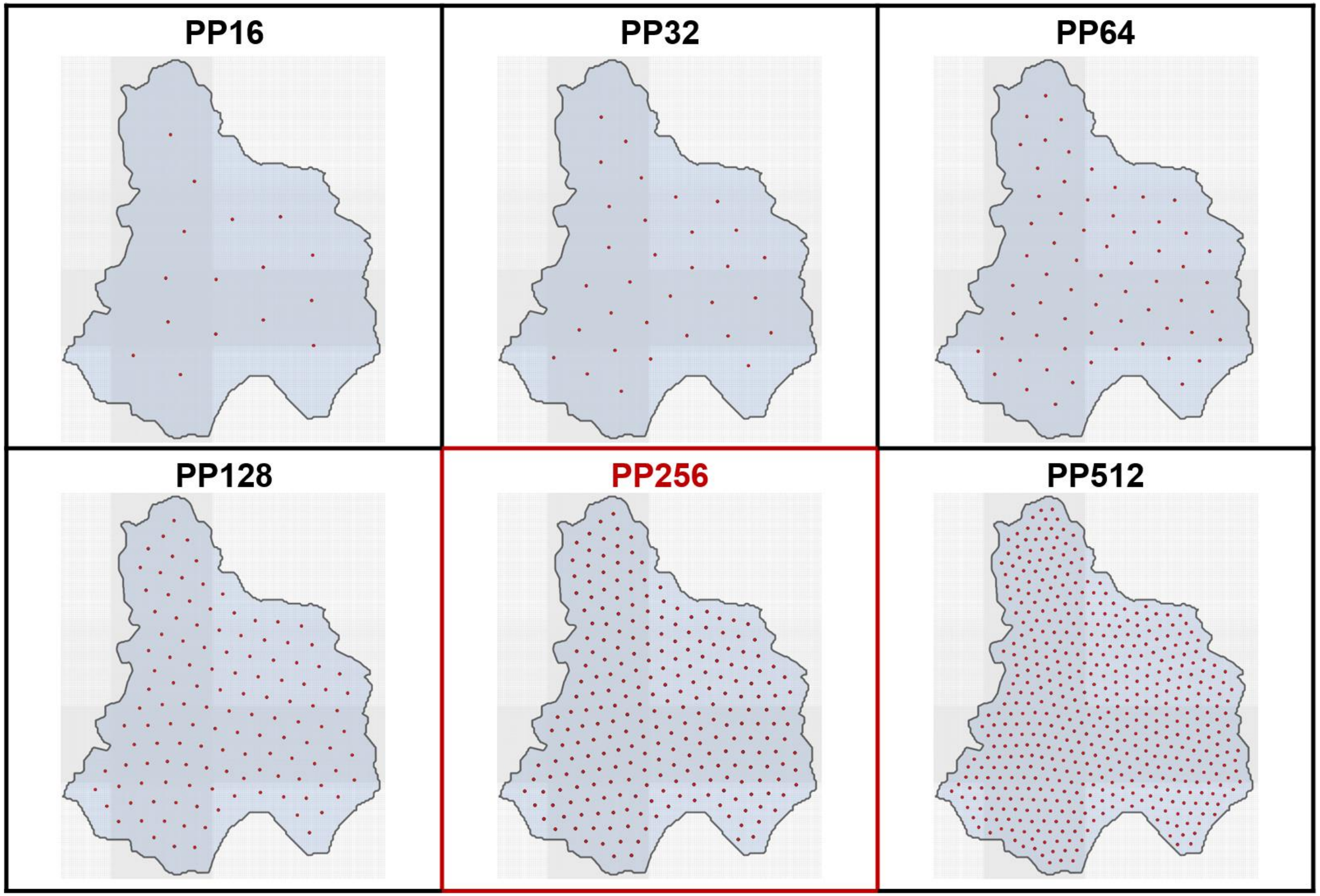


Figure 58 Pilot point spatial distributions in each of the six scenarios. The PP256 scenario, highlighted in red, was the distribution used in the uncertainty analysis.

MINE INFLOW

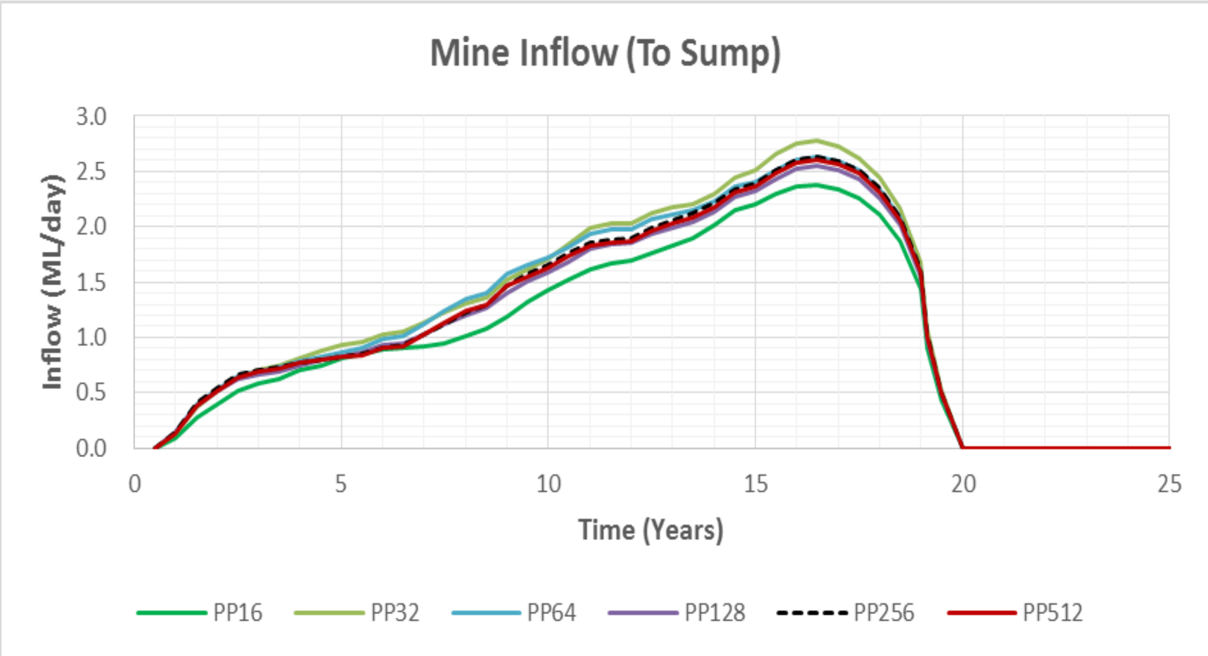


Figure 59 Mine Inflow to sump for pilot point sensitivity analysis

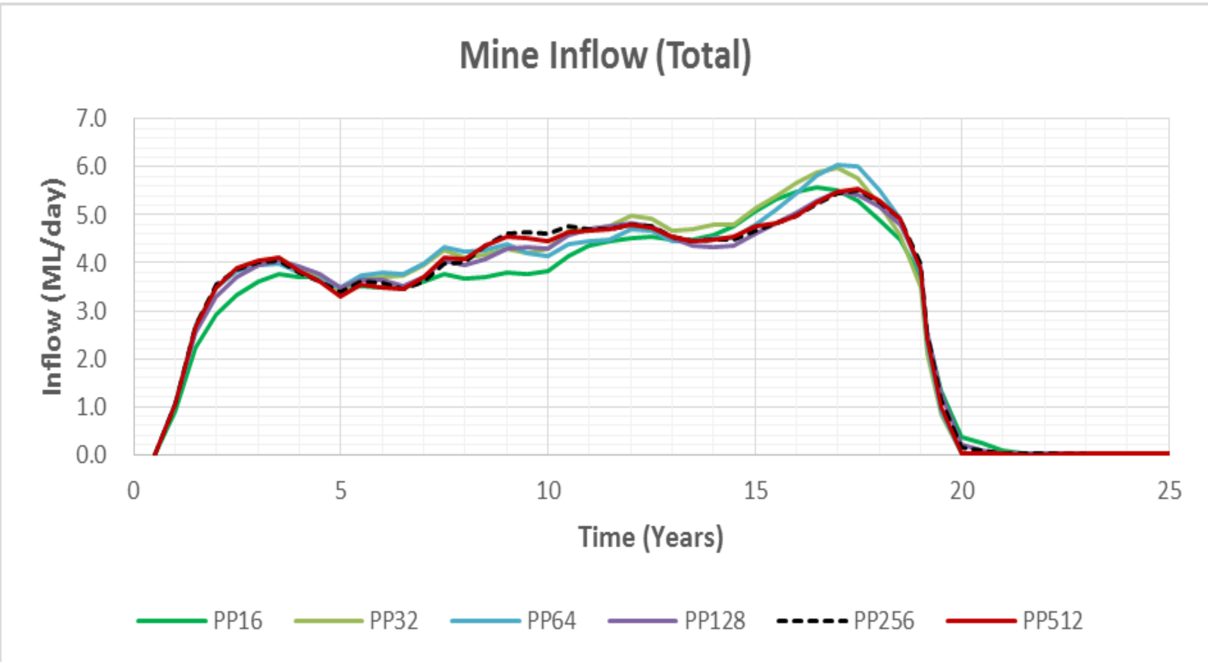


Figure 60 Total Mine Inflow for pilot point sensitivity analysis

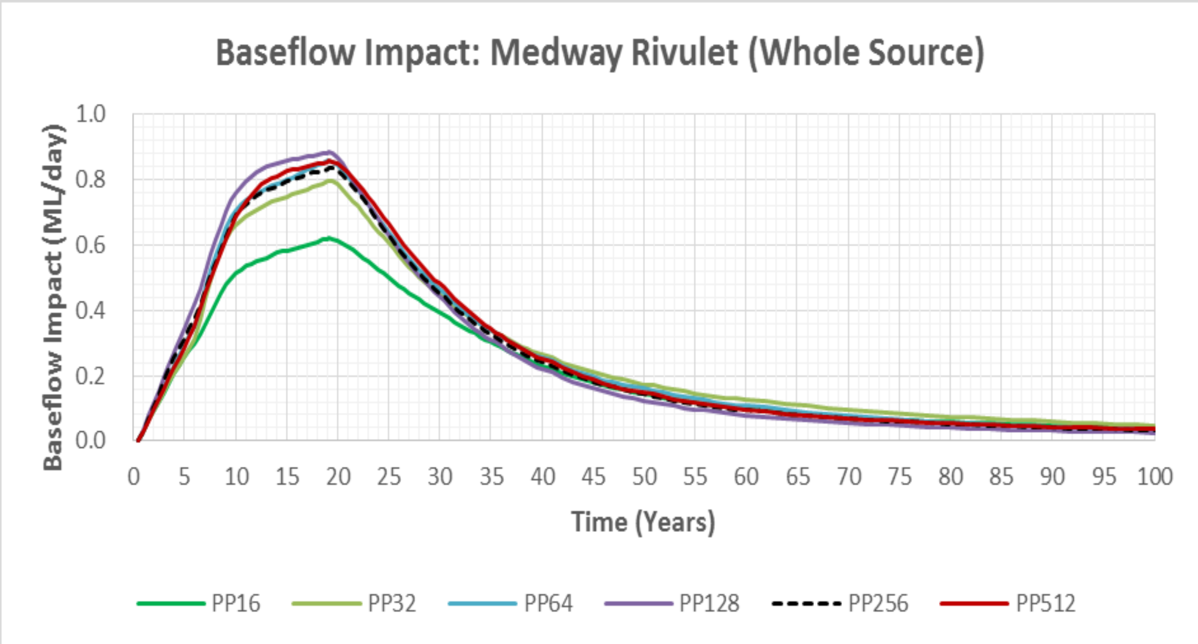


Figure 61 Medway Rivulet baseflow impact for pilot point sensitivity analysis

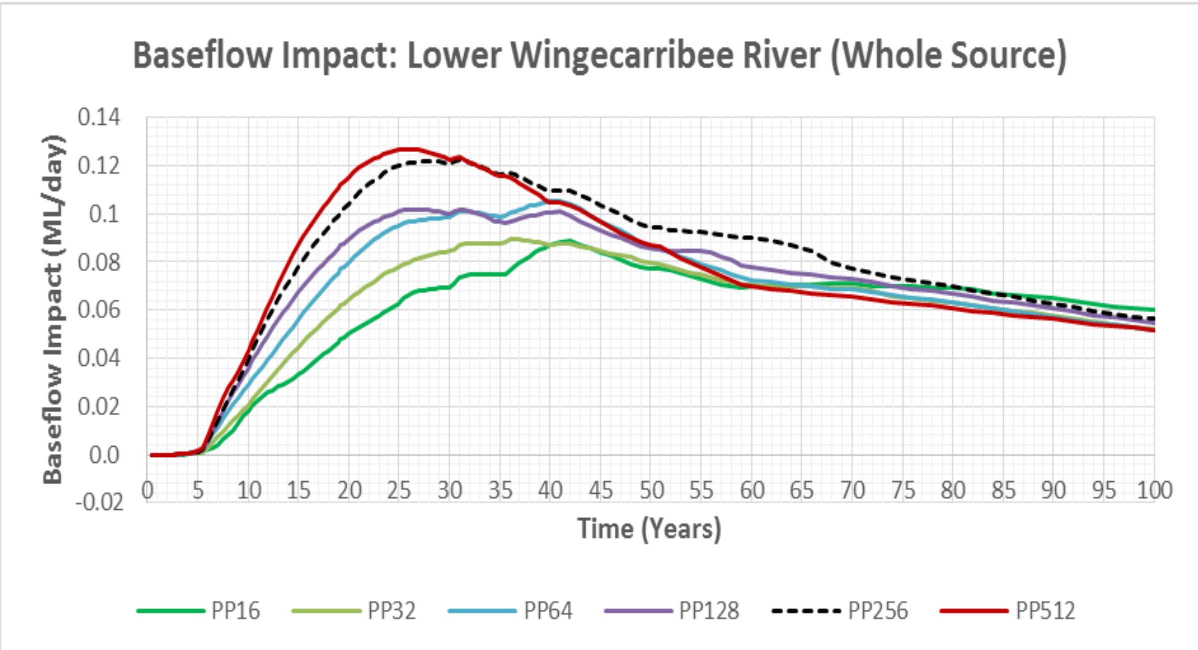


Figure 62 Lower Wingecarribee River baseflow impact for pilot point sensitivity analysis

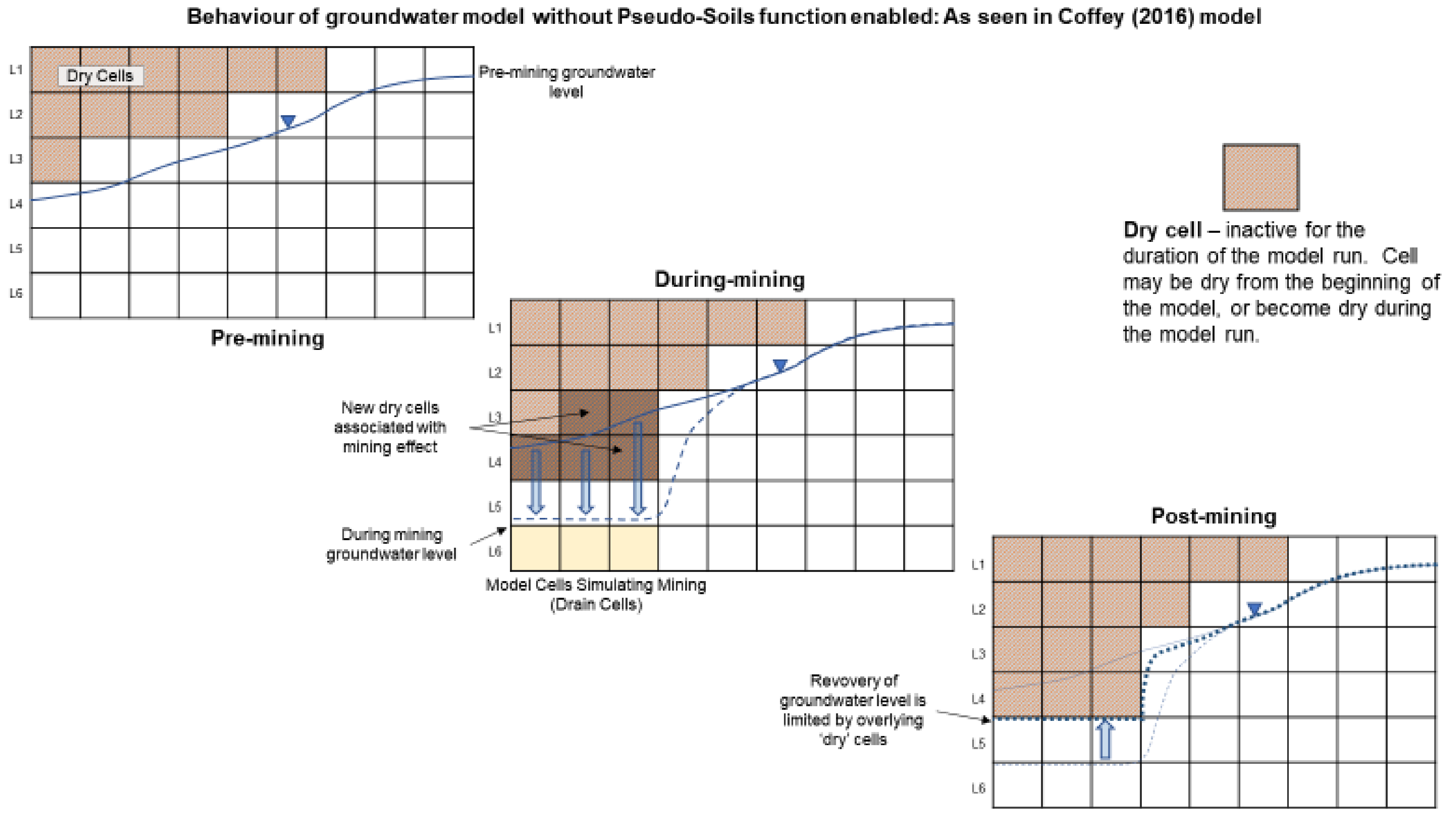


Figure 63 Cross section showing the behaviour of a groundwater model without pseudo soil function enabled (EIS Model)

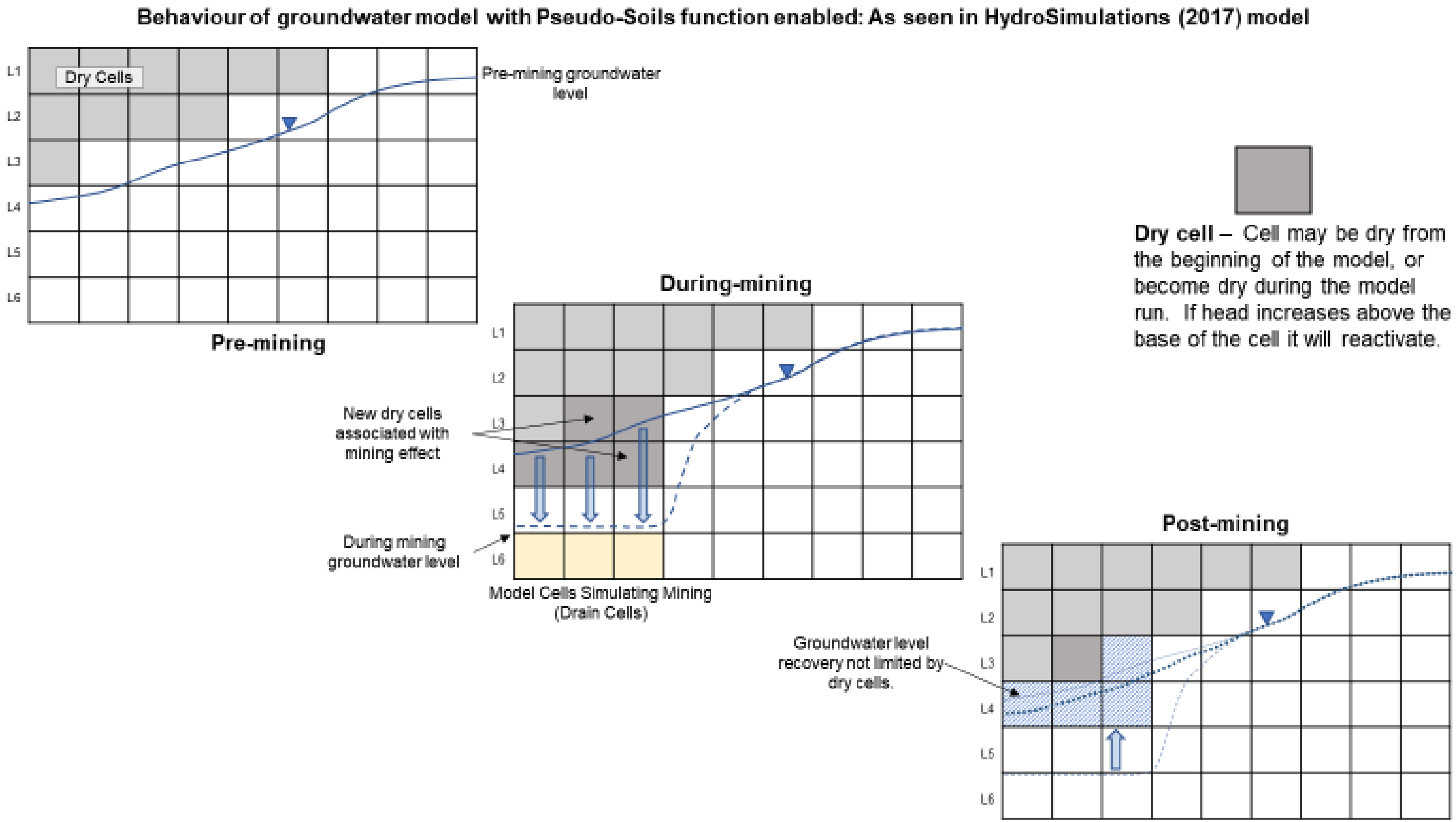


Figure 64 **Cross section showing the behaviour of a groundwater model with the pseudo-soil function enabled (Modified EIS model).**

HORIZONTAL FLOW BARRIERS

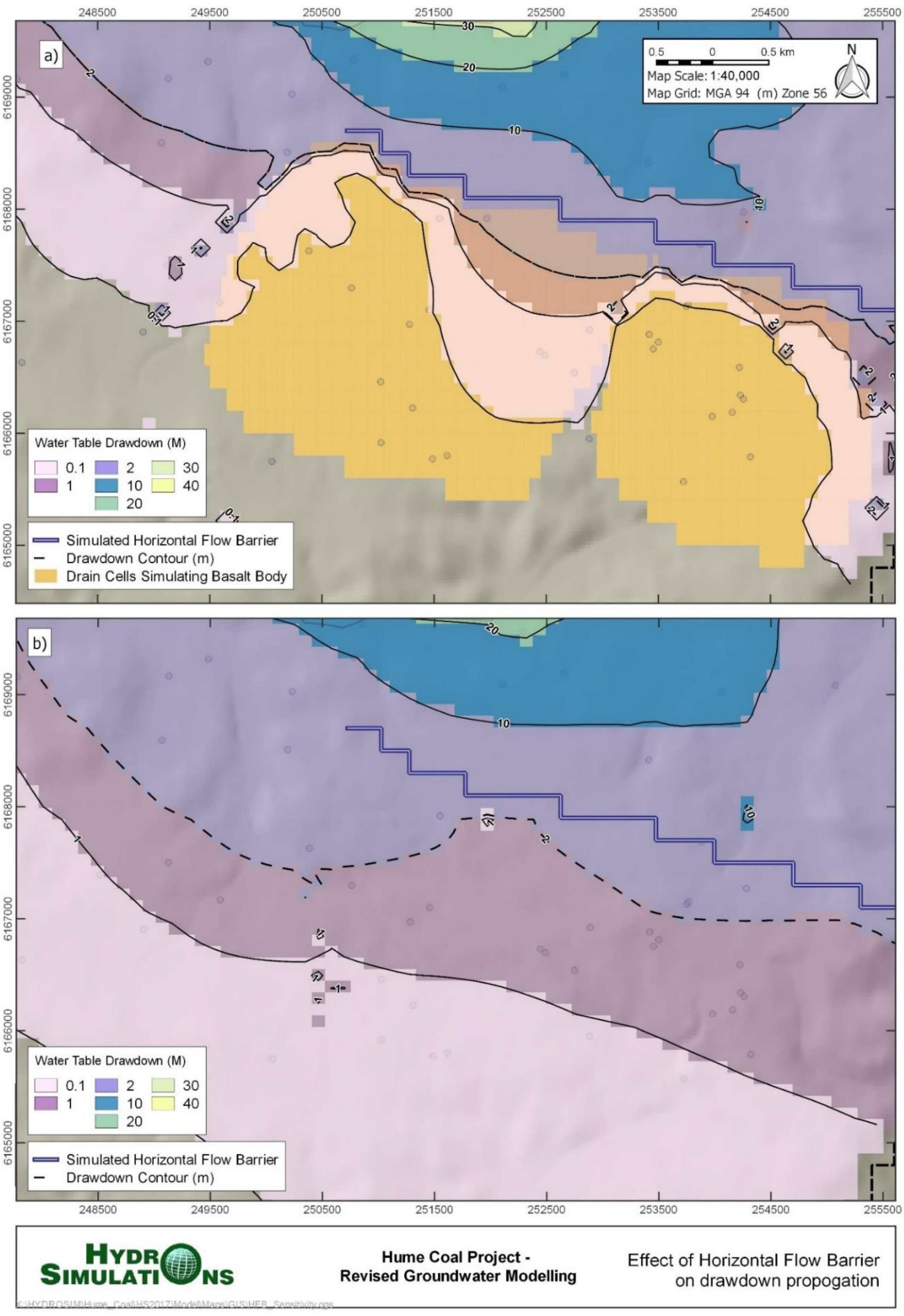


Figure 65 a) Spatial interaction of drawdown with basalt body simulated using Drain and Horizontal Flow Barrier cells b) spatial interaction of drawdown when only Horizontal Flow Barrier cells are present.

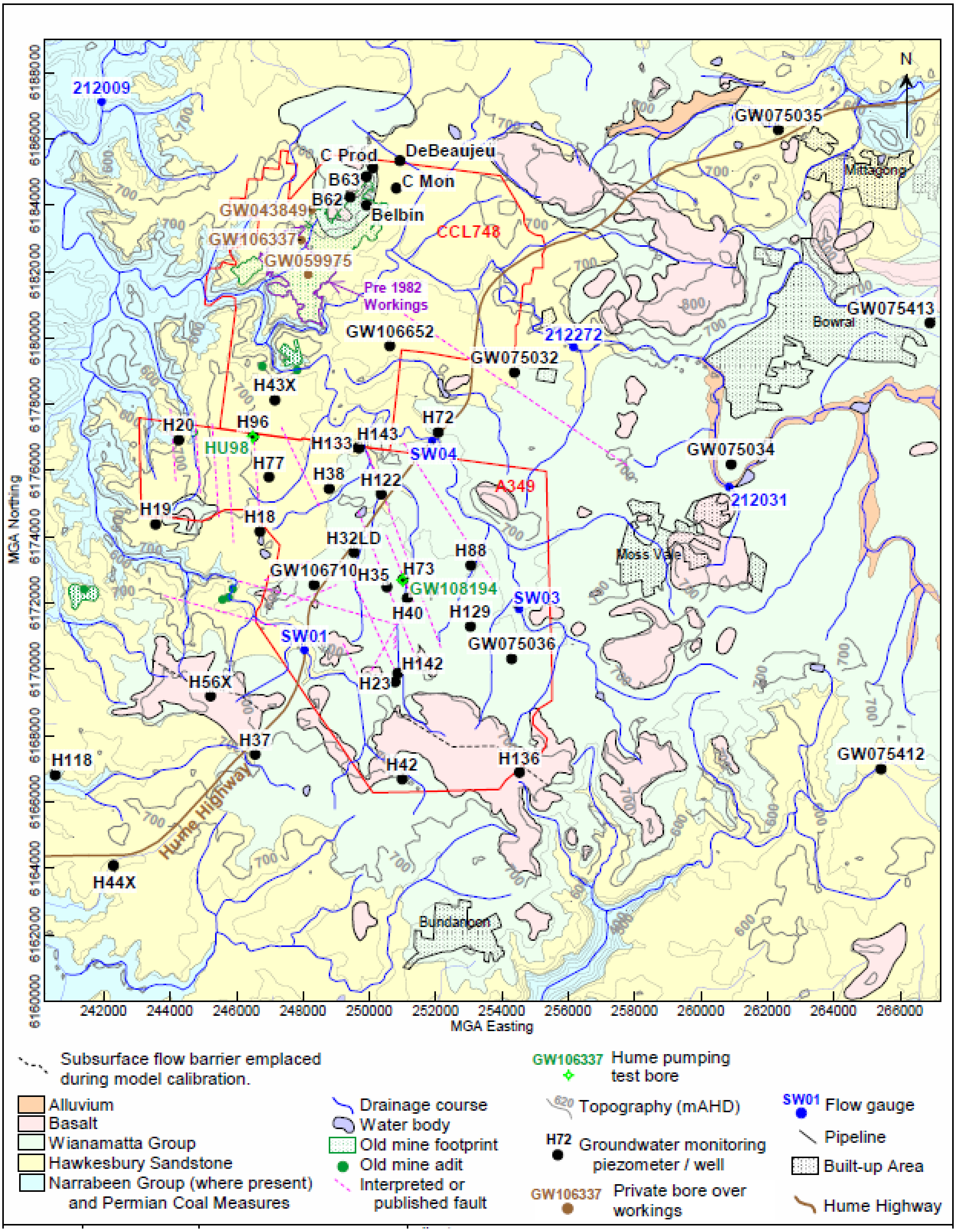


Figure 66 Monitoring piezometer and well locations [from Coffey, 2016a, Figure D1]

APPENDIX A – HYDROGEOLOGIC REVIEW SUMMARY TABLE

Issues Log

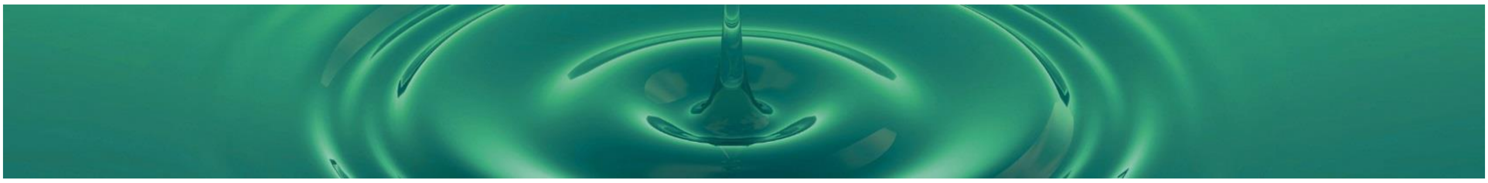
Hume Coal Project (SSD 7172) - Groundwater Model

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.

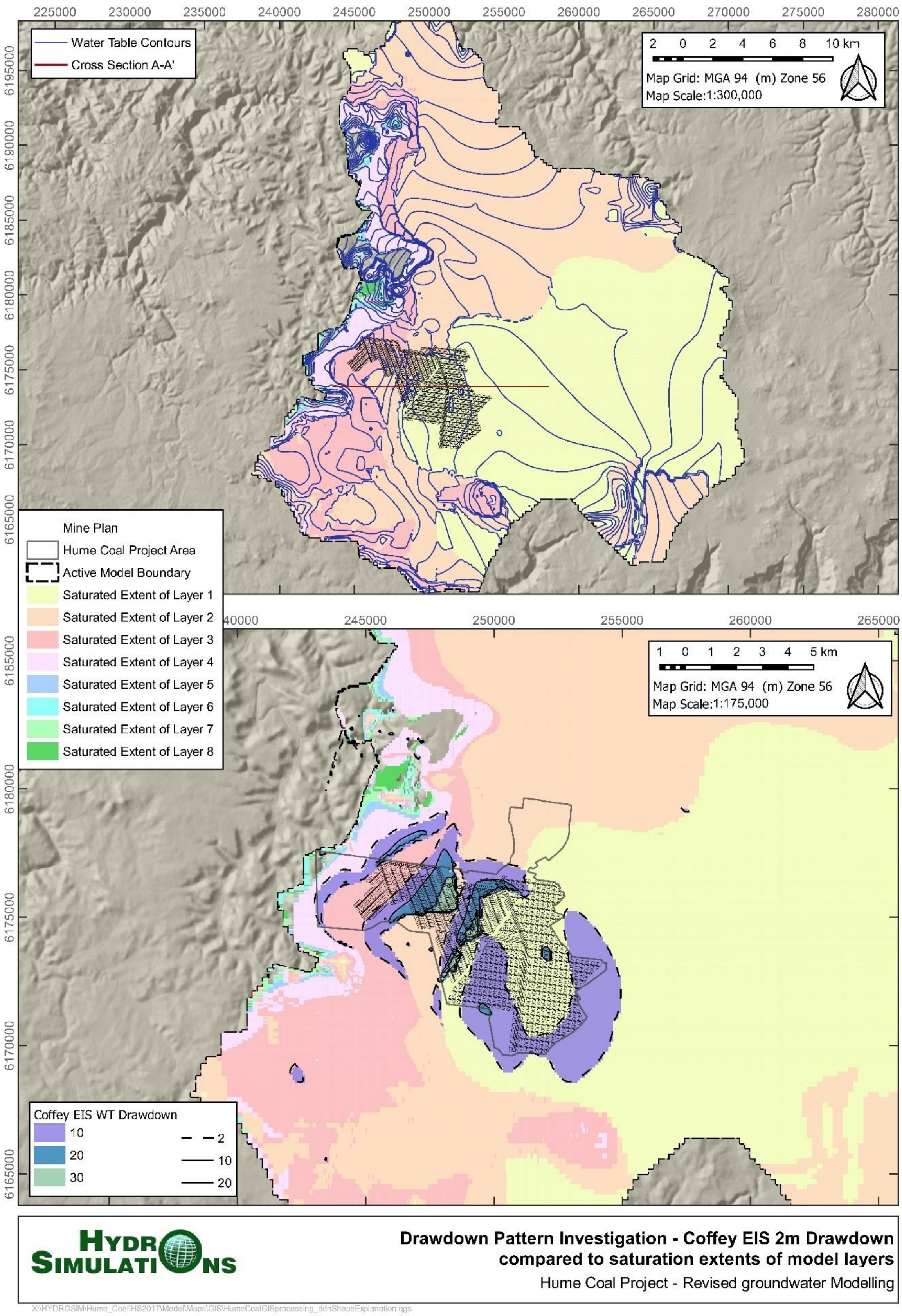


Figure B 1 Saturated extents of each model layer

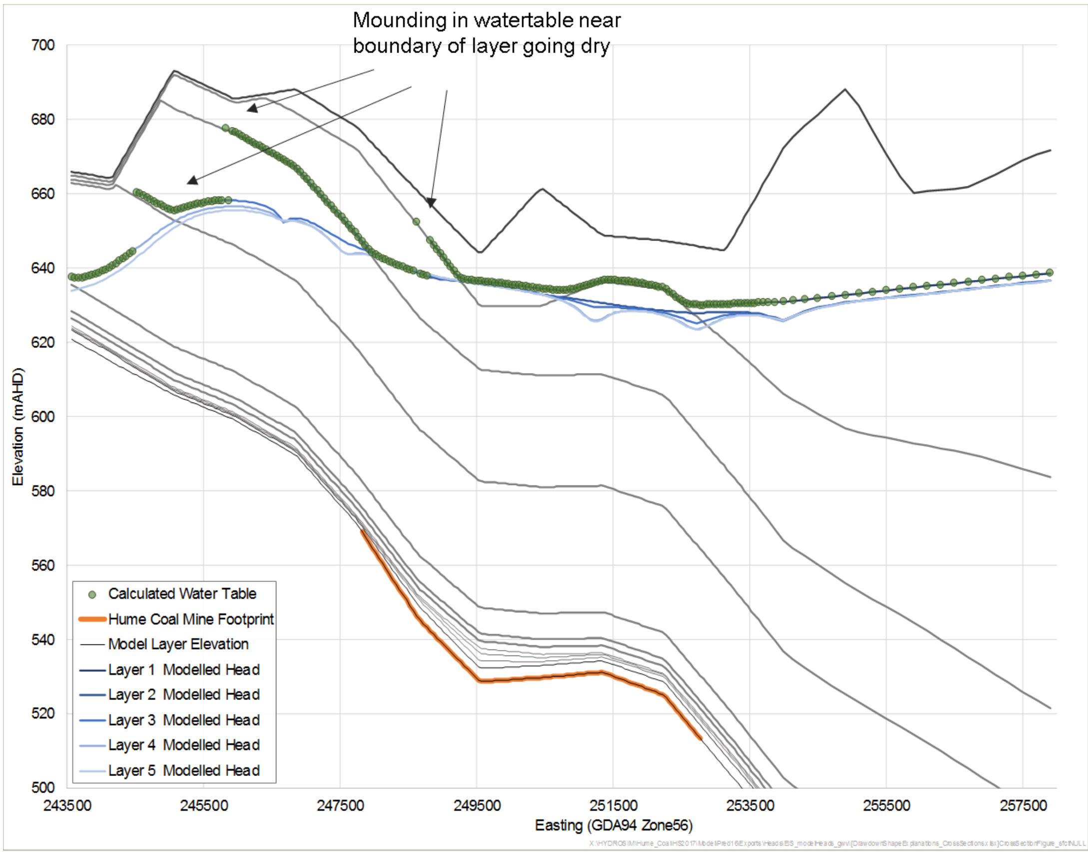


Figure B 2 Modelled head and water table elevation in mine year 17 for a 'Null' run using MODFLOW-SURFACT V4 Software

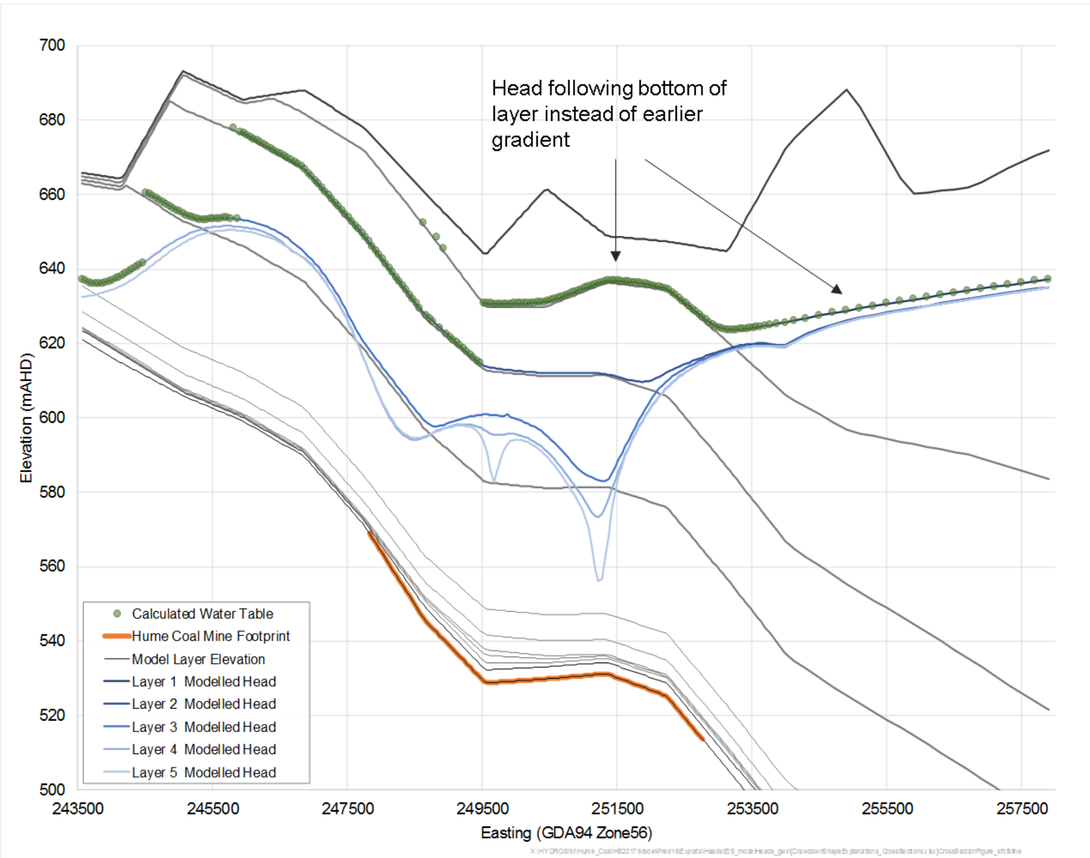


Figure B 3 Modelled head and water table elevation in mine year 17 for a Hume Coal 'mining' run using MODFLOW-SURFACT V4 Software

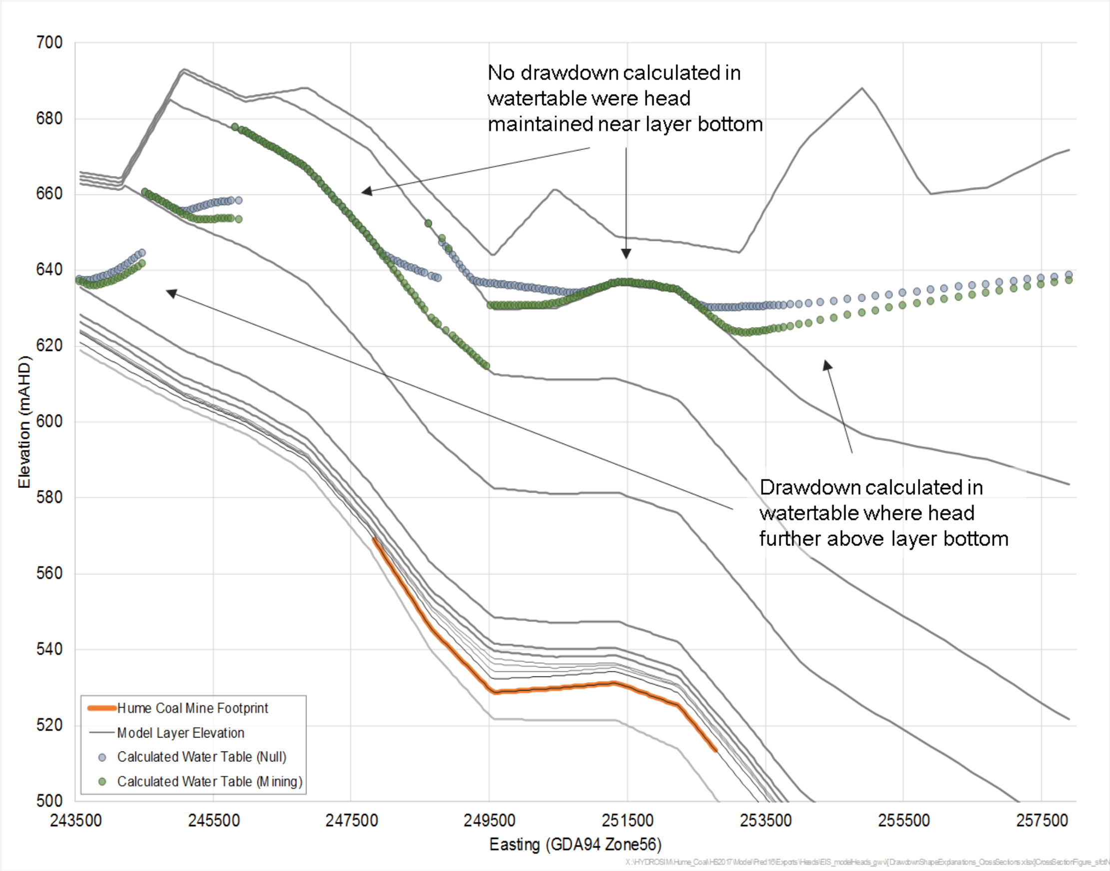


Figure B 4 Water table comparison in mine year 17 for the 'Null' and 'Mining' runs using MODFLOW-SURFACT V4 Software

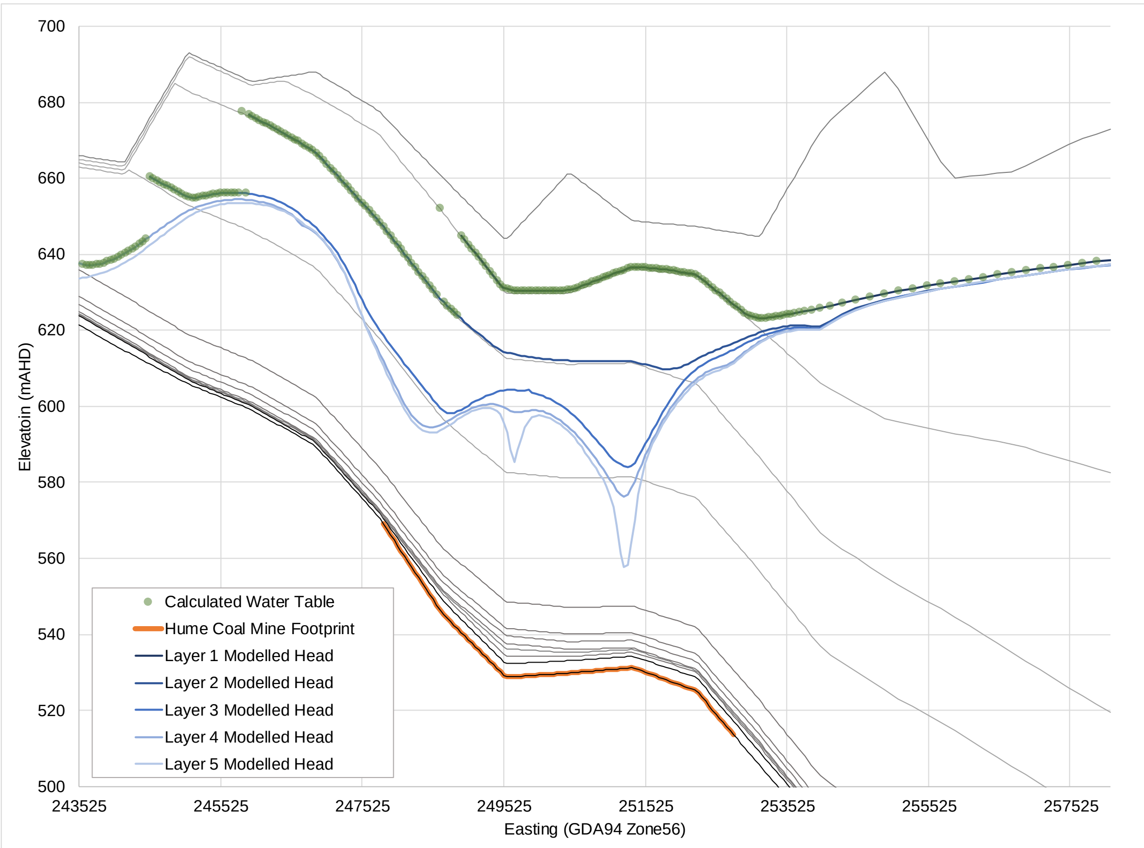


Figure B 5 Modelled head and water table elevation in mine year 17 from the EIS model 'mining' run using MODFLOW-SURFACT V3 Software

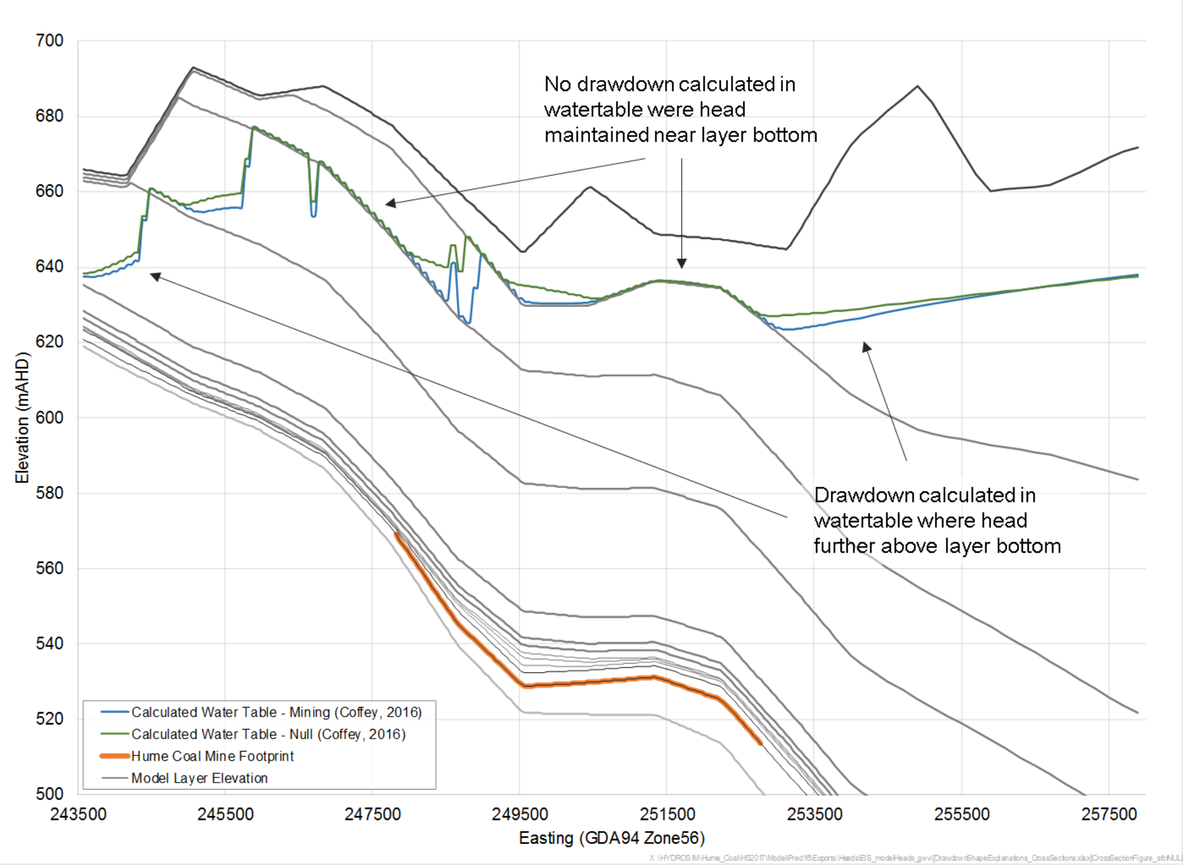


Figure B 6 Water table comparison in mine year 17 from the EIS Model for the 'Null' and 'Mining' runs using MODFLOW-SURFACT V3 Software

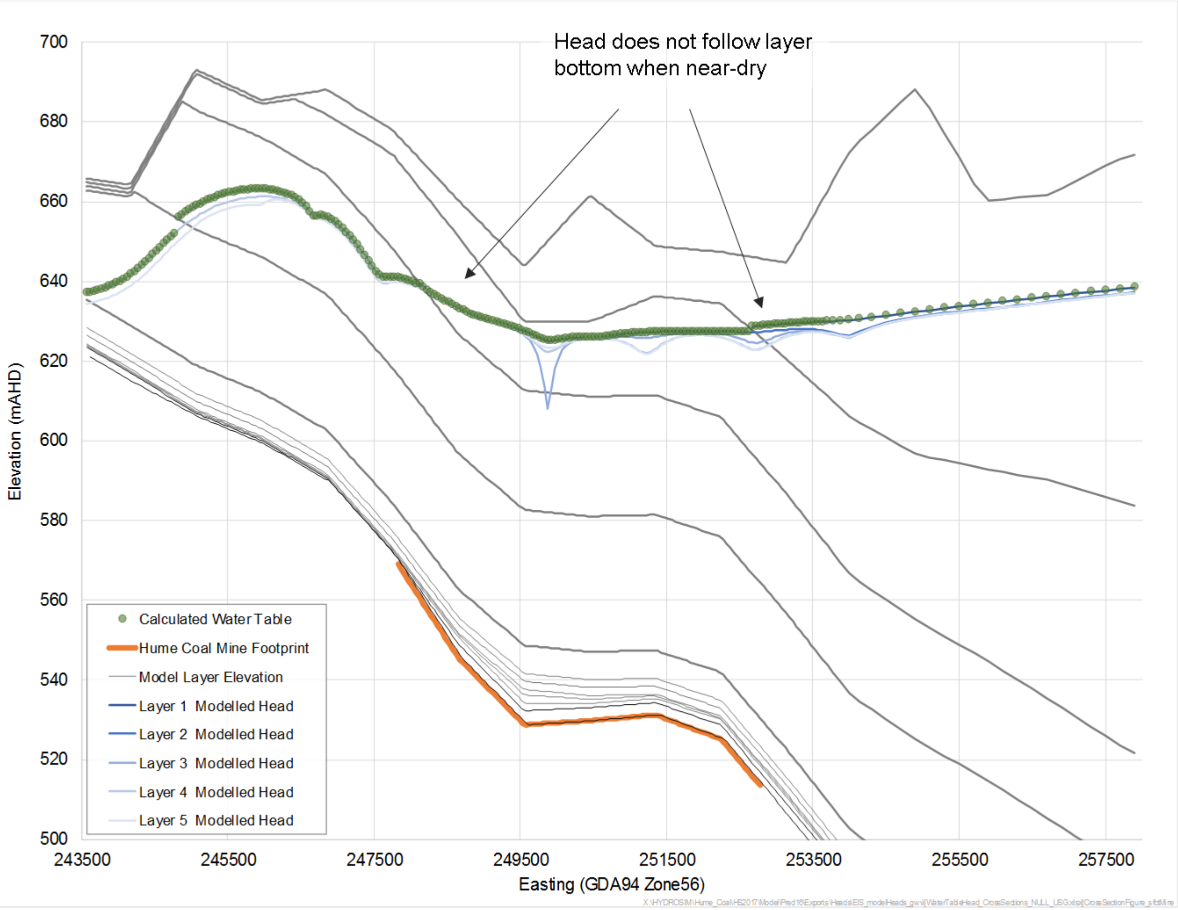


Figure B 7 Modelled head and water table elevation in mine year 17 for a 'Null' run using MODFLOW-USG Software with pseudo-soil function enabled

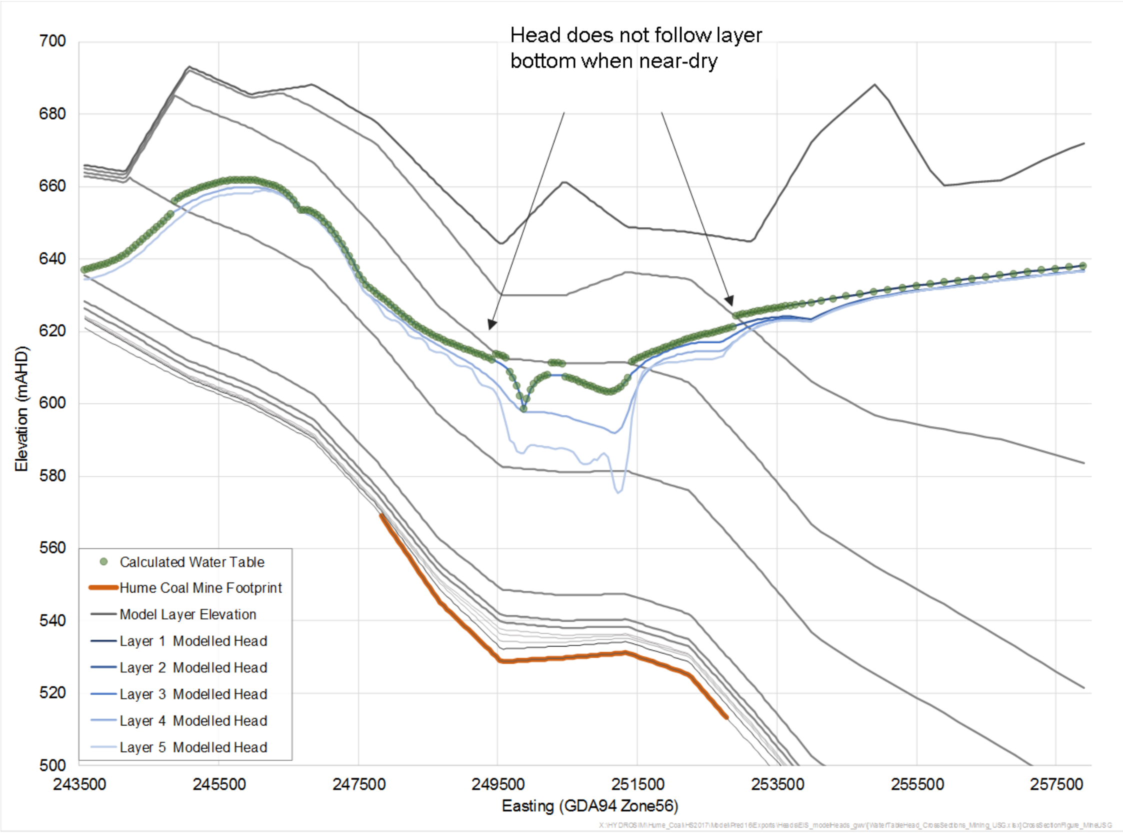


Figure B 8 Modelled head and water table elevation in mine year 17 for a Hume Coal 'mining' run using MODFLOW-USG Software with pseudo-soil function enabled

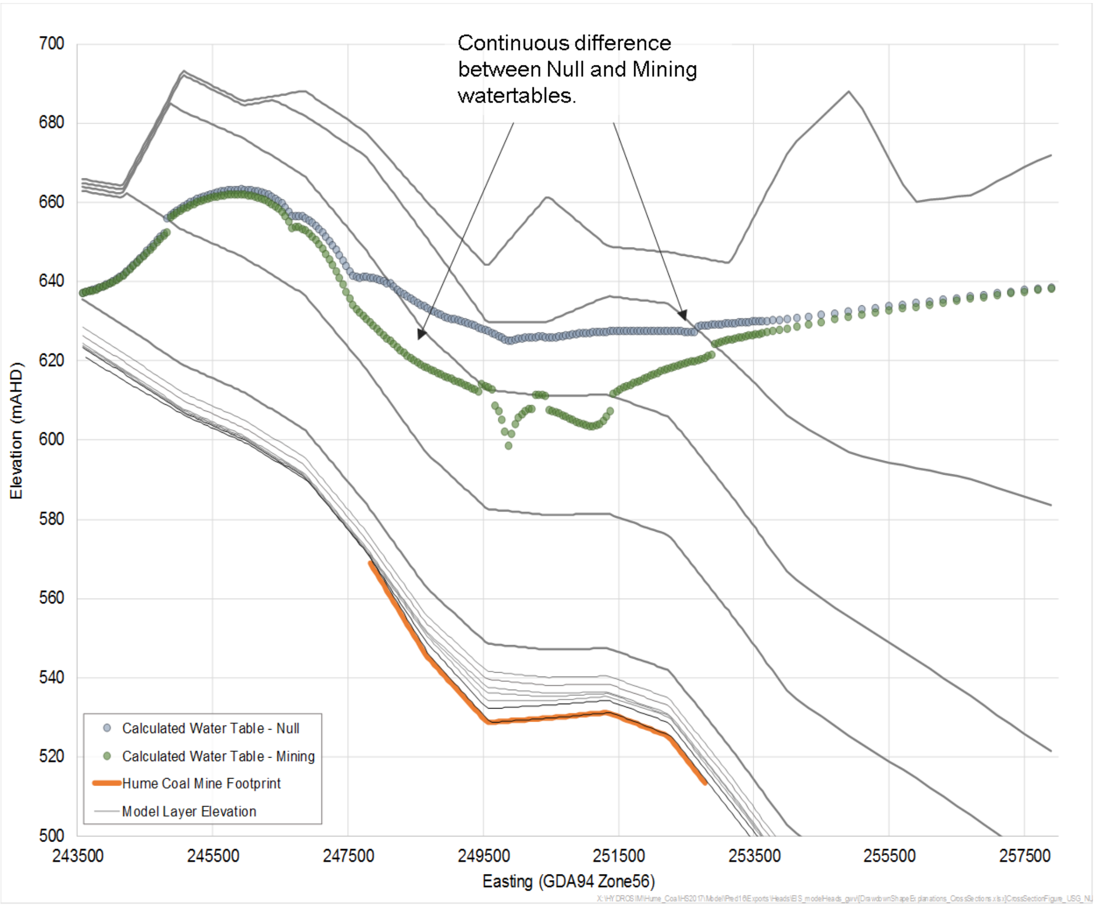


Figure B 9 Water table comparison in mine year 17 for 'Null' and 'Mining' runs using MODFLOW-USG Software with pseudo-soil function enabled

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.

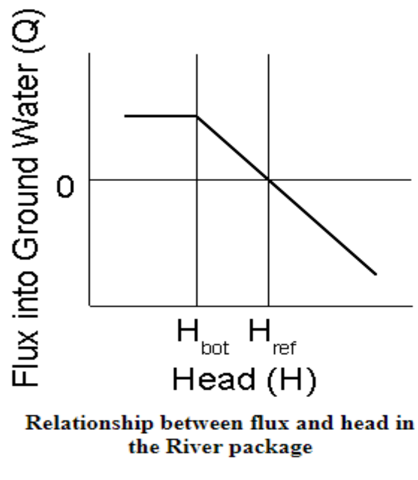


Figure C 1 Relationship between flux and head in the MODFLOW River package (USGS, 2018)

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 5th and 95th 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

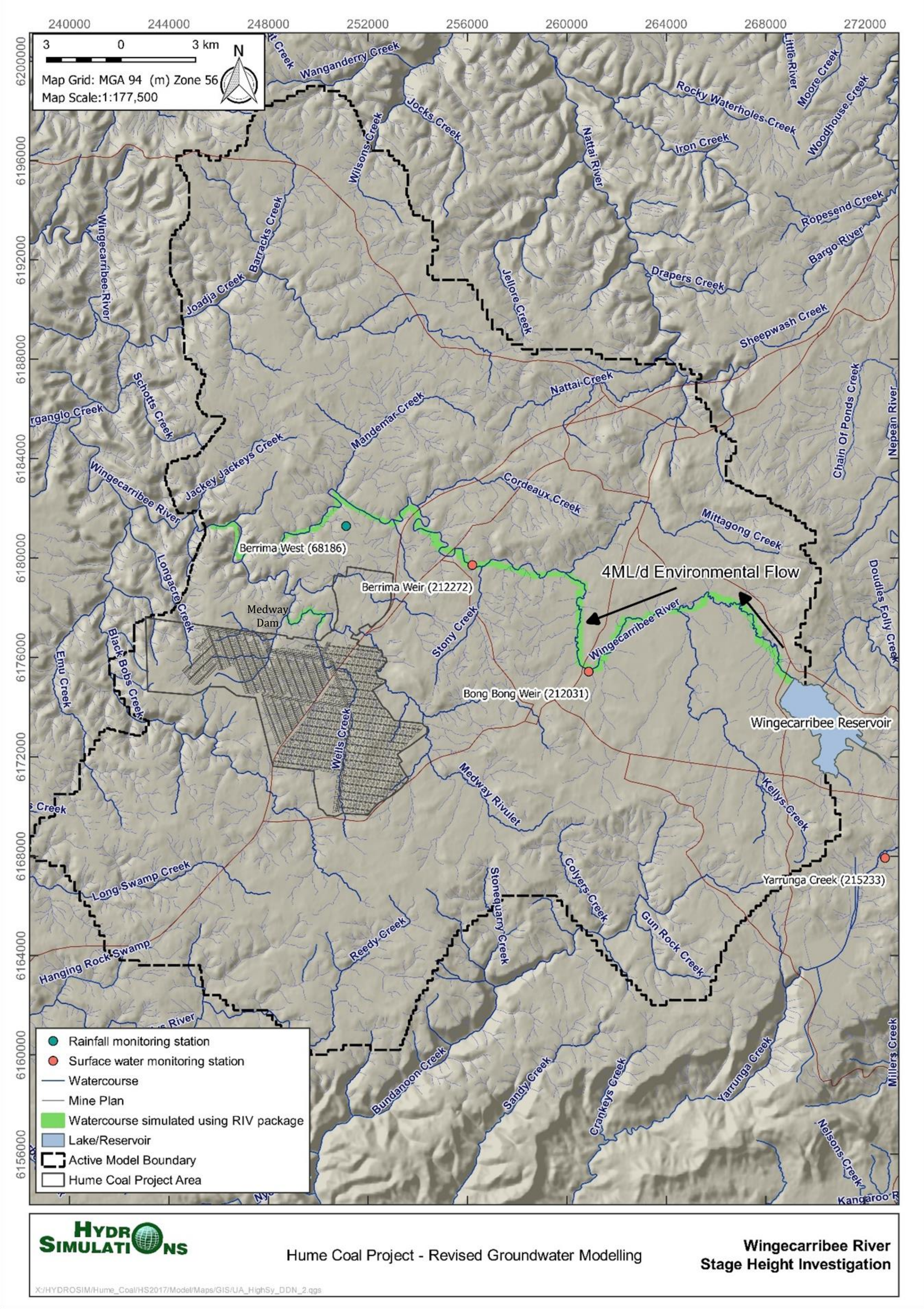


Figure C 2 Location of key features for the watercourse stage height investigation

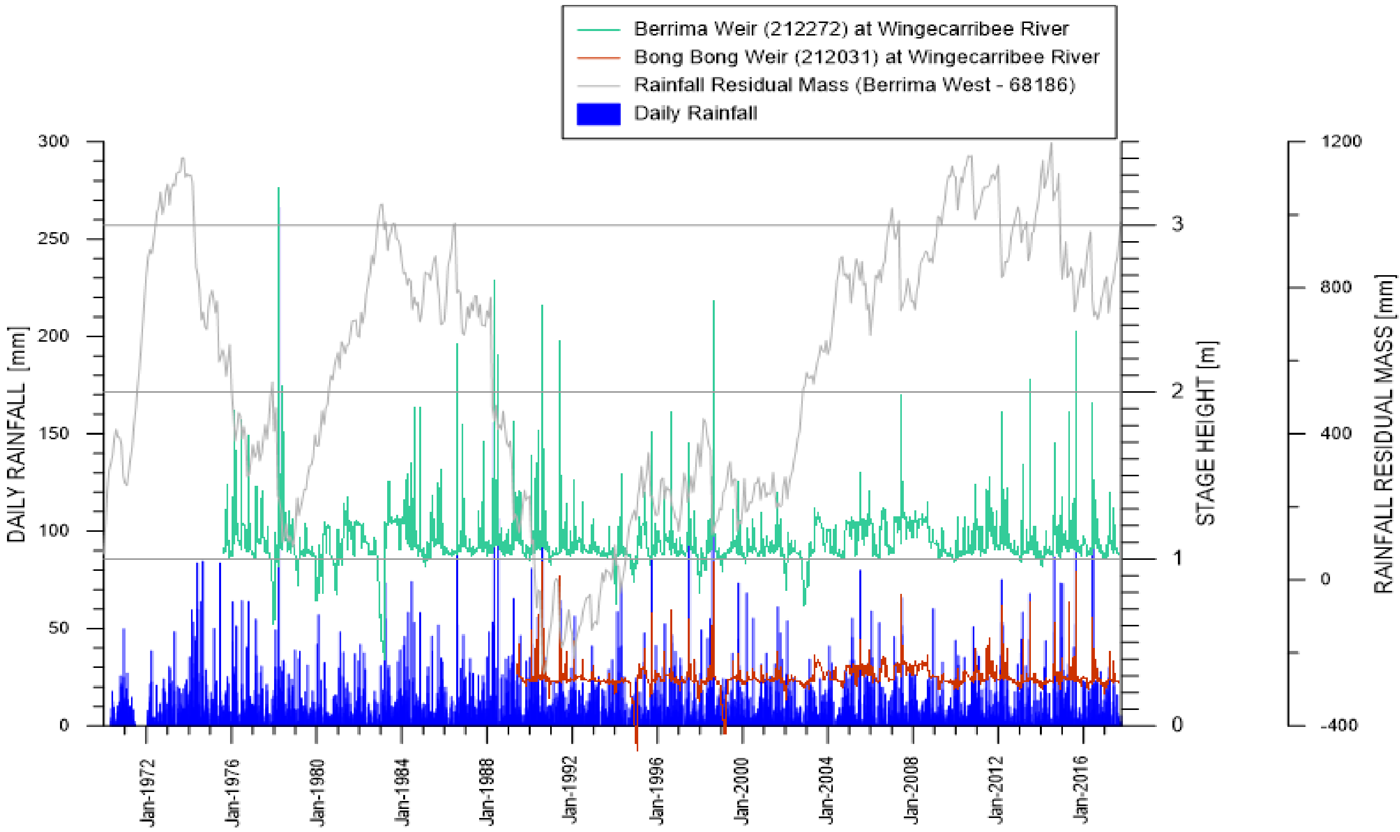


Figure C 3 Time-series stage height for Berrima Weir and Bong Bong Weir monitoring sites compared with rainfall

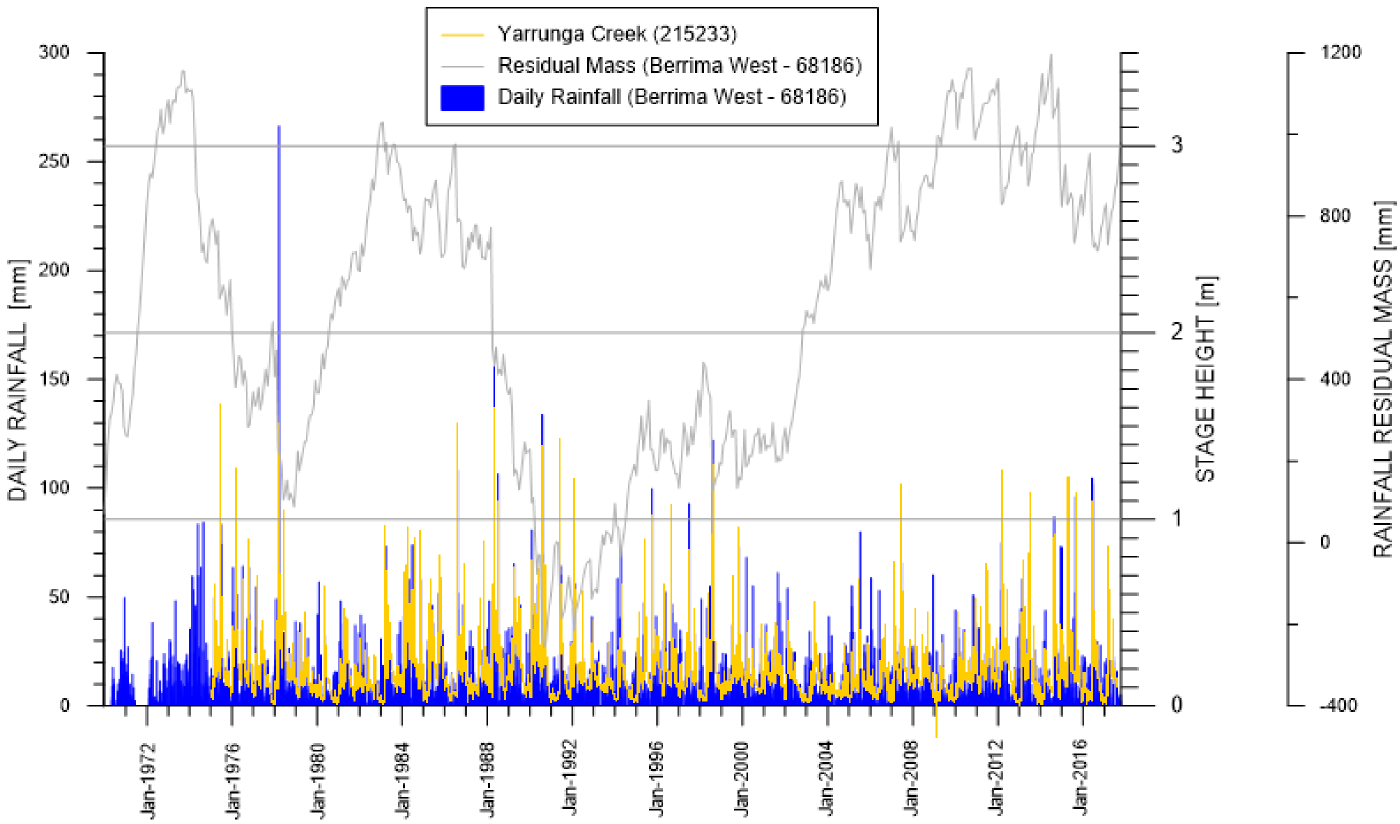


Figure C 4 -series stage height for Yarrunga Creek monitoring site compared with rainfall

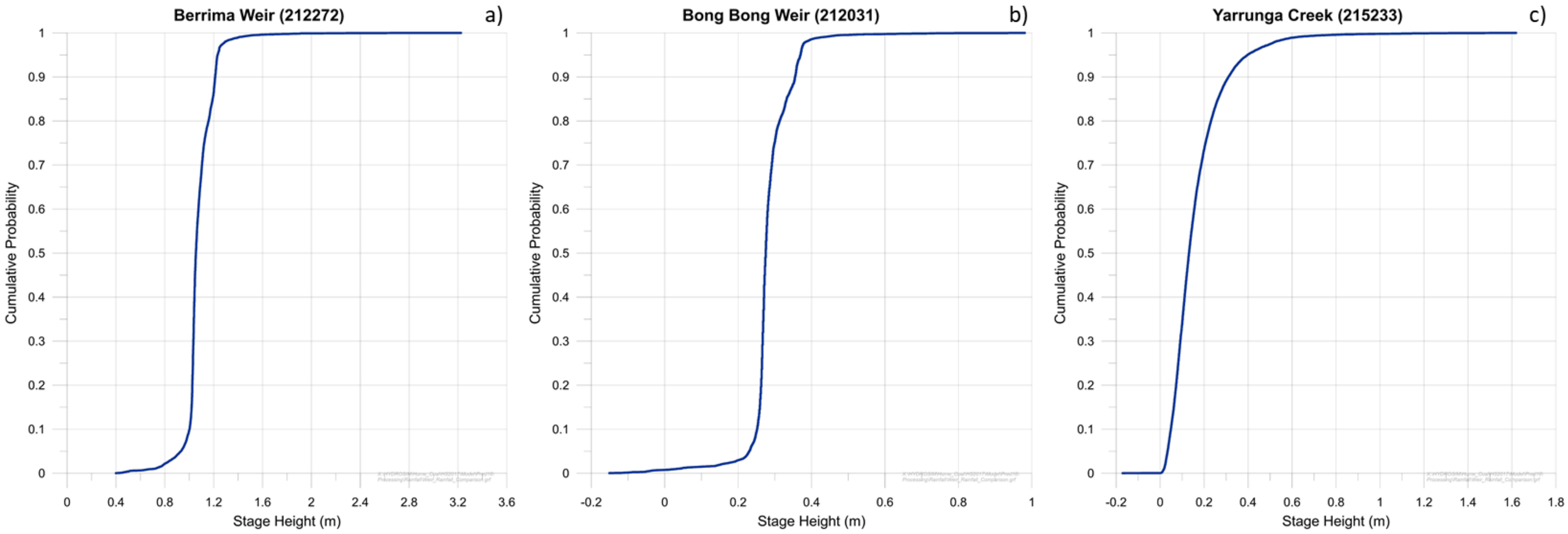


Figure C 5 Cumulative probability of stage height at: a) Berrima Weir, b) Bong Bong Weir, c) Yarrunga Creek

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.

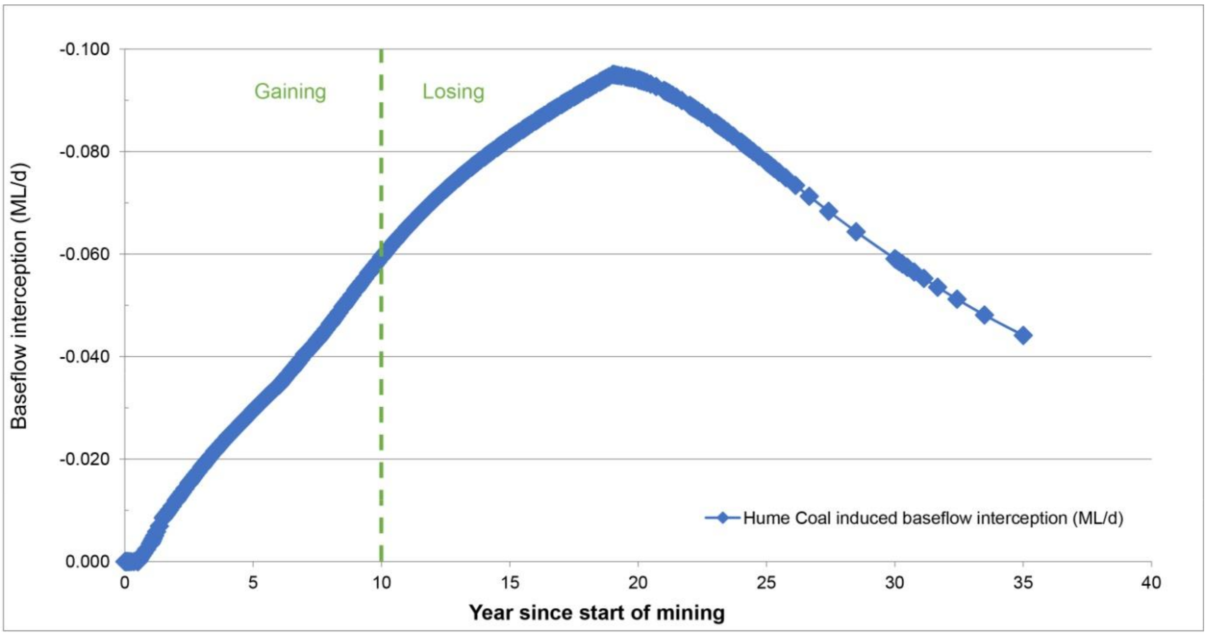
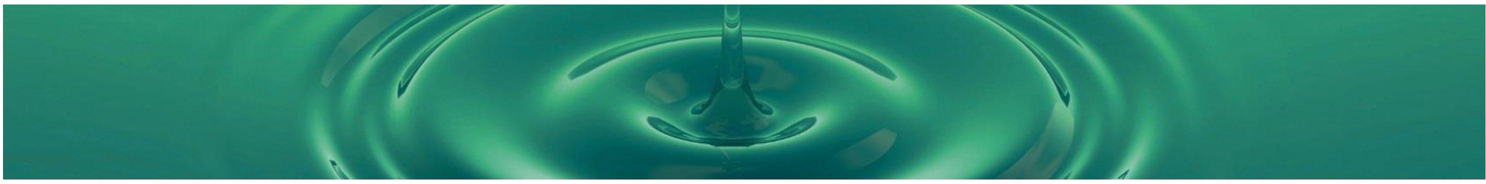


Figure D 1 Hume Coal induced baseflow interception at Medway Dam



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

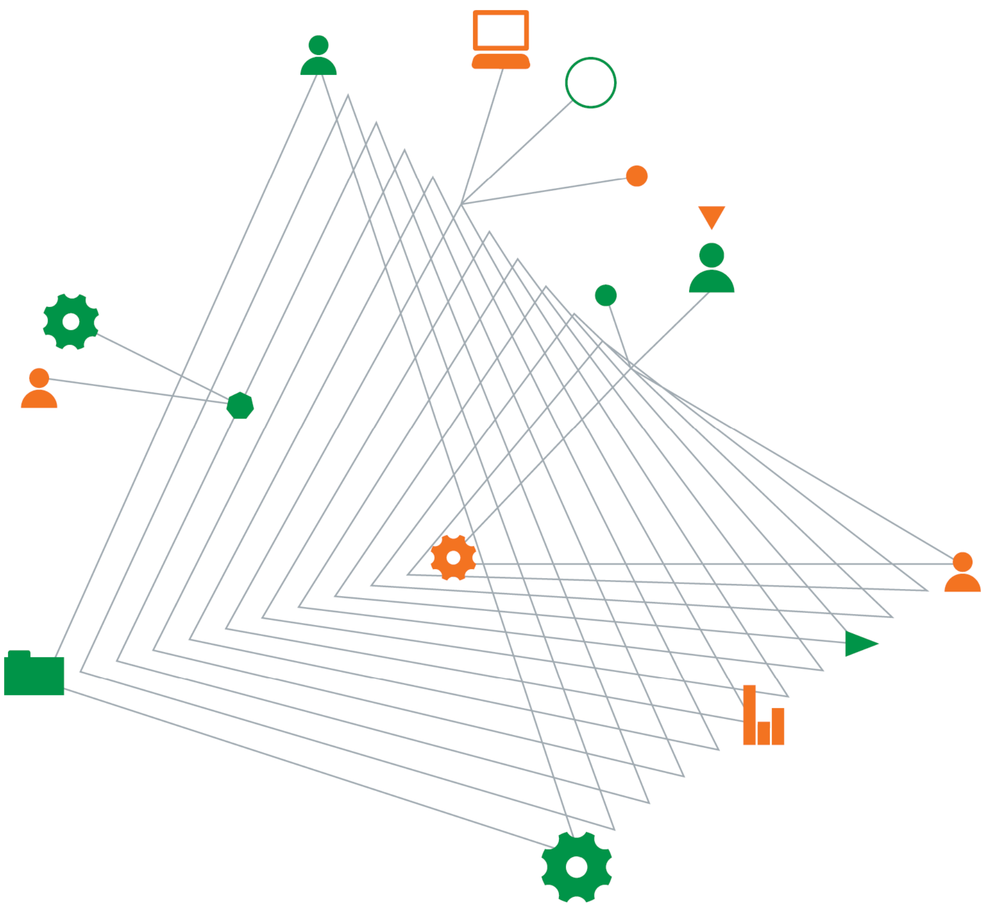
coffey
A TETRA TECH COMPANY

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

Hume Coal Project

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17 November 2016

Document authorisation

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For and on behalf of Coffey

Paul Tammetta
Associate Subsurface Hydrologist

Quality Information

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Final	GEOTLCOV25281AB-ACA	17 Nov 2016	PT	BR	PT

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Table of Contents

Tables

Figures

Drawings

Appendices

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.

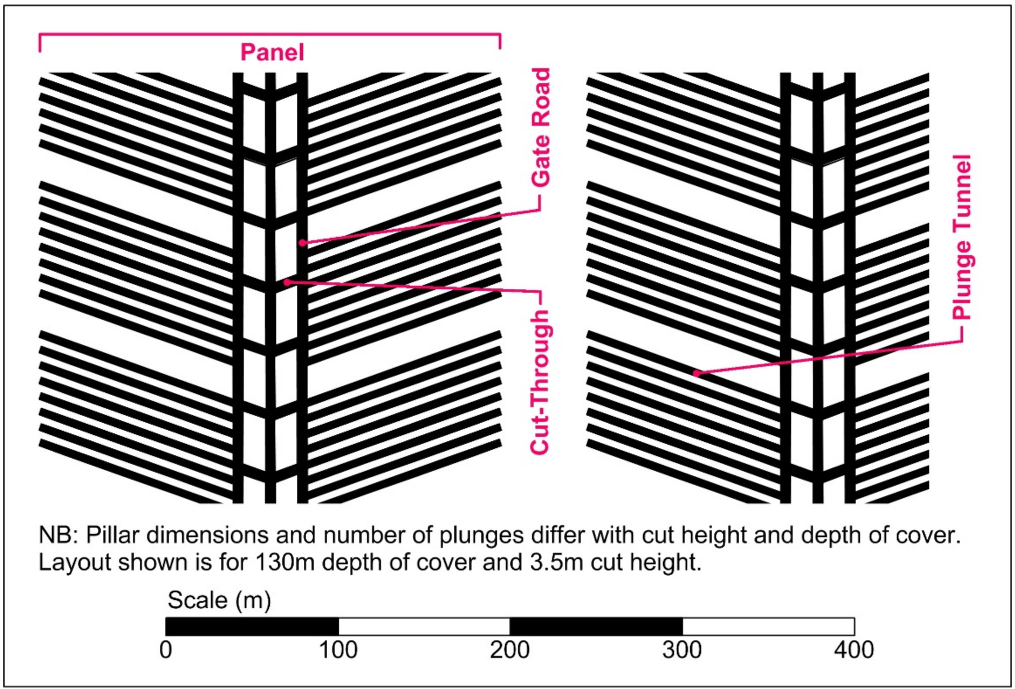

Figure 1.1. Detail of mine openings for the first workings mining method. Black areas indicate removed coal.

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.

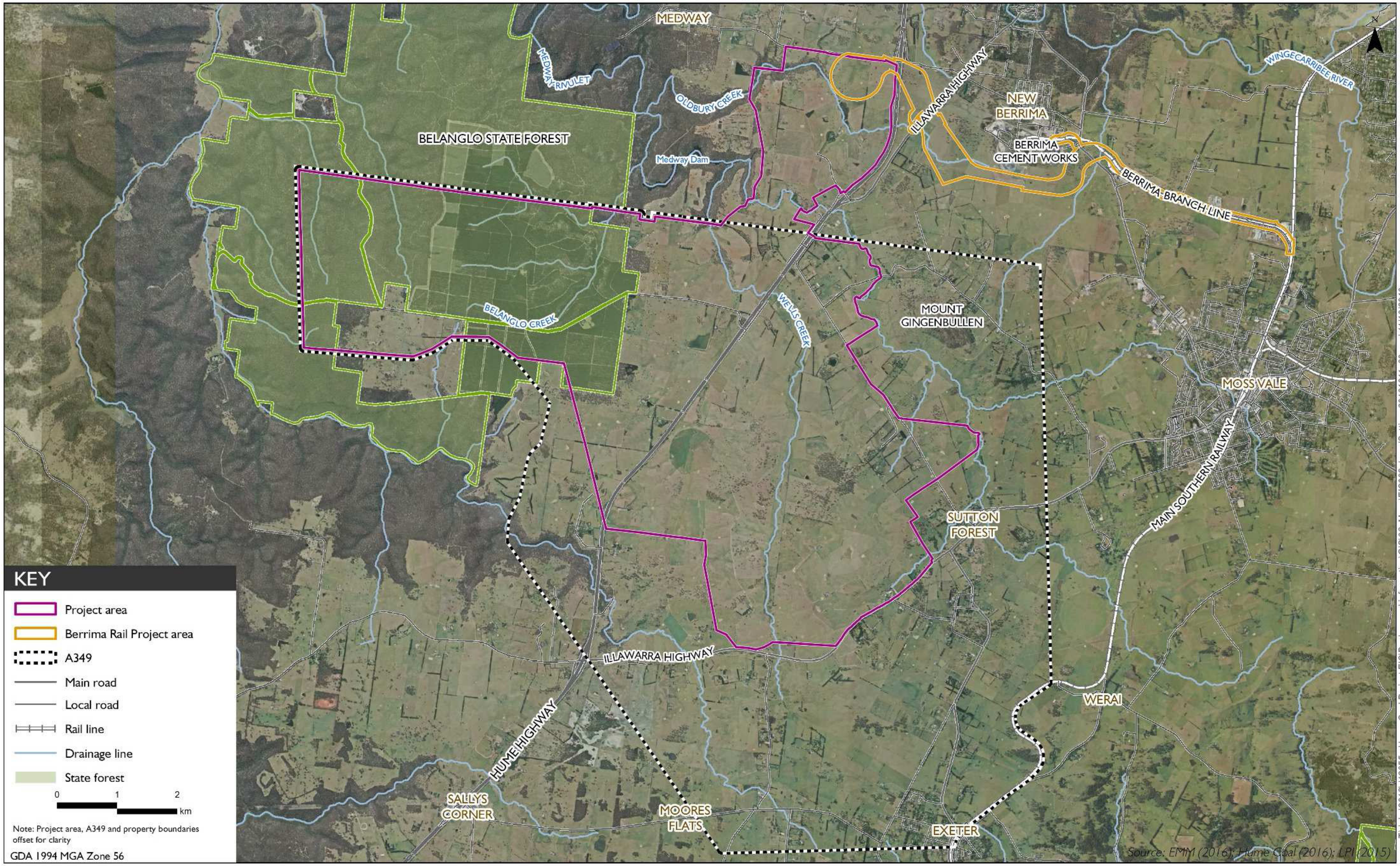

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Figure 1.2. Local context

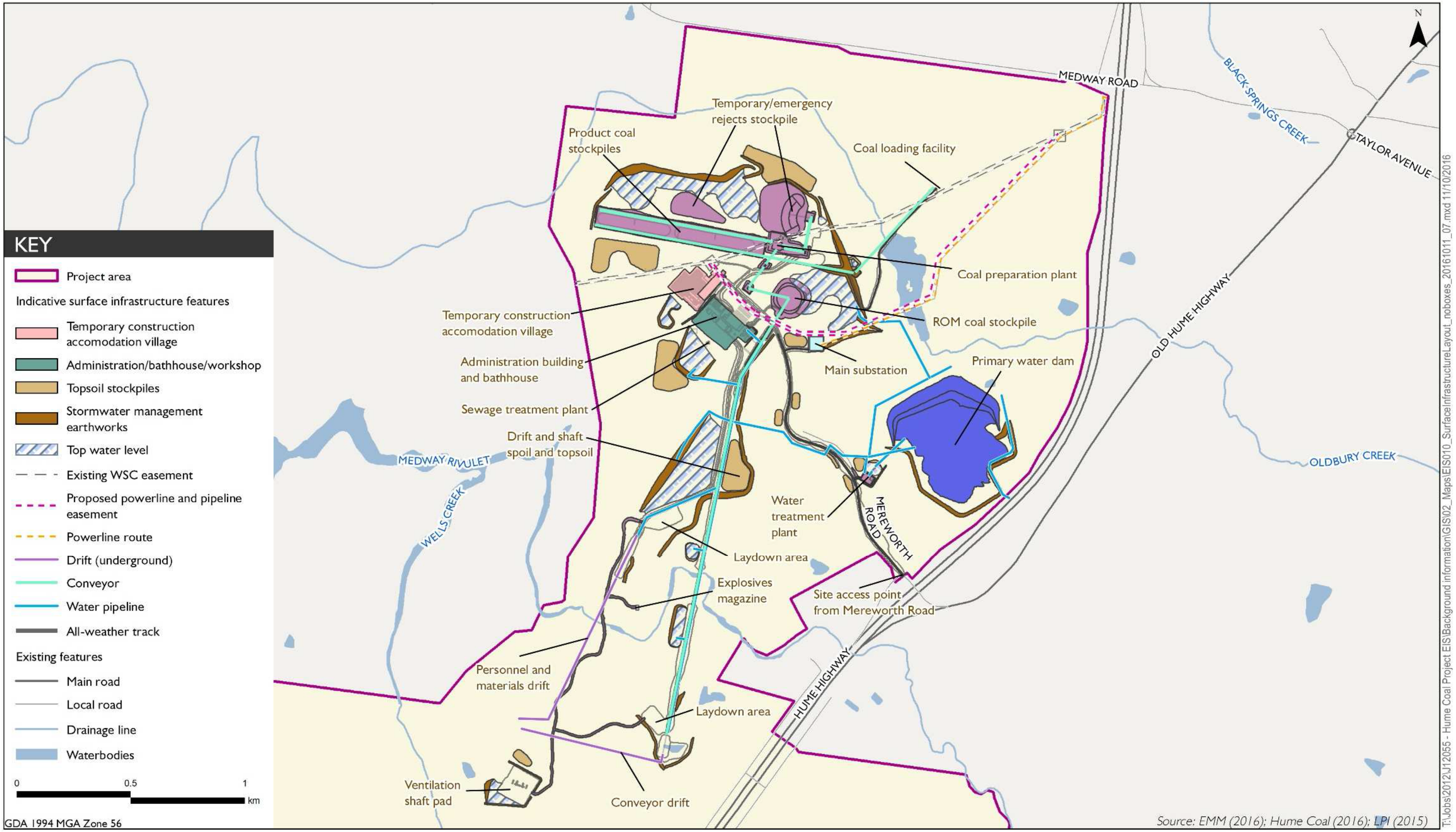


Figure 1.3. Indicative surface infrastructure layout.

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.

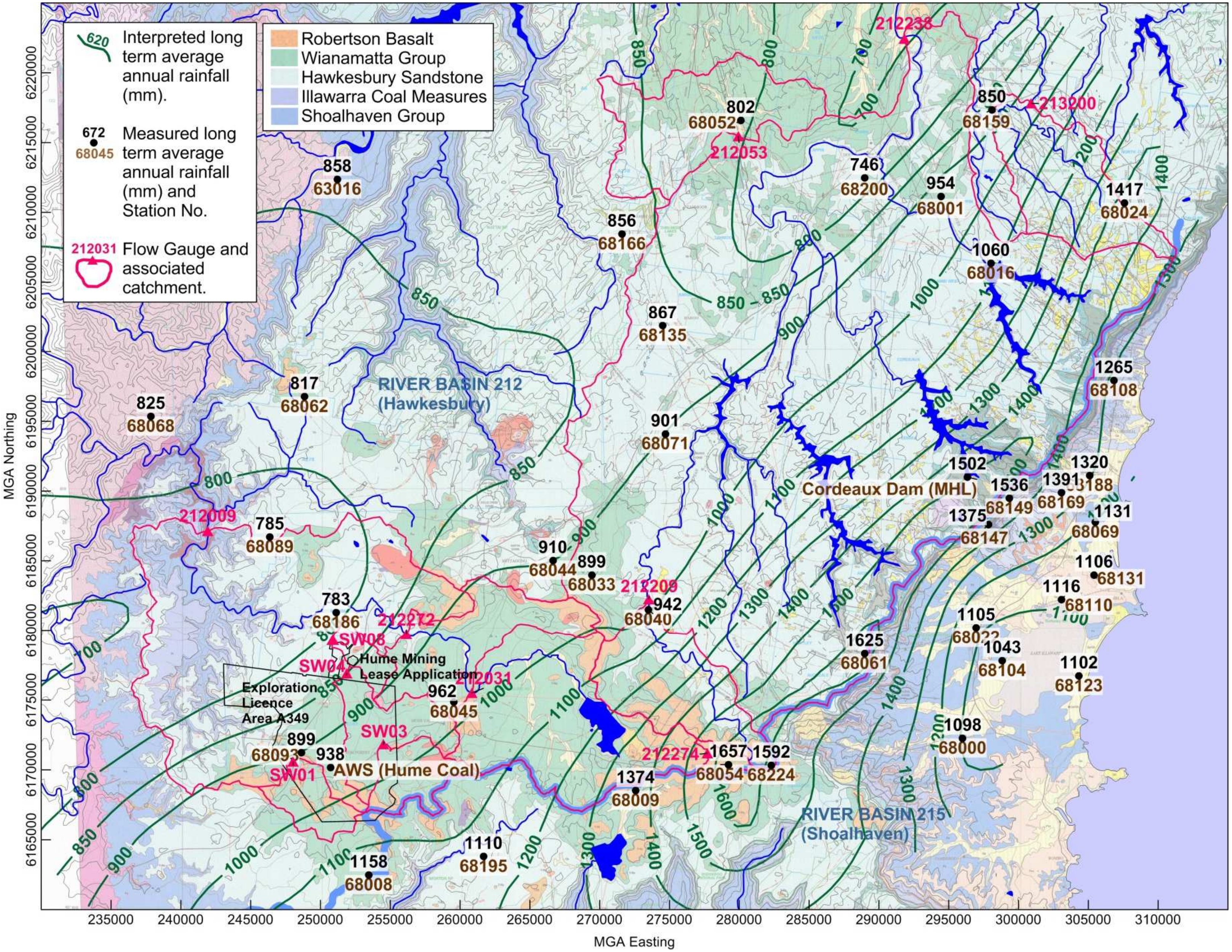


Figure 2.1. Interpreted pattern of average annual rainfall.

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.

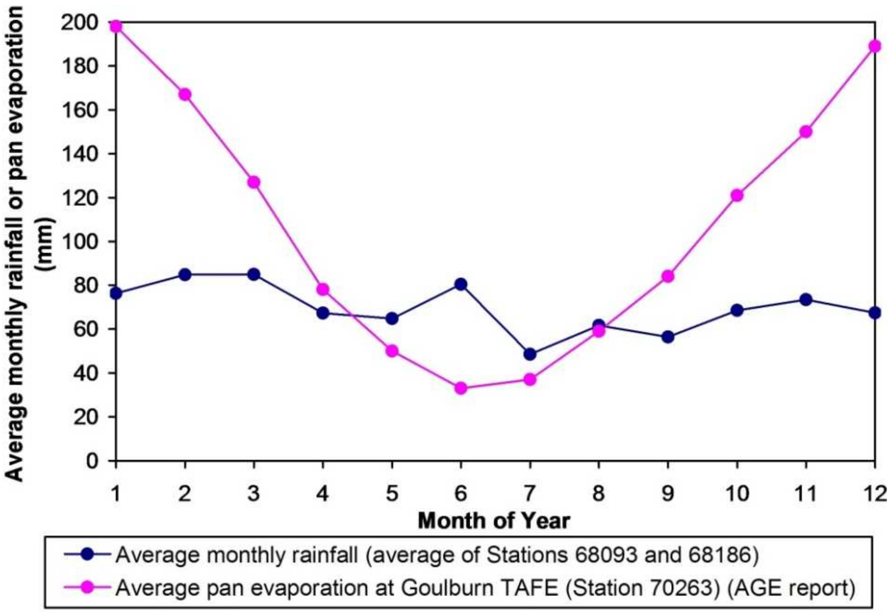


Figure 2.2. Estimated average monthly rainfall in the mine lease and average monthly pan evaporation at Goulburn.

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.

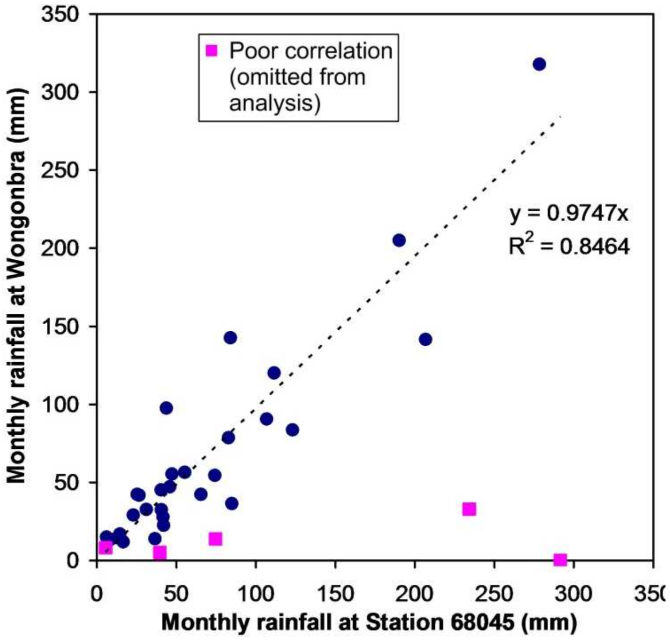


Figure 2.3. Correlation of monthly rainfall between Station 68045 (Moss Vale) and Hume's site gauge at Wongonbra.

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).

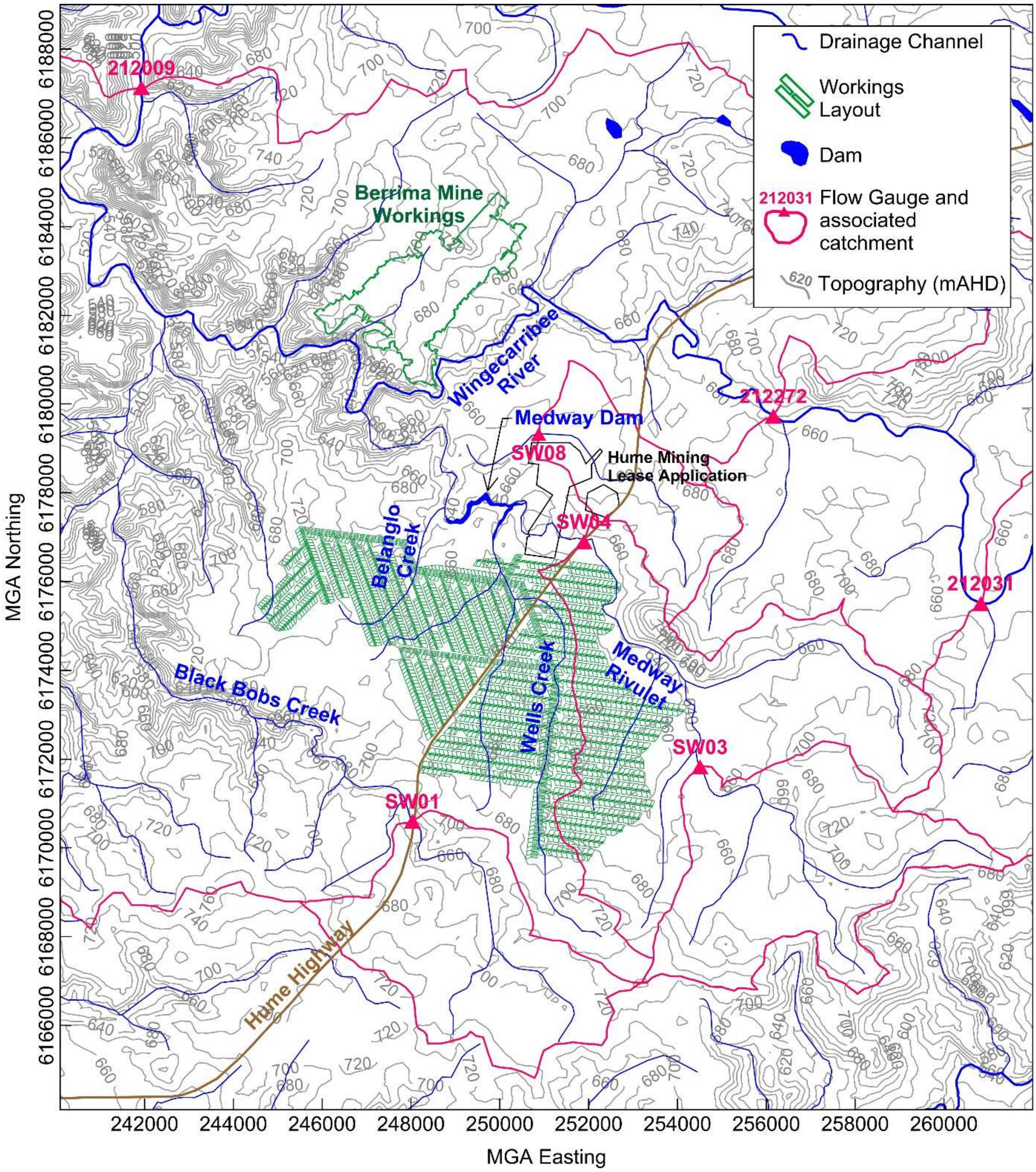


Figure 3.1. Detail of surface drainage over the mine lease.

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.

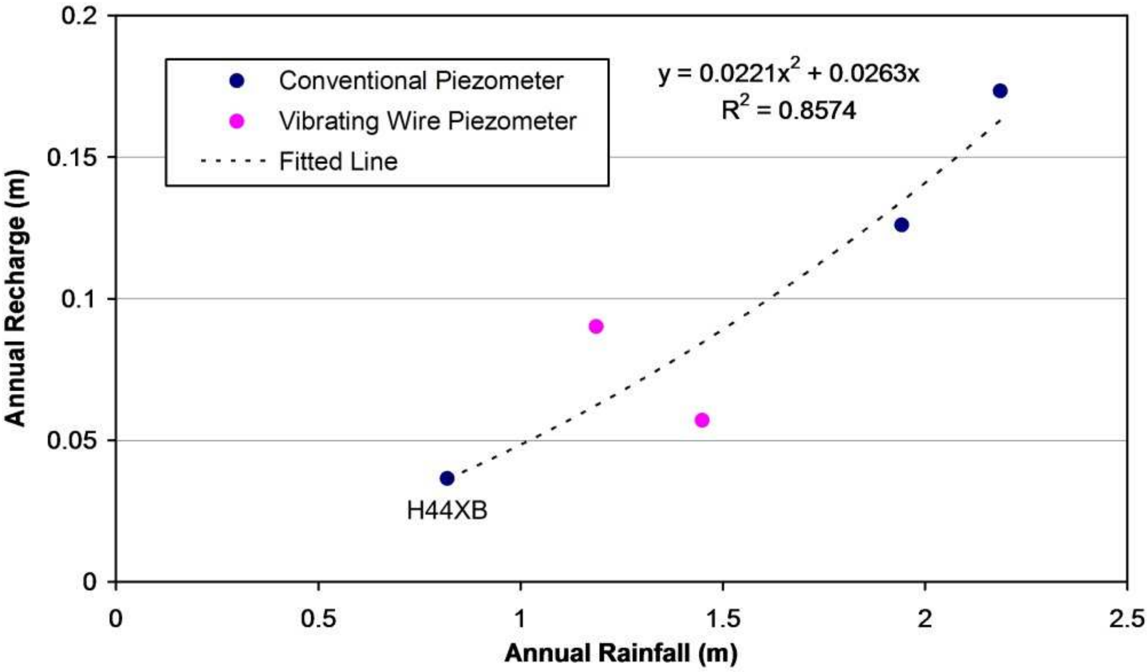


Figure 3.2. Interpreted recharge to the water table for Hawkesbury Sandstone overlain by residual soil, in the Southern Highlands.

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.

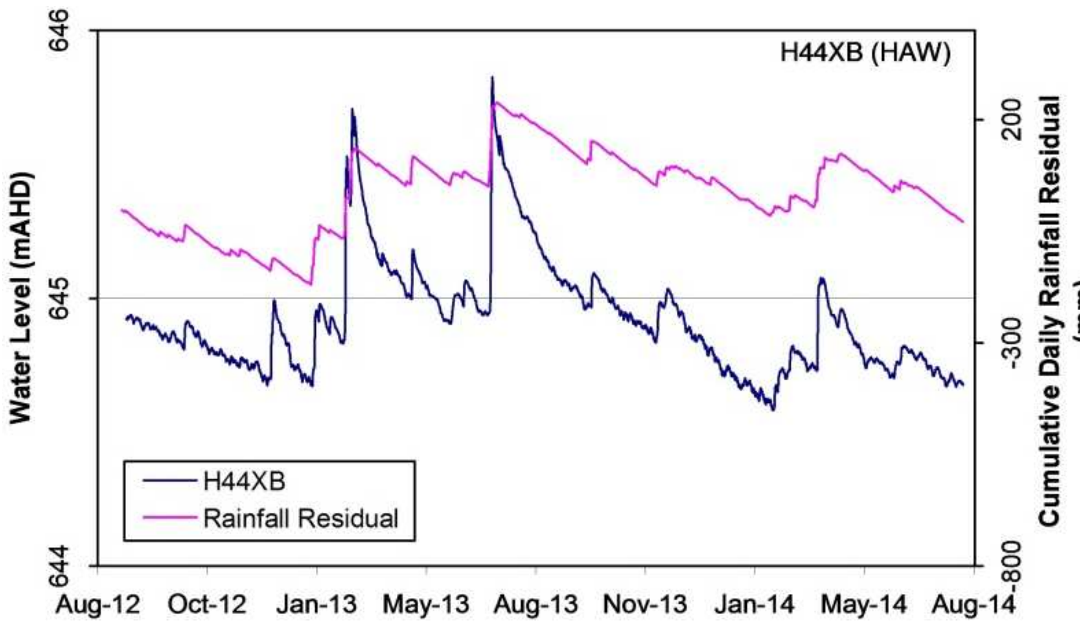


Figure 3.3. Response to rainfall at Hume Monitoring Piezometer H44XB.

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 (km^2)	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.

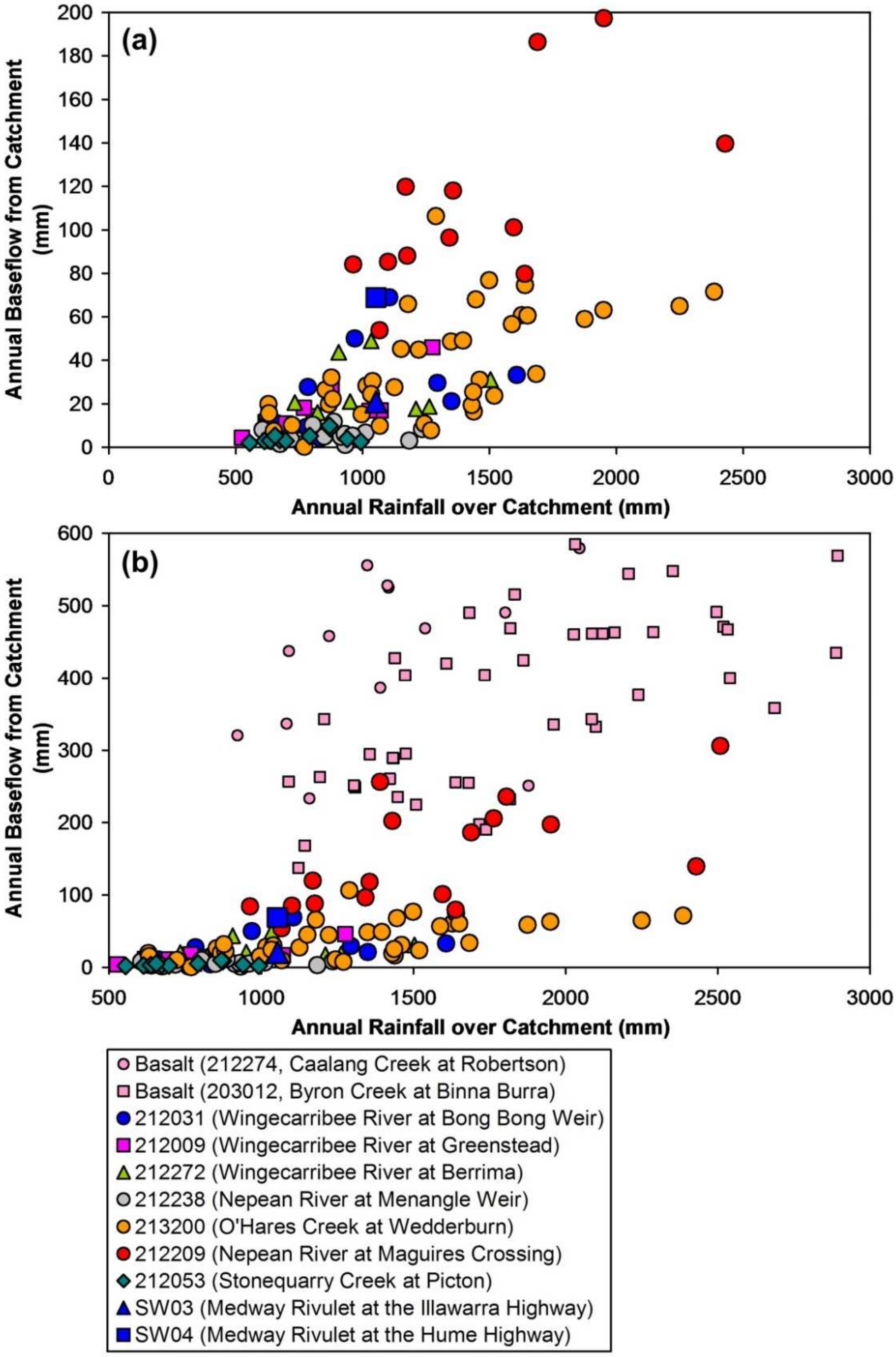


Figure 3.4. Annual estimated baseflow for (a) catchments not dominated by basalt, and (b) all analysed catchments.

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.

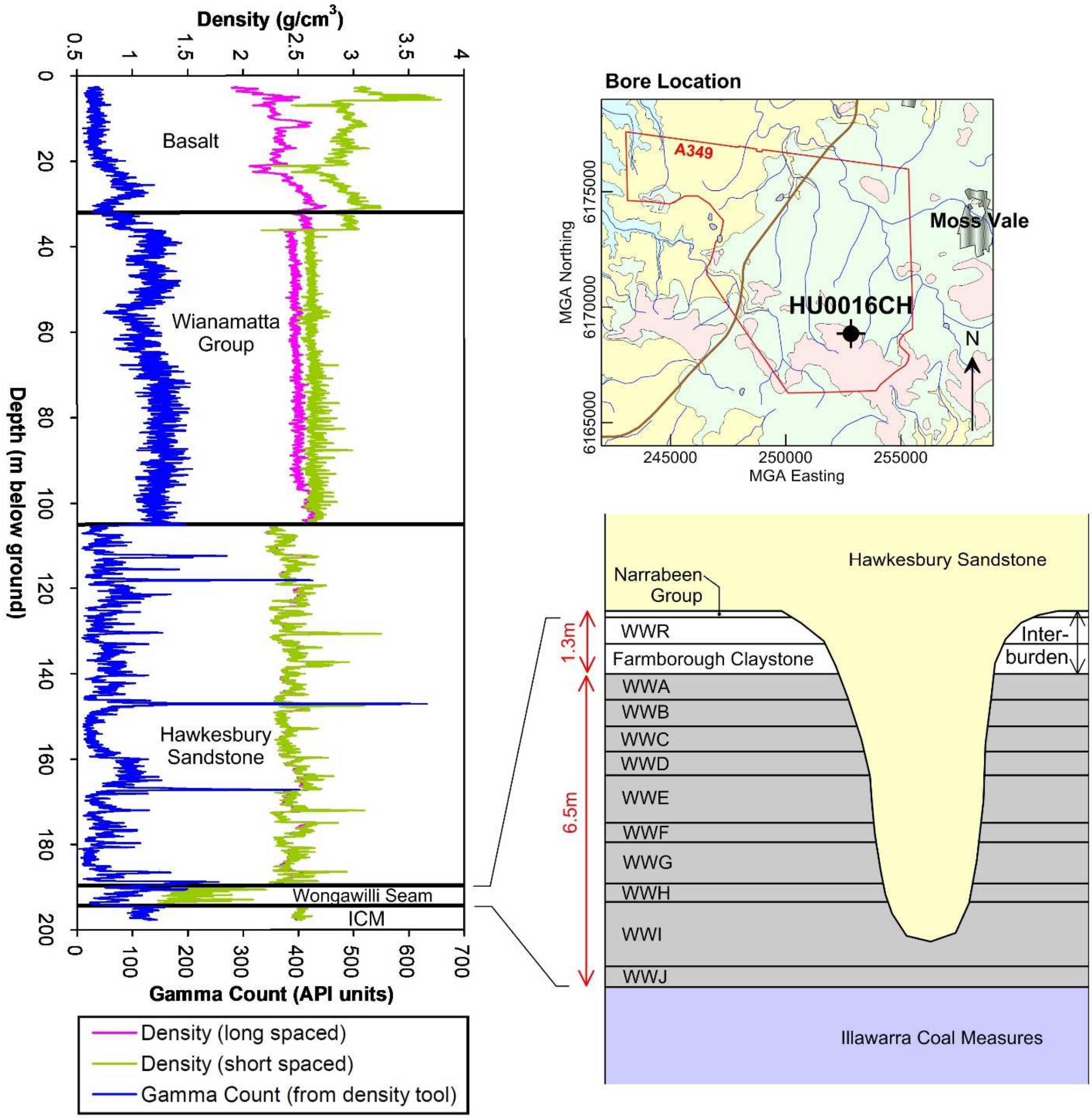


Figure 4.1. Stratigraphy and geophysical measurements for bore HU0016CH (left). The seam detail is shown to the right (colouring denotes adopted hydrostratigraphic subdivisons). Thicknesses are averages over the mine lease.

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.

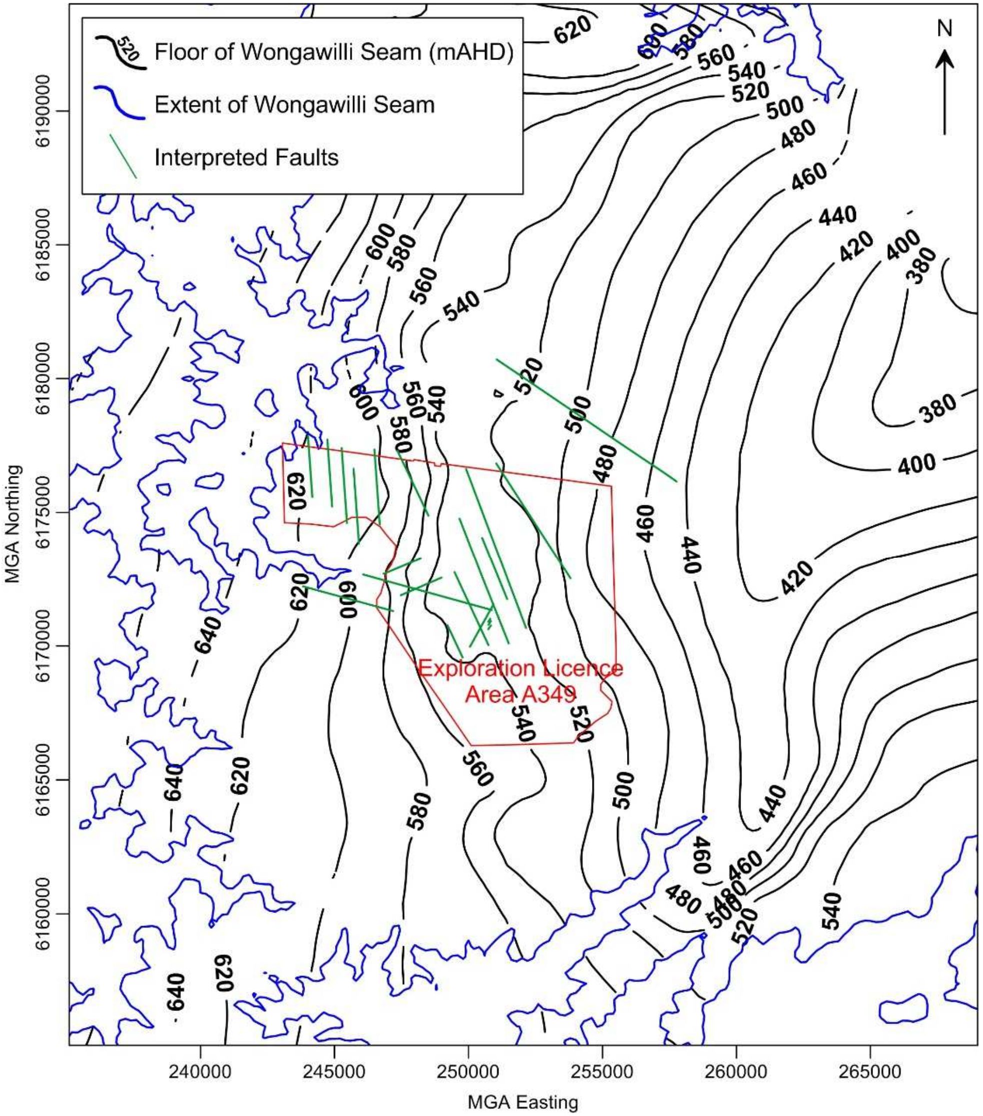


Figure 4.2 (left). Structure contours for the base of the Wongawilli Seam, and interpreted faults.

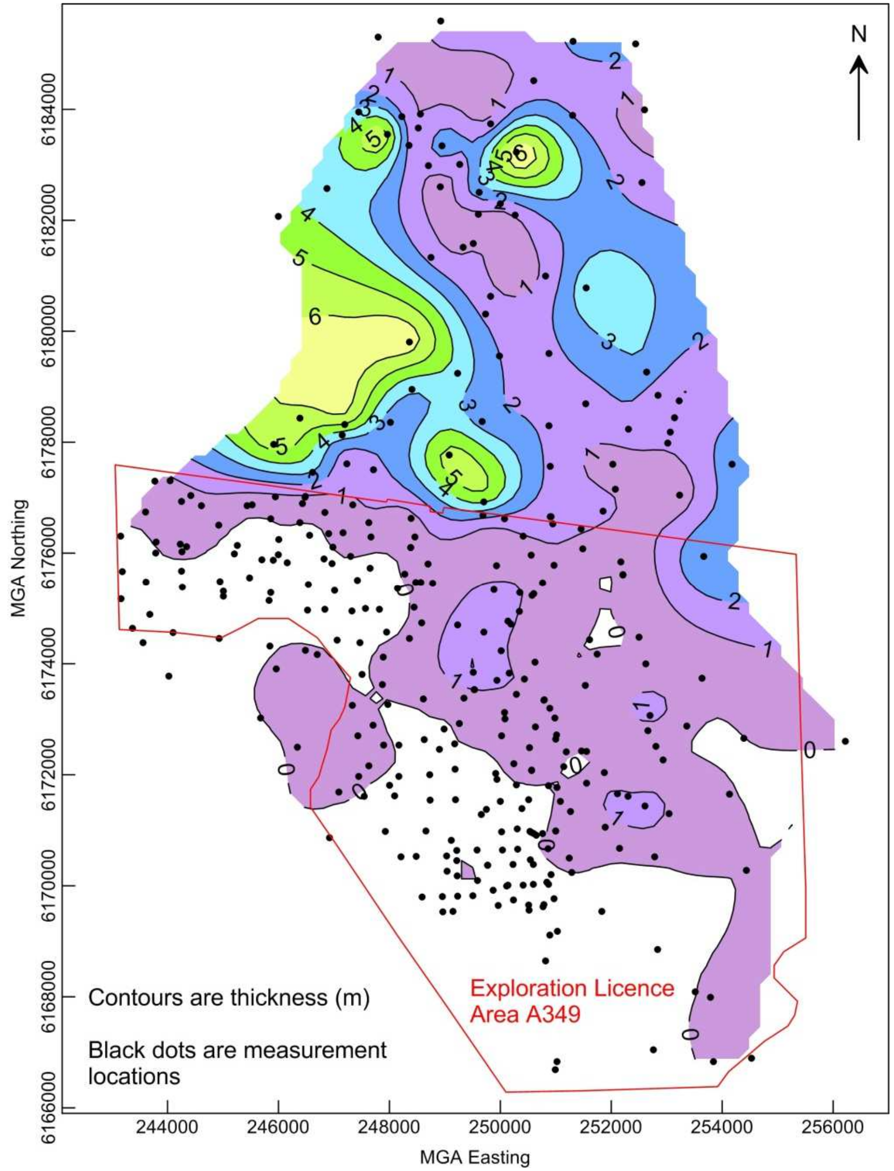


Figure 4.3 (right). Interburden thickness.

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).

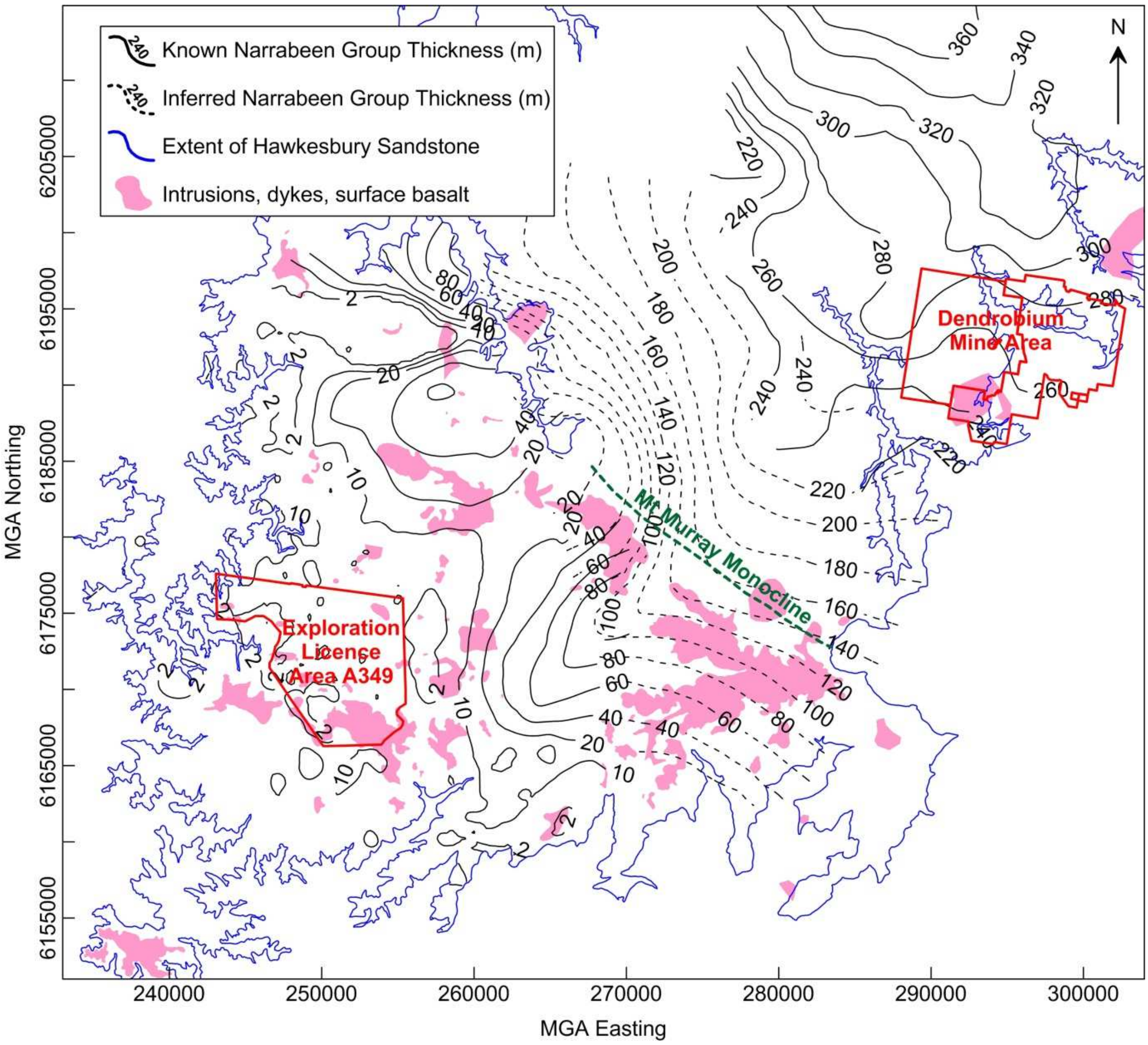


Figure 4.4. Interpreted regional thickness of the Narrabeen Group, from the quality control assessment.

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.

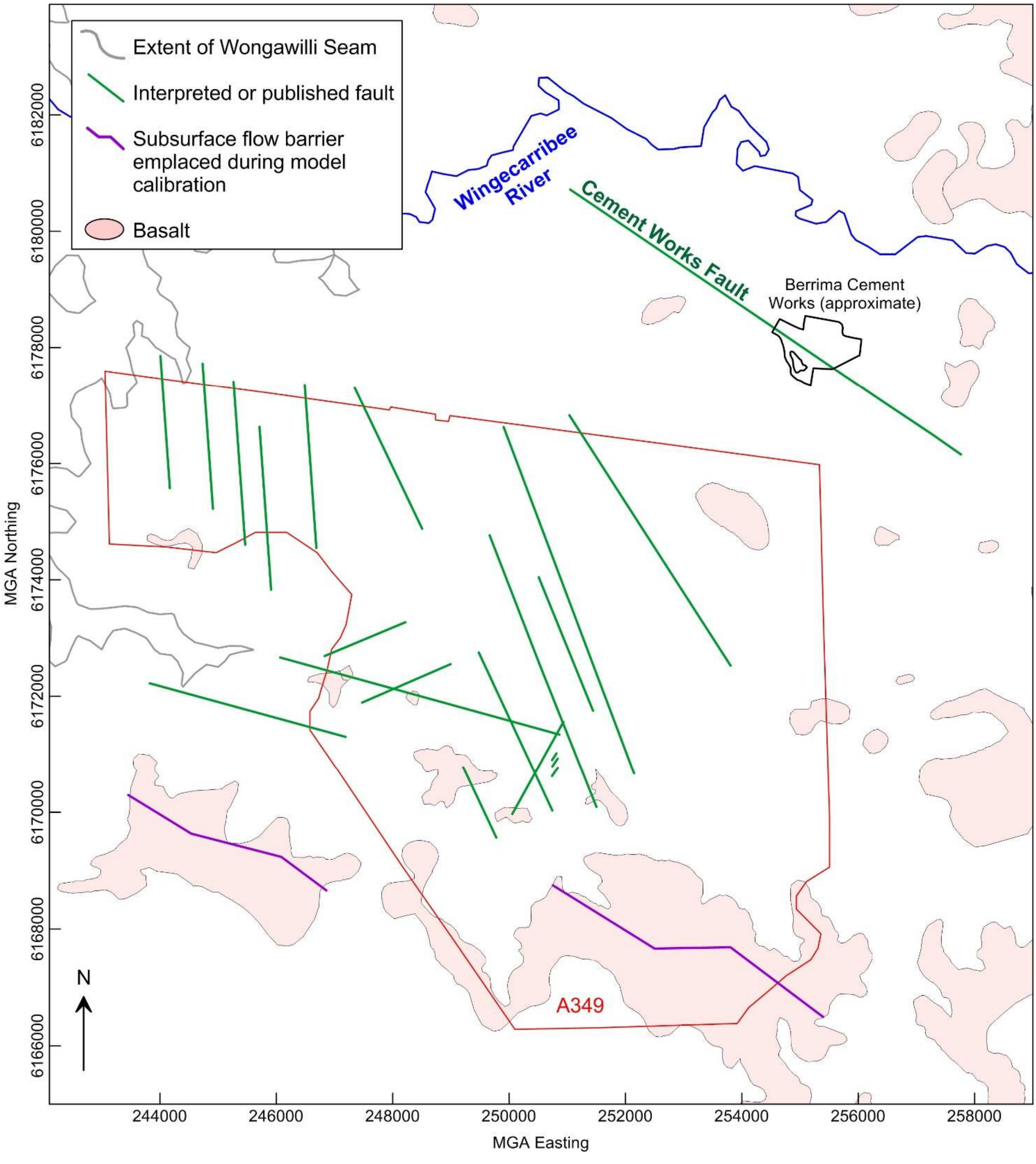


Figure 4.5. Interpreted and published faults in the Hume area, and subsurface barriers to groundwater flow interpreted during model calibration.

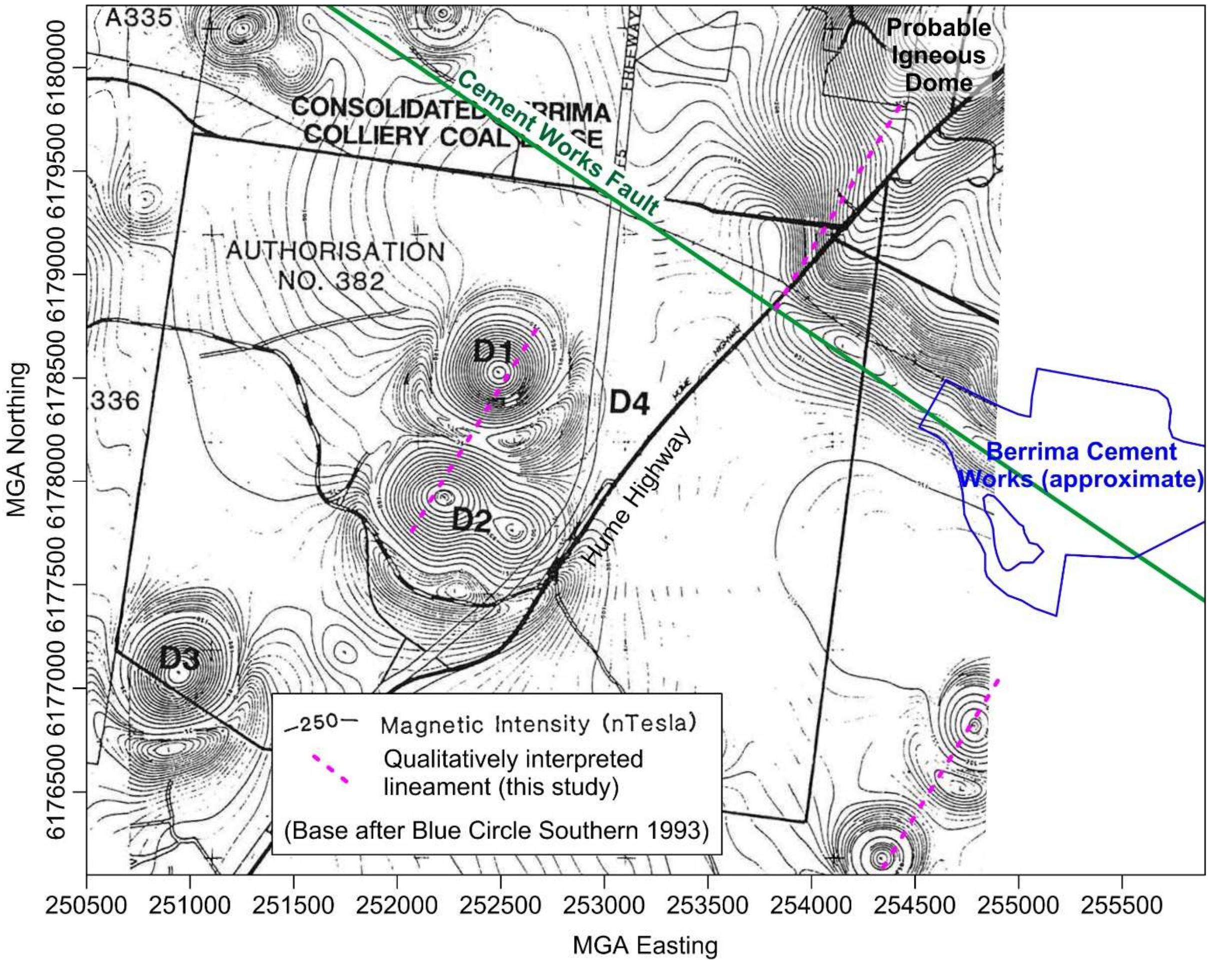


Figure 4.6. Magnetic field intensity compared to the Cement Works Fault (base after BCSC 1993).

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.

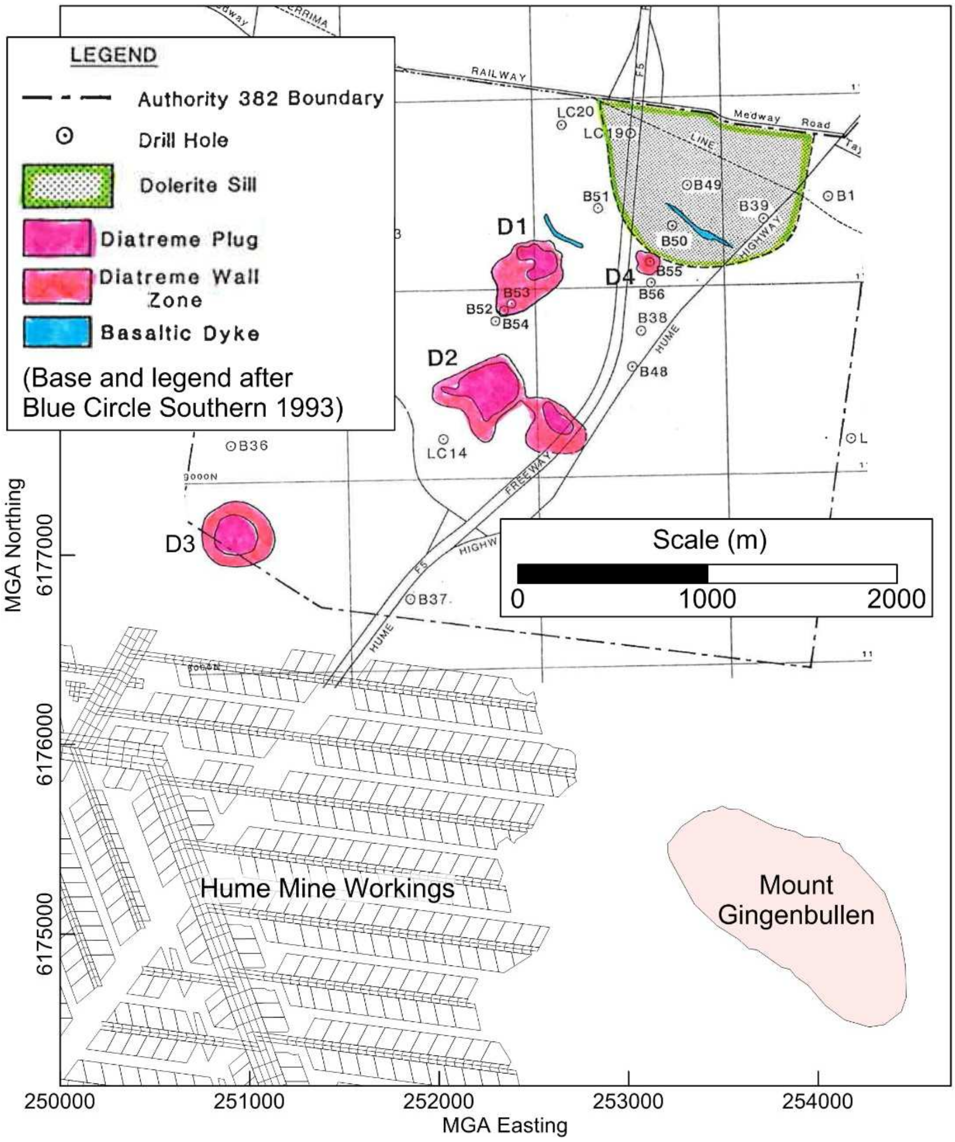


Figure 4.7. Known intrusions close to the proposed Hume mine workings (base and legend after BCSC 1993).

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.

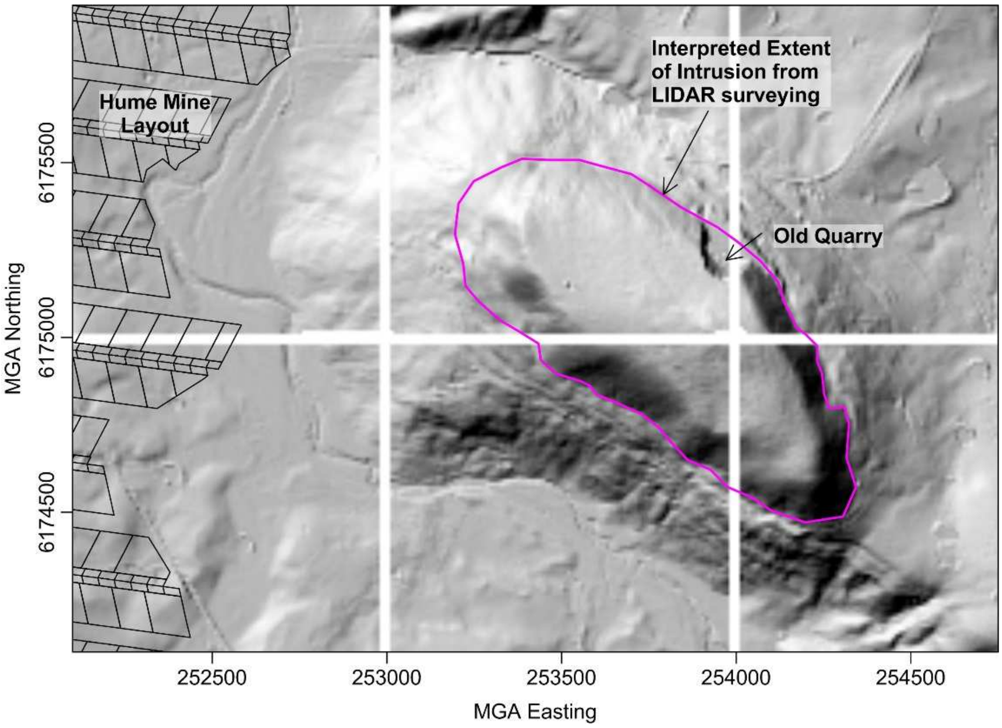


Figure 4.8. The Mt Gingenbullen intrusion as revealed by LIDAR topographic survey.

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.

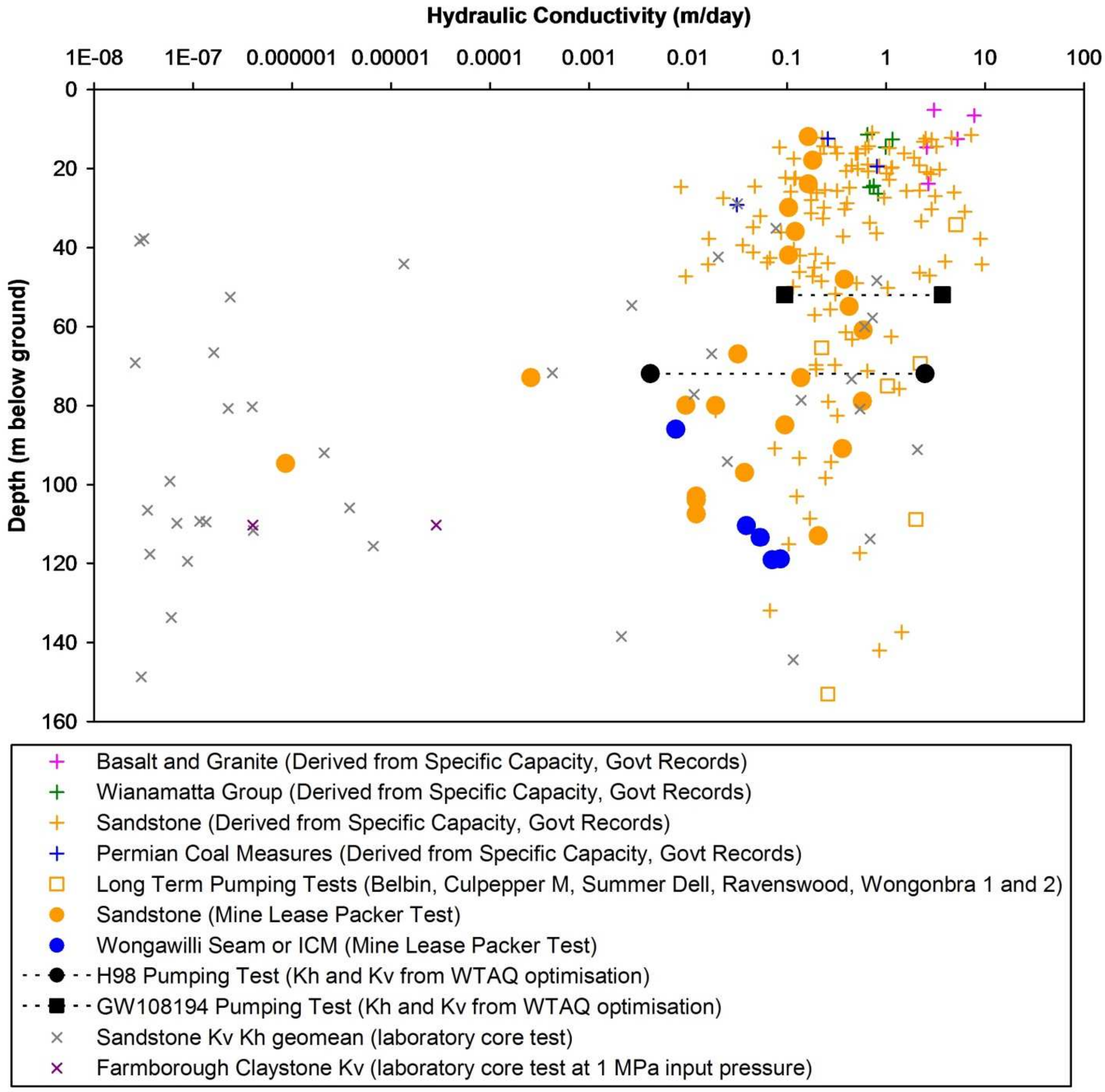


Figure 5.1. K database for the Hume area.

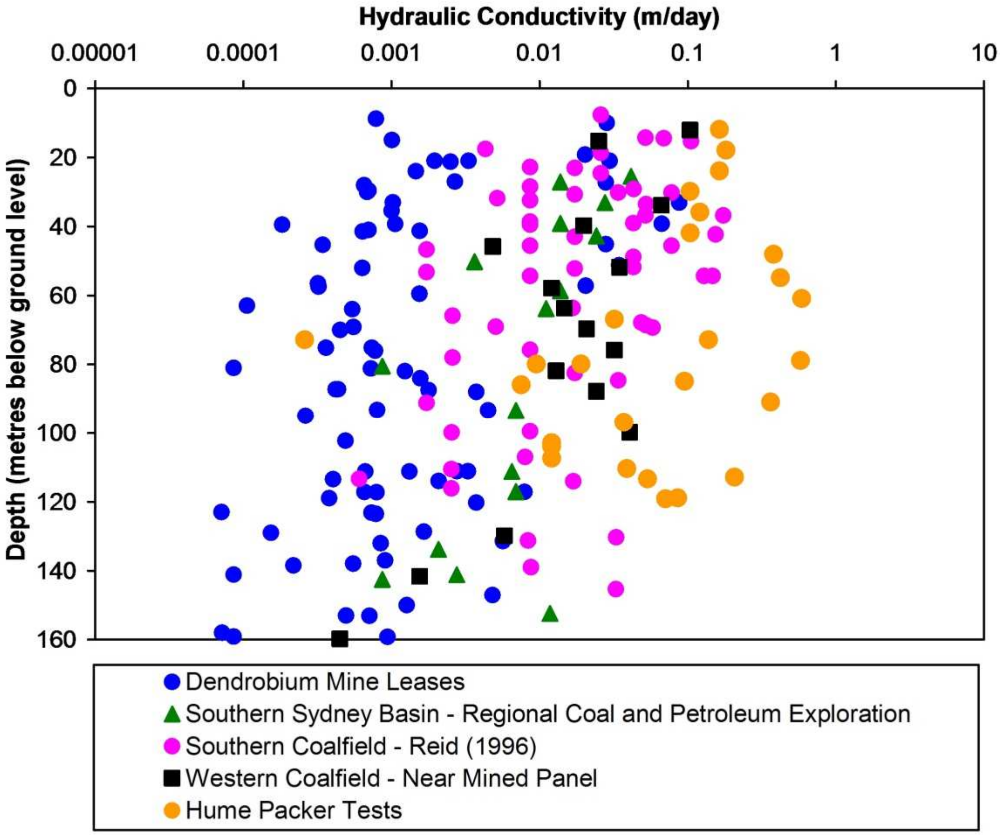


Figure 5.2. Packer test K distributions for the regional Southern Coalfield and the Dendrobium mine leases, compared to Hume area packer tests.

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).

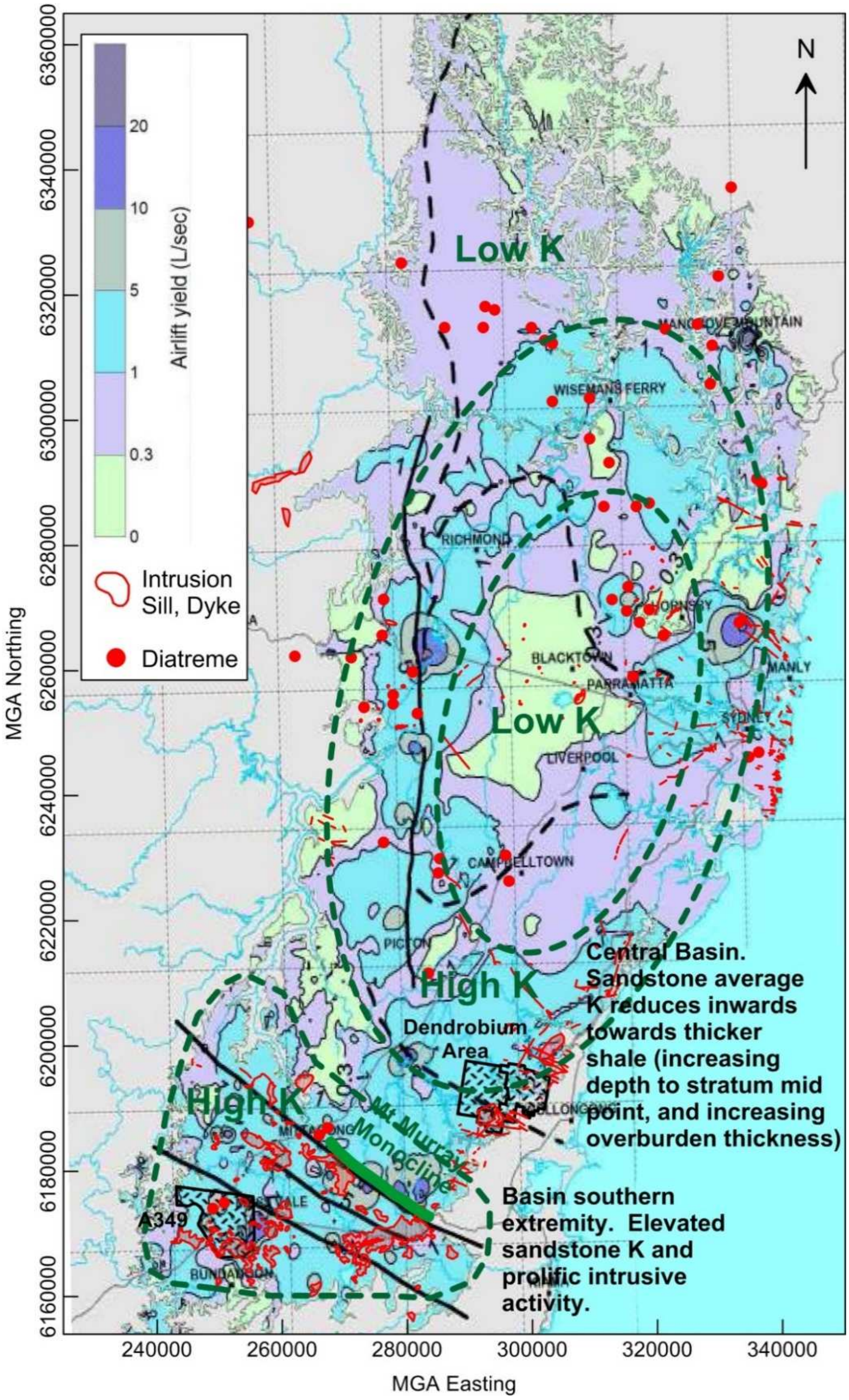


Figure 5.3. Airlift yields for the Hawkesbury Sandstone from government records (after Russell 2007), overlain with igneous structures, mine leases, and interpreted regional trends.

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).

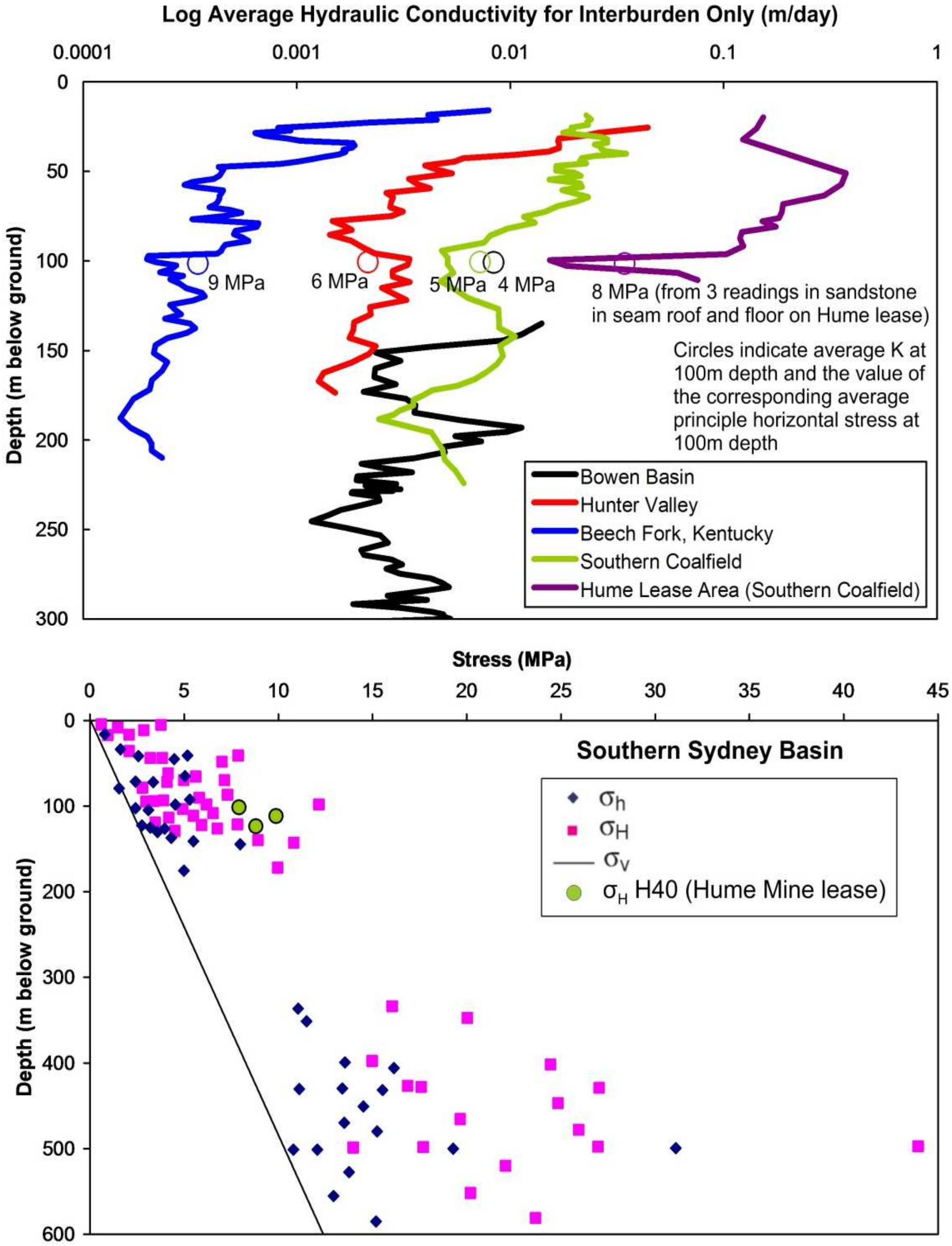


Figure 5.4. Comparison of stress and hydraulic conductivity (K). The upper chart shows K and regional stress magnitude for Permian Coal Measures (excluding coal seams) at four locations in Australia and one in the USA. The lower chart shows actual stress measurements unsegregated by media stiffness, 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).

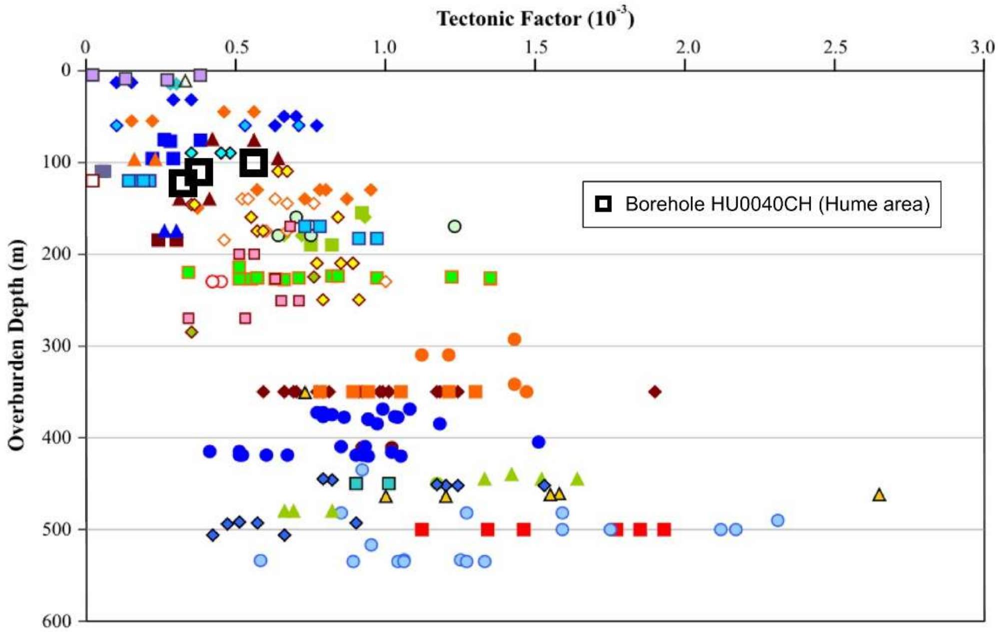


Figure 5.5. Tectonic factor calculated from results from borehole HU0040CH plotted on Figure 6 of Nemcik et al. (2006). Other data (coloured) are from SCT measurements only (Nemcik et al. 2006).

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.

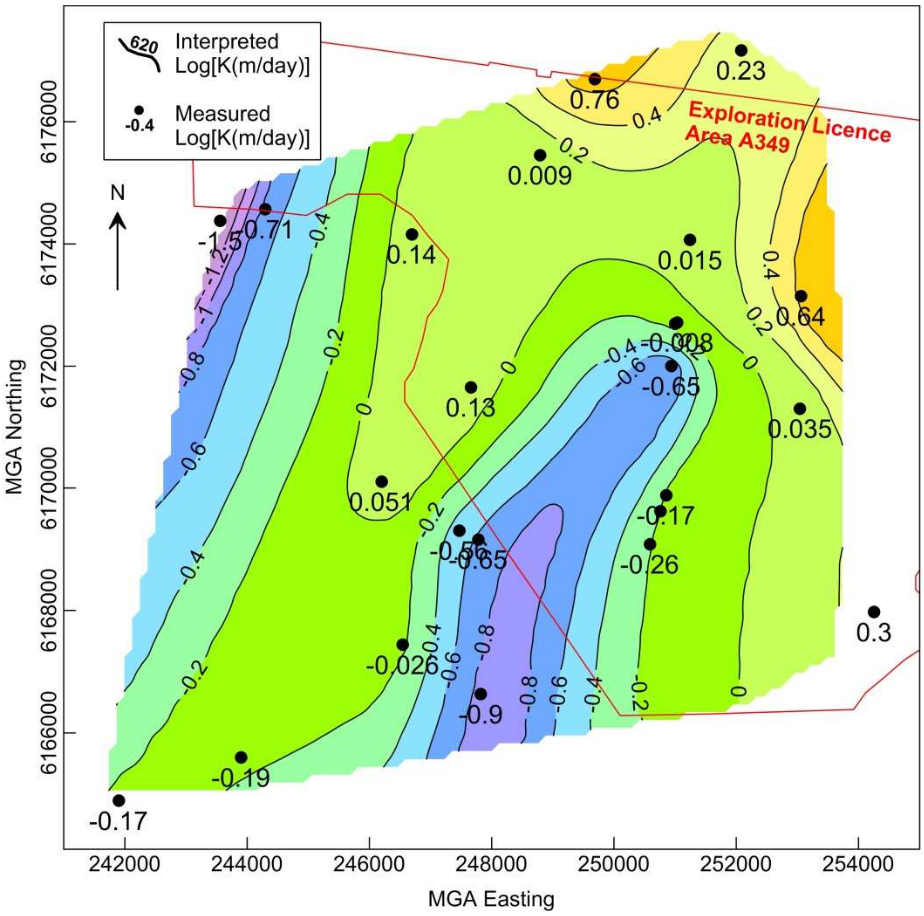


Figure 5.6. Log[K(m/day)] for Hawkesbury Sandstone between 14 m and 44 m above its base.

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.

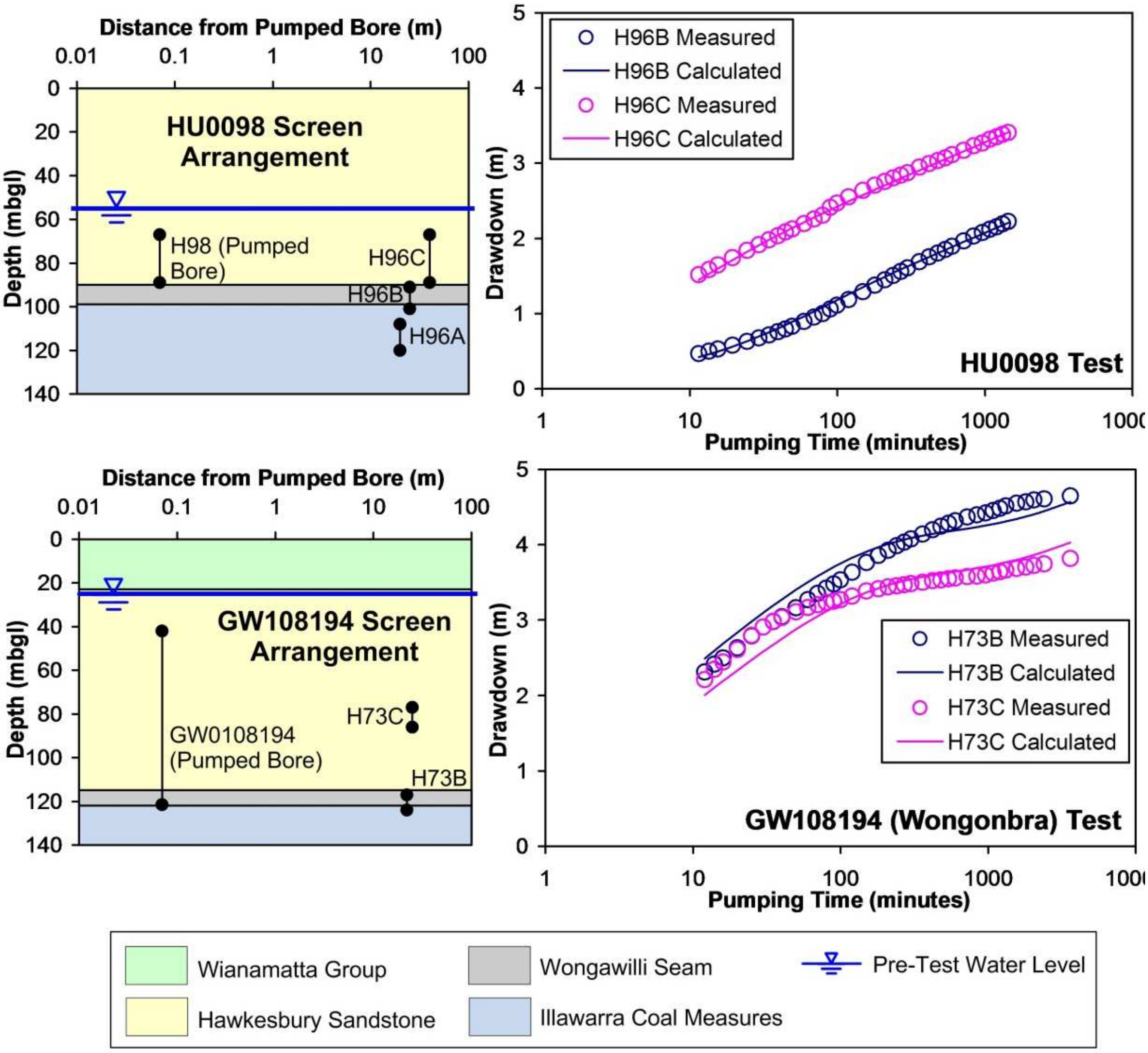


Figure 5.7. Calculated and observed drawdowns using the WTAQ algorithm in an optimisation capacity, for pumping tests at HU0098 and GW108194 on the Hume lease.

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.

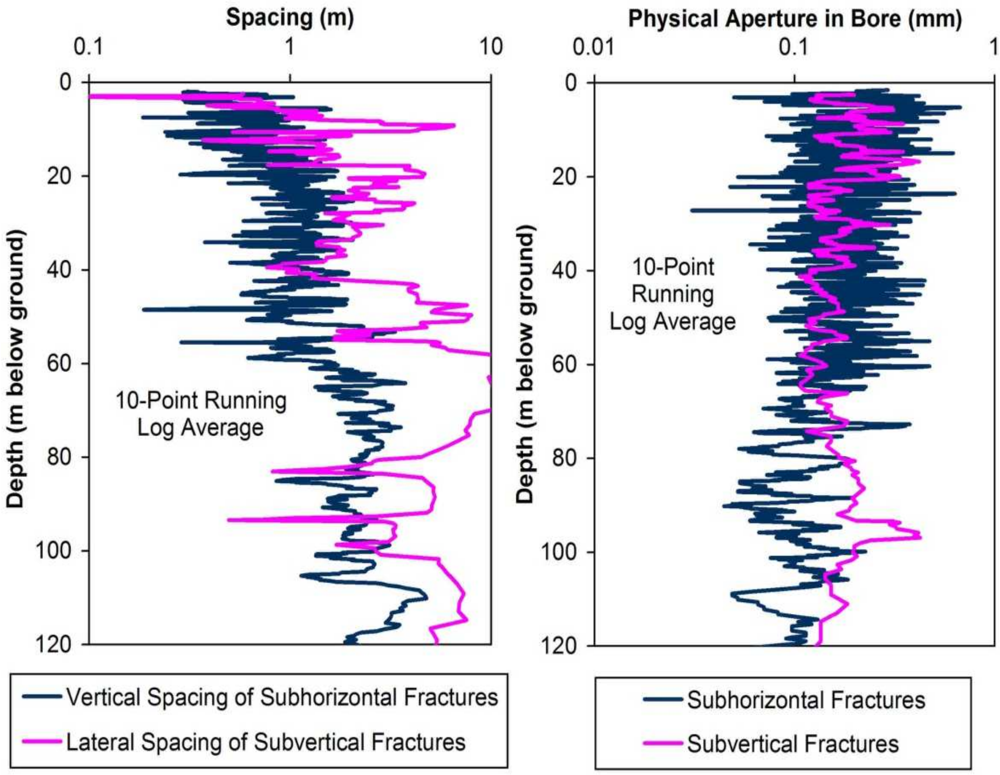


Figure 5.8. Defect spacing and aperture estimated from acoustic imaging of Hawkesbury Sandstone in the Sydney metropolitan area.

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.

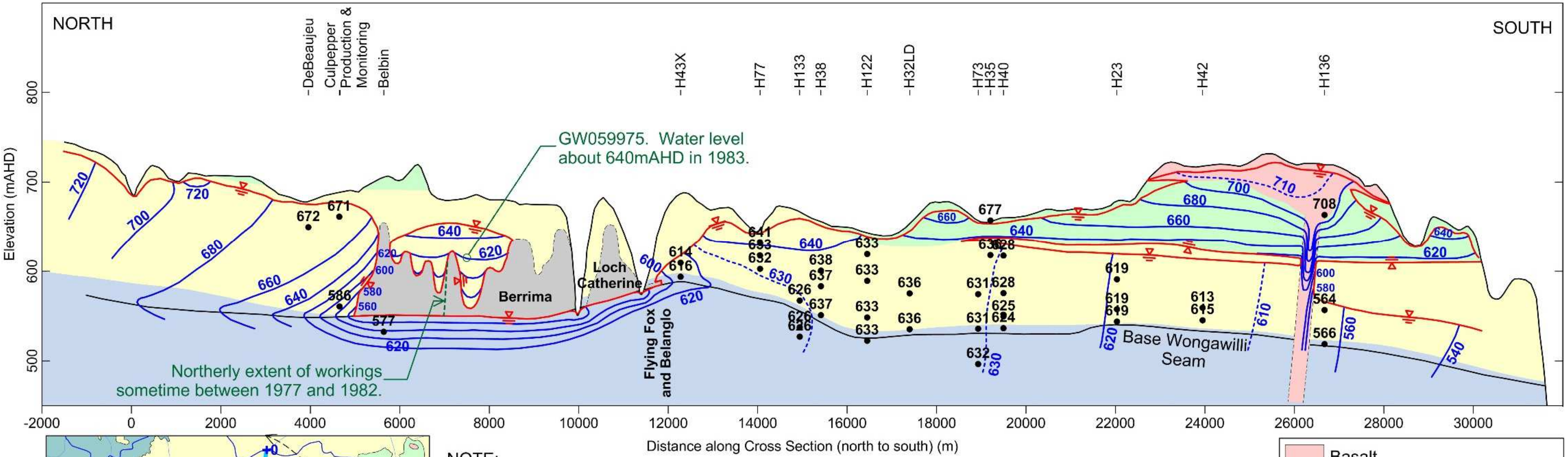
Bore GW106337 was installed in 2002, to a depth of 122 m, probably having intersected the Wongawilli Seam, in another portion of the 1st workings area mined prior to 1982. No measured water level is recorded at its installation, however it appears to have sustained a water level at installation since 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).

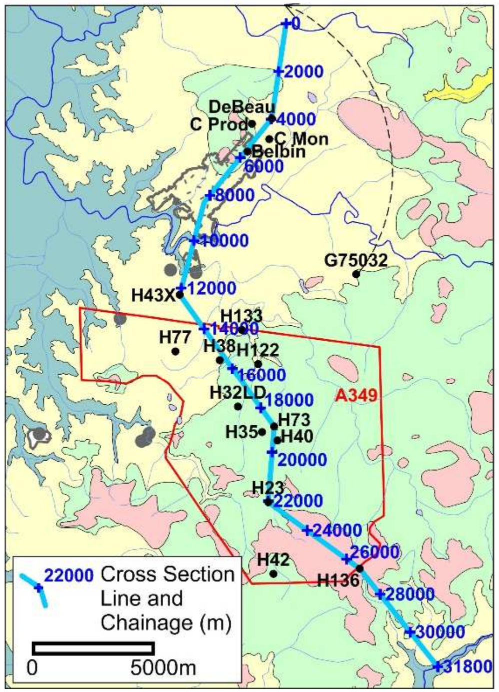
The current Belbin bore is a deeper replacement for a previous bore in the same location (overlying full extraction workings) which went dry after undermining. The previous bore was drilled in May 2004 to 115 m depth; it dried up and the replacement bore was drilled in April 2008 to 186 m depth. The 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.

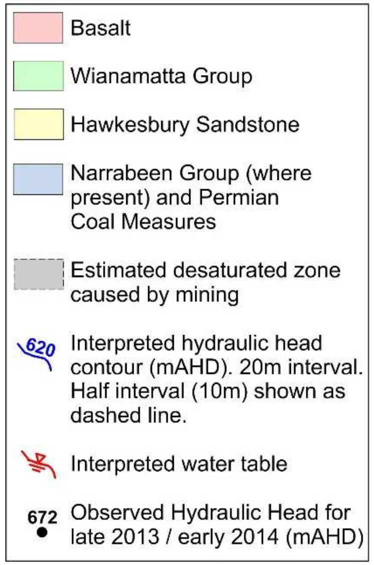


Figure 6.1. Interpreted hydraulic head cross-section for late 2013 / early 2014 through the Berrima and Hume mine leases.

Vertical hydraulic head gradients were also assessed by analysing the vertical pressure head distribution at each piezometer nest for late 2013 / early 2014 (Figure 6.2). The distributions support the hydraulic head cross-section, with the majority of sites indicating negligible vertical hydraulic head gradients. These are located in and around the mine lease, underneath WG. Strong vertical gradients due to depressurisation from the Berrima mine can be identified at piezometer nests B62 and B63. The lateral position of GW075032 suggests the vertical gradient at that location has been created by the existing mines. Drawdown from mining is not conspicuously observable in hydrographs for piezometers at H43X, the nearest Hume site to the existing mines; this site shows a negligible gradient in sandstone, probably due to insulation from the mined area via incision by drainage courses. H77 shows a moderate gradient at shallow depths, highly typical for outcropping Hawkesbury Sandstone in the Southern Highlands. The results suggest the drawdown from the Berrima mine has migrated mainly northwards and eastwards.

Sites H136 and H35 are interpreted to have potential unsaturated zones (of unknown vertical thickness) below the base of the basalt and WG respectively.

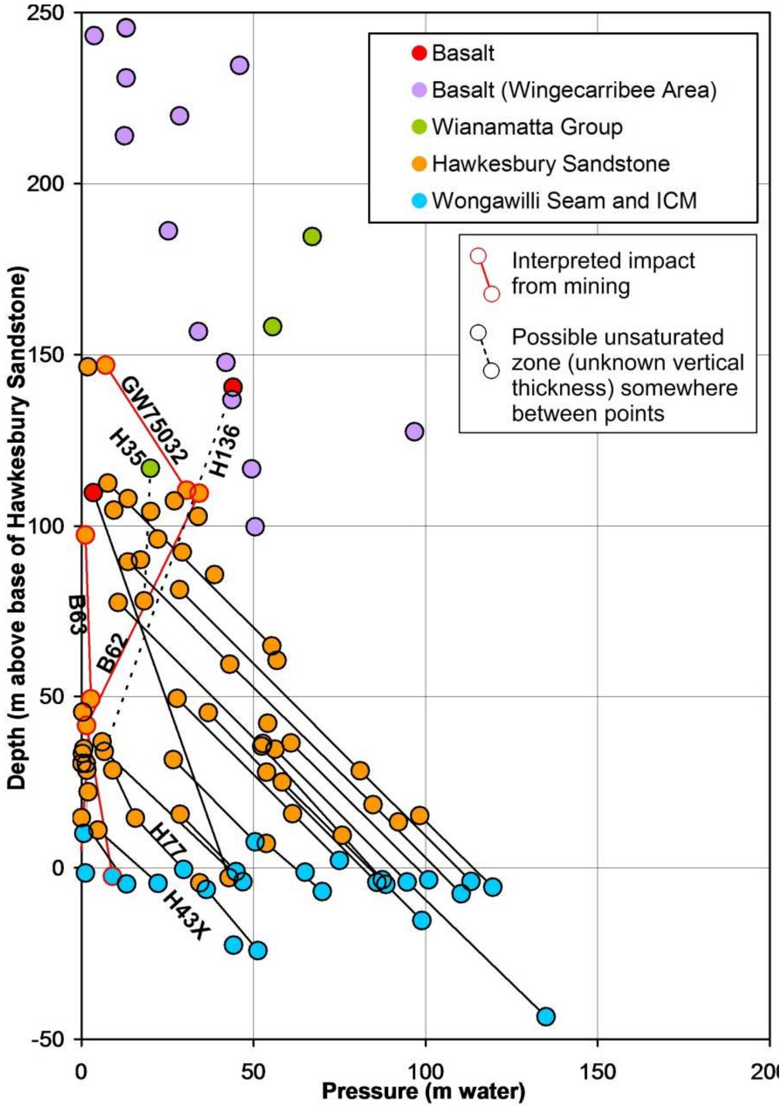


Figure 6.2. Vertical pressure head distributions for late 2013 / early 2014.

6.3. Hydraulic head surfaces for late 2013 / early 2014

Where vertical hydraulic head gradients are present, it is necessary to consider the vertical position of a piezometer in the profile when assessing hydraulic head surfaces. Surfaces are usually only useful if observations for a surface are located at the same stratigraphic horizon, since the K field is controlled by the structure of the medium. Horizons that are a given distance above or below an important depositional marker (such as the base of the Hawkesbury Sandstone) are generally required, however an element of variability from changing overburden thickness is present.

Hydraulic head surfaces for late 2013 / early 2014 (the period with the greatest overall lateral coverage in observations at the time of reporting) were compiled for the following horizons, to achieve a reasonable representation of the three-dimensional variation of hydraulic head over the area and at the same time using horizons where a sufficient number of observations were available to provide a meaningful surface:

- WG (7 observations, of which two are long-term elevations of water levels in Wingecarribee and Fitzroy Falls Rservoirs).
- Shallow Hawkesbury Sandstone (19 observations between 77 m and 108 m above the base of the Hawkesbury Sandstone, and application of zero pressure head at appropriate locations on the Berrima and Loch Catherine mine boundaries).
- Deep Hawkesbury Sandstone (23 observations between 22 m and 45 m above the base of the Hawkesbury Sandstone, and application of zero pressure head at appropriate locations on the Berrima and Loch Catherine mine boundaries).
- Wongawilli Seam and ICM (21 observations between 0 m and -24 m above the base of the Hawkesbury Sandstone, and application of zero pressure head at appropriate locations on the Berrima and Loch Catherine mine boundaries).

Figure 6.3 shows the hydraulic head surfaces for the WG and shallow Hawkesbury Sandstone. Appendix E has hydraulic head surfaces for deep Hawkesbury Sandstone and the Wongawilli Seam / ICM. 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 Wingecarribee 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.

Surfaces obtained from initial contouring of data were tied down with ground elevations wherever these initial surfaces intersected ground surface (mainly at drainage channels). Points where tie-down was undertaken are shown, and provide an approximation for the areas where baseflow to drainage channels occurs (recognising that the extent of tie-down zones are a function of data density, and that the actual hydraulic head in these zones, for the particular horizon, is not necessarily at ground surface).

The water table is difficult to locate, especially where vertical hydraulic head gradients are present. An approximation can be made by extrapolating the pressure head distributions in Figure 6.2 to obtain the y axis intercept (the depth where pressure head is zero) and taking the elevation of that point. However this is not possible where hydraulic head gradients are greater than 1, such as for B62.

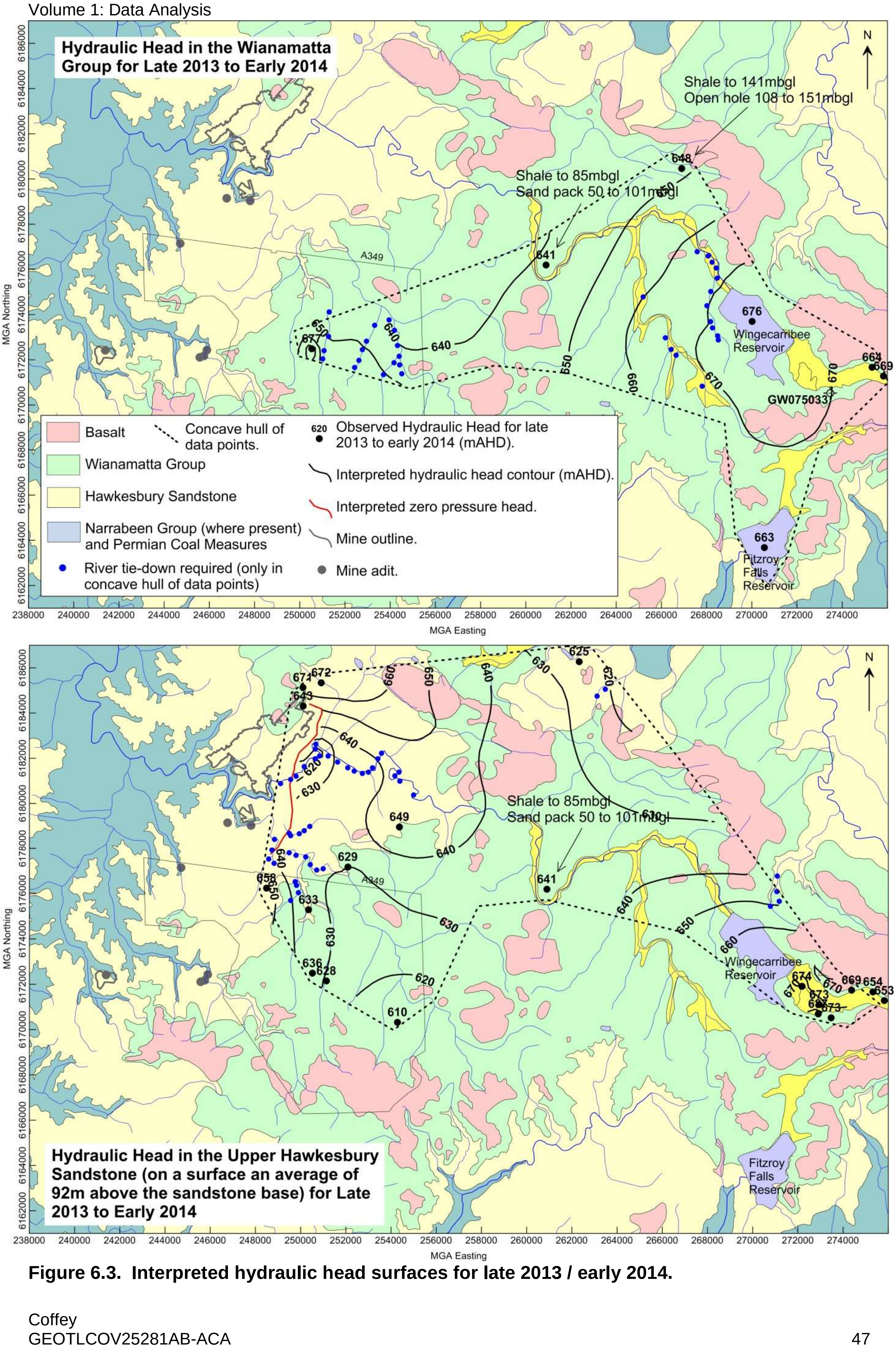


Figure 6.3. Interpreted hydraulic head surfaces for late 2013 / early 2014.

6.4. Hydraulic heads in basalt

The interpreted unsaturated zone below the Wianamatta Group (WG) over a large part of the study area (Figure 6.1) prompted a detailed assessment of the hydraulic relationship between basalt and underlying strata. This comprised assessment of the hydraulic head field present in the southeastern basalt body (see Figure 6.4), and underlying WG. The purpose of the assessment was to characterise the probable behaviour of hydraulic heads in the basalt groundwater system due to drawdown in underlying media, given the large number of private bores utilising the basalt groundwater system.

The southeastern basalt body is as shown in Figure 6.4. Most other basalt bodies in proximity to the proposed mine footprint are very small. Another large body is located just west of the southeastern basalt body however it likely hosts a smaller groundwater system, and also hosts fewer private bores.

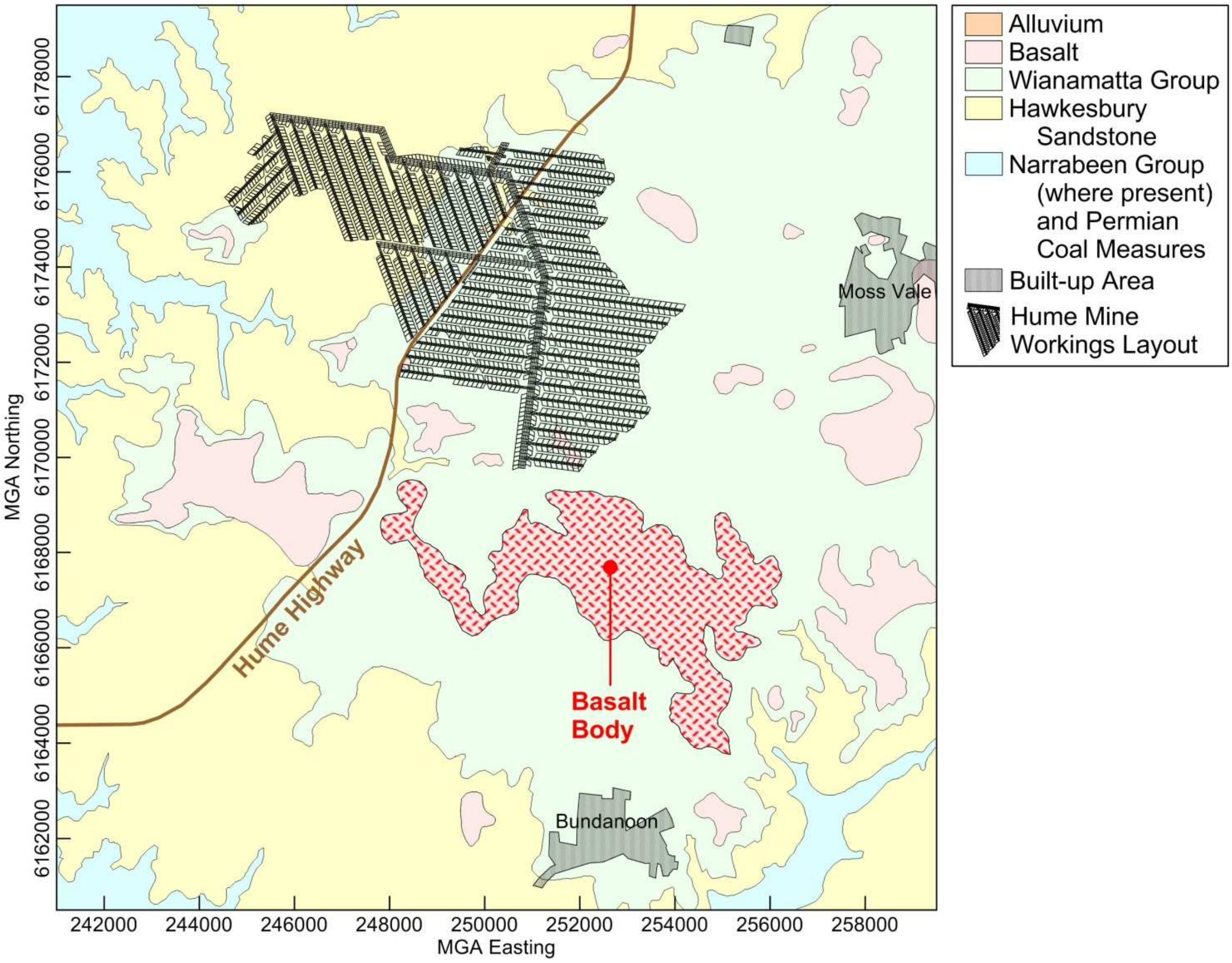


Figure 6.4. The southeastern basalt body.

A database of hydraulic head measurements, specifically for the basalt body and underlying media, was compiled from registered private bores penetrating this subsurface volume (DPI Water database extraction 2015). The analysis is more three-dimensional in nature than is possible using observations from monitoring networks alone.

Bore completions and measured water levels were obtained for 40 water bores, in hydraulic communication with the following media in and around the basalt body (see Figure 6.5):

- 30 in basalt only.
- 7 in Hawkesbury Sandstone (HAW) underlying basalt.
- 3 in HAW on the fringes of the basalt body.

Figure 6.5 shows private bores present in the area, and the 40 private bores for which the hydraulic connection has been interpreted from construction records and measured water levels. Data are provided in Appendix F. Lithologies recorded in bore logs may not agree with published geology maps. No measurements of hydraulic head for the WG were available for this volume. Measured water levels cover a period mainly between 1990 and 2010. Hydraulic heads were calculated for each bore. Observations from monitoring piezometer nests H136 (three piezometers in basalt, HAW, and ICM) and H42 (two piezometers in HAW and ICM), located at the basalt body, were added to the observation dataset to create a database of 45 hydraulic head observations in the subsurface volume.

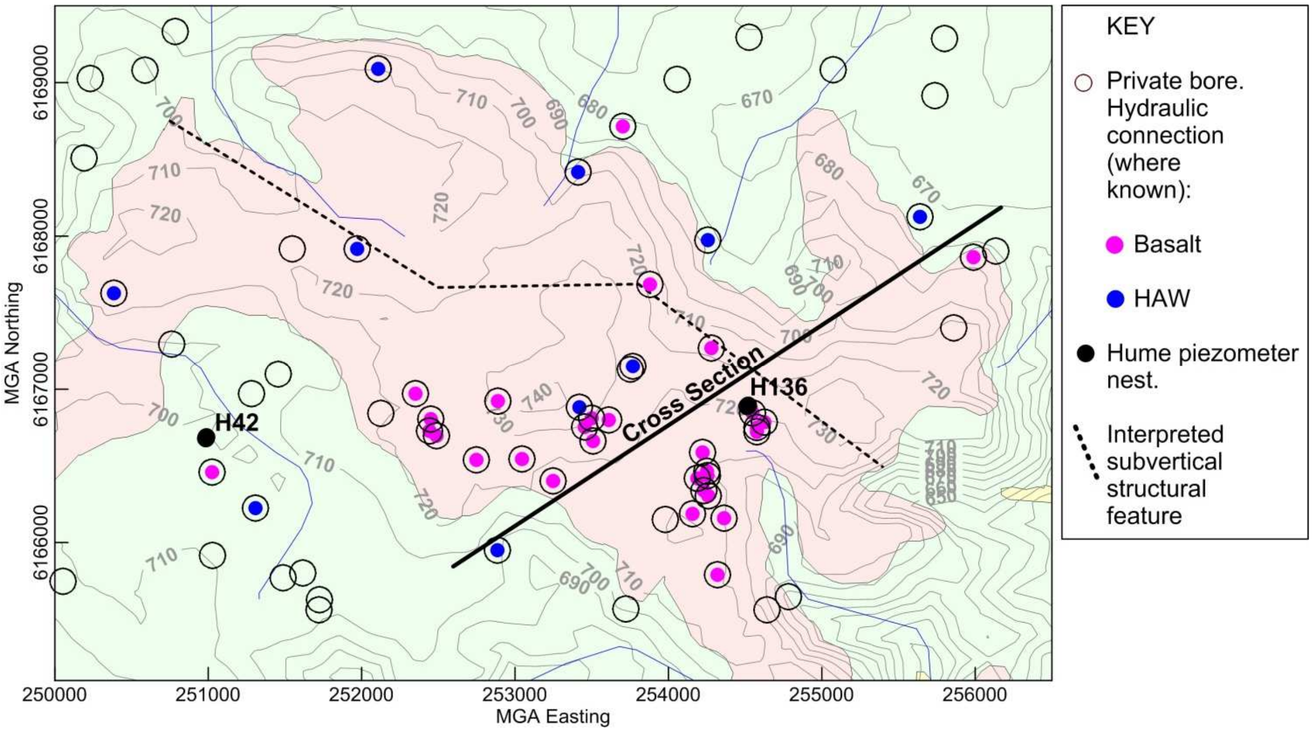


Figure 6.5. Private bores located in and around the southeastern basalt body. Those used for analysis are coloured (identified hydraulic connection).

The database was initially used to assess vertical pressure head gradients. This distribution is shown in Figure 6.6, and includes observations from piezometers in the wider lease area to assist with assessing gradients. Only one observation was available for the WG (H35B, in the centre of the Hume lease).

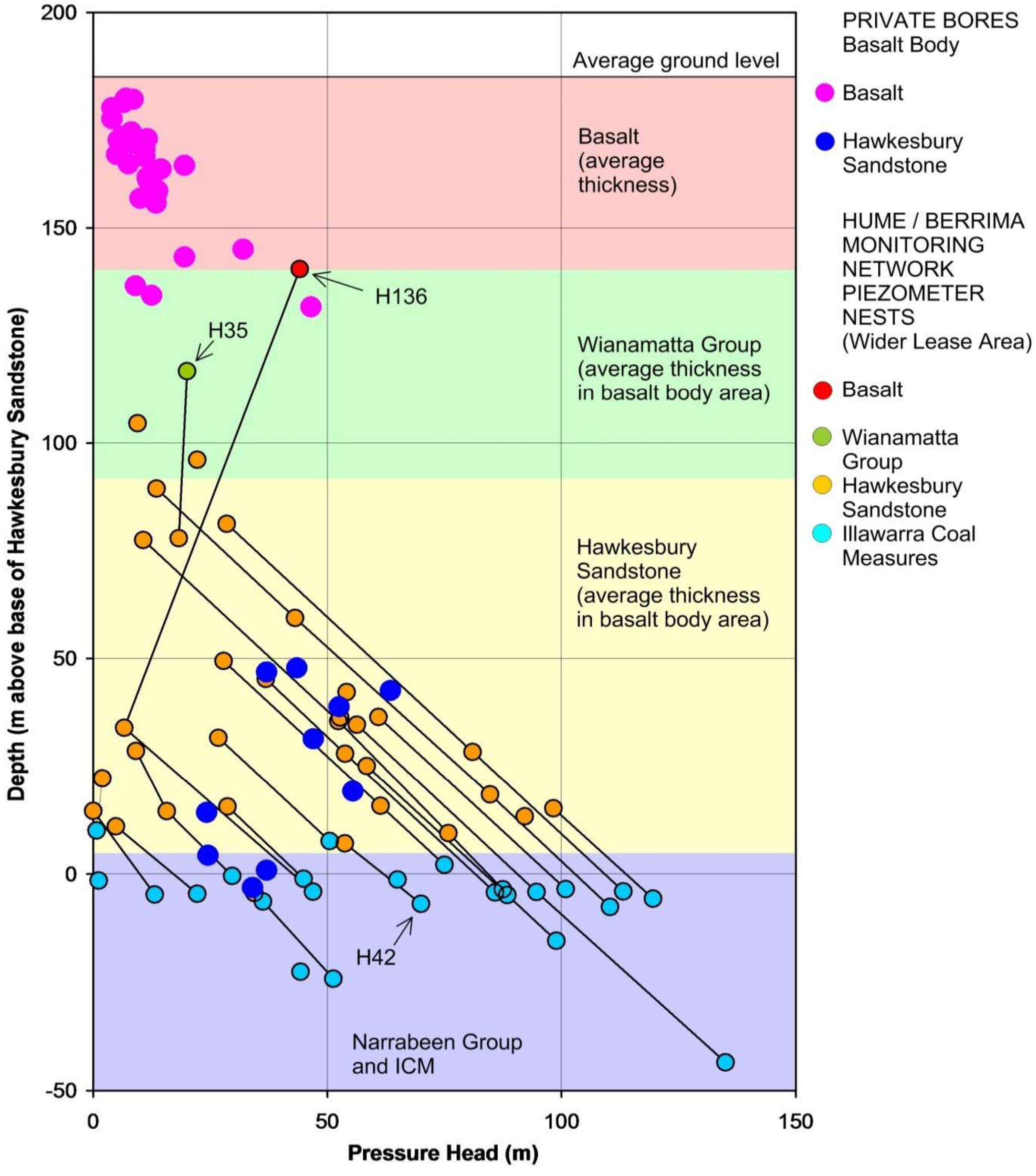


Figure 6.6. Pressure head versus depth distribution for the basalt body volume (mainly from private bores), and for the wider lease area (from monitoring piezometer networks).

Figure 6.6 (and Figure 6.7, see below) indicates that vertical hydraulic head gradients are small in the basalt and HAW, but likely to be significant (and downward) in the intervening WG. The pattern emerging from the large number of observations strongly indicates a largely unsaturated zone below the WG, in the basalt area. This was further investigated by compiling a hydraulic head cross section for the basalt body (see Figure 6.5 for section location). Observations made in basalt within 500 m (laterally) of the cross section were included for plotting.

Figure 6.7 shows the interpreted hydraulic head cross section. An unsaturated zone occurs below the WG south of the subvertical structural feature. North of the structural feature, the hydraulic head difference between the top of the HAW and the base of the basalt is about 80 m. The overall hydraulic gradient is about -1 downward. North of the structural feature, the pressure head at the top of the sandstone is an average of about 10 m.

The analysis indicates the following:

- Drawdown in the HAW south of the structural feature will not cause any change to the saturated flow regime in the basalt in the same area. The majority of private bores in the basalt are located here.
- North of the structural feature, the top of the sandstone can undergo a drawdown of about 10 m before desaturation occurs between the sandstone and WG, at which point any further drawdown will not impact the saturated flow regime in the overlying basalt. This is an increase in the magnitude of the vertical hydraulic head gradient of about 13%. This assumes saturation is maintained from the base of the WG (moving upwards); this is considered reasonable given the strong vertical anisotropy exhibited by the WG.
- It is estimated that of the recharge to the basalt, less than 10% drains vertically into the WG, with the remainder consumed by surface processes and baseflow. The realisation of drawdown greater than 10 m at the top of the HAW is therefore likely to increase the vertical drainage from the basalt by about 1% of the recharge to the basalt, or less.
- If maximum drawdown were to occur at the top of the HAW, drawdown in the basalt would initially be non-zero but negligible, as drainage from storage occurs. With time, drainage from storage ceases and water levels would re-establish (during mining), with the increased vertical drainage satisfied by decreased baseflow to streams.

No direct evidence (from bores) is available for the structural feature. Its presence is interpreted from hydraulic heads, regional lineaments, and structure contour surfaces considered in unison. The feature is considered major, 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.

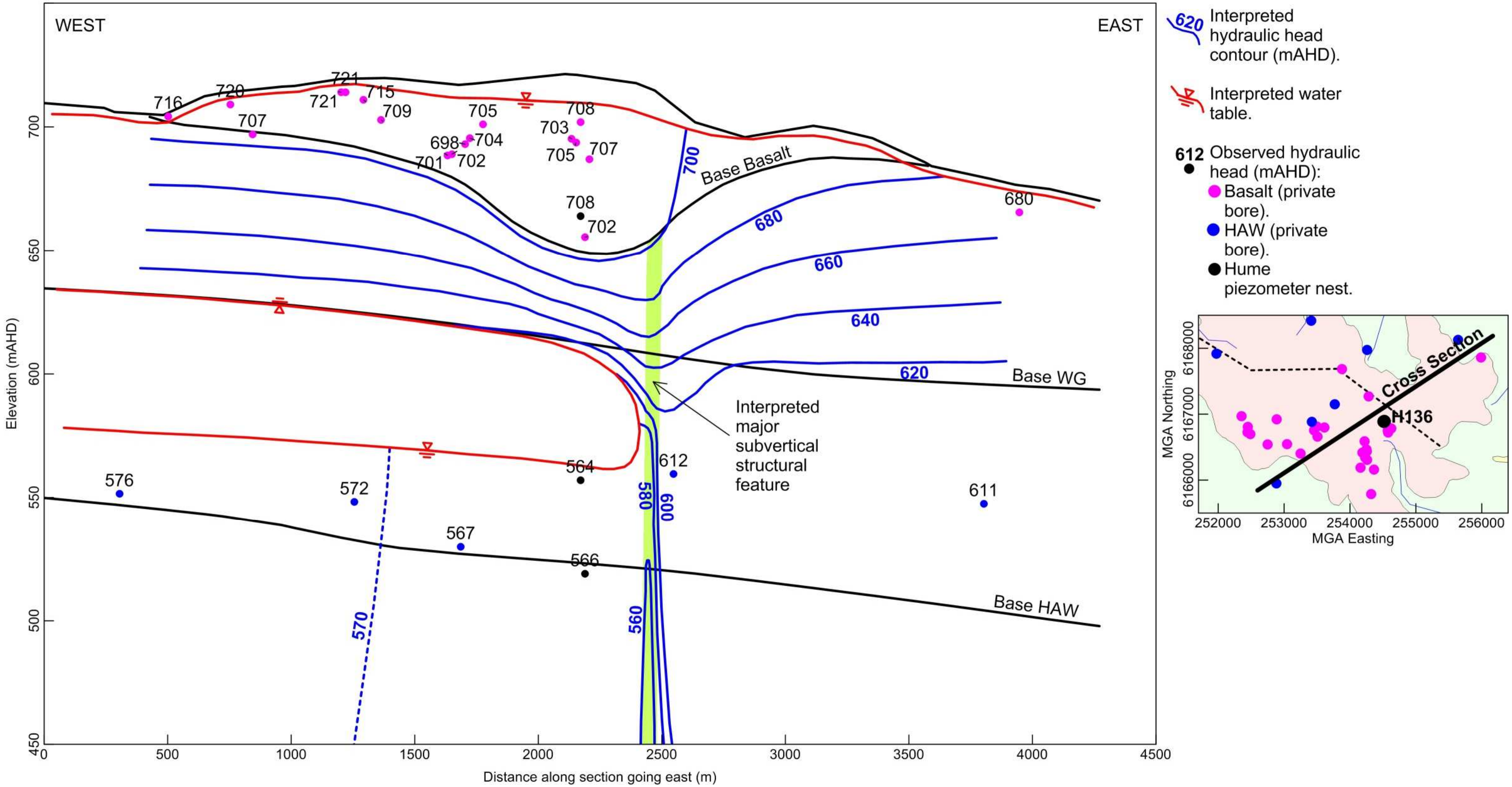


Figure 6.7. Hydraulic head cross section along the basalt body.

6.5. Reliability of Hydraulic Head Measurements

The reliability of a hydraulic head measurement is a necessary consideration for model calibration. Standpipe piezometers (SPs) provide the most reliable hydraulic head observations, however practical considerations limit the number of piezometers in the vertical profile at a single location. Vibrating wire piezometers (VWPs) provide hydraulic head measurements of lower accuracy than SPs, but practical considerations allow significantly greater coverage of the vertical profile with VWPs at a single location (up to five in the Hume network) than is possible with SPs. The Hume monitoring network contains a combination of SPs, VWPs, and private water bores for acquisition of hydraulic head observations and provides a substantial database for characterisation of the groundwater system in the Hume area.

An estimate of the resolution of VWPs was previously made for another project in the Southern Coalfield using measurements from VWPs located at two sites on a mine lease. It was found that simultaneous water level measurements from coincident VWPs varied. Results indicated that, 50% of the time, a VWP measurement at that site would have been within 7.8 m of the measurement from a coincident VWP. The ability of a VWP to provide the true hydraulic head adds an additional uncertainty to the measurement. This accuracy is considered not better than ±10 m most of the time. This accuracy may be acceptable in areas with a high vertical hydraulic head gradient (for example, for depressurisation due to underground mining, as at B62 and B63), but may be less suitable in areas with smaller vertical hydraulic head gradients.

The lower accuracy of VWP measurements has been taken into consideration when comparing model output to hydraulic head observations. The hydraulic head calibration dataset includes observations from VWPs at locations B62 and B63 in the Berrima monitoring network.

7. Groundwater inflows to the Berrima mine void

Measured discharge from the Berrima mine void provides an invaluable calibration aid for numerical modelling. When used in conjunction with hydraulic heads, the mine inflows are able to significantly reduce the uncertainty associated with the correlation between rainfall and K. Coupled with reliable a-priori estimates of rainfall recharge and the Kh distribution, deep discharges (mine inflows in this case) provide vital information in estimating the Kv distribution between the surface and the mining zone.

Mine operators have monitored discharge from the Berrima workings for several years, with discharge measurements available from 2005. Water is pumped from various points within the workings to the main sump where it flows through an old roadway to the Wingecarribee River where it is discharged through an adit under EPA Licence conditions (EMGA 2011). Water was previously pumped from the workings to storage tanks in the northern corner of the Berrima pit top, from where it was used for dust suppression, equipment washdown, bathhouse and ablutions, and piped under gravity to the township of Medway for non-potable water use (EMGA 2011). During the recent active mine life (2012/2013) these consumptions (plus an estimate for ventilation loss) are estimated to have been about 0.05 ML/day. At present, the consumption is estimated to be about 0.02 ML/day. These consumptions were or are taken from void inflow, with the remainder discharged to the Wingecarribee River.

Existing groundwater removed in coal moisture (during mining) is conservatively estimated to have been about 0.1 ML/day (about 2% existing groundwater, at 0.25 Mt/y). Coal removal is assumed to have ceased on 31 March 2013.

When the mine was active, mine workers observed that the void inflow rate appeared to be approximately proportional to the area of seam roof exposed, with no obvious lateral inflow from the Wongawilli seam. Anecdotal information indicates the following:

- Panels driven beneath basalt experienced higher inflows.
- Wet weather sometimes resulted in large volumes of water flowing down along the contact zones of dykes. There appeared to be a strong correlation between the occurrence (and distribution) of subvertical dykes and increases in inflow during 2008.

Monitoring of void discharge at the licensed discharge point up to October 2012 was undertaken using a v-notch weir. In October 2012 a more accurate cut throat weir outfitted with an automatic recorder was installed. Void discharge observations have the following limitations:

- Prior to 2009, it is understood that measurements may only have been made when discharge pumps were active, with resulting measurements excluding periods of no pumping. If pump on/off times were available, averages over periods larger than the pumping frequency would be useful, since void inflow during pump off times would report to void storages for future pumping. However, it is not clear if observations published prior to 2009 were averaged over large periods (compared to the pumping frequency). The data points present in published information would suggest this was not the case.
- It is understood that the original v-notch weir had a lower accuracy than the cut throat weir installed in 2012.
- The coincident installation of an automatic recorder with the cut throat weir suggests observations between 2009 and 2012 may also have suffered from biased sampling.

These limitations mean observation reliability is reasonable only after October 2012. Prior observations may be overestimates. Figure 7.1 shows the recorded discharge. Also shown is the monthly cumulative rainfall residual for the period 2000 to the present (incorporating an entire southern oscillation cycle with the major drought in the middle of last decade).

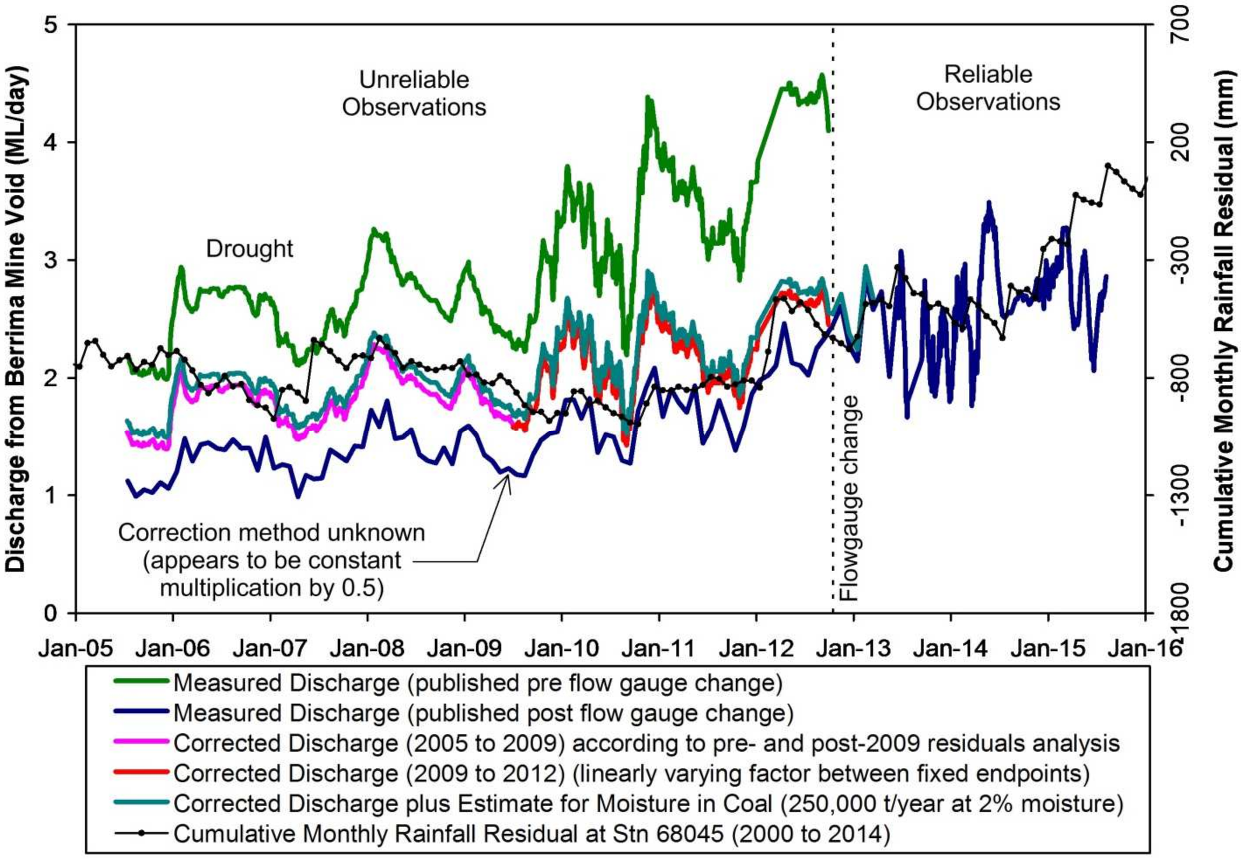


Figure 7.1. Measured discharge from the Berrima mine.

Observations take no account of changes in void storage or evaporation, however it is understood that in the last few years the void was kept virtually empty, and changes in the small underground sump storages are considered to negligibly affect average monthly flow volumes. Also, the void is not known to be artificially ventilated. The majority of the inflow to the void is discharged to the river, with the consumptions listed above accounting for about 2% (during mining) or 1% (post mining) of the total inflow.

Observations are considered reliable following the flow gauge change in October 2012. Observations prior to the change do not appear reliable. Pre-gauge-change observations published in 2014 appear to have been multiplied by 0.5 to obtain corrected observations. Uncorrected pre-gauge-change observations appear to begin increasing from 2009. Pre-gauge-change observations may also have been affected by drought conditions between 2005 and 2009.

Published corrected observations were assessed for any relationship with rainfall by correlating the departure of the rainfall and inflow patterns from their respective long-term trends. These departures are known as residuals and were calculated by first plotting the cumulative value of these variables over time, then fitting a polynomial trend line to the cumulative curves and finding the residuals via the difference between observations and the fitted polynomials.

Figure 7.2 shows discharge and rainfall residuals, and indicates the clear relationship between rainfall and inflow. The highest degree of correlation was for a 12-month lag between rainfall and inflow. The ratio of inflow to rainfall residuals prior to 2009 suggests the potentially applied reduction factor (50%), to obtain corrected observations, might be too large.

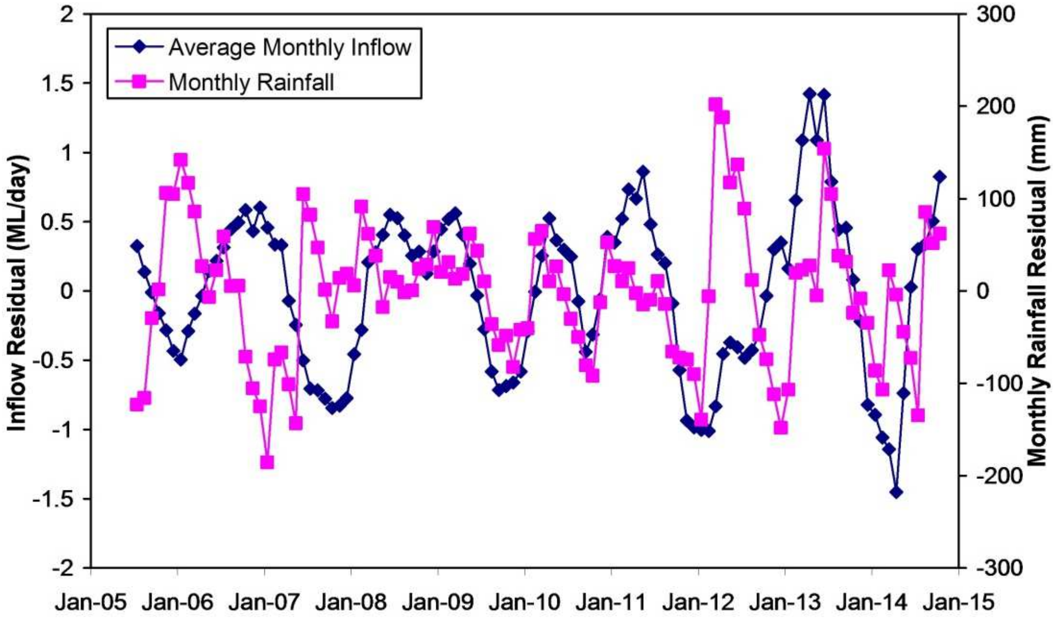


Figure 7.2. Departures of rainfall and Berrima mine discharge from their long-term trends.

Comparing pre- and post-2009 residuals ratios, the reduction to obtain corrected discharge is calculated to be a maximum of about 30%. This correction is based on residuals only, not magnitudes. Corrected discharge using a 30% reduction, for the period 2005 to 2009, is shown in Figure 7.1. Observations obtained after the gauge change are considered to be reliable. For observations made between 2009 and the gauge change, a correction has been applied comprising a linearly varying correction factor of 30% at 2009 to 41% at the gauge change (to obtain compliance in observations at that point); this dataset is also shown in Figure 7.1. The adopted observation dataset used for calibration therefore comprises the following three components:

- 2005 to mid-2009: Uncorrected observations reduced by 30%.
- Mid-2009 to October 2012: Reduction by 30% at mid-2009, increasing linearly to reduction by 41% at October 2012 (to obtain compliance in observations at that point).
- Post October 2012: Observations as published.

A nominal consumption of 0.1 ML/day is added to account for groundwater removed in mined coal (assumed to have ceased on 31 March 2013). The adopted dataset appears to accord more reasonably with the cumulative annual rainfall deficit than other datasets.

8. Groundwater character

Water quality monitoring has been undertaken at the Hume groundwater monitoring network (Parsons Brinckerhoff 2015). These data have been subjected to statistical analysis to assess groundwater character in the various hydrostratigraphic units. Table 4 lists statistics for these units, for electrical conductivity (EC) and sulphate.

Table 4. Electrical conductivity and sulphate of groundwater from the Hume monitoring network.

Analyte	Hydrostratigraphic Unit			
	Basalt	Wianamatta Group	Hawkesbury Sandstone	Wongawilli Seam and Illawarra Coal Measures
Electrical Conductivity				
Average (uS/cm)	748	2477	295	392
Standard Dev. (uS/cm)	13	158	243	261
Sulphate				
Average (mg/L)	64	80	7	17
Standard Dev. (mg/L)	27	9	9	26
Sample Information				
Number of Samples	2	2	69	56
Sampling Date Interval	Average interval 17 October 2011 to 23 May 2014			

In the Hume lease area, the Hawkesbury Sandstone (HAW) has the lowest average EC of the units, comparable to the Illawarra Coal Measures. EC of the Wianamatta group is more than 8 times larger than the HAW. This is also observed in the Sydney metropolitan area. Sulphate concentrations for the units follow similar proportions.

8.1. Stream flow and electrical conductivity

Concurrent streamflow and stream EC measurements are useful as an independent indicator of the flow range where groundwater seepage to the stream is a large proportion of the total flow.

Intermittent EC measurements for WaterNSW station E332 and concurrent daily flow measurements for the adjacent flow gauge (212272: Wingecarribee River at Berrima Weir) for the period 1991 to 2014 were correlated. Multiple EC readings taken on the same day were volume-averaged (where more frequent flow measurements were available), or time-averaged.

A strong inverse correlation is apparent when viewing flow and EC time series (see Figure 8.1). Figure 8.1 shows daily flow and EC correlated for two periods:

- 1991 to 2001 inclusive (weak regulation).
- 2002 to 2014 inclusive (strong regulation).

Stream regulation is conspicuous in the latter dataset, resulting mainly from the severe drought of the 2000s. Reservoir water has a large component of surface runoff and its EC will be lower than groundwater EC. Artificial discharges wash away high EC water at prevailing low flow, and replace it with lower EC water at moderate flows. In extreme cases, where streamflow ceases, a small artificial discharge reaching the gauge will have significantly lower EC than would be expected naturally.

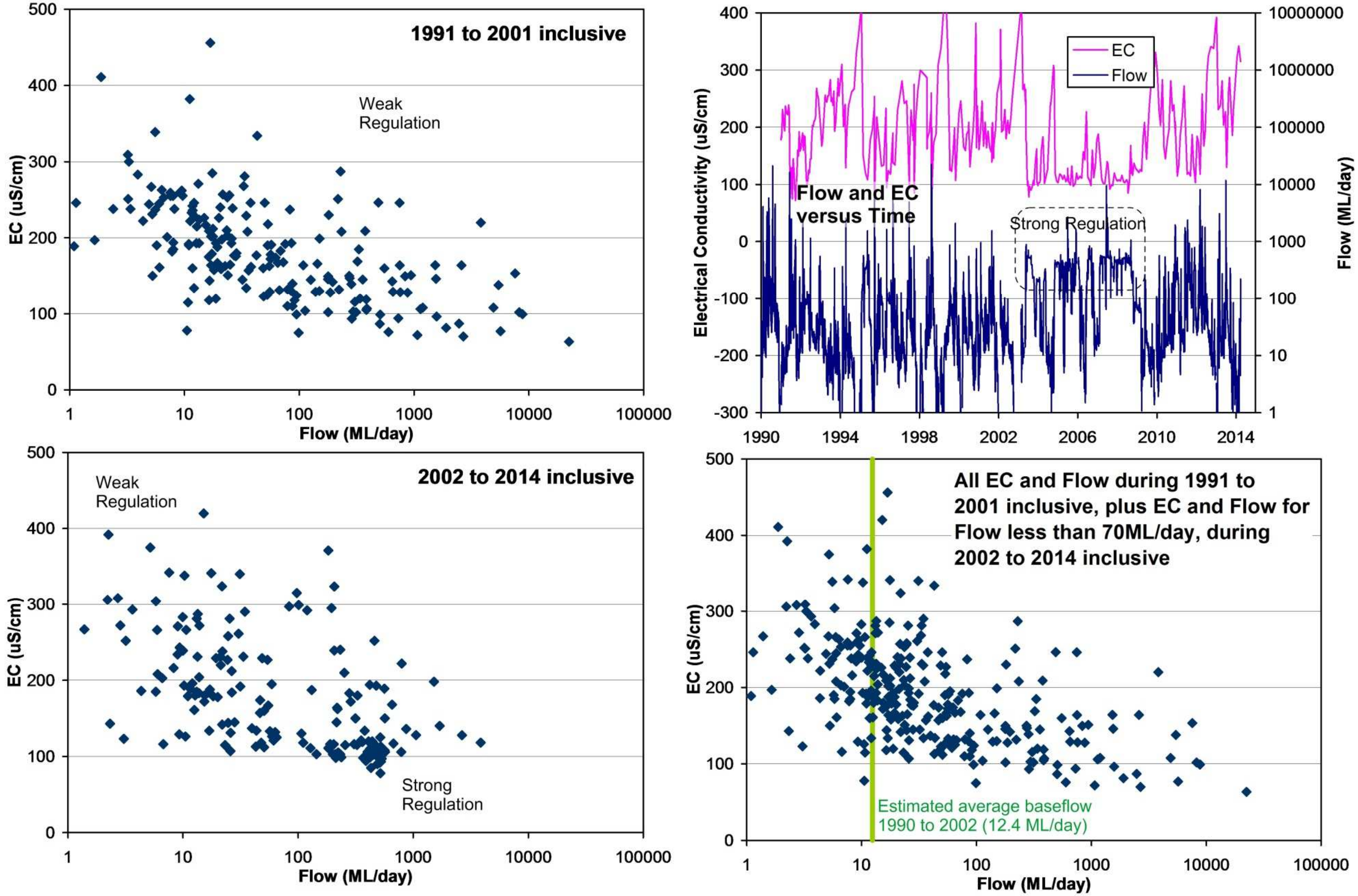


Figure 8.1. Flow at stream gauge 212272 and measured stream EC. Anticlockwise from top right: comparison of time series; correlation for 1991 to 2001; correlation for 2002 to 2014; selected dataset estimated to have reduced impact from regulation.

Considering only measurements occurring during weakly regulated times, a reasonable hyperbolic relationship is apparent between log[flow] and EC.

The baseflow at gauge 212272 calculated using the local minimum method (see above) is in reasonable agreement with the flow versus EC distribution, being located in the likely zone of major change of the distribution.

9. Groundwater use

9.1. Private bore use

Registered private water supply bores from the NSW State Government database are shown in Figure 9.1. A drawdown impact assessment for private water bores in the Hume area is reported in Volume 2. Over the mine lease, the majority of bores are reportedly deeper than 100 m, in an attempt to harness water supplies in the Hawkesbury Sandstone underneath reasonable thicknesses of WG. This trend continues north-eastwards, along the WG body (see Figure 9.1 and Drawing 1).

A search of private water bore access licences within 9 km of the Hume mine area centroid returned 83 known water access licences with a combined level of entitlement of 14.5 ML/day (5300 ML/year). It is understood that a significant number of unregistered bores also exists. No metering of usage is undertaken by regulatory agencies for the area, therefore actual usage from registered bores is not known.

The vast majority of private bores extract groundwater from the Hawkesbury Sandstone. A number of basic rights bores (registered for stock and domestic use) also exist; there is no volumetric entitlement associated with these bores. The total usage of basic rights bores within 9 km of the mine centroid is estimated to be about 2.6 ML/day. The total level of entitlement for the model area is likely to be in excess of 20 ML/day. Basic rights bores are estimated to have a combined usage of up to approximately 5 ML/day.

A search of surface water access licences in the regional area returned 173 licences with a combined entitlement of 26 ML/day (9495 ML/year). Table 5 lists the total entitlement by management area. Actual usage is estimated using published information for the catchment of gauge 212238 as a corollary, based on land use (and assuming 10% of intensive urban use areas are irrigated with water to maintain grass).

Table 5. Surface water entitlement by management zone.

Management Zone	Total Entitlement (ML/year)
Bundanoon Creek	1108
Lower Wingecarribee River	1135
Lower Wollondilly River	5411
Medway Rivulet	1027
Nattai River	124
Upper Wingecarribee River	690
Total	9495

Figure 9.2 shows the following:

- Monitoring piezometers where drawdown from pumping at proximal private bores is evident.
- Irrigation and intensive urban land uses according to government databases.

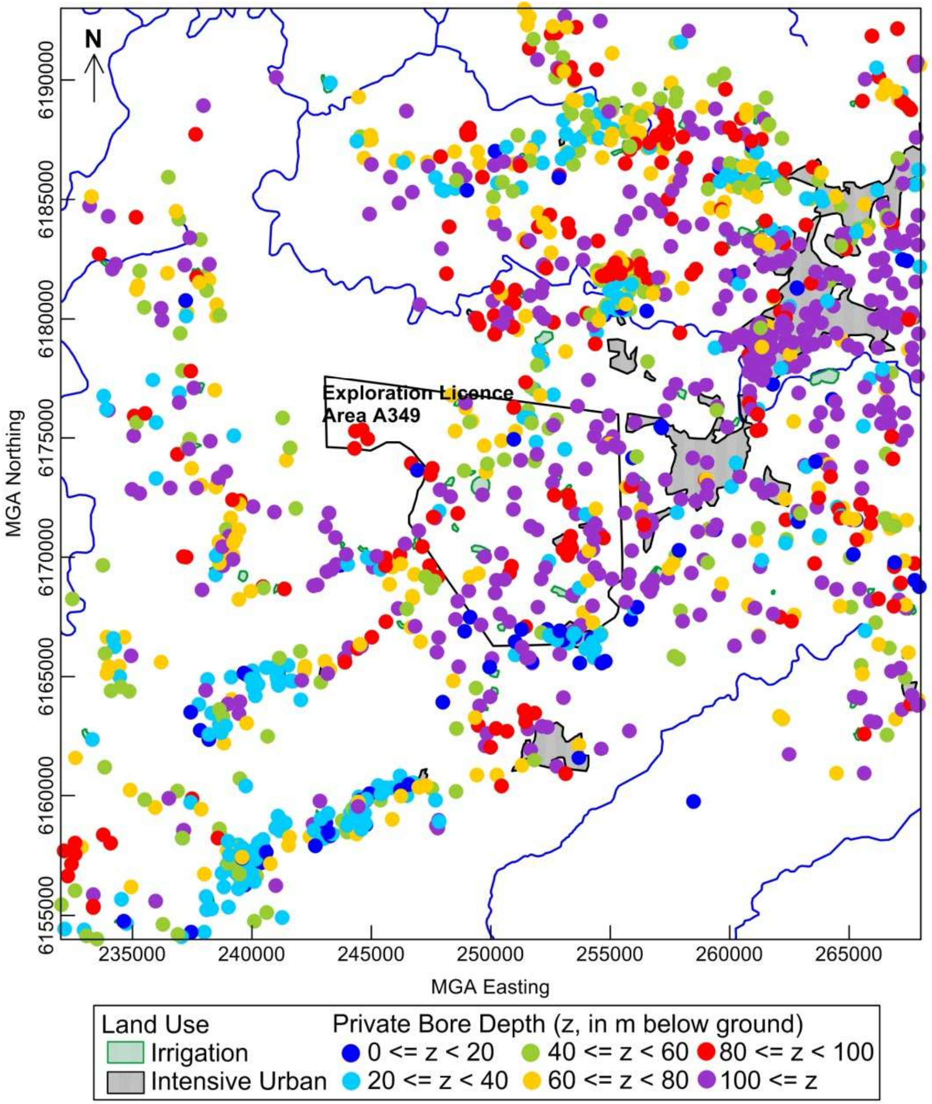


Figure 9.1. Registered private water bore locations, according to completed depth.

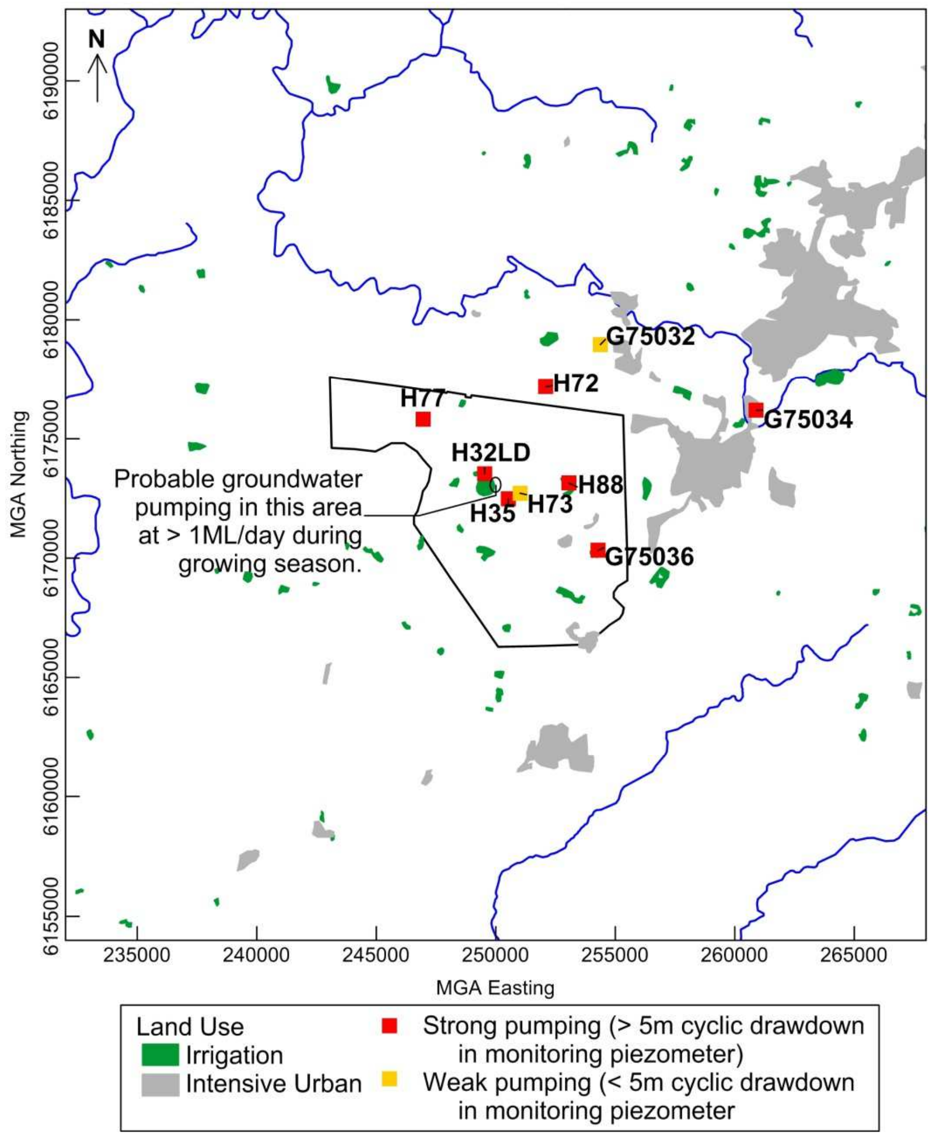


Figure 9.2. Land use and interpreted private pumping effects in monitoring hydrographs.

Drawdown seen at Hume monitoring piezometer locations H32, H35, and H73 between October 2013 and January 2014 is potentially related to pumping from the same private bore. At that location there is what appears to be an irrigated circular agricultural field of about 700 m diameter. Depending on the crop, and southern oscillation cycles, the additional water required (above rainfall) over the growing season, for this field, may be in excess of 1.0 ML/day. An approximate calculation using observed maximum drawdowns at the monitoring piezometers, an assumed transmissivity of 100 m^2/day, and a bore located on the northeast perimeter of the field, was undertaken using the Jacob equation, with results indicating a pumping rate in excess of 1.5 ML/day over the period October 2013 to January 2014.

10. Hydrogeological conceptual model

A hydrogeological conceptual model has been developed based on the data analysis conducted in the preceding sections. A large database of observations for Kh, hydraulic head, and fluxes provides a reliable platform for development of a numerical groundwater flow model for numerical simulation of the proposed Hume mining operations. In conjunction with a large number of baseflow estimates (shallow discharge of groundwater from the system), observed discharge from the Berrima mine (deep discharge of groundwater from the system) provides a vital observation dataset for large-scale reliable estimation of Kv down the media profile, an important parameter for simulation of deep discharges such as mine inflows, and vertical propagation of drawdown. Pumping tests undertaken by Hume at HU0098 and GW108194 provide useful independent estimates of large-scale Kv for sandstone, providing additional calibration targets.

10.1. Recharge

Recharge to the groundwater system occurs mainly by rainfall infiltration. Recharge may also occur from drainage channels wherever the stream stage is higher than the water table. Annual recharge to the water table is estimated to be about 2% of annual rainfall for the Hume area. Annual baseflow to drainage channels is estimated to be about 1.5% of rainfall from baseflow analysis.

10.2. Key hydraulic properties

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. For Kh 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.

Vertical anisotropy is also believed to decrease with depth, given the greater proportion of matrix flow at depth. Kv/Kh is estimated to be around 0.01 at the depths monitored during the pumping tests.

10.3. Discharge

Groundwater discharge or consumption occurs as follows:

- Baseflow discharge to drainage channels.
- Evapotranspiration in the unsaturated zone, in zones with shallow water tables, at escarpments, and at forested areas.
- Groundwater pumping or discharge to mined voids.

Discharge to the Berrima and Loch Catherine mine voids ultimately reports to drainage channels so that this term forms part of the baseflow to drainage channels.

10.4. Approximate water balance

Table 6 lists an approximate water balance for the model area (say 800 km^2), to the nearest 5 ML/day, for average rainfall conditions. The estimate for reservoir leakage considers only the proportion that would be surface runoff into the reservoir. Baseflow to streams includes discharge from mine voids in the area.

Table 6. Approximate water balance for the model area for average rainfall conditions.

IN (ML/day)		OUT (ML/day)	
Rainfall Recharge (just over 2% of annual rainfall)	45	Baseflow to streams (about 1.5% of annual rainfall)	30
Leakage from Reservoirs and release from groundwater storage.	5	Groundwater pumping	10
		Surface water pumping	5
		Evapotranspiration	5
TOTAL	50	TOTAL	50

10.5.Ground deformation

Hume will use the PF mining method which comprises a non-caving system where ground response is similar to conventional 1st workings mining methods. These methods were extensively practised prior to the advent of mechanisation but are rarely undertaken now. The PF method is the preferred mining method for the Hume project as it significantly minimises groundwater impacts compared to full extraction mining. Deformation (dilation) from 1st workings is limited to minor movement in the roof above roadways, extending upwards a maximum of about 3 m, depending on road width, horizontal stress magnitudes, roof rock strength, and rock bolting (or other support) strategy. Dilation typically extends about 2 m into the roof for common 1st workings mine plans. Extensional strains in the overburden are significantly smaller, and extend a shorter vertical distance, than for full extraction mining. Deformation in the dilated zone comprises enlargement of defect apertures and minor cracking. The dilated zone undergoes a marked increase in K, and is usually completely drained. Above the dilated zone, negligible deformation occurs and saturation is maintained.

Anecdotal information from the Berrima mine indicates the roof was extremely competent except in areas mined towards the end of the mine life (to the north), where a significant structural zone was encountered.

For the Hume project, intervening pillars are designed to remain intact and receive the overburden weight shed from over the roadways.

The dilated zone and coal seam are surrounded by a compressional zone (the pressure arch and abutments) (Booth 1986) within which K decreases. In numerical simulation, the compressional zone is described using a drain conductance. In a 1st workings operation where the workings are a network of headings, rooms, and pillars, a multicellular hydraulic head pattern will be induced in the lower strata around the mine openings (Booth 1986). Higher in the profile, the cellularity diminishes and hydraulic head contours flatten (Booth 1986), inducing more diffuse effects in the hydraulic head field. Figure 10.1 presents a typical hydraulic head field generated around square mine openings for a 1st workings operation (after Figure 3 of Booth 1986).

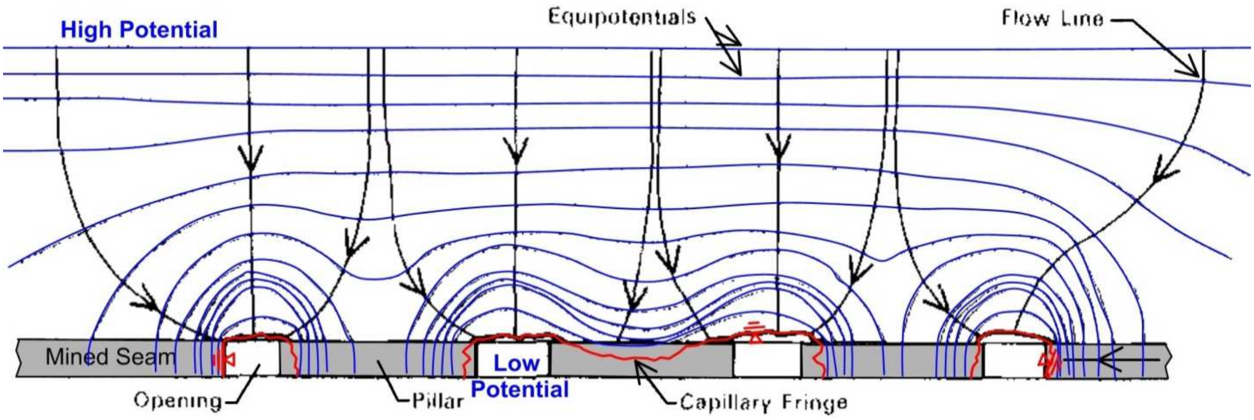


Figure 10.1. A typical hydraulic head field generated around a 1st workings network of openings (after Booth 1986).

10.5.1. Full extraction

Full extraction (longwalls or pillar removal) is not proposed at Hume, but was practiced at the Berrima mine (as pillar extraction). This method creates deformation which extends significantly higher into the overburden than for non-caving methods. Caving from full extraction results in the creation of two distinct zones above a panel (Tammetta 2013): the Collapsed Zone and the Disturbed Zone (Figure 10.2, after Tammetta 2016). The Collapsed Zone is severely disturbed and is completely drained of groundwater during caving, and is subsequently unable to maintain a positive pressure head. Groundwater flow is not laminar and Darcy's law is unlikely to be obeyed. The Disturbed Zone overlies the Collapsed Zone, and maintains positive groundwater pressure heads. Mine-induced desaturation in the Disturbed Zone occurs above the chain pillars. Results from Tammetta (2013) indicate the height of desaturation (H) for pillar extraction panels is between 50% and 60% of their longwall counterparts. This is caused by the differing patterns of caving between these types.

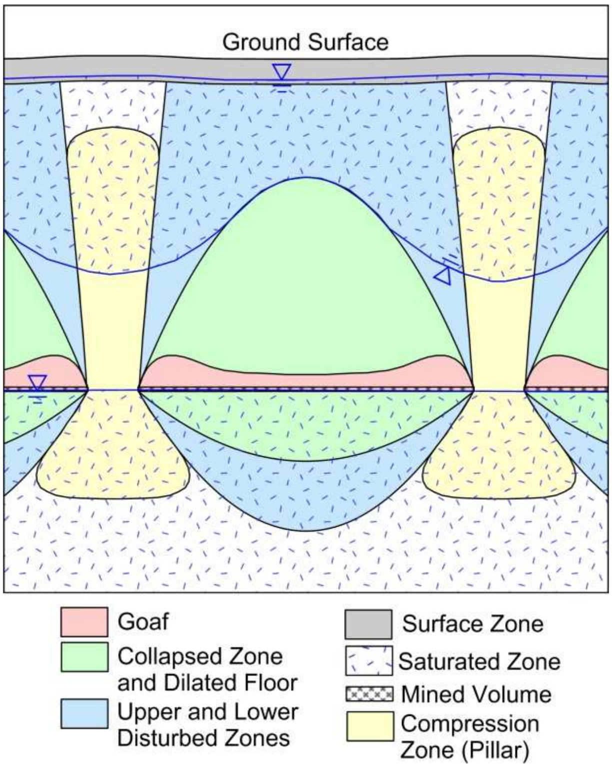


Figure 10.2. Adopted conceptual model for desaturation above full extraction workings (after Tammetta 2016). The subsurface is shown as a cross-section normal to the panel long dimension.

In the study area, the Berrima mine practiced full extraction (pillar extraction). H for mined pillar extraction panels is calculated using the equation in Tammetta (2013) for longwall panels, with pillar extraction H taken as 60% of longwall H for the same panel geometry.

10.6.Conceptual model

The elements of the conceptual model discussed above are presented pictorially in Figure 10.3, based on the hydraulic head cross section of Figure 6.1. It shows a schematic representation of the hydraulic head field that will be created by the PF mining method of the Hume Mine.

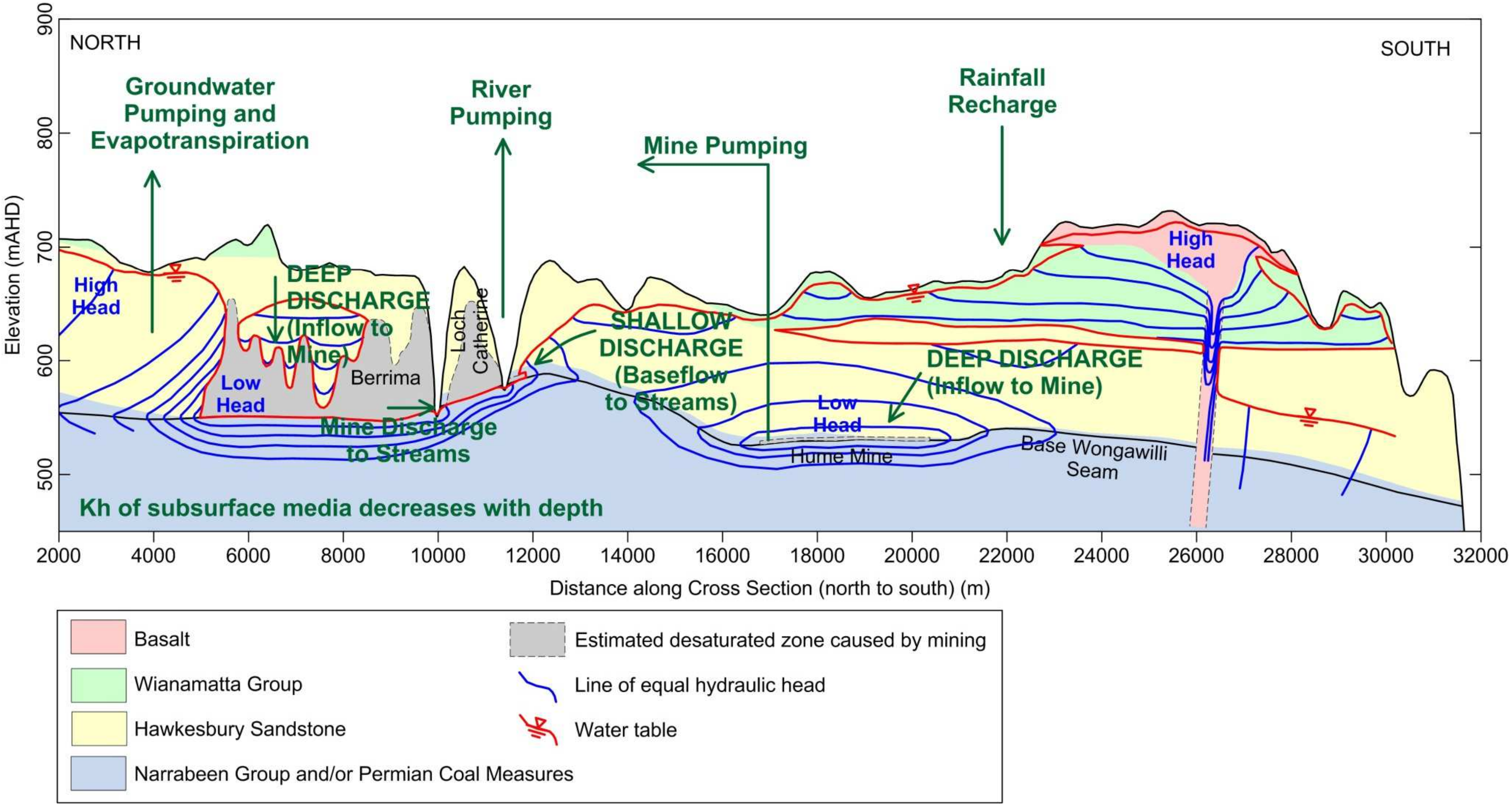


Figure 10.3. Hydrogeological conceptual model.

11. References

Bamberry WJ. 1991. Stratigraphy and sedimentology of the late Permian Illawarra Coal Measures, Southern Sydney Basin, NSW. Doctoral thesis, University of Wollongong,

Barlow PM and Moench AF. 1999. WTAQ - A Computer Program for Calculating Drawdowns and Estimating Hydraulic Properties for Confined and Water-Table Aquifers. USGS Water-Resources Investigations Report 99-4225.

Barlow PM, Cunningham WL, Zhai T, and Gray M. 2015. U.S. Geological Survey Groundwater Toolbox, a graphical and mapping interface for analysis of hydrologic data (version 1.0)—User guide for estimation of base flow, runoff, and groundwater recharge from streamflow data: U.S. Geological Survey Techniques and Methods, book 3, chap. B10, 27p.

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. June.

Booth CJ. 1986. Strata-Movement Concepts and the Hydrogeological Impact of Underground Coal Mining. Ground Water, Volume 24, No. 4, p. 507-515

Boughton, W. C. 1993. A hydrograph-based model for estimating the water yield of ungauged catchments. Hydrology and Water Resources Symposium, Institution of Engineers Australia, Newcastle, p. 317-324.

Blue Circle Southern Cement Limited (BCSC). 1993. Geological Assessment, Coal Authorisation Area No. 382. December.

Boral Cement. 2013a Berrima Colliery in Medway POELA Act 2011 Monitoring Data 7 June 2013.

Boral Cement. 2013b Berrima Colliery in Medway POELA Act 2011 Monitoring Data 31 December 2013.

Boral Cement. 2015 Berrima Colliery in Medway POELA Act 2011 Monitoring Data 10 February 2015.

Boral Cement. 2016 Berrima Colliery in Medway POELA Act 2011 Monitoring Data 11 April 2016.

Boyle D.R. 1994. Design of a seepage meter for measuring groundwater fluxes in the nonlittoral zones of lakes-Evaluation in a boreal forest lake. Limnology and Oceanography, Volume 39, Issue 3, p. 670-681.

Chapman TG and Maxwell AI. 1996. Baseflow separation – Comparison of numerical methods with tracer experiments. Hydrological and Water Resources Symposium, Institution of Engineers Australia, Hobart, p. 539-545.

Eckhardt K. 2012. Technical Note: Analytical sensitivity analysis of a two parameter recursive digital baseflow separation filter. Hydrology and Earth System Sciences, 16, p. 451-455.

Eckhardt, K. 2005. How to construct recursive digital filters for baseflow separation, Hydrol. Process., 19, p. 507-515.

EMGA Mitchell McLennan 2011 Environmental assessment, Berrima Colliery continued operations. May 2011.

EMM. 2016. Hume Coal Project Environmental Impact Assessment.

Furey P and Gupta VK. 2001. A physically based filter for separating base flow from streamflow time series. Water Resources Research, 37, p. 2709-2722.

Hart DJ, Bradbury KR, and Feinstein DT. 2006. The vertical hydraulic conductivity of an aquitard at two spatial scales. Ground Water, 44(2), p. 201-211.

Heywood CE. 1997. Piezometric-extensometric estimations of specific storage in the Albuquerque Basin, New Mexico. USGS Open-File Report 97-47.

Hillis RR, Enever JR, and Reynolds D. 1999. In Situ Stress Field of Eastern Australia. Australian Journal of Earth Sciences, Volume 46, p. 813-825.

Hutcheson, SM, Kipp JA, Dinger JS, Sendlein LVA, Carey DI, and Secrist GI. 2000a. Effects of Longwall Mining on Hydrology, Leslie County, Kentucky; Part 2: During-Mining Conditions. Kentucky Geological Survey, Report of Investigations 4, Series XII.

Hutcheson, SM, Kipp JA, Dinger JS, Carey DI, Sendlein LVA, and Secrist GI. 2000b. Effects of Longwall Mining on Hydrogeology, Leslie County, Kentucky; Part 3: Post-Mining Conditions. Kentucky Geological Survey, Report of Investigations 6, Series XII.

Huyck AAO, Pauwels VRN, and Verhoest NEC. 2005. A base flow separation algorithm based on the linearized Boussinesq equation for complex hillslopes. Water Resources Research, 41, W08415, doi:10.1029/2004WR003789.

Institute of Hydrology. 1980a. Low Flow Studies. Research report Volume 1. Institute of Hydrology, Wallingford, United Kingdom, 42 p.

Institute of Hydrology. 1980b. Low Flow Studies. Research report Volume 3: Catchment characteristic estimation manual. Institute of Hydrology, Wallingford, United Kingdom, 27 p.

International Environmental Consultants Pty Ltd (IEC). 2008. Berrima Colliery CCL748 SMP Application: Assessment of Mining Related Subsidence Impacts. Report prepared for Centennial Coal. September.

Kelly B, Brown S, and Merrick N. 2005. Hydrogeology of the Blue Mountains, NSW: Simulating impacts of bore abstraction and sewer tunnel inflows on stream base-flow. New Zealand Hydrological Society, IAH Australian Chapter, New Zealand Society of Soil Science.

McElroy Brian and Associates Pty Ltd (MBA). 1980. Authorisation No. 31 Half-Yearly Report for the Period 27.12.79 to 26.6.80. Report 1/7/7 prepared for Austen and Butta Limited. July.

Minova International Limited. 2006. The Minova Guide to Resin-Grouted Rockbolts. Piggott Black Bear, Cambridge, UK.

Nemcik J, Gale WJ, and Fabjanczyk MW. 2006. Methods of Interpreting Ground Stress Based on Underground Stress Measurements and Numerical Modelling. Proceedings, 2006 Coal Operators' Conference, University of Wollongong. Australasian Institute of Mining and Metallurgy Illawarra Branch.

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.

Parsons Brinckerhoff. 2015. Water Fieldwork and Monitoring Report. Draft Report 2200539A-RES-REP-7812 RevA prepared for Hume Coal Pty Ltd. November.

Paul PK, Zoback MD, and Hennings PH. 2009. Fluid flow in a fractured reservoir using a geomechanically constrained fault-zone-damage model for reservoir simulation. SPE Reservoir Evaluation and Engineering, Volume 12, No. 4, p. 562 – 575.

Pritchard S, Hehir W, Russell G. 2004. A review of the status of the groundwater resources in the Southern Highlands, NSW. NSW Department of Infrastructure, Planning, and Natural Resources. May.

Quinton WL, Hayashi M, and Carey SK. 2008. Peat hydraulic conductivity in cold regions and its relation to pore size and geometry. Hydrological Processes 22, p. 2829–2837.

Reid P. 1996. Effect of mining on permeability of rock strata in the Southern Coalfield. Symposium on Geology in Longwall Mining, 12–13 November, p. 273-280.

Risser DW, Gburek WJ, and Folmar GJ. 2005. Comparison of methods for estimating ground-water recharge and base flow at a small watershed underlain by fractured bedrock in the eastern United States. USGS Scientific Investigations Report 2005-5038, 31p.

Risser DW, Williams JH, Hand KL, Behr RA, and Markowski AK. 2013. Geohydrologic and water-quality characterization of a fractured-bedrock test hole in an area of Marcellus shale gas development, Bradford County, Pennsylvania. Pennsylvania Geological Survey, 4th ser., Open-File Report OFMI 13–01.0, 49 p.

Rosenberry, DO and LaBaugh JW. 2008. Field techniques for estimating water fluxes between surface water and ground water: USGS Techniques and Methods 4–D2, 128p.

Russell GN. 2007. Hawkesbury Sandstone: groundwater attributes and geological influences. Poster presentation, UTS Hydrogeology 20th Anniversary Symposium, Sydney.

SCT Operations Pty Ltd. 2014. Hume Coal Geotechnical Studies as Part of the PFS Review. Report HUME4132_REV1 prepared for the Hume Coal Project. May.

Sigra Pty Ltd. 2012. In situ stress testing on borehole HU0040CH. Report Reference Number 343 prepared for Cockatoo Coal Pty Ltd. December.

Tammetta and Hawkes. 2009. Pump testing of Mesozoic Sandstones. IAH Sydney Basin Symposium, Sydney.

Tammetta P and Hewitt P. 2004. Hydrogeological properties of the Hawkesbury Sandstone in the Sydney Region. Australian Geomechanics, Volume 39, No. 3, p. 91-107.

Tammetta P. 2016. Estimation of the Change in Storage Capacity above Mined Longwall Panels. Ground Water, early view, January 2016, doi: 10.1111/gwat.12405.

Tammetta P. 2015. Estimation of the Change in Hydraulic Conductivity above Mined Longwall Panels. Ground Water, Volume 53, Issue 1, p. 122-129.

Tammetta P. 2013. Estimation of the Height of Complete Groundwater Drainage above Mined Longwall Panels. Groundwater, Volume 51, Number 5, p. 723-734.

Taniguchi M, Burnett WC, Cable JE, and Turner JV. 2002. Investigation of submarine groundwater discharge. Hydrological Processes, Volume 16, Issue 11, pages 2115 - 2129, Special Issue: Japan Society of Hydrology and Water Resources.

Taniguchi M. and Fukuo Y. 1993. Continuous Measurements of Ground-Water Seepage Using an Automatic Seepage Meter. Groundwater, Volume 31, Number 4, p. 675 – 679.

Thomas DN, Biggin AJ, and Schmidt PW. 2000. A palaeomagnetic study of Jurassic intrusives from southern New SouthWales: further evidence for a pre-Cenozoic dipole low. Geophysical Journal International, Volume 140, p. 621–635.

Turner J.V. 2009. Estimation and prediction of the exchange of groundwater and surface water: field methodologies. eWater Technical Report. eWater Cooperative Research Centre, Canberra.

USDoE. 2008. Hydraulic Conductivity of Essentially Saturated Peat. Report No. WSRC-STI-2008-00113. Contract No. DE-AC09-96SR18500 with the U.S. Department of Energy.

Wahl KL and Wahl TL. 1988. Effects of Regional Ground-Water Declines on Streamflows in the Oklahoma Panhandle. Symposium on Water-Use Data for Water Resources Management, American Water Resources Association, Tucson, Arizona, pp. 239-249.

Wahl KL and Wahl TL. 1995. Determining the flow of Comal Springs at New Braunfels, Texas, in Proceedings of Texas Water 95, August 16–17, 1995, San Antonio, Tex.: American Society of Civil Engineers, p. 77-86.

Wong LS, Hashim R, and Ali FH. 2009. A Review on Hydraulic Conductivity and Compressibility of Peat. Journal of Applied Sciences, 9, p. 3207-3218.

Woods L and Wright G. 2003. Roundwood Water Supply – Groundwater Source Protection Report. Groundwater Section, Geological Survey of Ireland. March.

Zamora C. 2008. Estimating Water Fluxes Across the Sediment–Water Interface in the Lower Merced River, California. USGS Scientific Investigations Report 2007–5216, 47p.

coffey

Important information about your **Coffey** Report

As a client of Coffey you should know that site subsurface conditions cause more construction problems than any other factor. These notes have been prepared by Coffey to help you interpret and understand the limitations of your report.

Your report is based on project specific criteria

Your report has been developed on the basis of your unique project specific requirements as understood by Coffey and applies only to the site investigated. Project criteria typically include the general nature of the project; its size and configuration; the location of any structures on the site; other site improvements; the presence of underground utilities; and the additional risk imposed by scope-of-service limitations imposed by the client. Your report should not be used if there are any changes to the project without first asking Coffey to assess how factors that changed subsequent to the date of the report affect the report's recommendations. Coffey cannot accept responsibility for problems that may occur due to changed factors if they are not consulted.

Subsurface conditions can change

Subsurface conditions are created by natural processes and the activity of man. For example, water levels can vary with time, fill may be placed on a site and pollutants may migrate with time. Because a report is based on conditions which existed at the time of subsurface exploration, decisions should not be based on a report whose adequacy may have been affected by time. Consult Coffey to be advised how time may have impacted on the project.

Interpretation of factual data

Site assessment identifies actual subsurface conditions only at those points where samples are taken and when they are taken. Data derived from literature and external data source review, sampling and subsequent laboratory testing are interpreted by geologists, engineers or scientists to provide an opinion about overall site conditions, their likely impact on the proposed development and recommended actions. Actual conditions may differ from those inferred to exist, because no professional, no matter how qualified, can reveal what is hidden by earth, rock and time. The actual interface between materials may be far more gradual or abrupt than assumed based on the facts obtained. Nothing can be done to change the actual site conditions which exist, but steps can be taken to reduce the impact of unexpected conditions. For this reason, owners should retain the services of Coffey through the development stage, to identify variances, conduct additional tests if required, and recommend solutions to problems encountered on site.

Your report will only give preliminary recommendations

Your report is based on the assumption that the site conditions as revealed through selective point sampling are indicative of actual conditions throughout an area. This assumption cannot be substantiated until project implementation has commenced and therefore your report recommendations can only be regarded as preliminary. Only Coffey, who prepared the report, is fully familiar with the background information needed to assess whether or not the report's recommendations are valid and whether or not changes should be considered as the project develops. If another party undertakes the implementation of the recommendations of this report there is a risk that the report will be misinterpreted and Coffey cannot be held responsible for such misinterpretation.

Your report is prepared for specific purposes and persons

To avoid misuse of the information contained in your report it is recommended that you confer with Coffey before passing your report on to another party who may not be familiar with the background and the purpose of the report. Your report should not be applied to any project other than that originally specified at the time the report was issued.

Interpretation by other design professionals

Costly problems can occur when other design professionals develop their plans based on misinterpretations of a report. To help avoid misinterpretations, retain Coffey to work with other project design professionals who are affected by the report. Have Coffey explain the report implications to design professionals affected by them and then review plans and specifications produced to see how they incorporate the report findings.

Important information about your **Coffey** Report

Data should not be separated from the report*

The report as a whole presents the findings of the site assessment and the report should not be copied in part or altered in any way. Logs, figures, drawings, etc. are customarily included in our reports and are developed by scientists, engineers or geologists based on their interpretation of field logs (assembled by field personnel) and laboratory evaluation of field samples. These logs etc. should not under any circumstances be redrawn for inclusion in other documents or separated from the report in any way.

Geoenvironmental concerns are not at issue

Your report is not likely to relate any findings, conclusions, or recommendations about the potential for hazardous materials existing at the site unless specifically required to do so by the client. Specialist equipment, techniques, and personnel are used to perform a geoenvironmental assessment. Contamination can create major health, safety and environmental risks. If you have no information about the potential for your site to be contaminated or create an environmental hazard, you are advised to contact Coffey for information relating to geoenvironmental issues.

Rely on Coffey for additional assistance

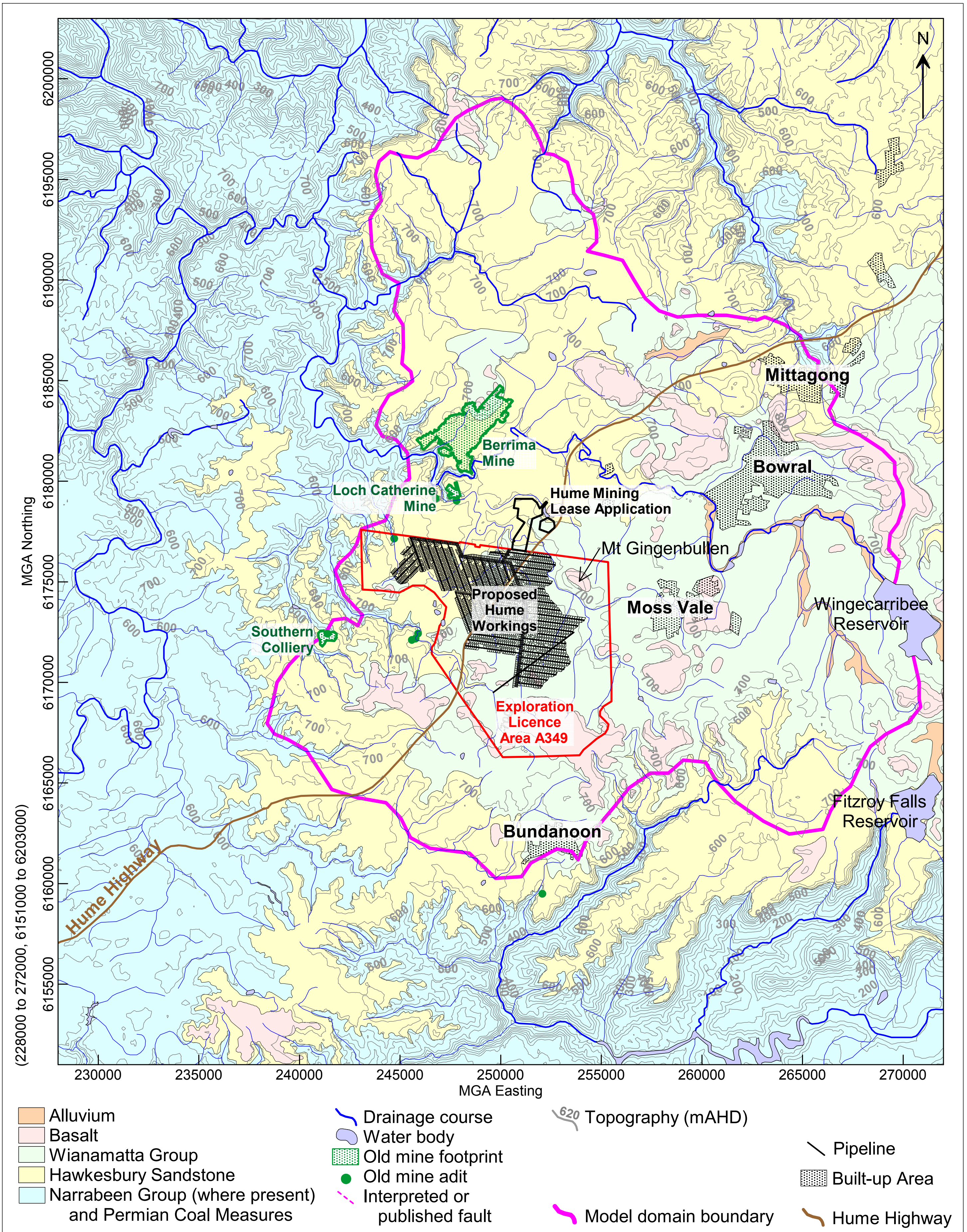
Coffey is familiar with a variety of techniques and approaches that can be used to help reduce risks for all parties to a project, from design to construction. It is common that not all approaches will be necessarily dealt with in your site assessment report due to concepts proposed at that time. As the project progresses through design towards construction,
speak with Coffey to develop alternative approaches to problems that may be of genuine benefit both in time and cost.

Responsibility

Reporting relies on interpretation of factual information based on judgement and opinion and has a level of uncertainty attached to it, which is far less exact than the design disciplines. This has often resulted in claims being lodged against consultants, which are unfounded. To help prevent this problem, a number of clauses have been developed for use in contracts, reports and other documents. Responsibility clauses do not transfer appropriate liabilities from Coffey to other parties but are included to identify where Coffey's responsibilities begin and end. Their use is intended to help all parties involved to recognise their individual responsibilities. Read all documents from Coffey closely and do not hesitate to ask any questions you may have.

* For further information on this aspect reference should be made to "Guidelines for the Provision of Geotechnical information in Construction Contracts" published by the Institution of Engineers Australia, National headquarters, Canberra, 1987.

Drawings



drawn	PT	coffey A TETRA TECH COMPANY	client:	Hume Coal Pty Limited
approved	RJB		project:	Hume Coal Project Groundwater Assessment
date	30 Jun 2016			
scale	1:250,000		title:	**Regional Locality Plan**
original size	A4		project no: GEOTLCOV25281AB	figure no: **Drawing 1**

Appendix A - Baseflow Analysis

1. Baseflow Analysis

The aim of baseflow separation for a streamflow record is to distinguish the following two streamflow components (Eckhardt 2012):

- Baseflow (groundwater discharging into the stream).
- Quick flow (surface runoff and interflow).

The term “runoff” refers to quick flow, or the higher frequency component of the two components extracted from a streamflow series.

Two commonly used methods for baseflow separation are filtering and local minimum searches. For the Hume Coal project the local minimum search is adopted. Both methods are discussed below.

1.1. Filtering method

Eckhardt (2012) provides a useful summary of filtering techniques for baseflow separation. The following text is a summary from that paper.

In the past, many baseflow separation methods have been proposed, amongst them the two parameter recursive digital filter of Eckhardt (2005), which has since been applied in numerous studies, sometimes under the name of “Eckhardt filter”. The equation for the Eckhardt Filter defines a low-pass filter, and represents a whole class of filter algorithms which are based on the widely accepted linear storage model (Eckhardt 2005).

Examples are the algorithms of Chapman and Maxwell (1996) and Boughton (1993). The filter of Chapman and Maxwell (1996) is derived from the Eckhardt Filter by fixing one of the filtering parameters (BFImax) to 0.5 (where BFImax is the maximum value of the baseflow index [the long-term ratio of baseflow to total streamflow] that can be modelled by the algorithm). These methods use only a time-series of streamflow as the observational input.

Filter algorithms which rely more on physics have been presented by Furey and Gupta (2001) and Huyck et al. (2005). In the algorithm of Furey and Gupta (2001), time series of streamflow and precipitation are required, and the following four parameters have to be specified:

- d (the time delay between precipitation and groundwater recharge).
- c1 (the ratio of overland flow to precipitation).
- c3 (the ratio of groundwater recharge to precipitation).
- a (the recession constant).

In the algorithm of Huyck et al. (2005) bk is a function of bk−1, bk−d , bk−d−1, yk−d , and yk−d−1. Twelve parameters have to be specified: d, c1, c3, and nine other parameters describing hydraulic characteristics and the shape of the hydrostratigraphic unit. Required are not only time series of streamflow and precipitation, but also a digital elevation model and information on the drainable porosity of the soil.

Filtering methods are prone to the error where calculated baseflow can be greater than streamflow. This is because a single recession constant is (usually) used, which may perform poorly when confronted with several accumulated recession pulses. When trimming is employed (ensuring baseflow is never larger than total flow), they are useful for analysis of the annual variation in baseflow, when magnitudes are constrained by results from the local minimum method.

1.2. Local minimum method

In the local minimum method, baseflow is estimated by analysing the minima in streamflow time series when partitioned into N-day periods. Unlike filtering methods, the local minimum method cannot calculate baseflows that are greater than streamflow, and makes no assumptions about recession character. Based on experience, and the preferred use of the method by overseas agencies, this method is considered superior to filtering for extraction of baseflow magnitudes. This method was therefore adopted for the current work.

For the Hume Coal Project, the local minimum method is implemented using the program BFI and the procedure of Wahl and Wahl (1995). The BFI program (Wahl and Wahl 1995) is based on a set of procedures developed by the Institute of Hydrology (1980a, b) in which the streamflow record is partitioned into intervals of length N-days.

In the standard method (the one used in the current work), the minimum streamflow during each N-day interval is then identified and compared to adjacent minimums to determine turning points. If 90% of a given minimum (the turning point test factor, f) is less than both adjacent minimums, then that minimum is a turning point. The baseflow hydrograph is completed by connecting the turning points. The current version allows the user to vary the values of N and f to permit tuning the algorithm for different catchments or to match other baseflow separation methods (Wahl and Wahl 1995). In the USGS Toolbox implementation (Barlow et al 2015) (the one used in the current work), turning points are identified continuously throughout the entire period of record, which avoids the creation of artificial turning points at the end of each year. This modification also changes how the daily values are partitioned after a year is completed in which the number of days in the year is not an even multiple of N.

In the modified approach, parameter f is replaced by a daily recession index K′, and the turning-point test considers the exact number of days between turning-point candidates. Results obtained using the modified approach will usually be very similar to those obtained by the standard approach if $K' = f^{1/N}$.

For each year of data, the flow record is analysed for varying values of N. The output is then visually examined on a graph to find the inflection point in the baseflow response. Figure 1 shows the interpretation graph for Gauge 212272 (Wingecarribee River at Berrima). Excluding dam release years, the inflection point is taken as 6 days. 1995 is a conspicuous dam release year. The apparent baseflow versus N function for these years has a more significant convex-up form, at large N.

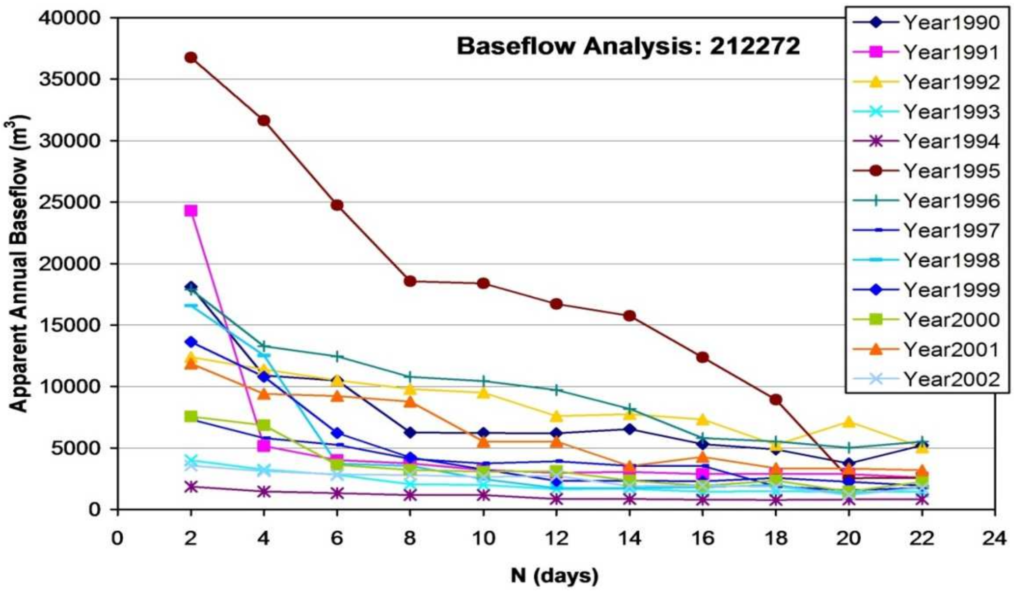


Figure 1. Baseflow analysis for gauge 212272.

The Nepean and Wingecarribee Rivers are regulated. Figure 2 shows the effect of controlled release from Wingecarribee Reservoir on the three Wingecarribee River Gauges (years with conspicuous dam releases are circled). Controlled dam releases do not affect the overall water balance of a drainage channel on a regional basis, except to afford increased consumption by evaporation from the increased surface area of a dam (which would otherwise not exist). However, over small periods and in proximity to such a dam (and depending on the release discharge versus time function), controlled releases can cause a component of surface runoff to masquerade as baseflow. The dam storage acts as a weak to moderate low-pass filter on the response of the drainage channel. However, this effect is attenuated with increasing distance downstream from the dam. Because of the complicating factors associated with dam releases, years with dam releases are removed from the analysis.

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 northern part of the 212238 catchment is similar to the central parts of the Wingecarribee River catchment, where Wianamatta Group soils are exploited for horticultural use (with a similar concentration of such enterprises). The analysis also accounts for evaporation from major dams (Wingecarribee Reservoir for gauges 212009, 212031, and 212272), and changes in dam storage.

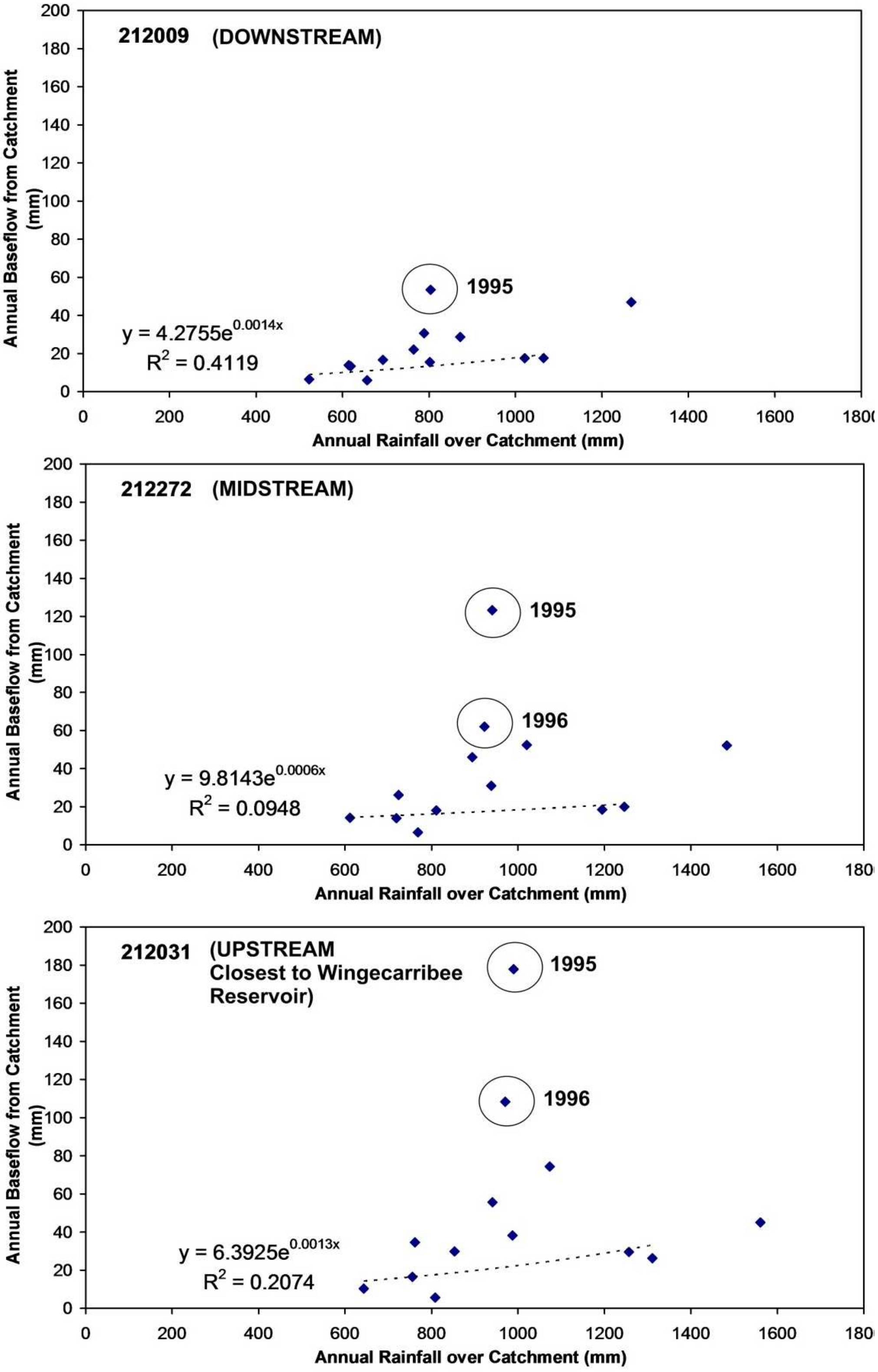
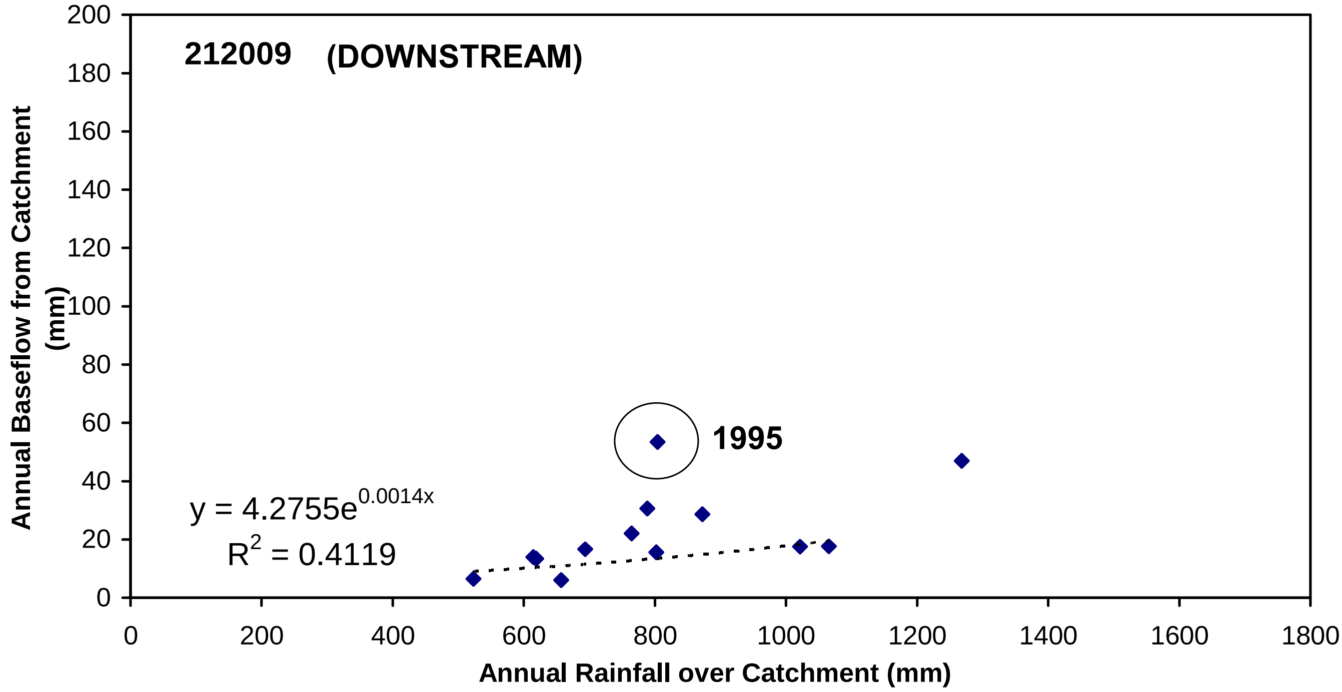


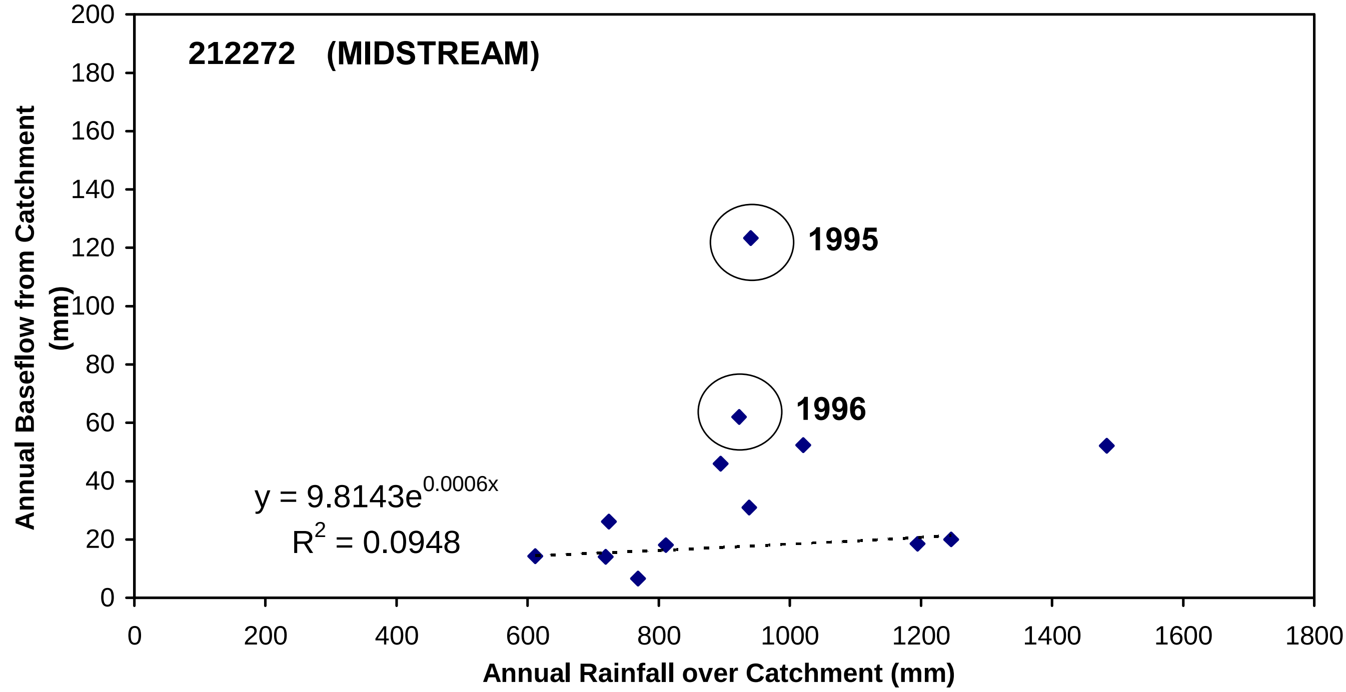
Figure 2. Estimated annual baseflow for the three Wingecarribee River gauges.

1.3. Results

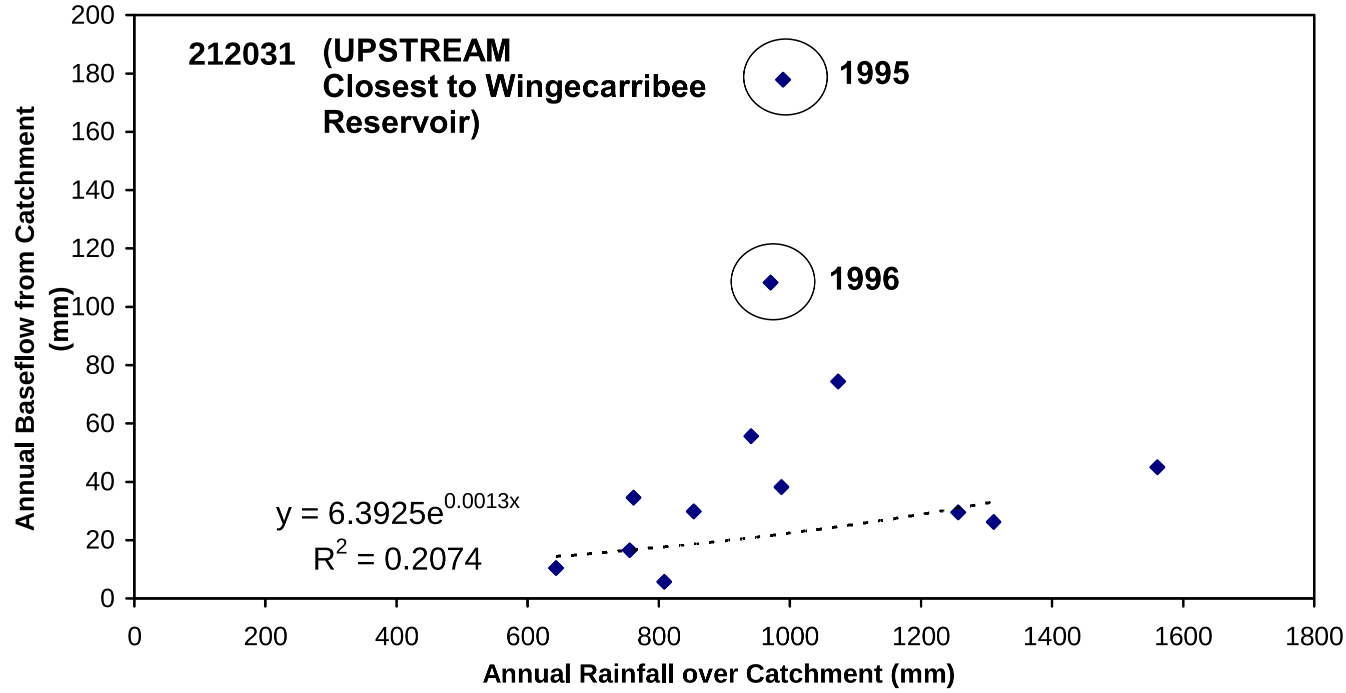
The following pages present additional results of the baseflow analysis undertaken for the Hume project, as charts of baseflow and surface runoff depths over the catchments. See the main report for a summary of the results.



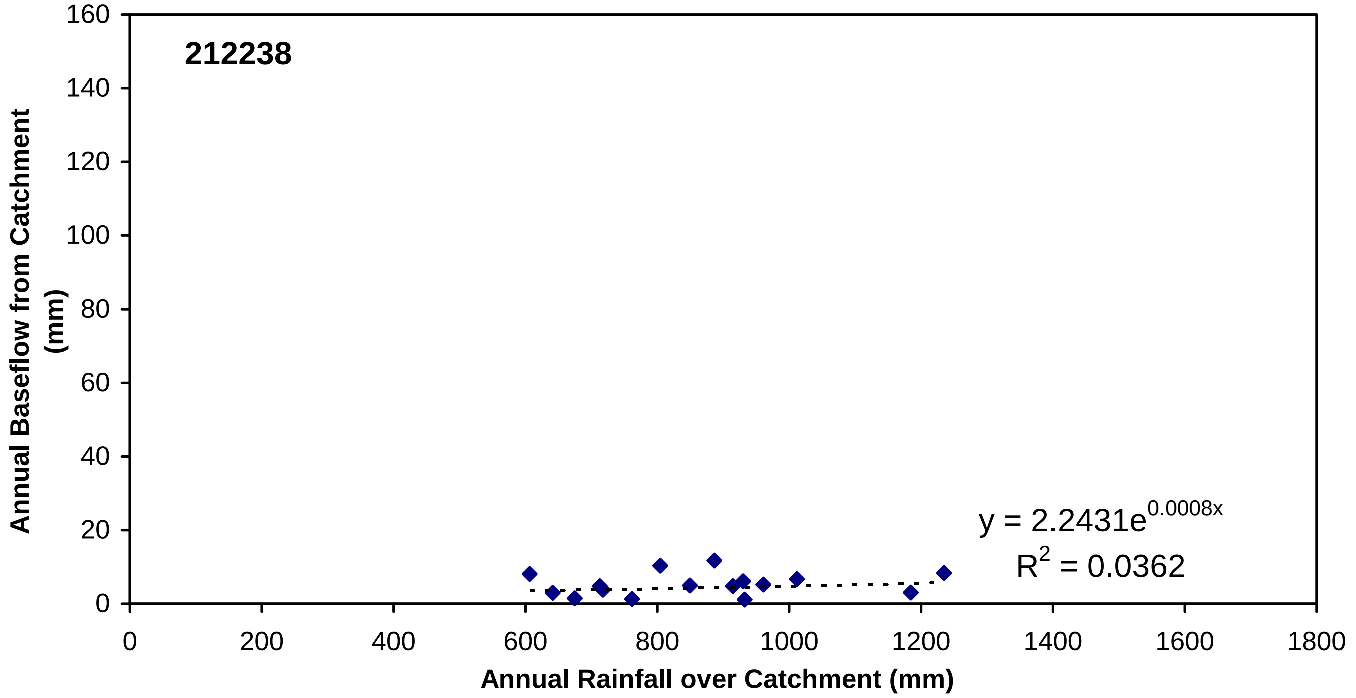
212009 (DOWNSTREAM)
1995
y = 4.2755e^0.0014x
R^2 = 0.4119
Annual Baseflow from Catchment (mm)
Annual Rainfall over Catchment (mm)
0
20
40
60
80
100
120
140
160
180
200
0
200
400
600
800
1000
1200
1400
1600
1800



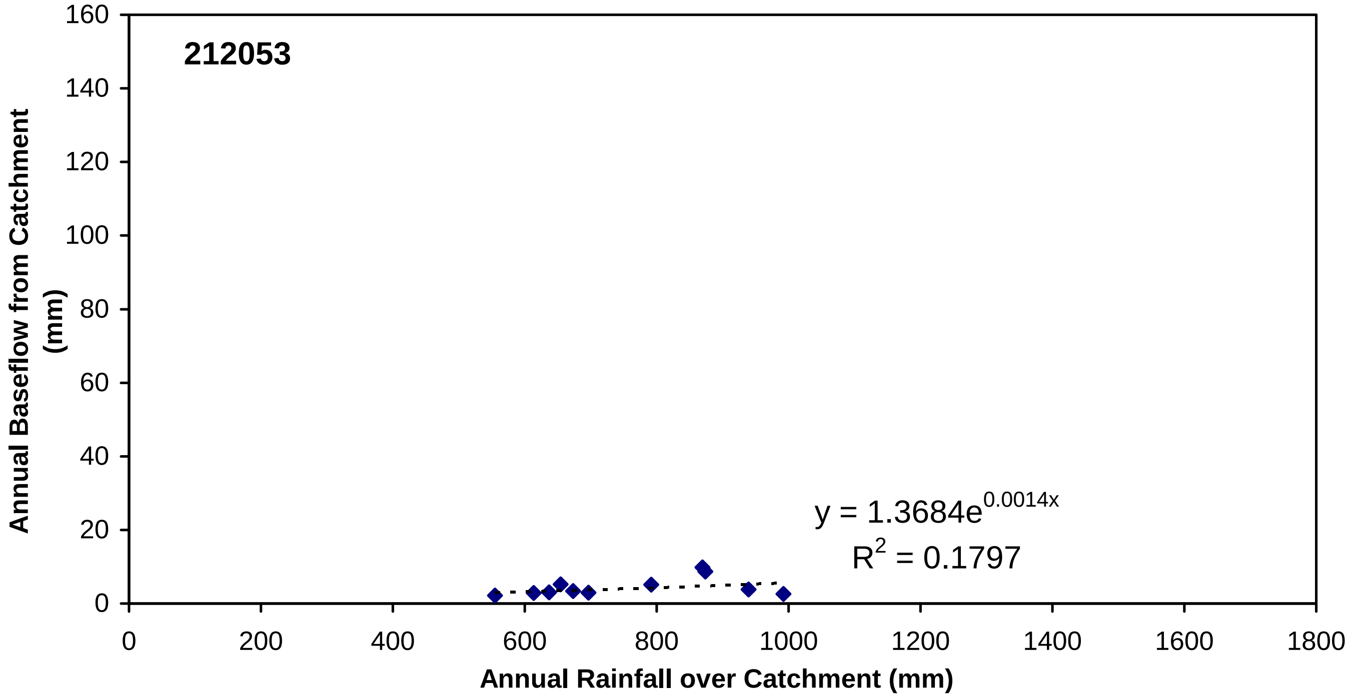
212272 (MIDSTREAM)
1995
1996
y = 9.8143e^0.0006x
R^2 = 0.0948
Annual Baseflow from Catchment (mm)
Annual Rainfall over Catchment (mm)
0
20
40
60
80
100
120
140
160
180
200
0
200
400
600
800
1000
1200
1400
1600
1800



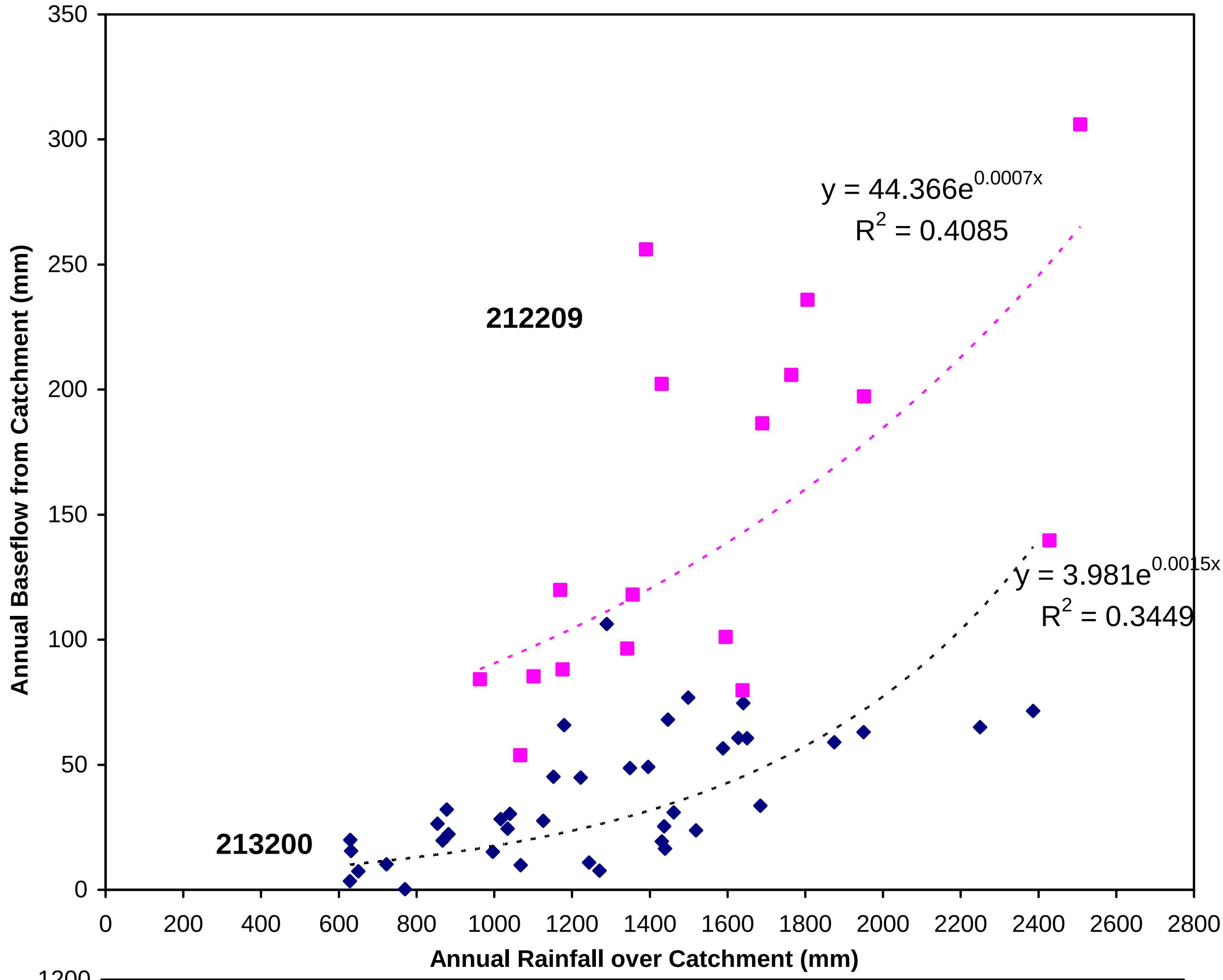
212031 (UPSTREAM
Closest to Wingecarribee
Reservoir)
1995
1996
y = 6.3925e^0.0013x
R^2 = 0.2074
Annual Baseflow from Catchment (mm)
Annual Rainfall over Catchment (mm)
0
20
40
60
80
100
120
140
160
180
200
0
200
400
600
800
1000
1200
1400
1600
1800



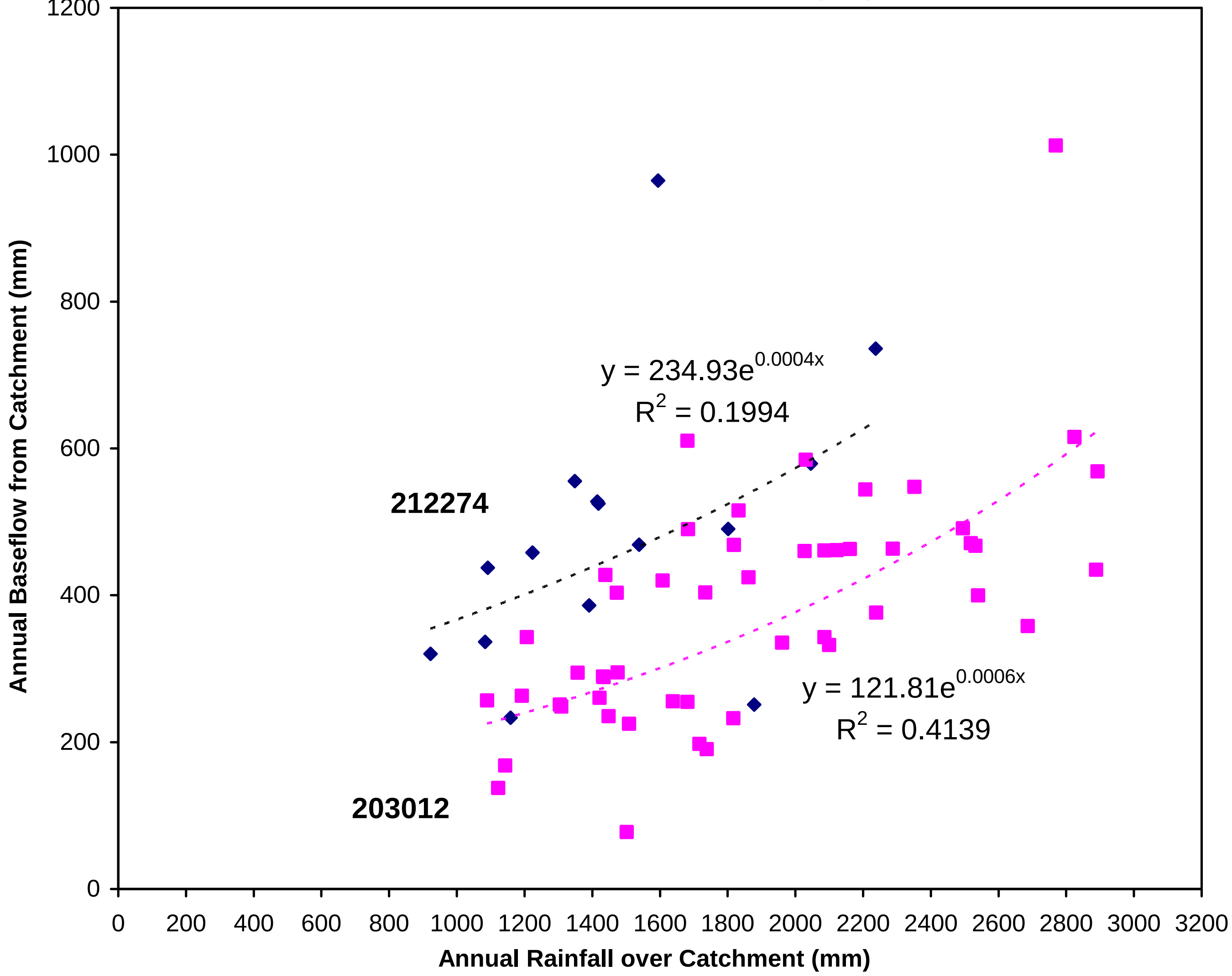
212238
y = 2.2431e^0.0008x
R^2 = 0.0362
Annual Baseflow from Catchment (mm)
Annual Rainfall over Catchment (mm)
0
20
40
60
80
100
120
140
160
0
200
400
600
800
1000
1200
1400
1600
1800



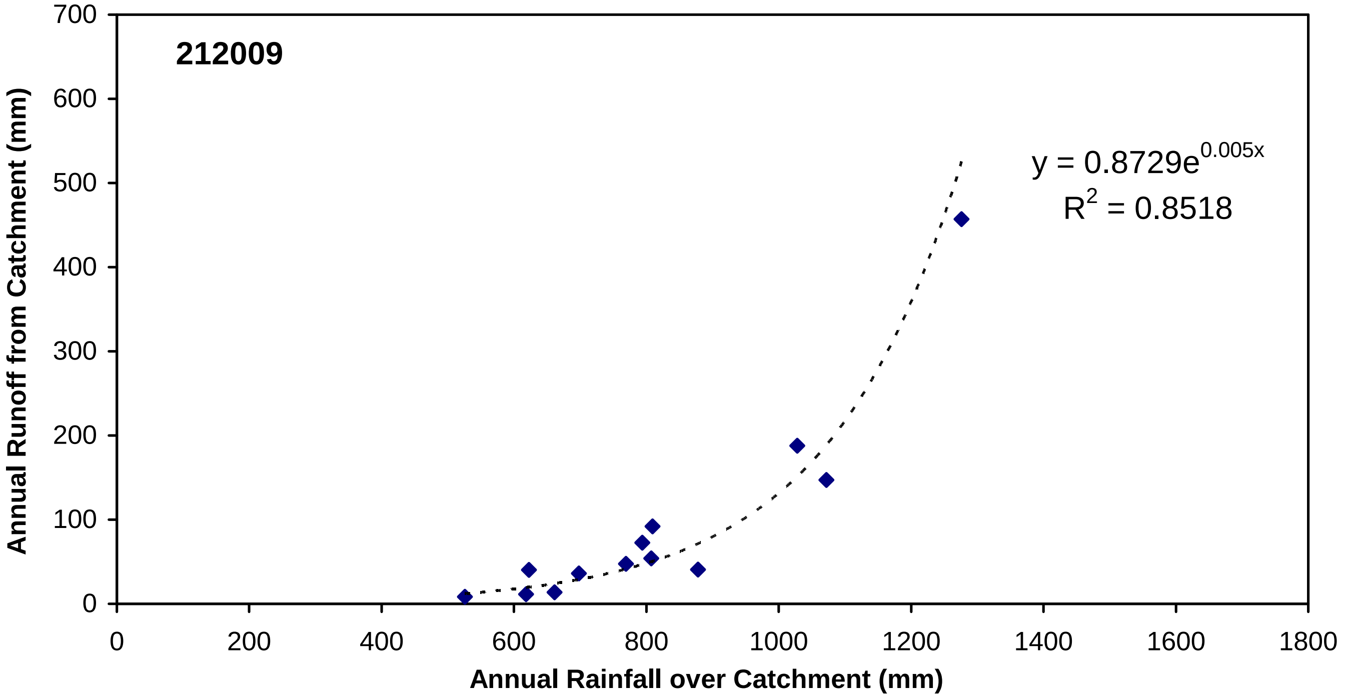
212053
y = 1.3684e^0.0014x
R^2 = 0.1797
Annual Baseflow from Catchment (mm)
Annual Rainfall over Catchment (mm)
0
20
40
60
80
100
120
140
160
0
200
400
600
800
1000
1200
1400
1600
1800

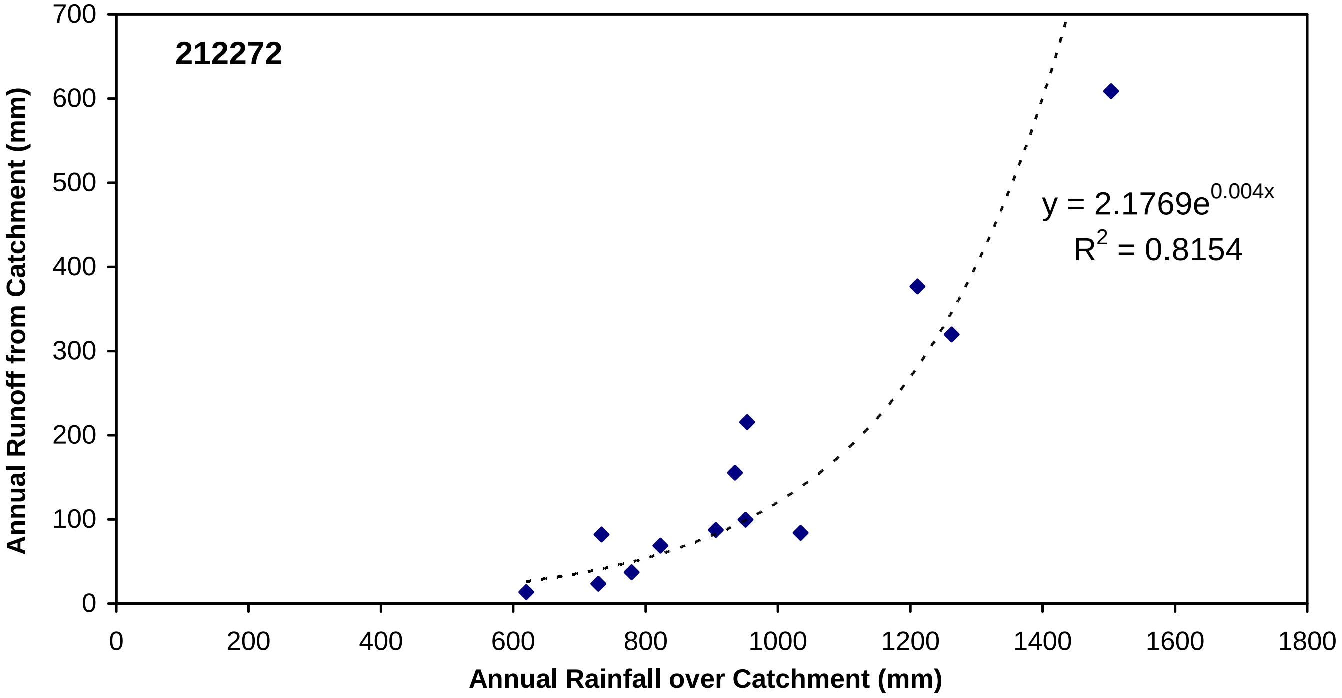


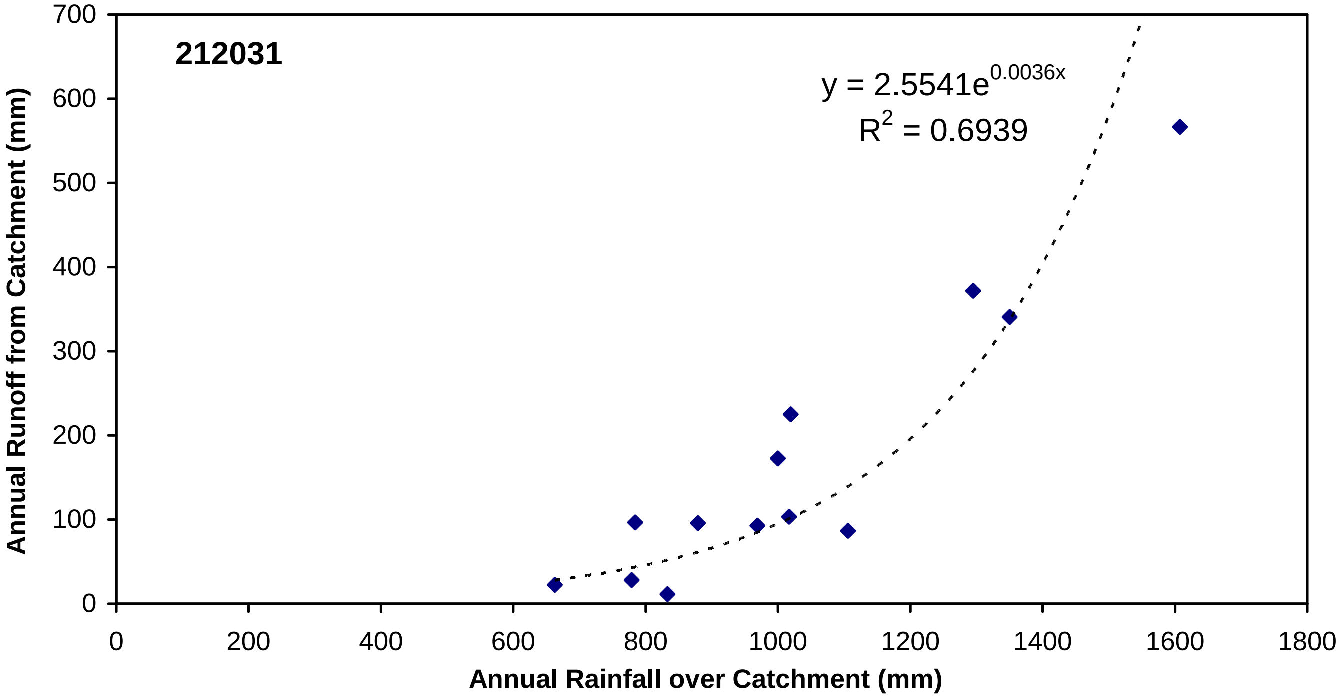
y = 44.366e^0.0007x
R^2 = 0.4085
212209
y = 3.981e^0.0015x
R^2 = 0.3449
213200
Annual Baseflow from Catchment (mm)
Annual Rainfall over Catchment (mm)

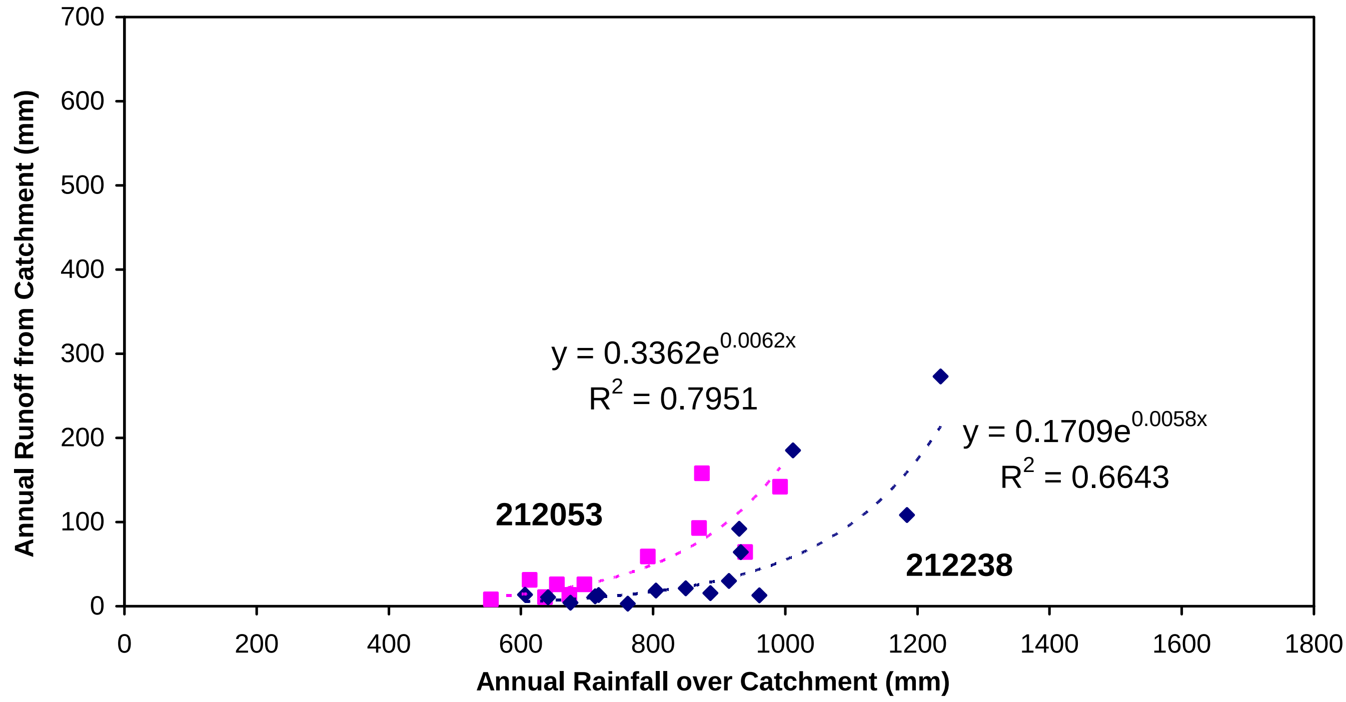


y = 234.93e^0.0004x
R^2 = 0.1994
212274
y = 121.81e^0.0006x
R^2 = 0.4139
203012
Annual Baseflow from Catchment (mm)
Annual Rainfall over Catchment (mm)

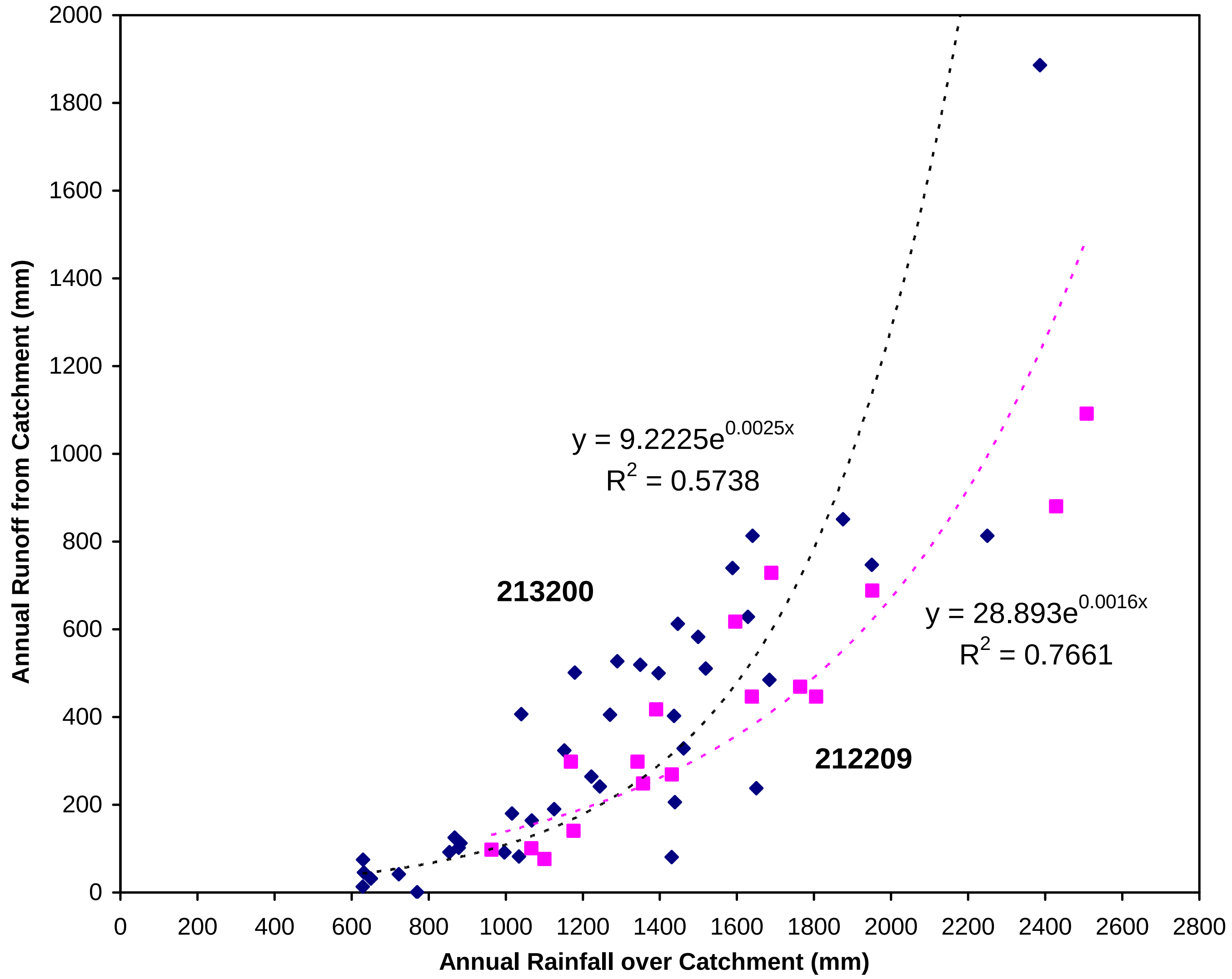

212009
y = 0.8729e^0.005x
R^2 = 0.8518
Annual Runoff from Catchment (mm)
Annual Rainfall over Catchment (mm)
0
100
200
300
400
500
600
700
0
200
400
600
800
1000
1200
1400
1600
1800


212272
y = 2.1769e^0.004x
R^2 = 0.8154
Annual Runoff from Catchment (mm)
Annual Rainfall over Catchment (mm)
0
100
200
300
400
500
600
700
0
200
400
600
800
1000
1200
1400
1600
1800

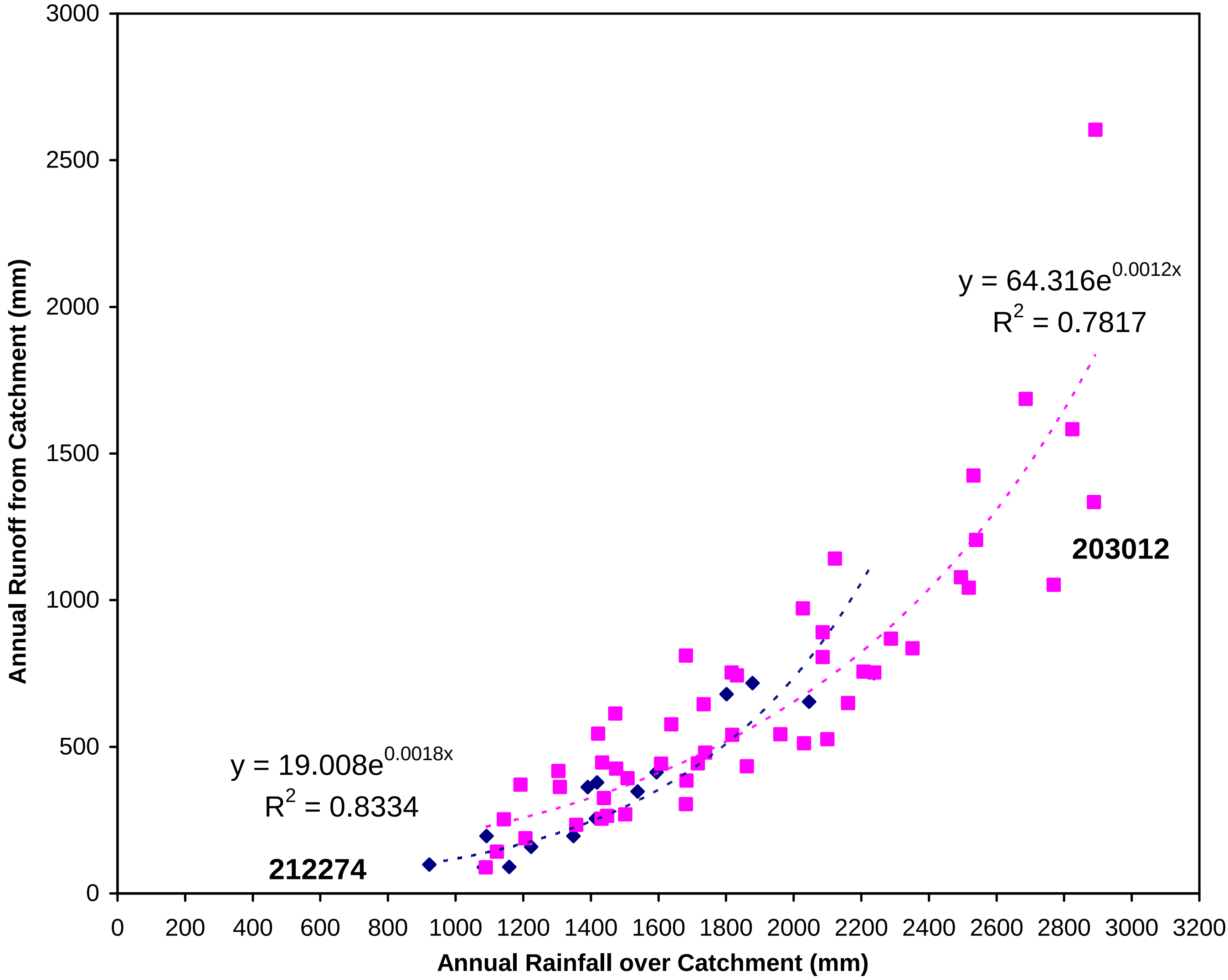

212031
y = 2.5541e^0.0036x
R^2 = 0.6939
Annual Runoff from Catchment (mm)
Annual Rainfall over Catchment (mm)
0
100
200
300
400
500
600
700
0
200
400
600
800
1000
1200
1400
1600
1800



y = 0.3362e^0.0062x
R^2 = 0.7951
y = 0.1709e^0.0058x
R^2 = 0.6643
212053
212238
Annual Runoff from Catchment (mm)
Annual Rainfall over Catchment (mm)
0
100
200
300
400
500
600
700
0
200
400
600
800
1000
1200
1400
1600
1800



y = 9.2225e^0.0025x
R^2 = 0.5738
y = 28.893e^0.0016x
R^2 = 0.7661
213200
212209
Annual Runoff from Catchment (mm)
Annual Rainfall over Catchment (mm)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800



3000
2500
2000
1500
1000
500
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
Annual Runoff from Catchment (mm)
Annual Rainfall over Catchment (mm)
y = 64.316e0.0012x
R2 = 0.7817
203012
y = 19.008e0.0018x
R2 = 0.8334
212274

Appendix B - Specific Capacity Analysis

Specific capacity (Sc) is the pumping rate divided by the drawdown in the pumped bore at a specified time. Most tests in the database were of 1 day duration, so the drawdown at 1 day is selected or estimated.

An analysis is undertaken using tests where temporal drawdown data are available. For each test, Sc is calculated at 1 day. Transmissivity is interpreted from temporal drawdown at the pumped bore using the Jacob method for confined conditions (Tj). The quantity (Tj – Sc)/Tj is then plotted against pumping rate and the relationship approximated with a trendline. This relationship is then used to convert Sc for tests where temporal drawdown is unavailable (the majority of government records).

The method assumes the bores in the database are approximately similar in hydraulic behaviour (well loss component), reasonable for the current database. It also assumes that dissimilarities in screened lithology are minor.

Table B1 lists the eight bores used to find a relationship, and Figure B1 shows the resulting relationship.

Table B1. Bore tests used for specific capacity analysis.

Bore	Registration Number	Hole diameter (mm)	Casing diamete (mm)	Pumping Rate (L/s)	Test Duratio (days)	Tj* (m2/day)	Interpretation	Specific Capacity for Pumping Time = 1 day			
								Pumping Rate (m3	Drawdow (m)	Sc (m2/day)	(Tj - Sc)/Tj
Belbin	GW106150	165	160	0.8	1	14	AGE 2010	69	7.4	9	0.33
Culpepper M	GW066593			0.3	0.07	56	AGE 2010	26	0.58^	45	0.20
H98		165	160	5.2	1	103	This study	449	8.0	56	0.45
Wongonbra	GW108194	200	N/A	20	7	243	This study	1728	34.8	50	0.80
Summer Dell	GW105950	200	N/A	11.4	2	180	This study (dat	985	16.0	62	0.66
Ravenswood	GW110236	200	N/A	9.2	1	56	This study (dat	795	20.5	39	0.31
Wongonbra	GW108194	200	N/A	17.8	2	176	This study (dat	1538	14.6	105	0.40
Wongonbra 2	GW108195	200	N/A	8.3	1.2	20	This study (dat	717	47.0	15	0.24

* Tj = Jacob T
^ Estimated for pumping time of 1 day

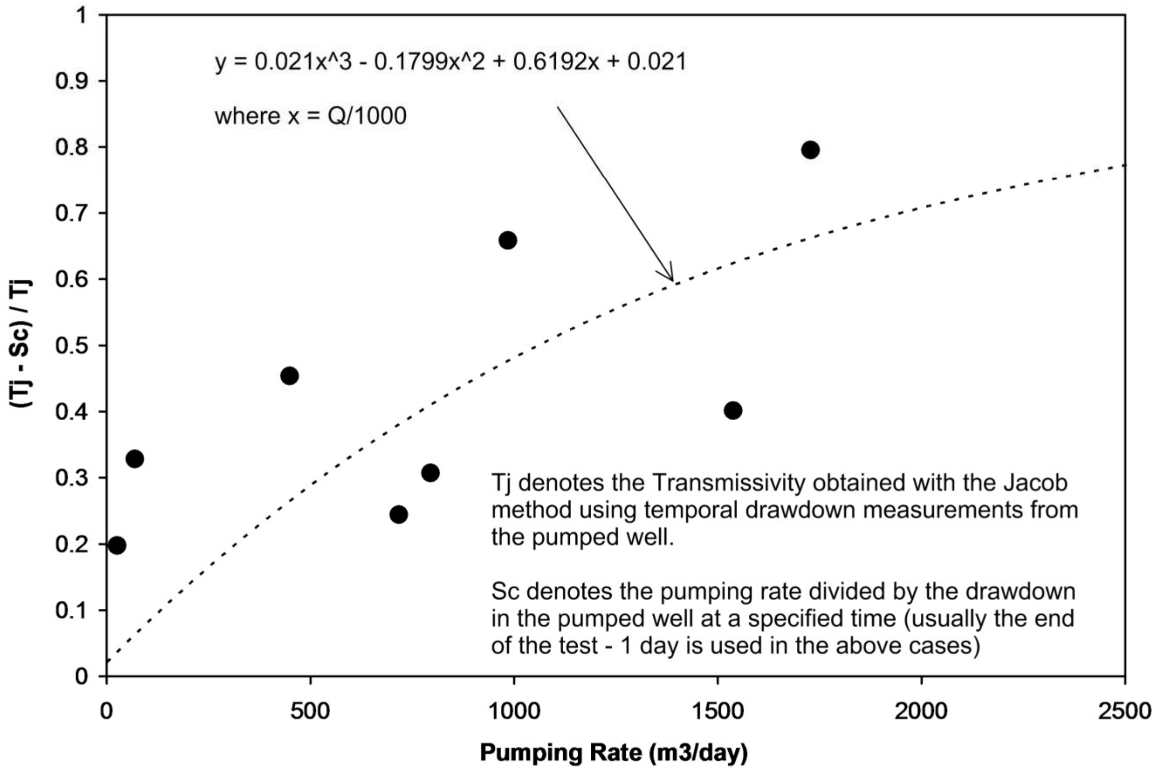


Figure B1. Results of specific capacity analysis for tests in Table B1.

Appendix C - Additional Hydraulic Conductivity Analysis

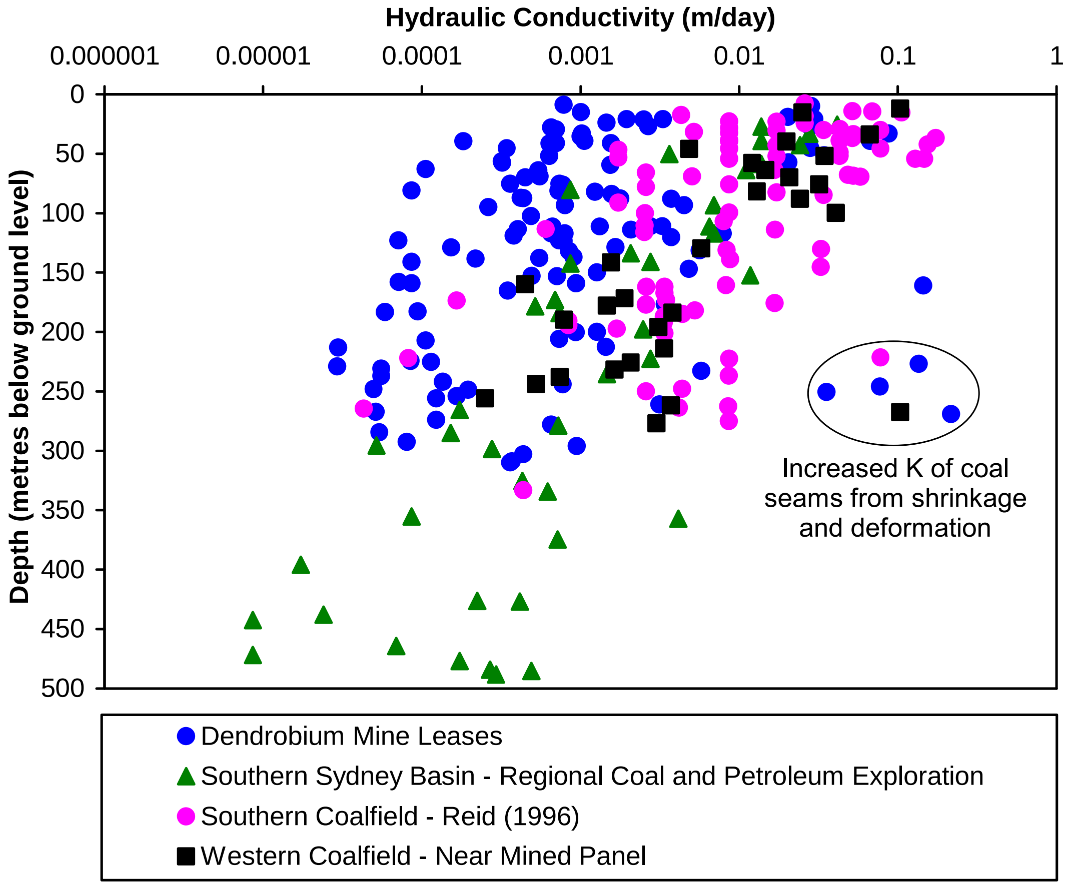
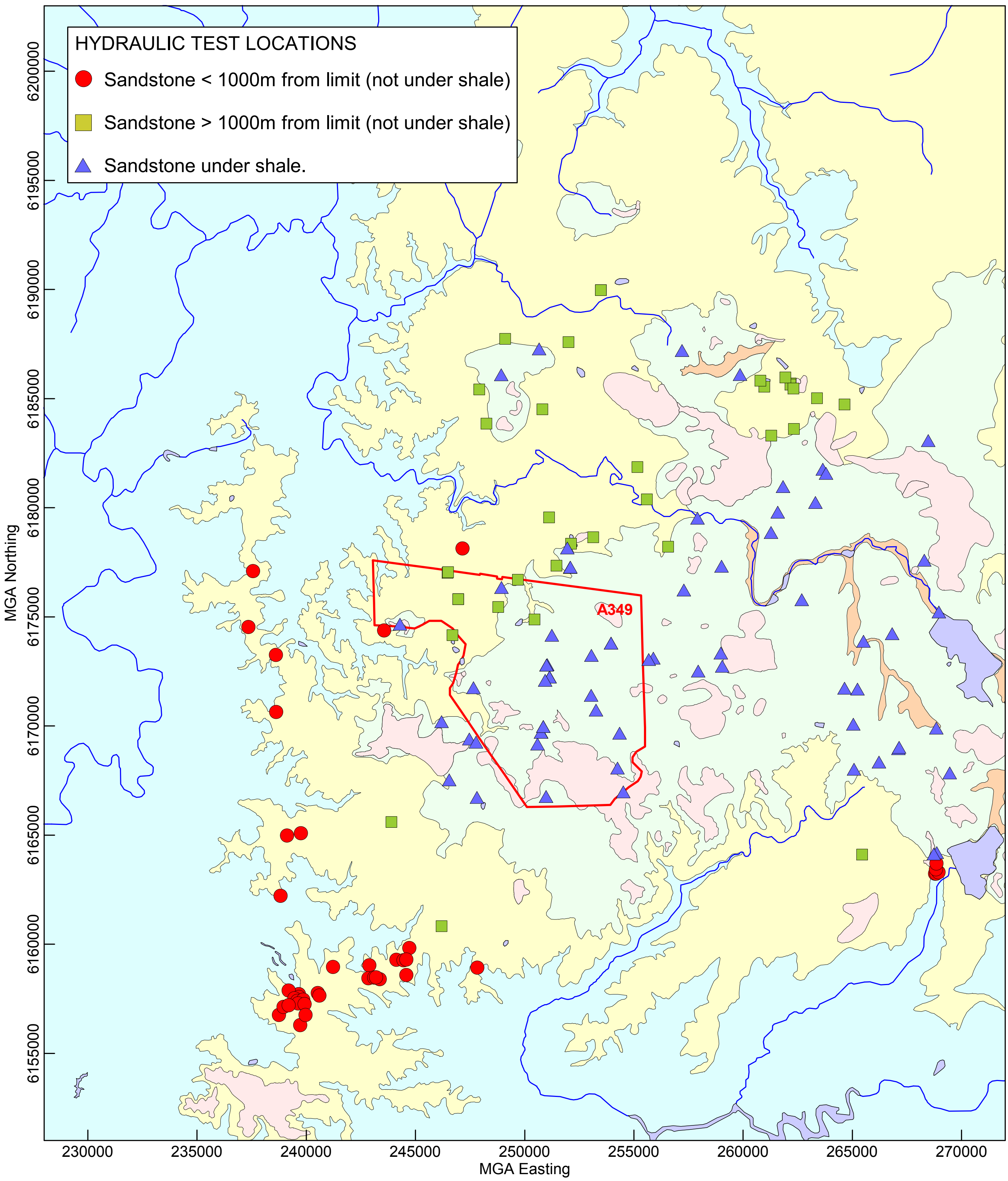
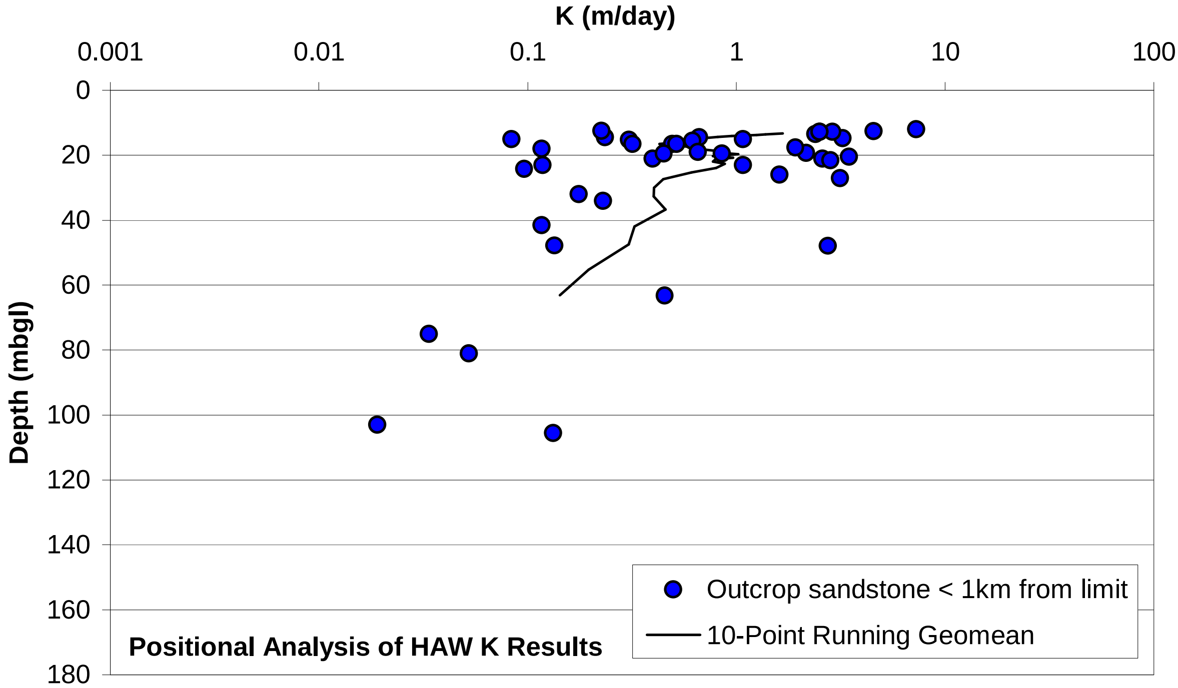
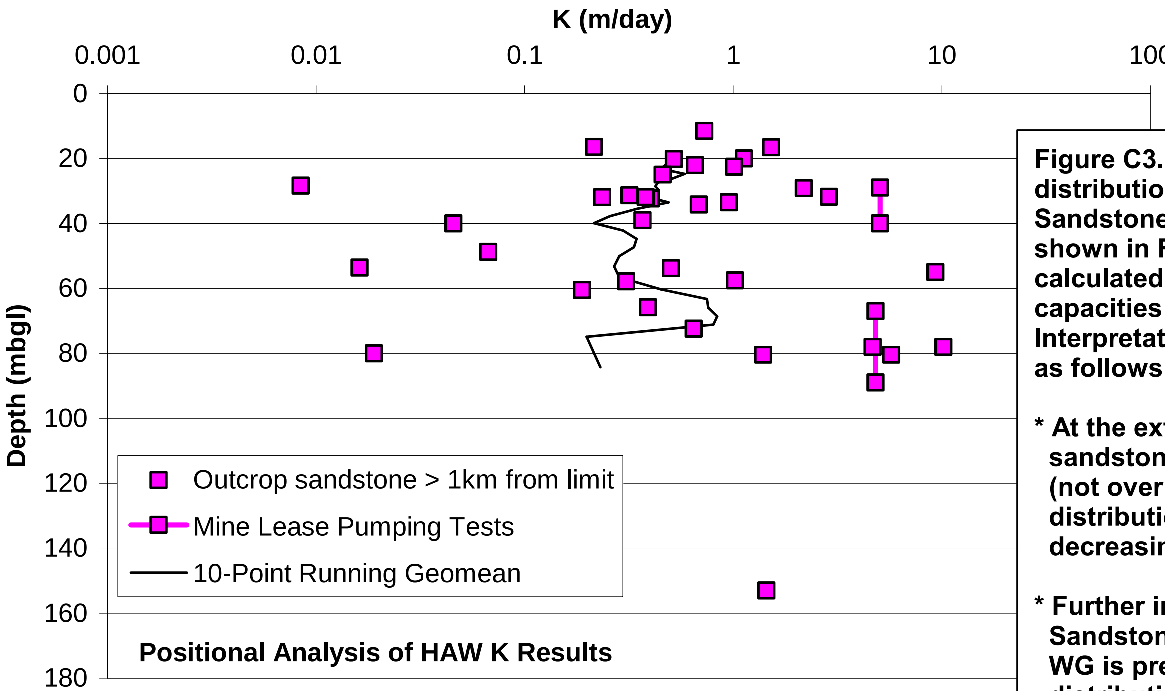


Figure C1. Packer test K distributions for the regional Southern Coalfield and the Dendrobium mine leases, showing measurements obtained in coal seams proximal to full extraction workings, which have been deformed by shrinkage (from degassification) and stress reduction.

Figure C2. Positional analysis of Hawkesbury Sandstone K using specific capacities and pumping test results. The map shows the segregation of data into the following locations:
*** Less than 1km from the lateral sandstone limit.**
*** Greater than 1km from the lateral sandstone limit, but not overlain by the Wianamatta Group.**
*** Wherever overlain by the Wianamatta Group.**
Trends for Sandstone K versus depth for each grouping are shown overleaf.







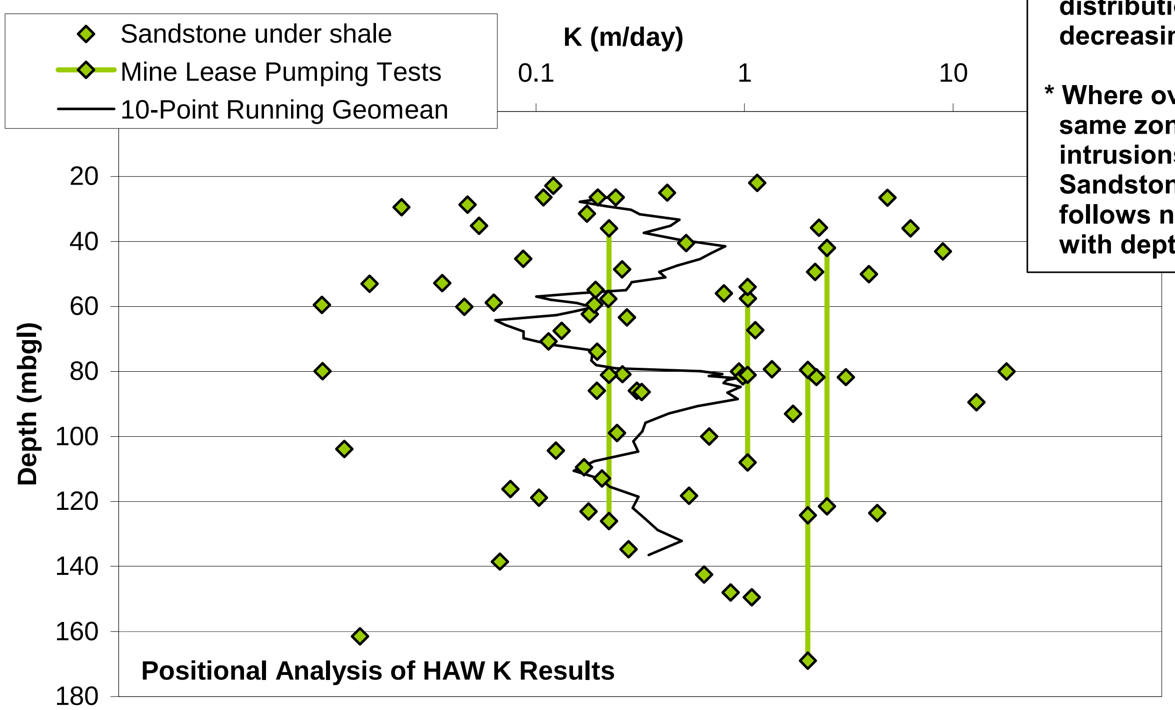


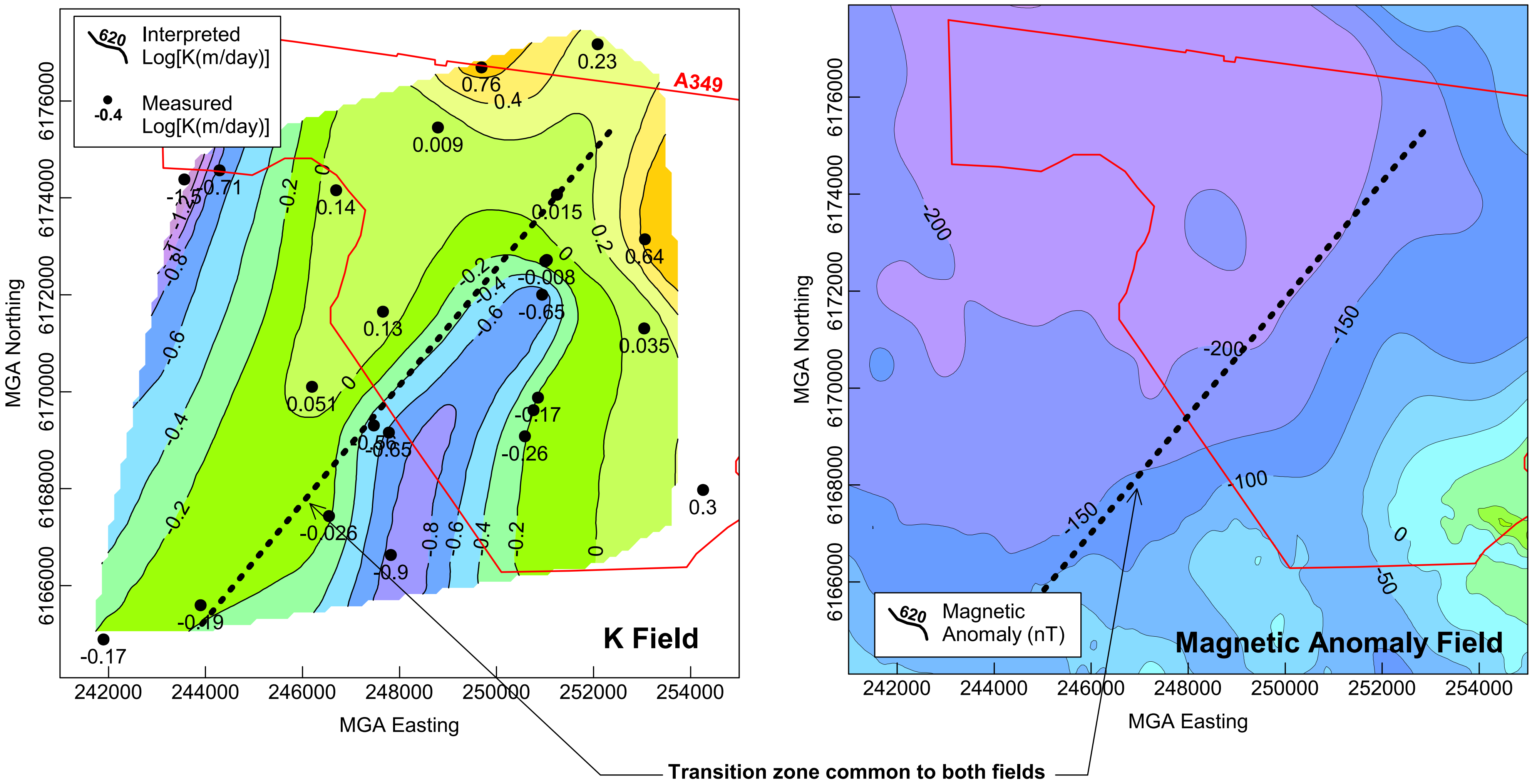
Figure C3. The K versus depth distributions for Hawkesbury Sandstone, for the groupings shown in Figure C2. K is calculated from specific capacities and pumping tests. Interpretation of the results is as follows:

*** At the extremities of the sandstone lateral extent (not overlain by WG), the K distribution follows a typical decreasing trend with depth.**

*** Further into the body of the Sandstone unit, but where no WG is present, the K distribution follows a weaker decreasing trend with depth.**

*** Where overlain by WG (the same zone as where igneous intrusions are present) the Sandstone K distribution follows no discernable trend with depth.**

Figure C4. Comparison of the interpreted K distribution for Hawkesbury Sandstone (over a vertical interval between 14m to 44m above its base) to the regional magnetic anomaly.



Appendix D - Hydraulic Head Database

Piezometer	Easting (MGA)	Northing (MGA)	RL Ground (mAHD)	RL Casing (mAHD)	Drilled Depth (mbgl)	Screen (mbgl) From	Screen (mbgl) To	Sandpack (mbgl) From	Sandpack (mbgl) To	Screened Stratum	L (m)	Comment
Hume Coal Monitoring												
H18A	246696	6174166	691.74	691.67	108	96	99	95	99	WW	4	
H18B	246695	6174159	691.97	691.89	114	75	88	73	88	HAW	15	
H19A	243557	6174381	720.65	720.55	108	100	103	100	103	WW	3	
H19B	243562	6174379	720.46	720.36	88	70	81	69	81	HAW	12	
H20A	244258	6176920	703.25	703.18	80	71	77	71	77	HAW	6	Dry (SWL < 626 mAHD)
H20B	244255	6176930	703.67	703.59	114	80	86	78	86	WW	8	
H23A	250769	6169622	680.47	680.38	140	135	138	135	138	WW	3	Decommissioned.
H23B	250763	6169620	680.63	680.55	132	118	130	116	130	HAW	14	Replaced by H142A to
H23C	250755	6169617	680.76	680.69	100	84	97	82	97	HAW	15	H142C
H32LDA	249532	6173533	646.60	646.78	152	108	114	106	117	WW	11	A and B in same hole
H32LDB	249532	6173533	646.60	646.73	152	57	88	54	89	HAW	35	
H35A	250523	6172486	681.43	682.16	152	53	77	50	78	HAW	28	
H35B	250531	6172487	680.84	681.52	35	15	34	14	35	WG	21	
H37A	246551	6167440	703.79	703.70	111	101	105	101	107	ICM	6	WW absent
H37B	246546	6167438	703.77	703.69	90	72	87	70	90	HAW	20	
H38A	248783	6175453	658.53	657.67	117	105	108	103	110	WW	7	
H38B	248788	6175452	658.44	658.33	78	74	77	72	78	HAW	6	
H38C	248793	6175452	658.31	658.17	63	55	62	52	63	HAW	11	
H42A	250988	6166688	702.50	702.43	173	156	159	153	161	WW	8	
H42C	250985	6166678	702.00	701.92	150	142	150	135	150	HAW	15	
H43XA	247147	6178127	692.04	691.96	111	95	101	93	103	WW	10	
H43XB	247152	6178133	691.77	691.69	87	77	86	75	87	HAW	12	
H44XA	242285	6164084	641.94	641.92	12	8	11	7	12	WW	5	
H44XB	242281	6164077	647.00	646.96	5	4	5	3.5	5	HAW	2	
H56XB	245225	6169198	735.45		140	132	140	130	140	HAW	10	
H56XC	245234	6169198	735.51		26	19	25	17	26	Basalt	9	
H72A	252074	6177157	640.12	640.05	129	124	128	121	129	WW	8	
H72B	252083	6177169	640.43	640.36	99	92	98	88	98	HAW	10	
H72C	252091	6177180	640.85	640.77	46	39	45	35	46	HAW	11	
H73A	251015	6172718	656.46	657.00	172	151	169	149	172	ICM Lower	23	
H73B	251029	6172717	655.78	656.35	124	119	123	117	124	WW	7	
H73C	251035	6172717	655.50	656.13	86	79	85	77	86	HAW	9	
H88A	253059	6173144	655.44	655.37	156	143	146	141	148	WW	7	
H88B	253059	6173144	655.33	655.26	150	121	126	119	128	HAW	9	

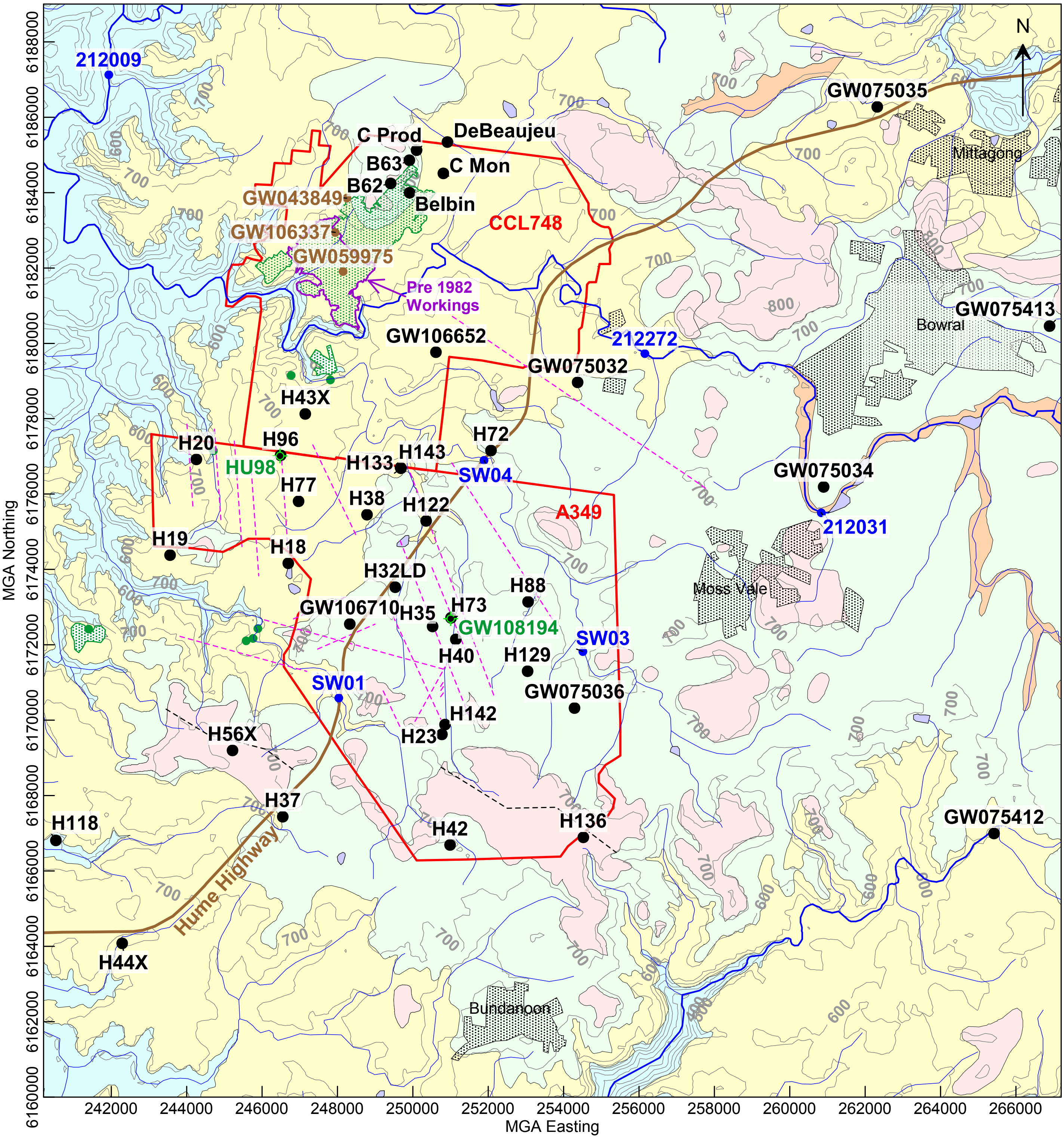
HAW: Hawkesbury Sandstone. WW: Wongawilli Seam. WG: Wianamatta Group. ICM: Illawarra Coal Measures. SS: Sandstone. Sh: Shale.

Piezometer	Easting (MGA)	Northing (MGA)	RL Ground (mAHD)	RL Casing (mAHD)	Drilled Depth (mbgl)	Screen (mbgl)		Sandpack (mbgl)		Screened Stratum	L (m)	Comment
						From	To	From	To			
Hume Coal Monitoring												
H96A	246489	6177025	699.21	699.14	147	111	120	108	120	ICM Lower	12	
H96B	246491	6177029	699.10	699.00	101	92	98	91	101	WW	10	
H96C	246494	6177045	683.00	682.94	89	69	87	67	89	HAW	22	
H118A	240529	6166811	612.50		15.3	7	13	5	15.3	HAW	10	Near swamp (under peat)
H129A	253042	6171301	679.10	679.04	177	166	170	165	171	WW	6	
H129B	253044	6171306	679.20	679.11	177	146	153	146	153	HAW	7	
H133A	249685	6176683	648.15	647.98	141	119	126	115	127	ICM Lower	12	Decommissioned.
H133B	249688	6176688	648.17	648.04	113	108	113	108	113	WW	5	Replaced by H143A to
H133C	249690	6176694	648.03	647.94	84	80	83	77	84	HAW	7	H143C
H136A	254521	6166894	718.49	718.36	216	199	203	196	203	WW	7	
H136B	254517	6166890	718.52	718.40	168	157	168	155	168	HAW	13	
H136C	254513	6166887	718.51	718.40	60	52	59	50	60	Basalt	10	
H142A	250856	6169881	672.43		130.8	127	130	126	131	WW	5	Replacement for H23A
H142B	250855	6169886	672.32		119.8	112	118	110	120	HAW	10	Replacement for H23B
H142C	250855	6169892	672.23		86.8	81	84	79	86.8	HAW	8	Replacement for H23C
H143A	249671	6176708	649.55		125.8	115	125	116	126	ICM Lower	10	Replacement for H133A
H143B	249672	6176703	649.59		113	109	112	107	113	WW	6	Replacement for H133B
H143C	249673	6176697	649.45		95.9	92	95	88	95.9	HAW	8	Replacement for H133C
H40_1	251140	6172143	656.51	656.51	129	120	120	VWP	VWP	WW	Point	Packer testing. Core K.
H40_2	251140	6172143	656.51	656.51	129	107	107	VWP	VWP	HAW	Point	
H40_3	251140	6172143	656.51	656.51	129	81	81	VWP	VWP	HAW	Point	
H40_4	251140	6172143	656.51	656.51	129	39	39	VWP	VWP	HAW	Point	
H77_1	246966	6175811	689.74	689.74	98	87	87	VWP	VWP	WW	Point	Packer testing. Core K.
H77_2	246966	6175811	689.74	689.74	98	72	72	VWP	VWP	HAW	Point	
H77_3	246966	6175811	689.74	689.74	98	58	58	VWP	VWP	HAW	Point	
H122_1	250352	6175286	634.50	634.50	120	112	112	VWP	VWP	WW	Point	Packer testing. Core K.
H122_2	250352	6175286	634.50	634.50	120	86	86	VWP	VWP	HAW	Point	
H122_3	250352	6175286	634.50	634.50	120	45	45	VWP	VWP	HAW	Point	
H122_4	250352	6175286	634.50	634.50	120	15	15	VWP	VWP	HAW	Point	
GW106652	250614	6179763	652.32	652.85	120	25	120	Open hole		HAW	95	Intersects WW seam.
GW106710	248326	6172551	672.39	672.70	115	64	108	Open hole		HAW	44	

HAW: Hawkesbury Sandstone. WW: Wongawilli Seam. WG: Wianamatta Group. ICM: Illawarra Coal Measures. SS: Sandstone. Sh: Shale.

Piezometer	Easting (MGA)	Northing (MGA)	RL Ground (mAHD)	RL Casing (mAHD)	Drilled Depth (mbgl)	Screen (mbgl)		Sandpack (mbgl)		Screened Stratum	L (m)	Comment
						From	To	From	To			
Berrima Mine Monitoring												
Belbin (GW106150)	249914	6183996		691.40	186	132	186	Open hole		HAW	54	
Culpepper P (GW101581)	250100	6185126		693.00	41		41	Open hole		HAW	< 41	
Culpepper M (B28)	250809	6184507		677.90	143		143	Open hole		HAW	> 100	Bore collapsed mid 2012
DeBeaujeu (GW028373)	250915	6185343	678.00	678.00	50	7	50	Open hole		HAW	42	RL estimated from DEM
B62_1	249411	6184243	727.00	727.00	181	58	58	VWP	VWP	HAW	Point	
B62_2	249411	6184243	727.00	727.00	181	126	126	VWP	VWP	HAW	Point	
B62_3	249411	6184243	727.00	727.00	181	170	170	VWP	VWP	WW	Point	
B63_1	249907	6184861	738.00	738.00	185	85	85	VWP	VWP	HAW	Point	
B63_2	249907	6184861	738.00	738.00	185	133	133	VWP	VWP	HAW	Point	
B63_3	249907	6184861	738.00	738.00	185	177	177	VWP	VWP	WW	Point	
Regional Government Monitoring												
G75032_1	254374	6178962	678.23	678.75	91	24	29	1	31	HAW	30	
G75032_2	254374	6178962	678.23	678.65	91	73	88	2	91	HAW	90	
G75033_1	273474	6170523	692.96	693.58	101	30	35	1	36	SS	35	
G75033_2	273474	6170523	692.96	693.04	101	89	99	50	101	SS/Sh	51	
G75034	260898	6176191	660.01	660.73	101	90	100	50	101	WG	51	
G75035	262322	6186276	648.25	648.17	91	74	89	1	91	HAW	90	
G75036	254286	6170323	660.24	660.87	100	73	84	2	85	SS	84	
G75412	265421	6166998	650.07		70	52	64	44	70	SS	26	
G75413	266895	6180460	710.69		151	108	151	Open hole		WG	43	
Private Bores Overlying Berrima Mine Workings												
GW043849	248247	6183852			99	4	99	Open hole				WW top appr. 125mbgl.
Stock. Installed 01.02.1974. Water Level 76.2m below ground. Area mined after 1977.												
GW106337	247940	6182940			122		122					WW top appr. 125mbgl.
Stock / Domestic. Installed 16.11.2002. Intersected coal seams. Went dry 17.08.2005 then backfilled (license cancelled). Area mined before 1977.												
GW059975	248146	6181907			92	3	92	Open hole				WW top appr. 125mbgl.
Stock / Domestic. Installed 01.04.1983. Water Level 36.6m below ground. Area mined before 1977.												

HAW: Hawkesbury Sandstone. WW: Wongawilli Seam. WG: Wianamatta Group. ICM: Illawarra Coal Measures. SS: Sandstone. Sh: Shale.



Subsurface flow barrier emplaced during model calibration.

- Alluvium
- Basalt
- Wianamatta Group
- Hawkesbury Sandstone
- Narrabeen Group (where present) and Permian Coal Measures

- Drainage course
- Water body
- Old mine footprint
- Old mine adit
- Interpreted or published fault

- GW106337 Hume pumping test bore
- 620 Topography (mAHD)
- H72 Groundwater monitoring piezometer / well
- GW106337 Private bore over workings

- SW01 Flow gauge
- Pipeline
- Built-up Area
- Hume Highway

drawn	PT	client:	Hume Coal Pty Limited
approved	RJB	project:	Hume Coal Project Groundwater Assessment
date	29 Jul 2016		
scale	1:150,000	title:	**Monitoring Piezometer and Well Locations**
original size	A4	project no: GEOTLCOV25281AB	figure no: **Figure D1**

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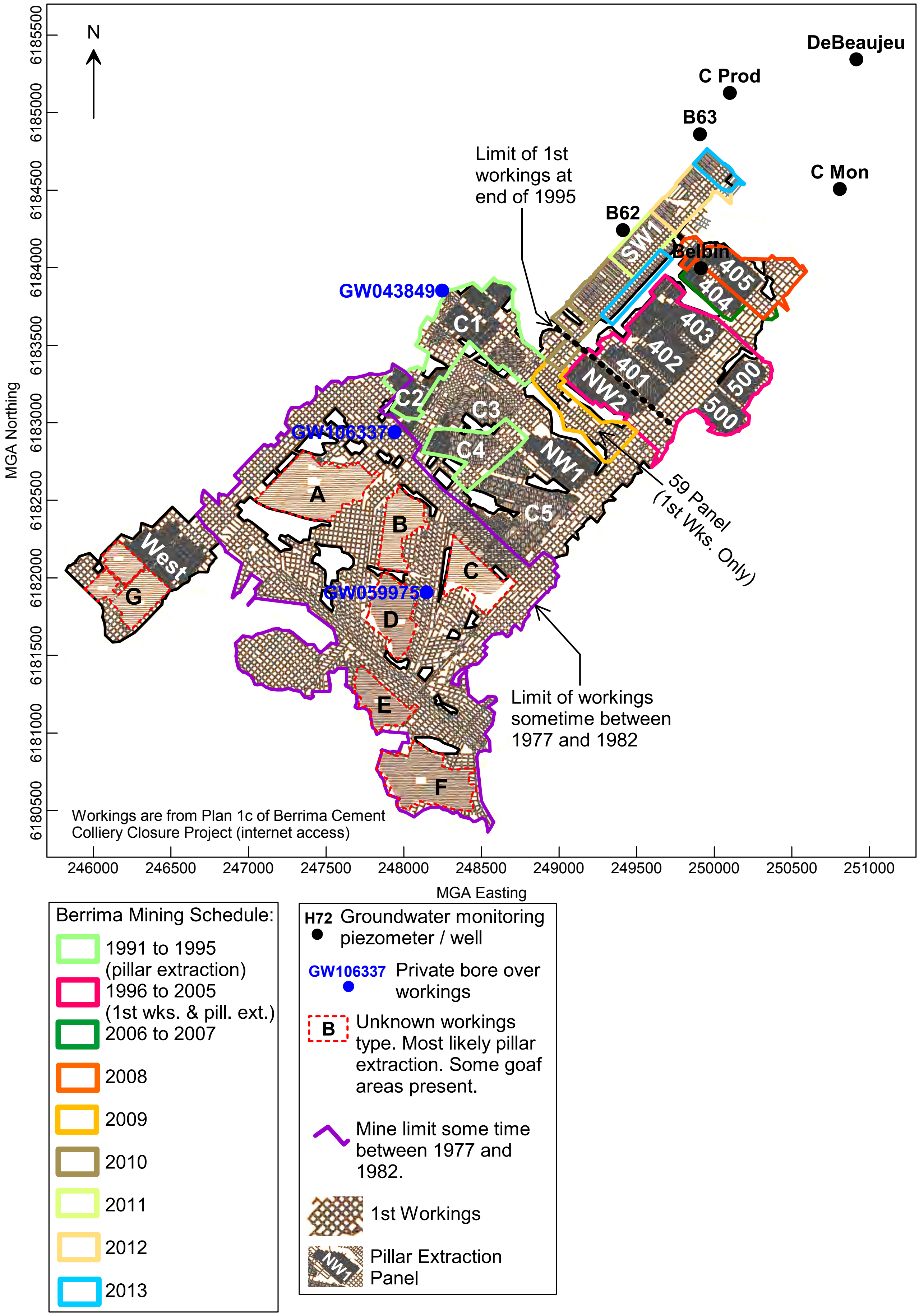
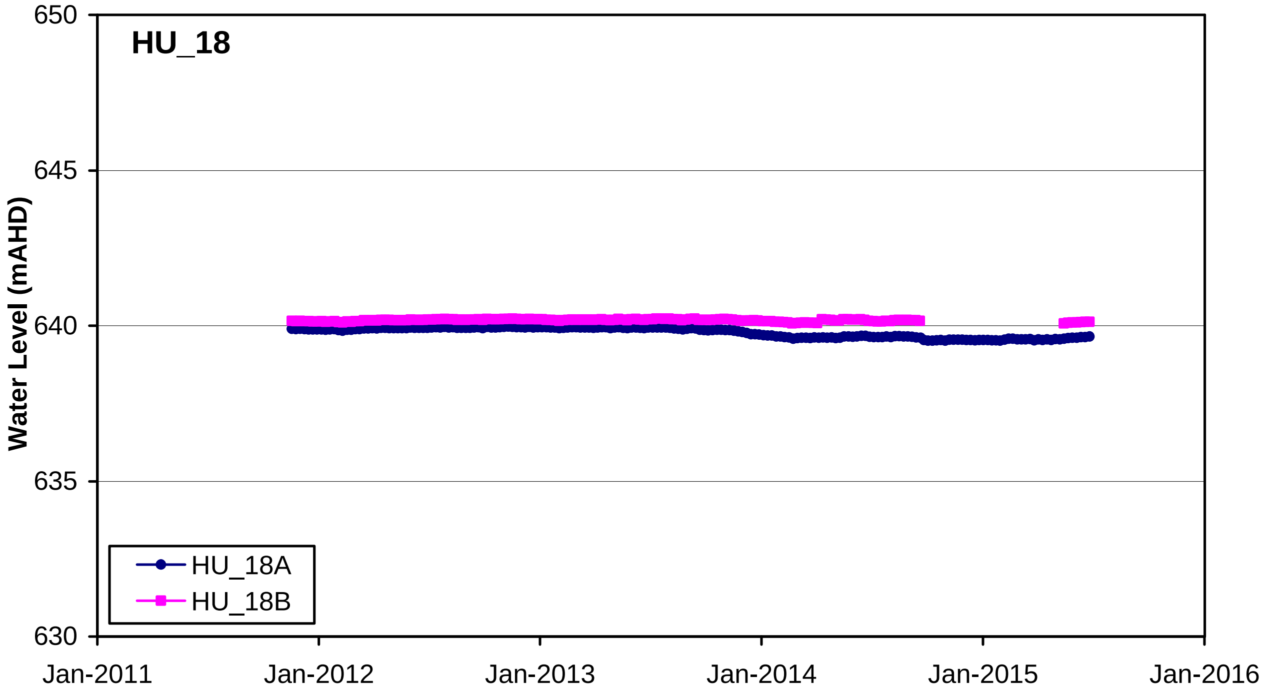


drawn	PT	client:	Hume Coal Pty Limited
approved	RJB	project:	Hume Coal Project Groundwater Assessment
date	6 Jun 2016		
scale	1:35,000	title:	**Monitoring Piezometers/Wells (Berrima Mine)**
original size	A4	project no: GEOTLCOV25281AB	figure no: **Figure D2**

coffey
A TETRA TECH COMPANY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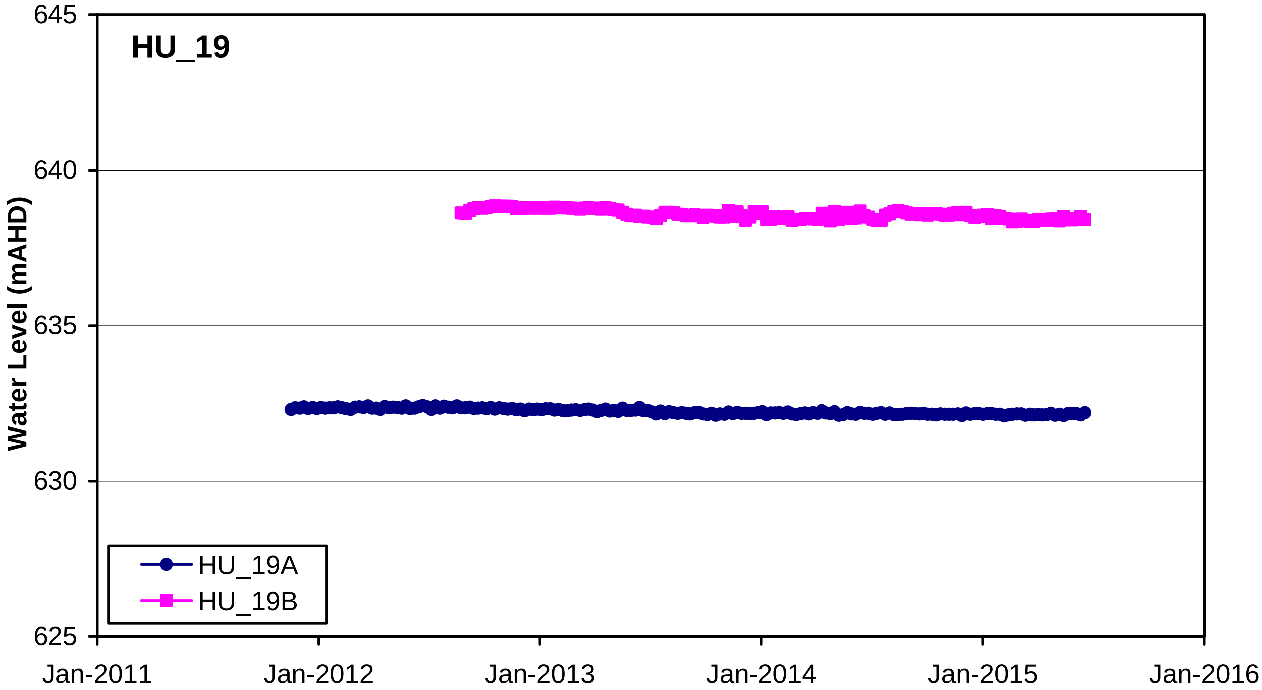
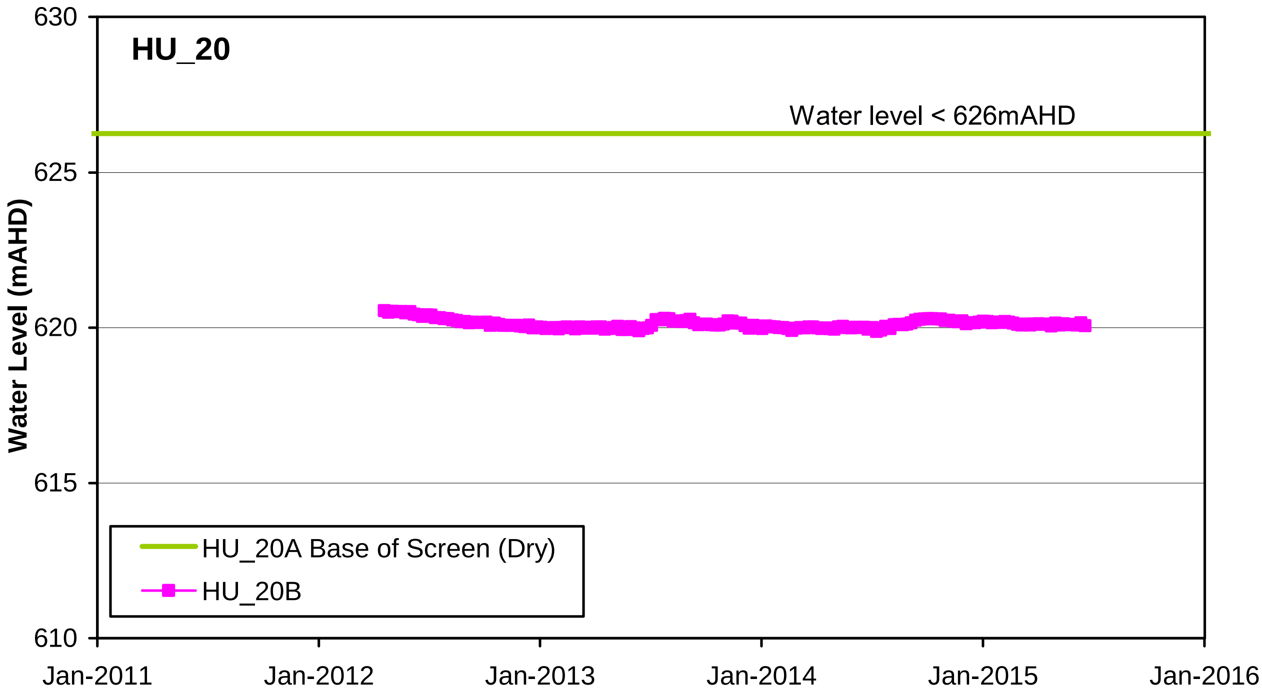
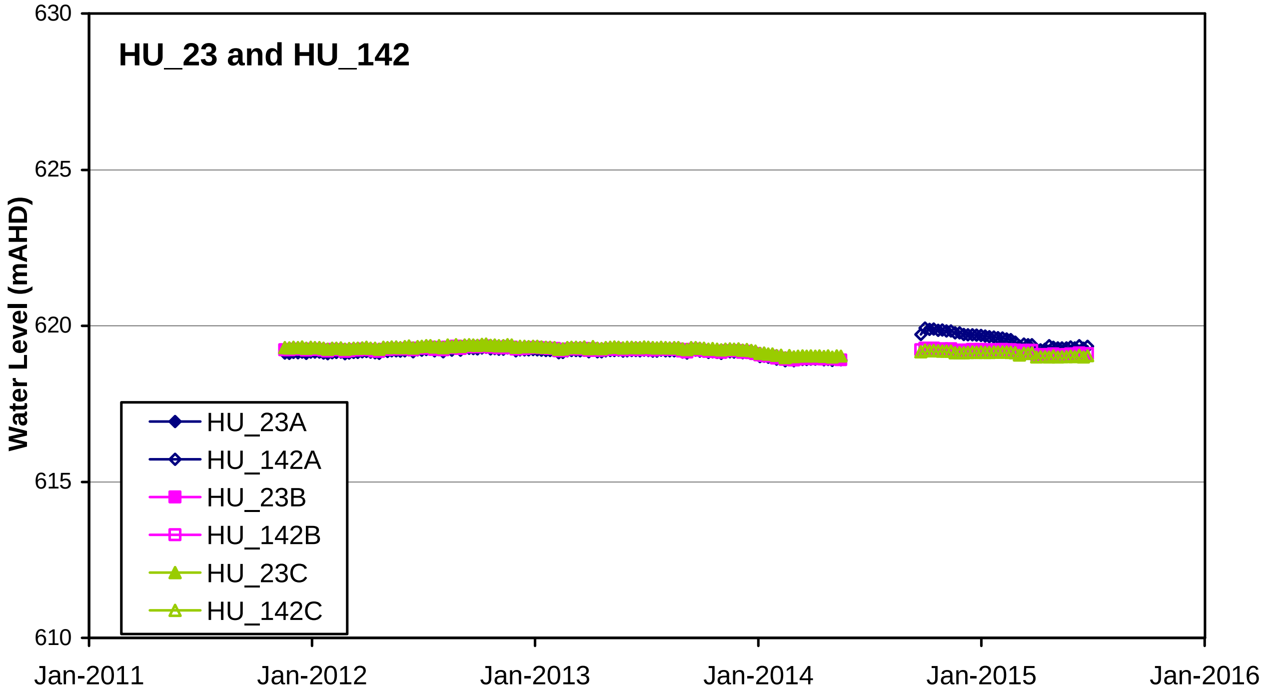
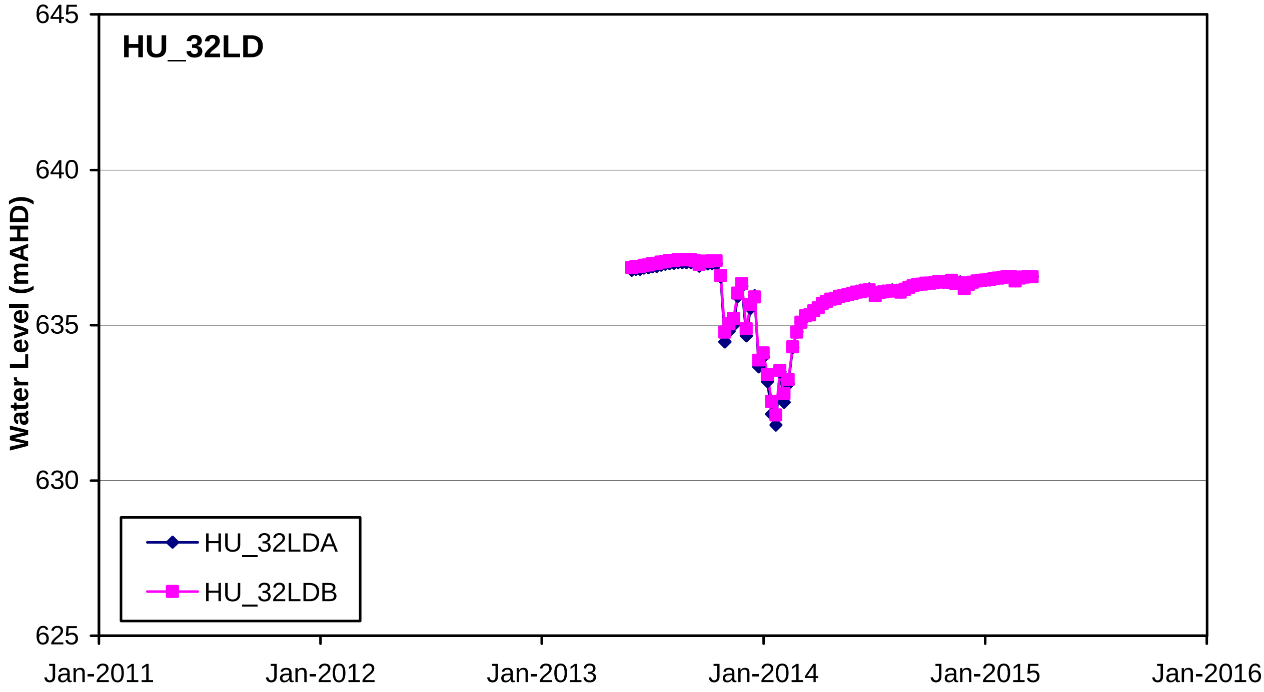
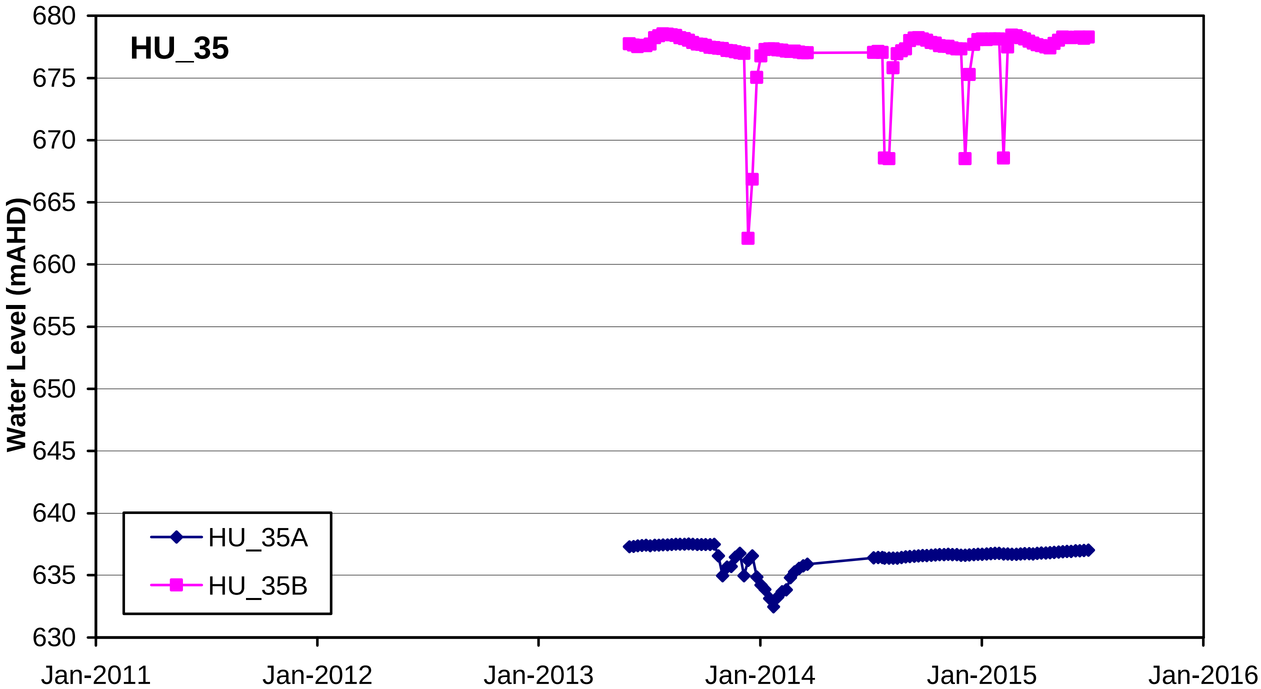
Water Level (mAHD)
650
645
640
635
630
HU_18A
HU_18B
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016

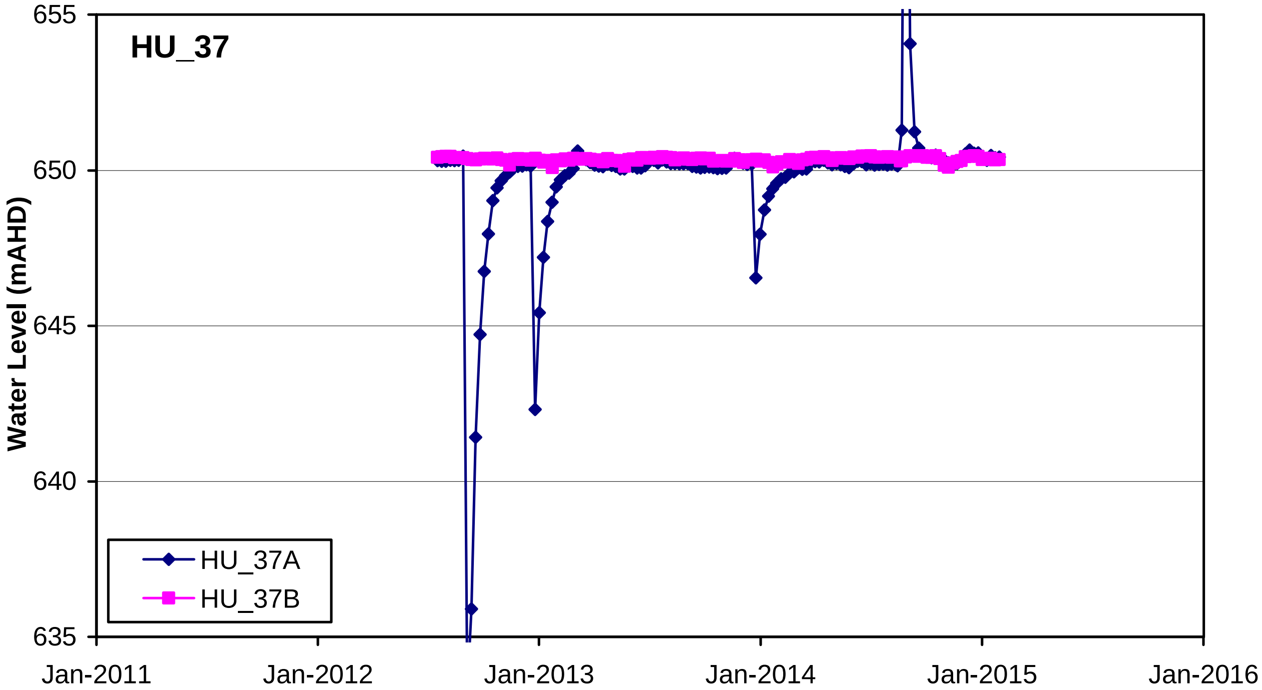

HU_19
Water Level (mAHD)
645
640
635
630
625
HU_19A
HU_19B
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016

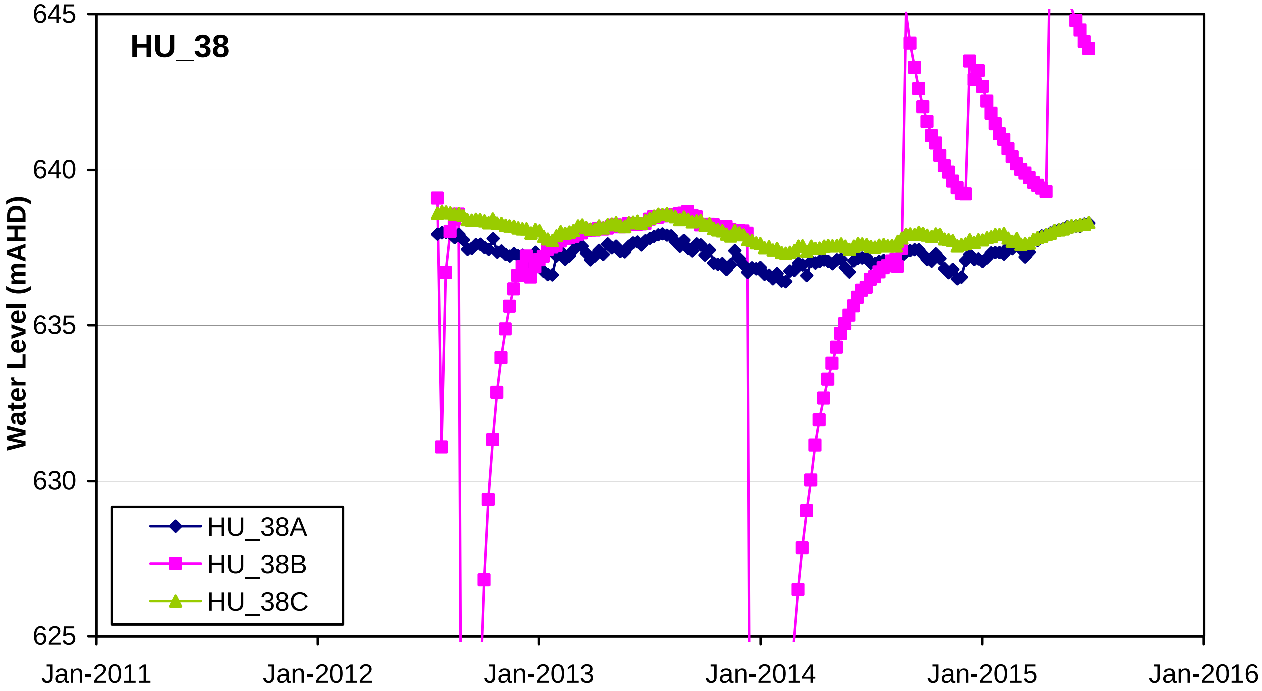

HU_20
Water level < 626mAHD
Water Level (mAHD)
630
625
620
615
610
HU_20A Base of Screen (Dry)
HU_20B
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016

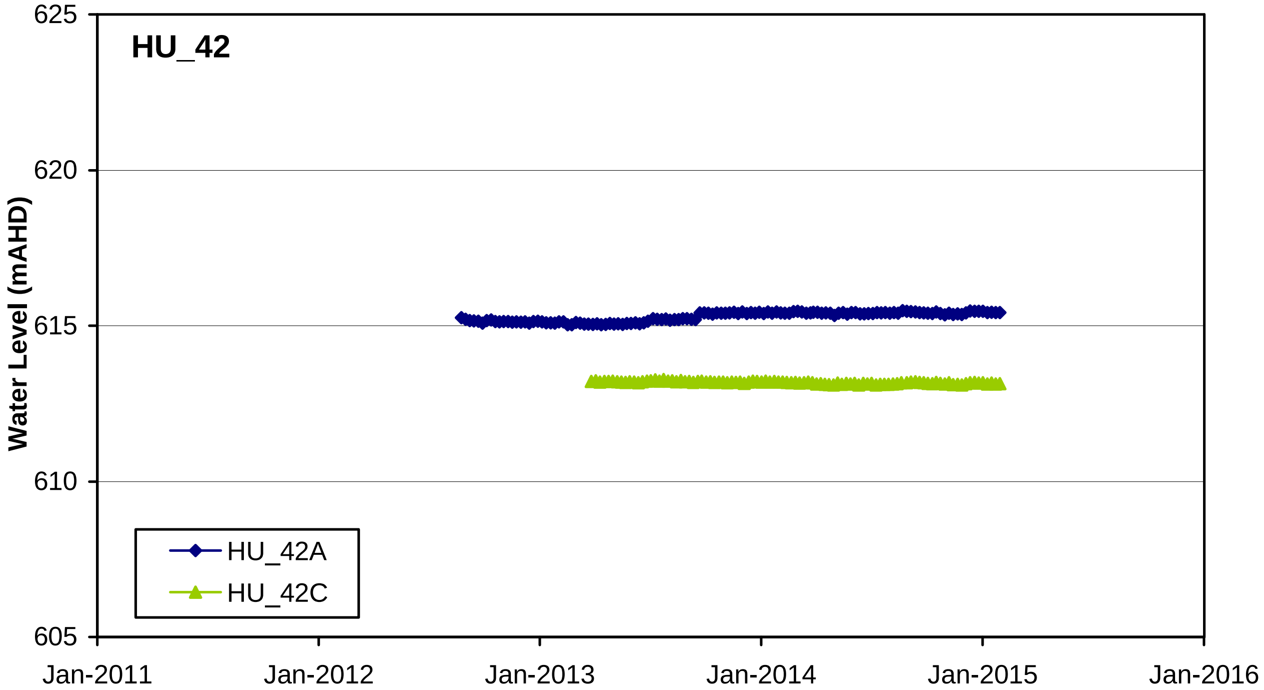

HU_23 and HU_142
Water Level (mAHD)
630
625
620
615
610
HU_23A
HU_142A
HU_23B
HU_142B
HU_23C
HU_142C
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016

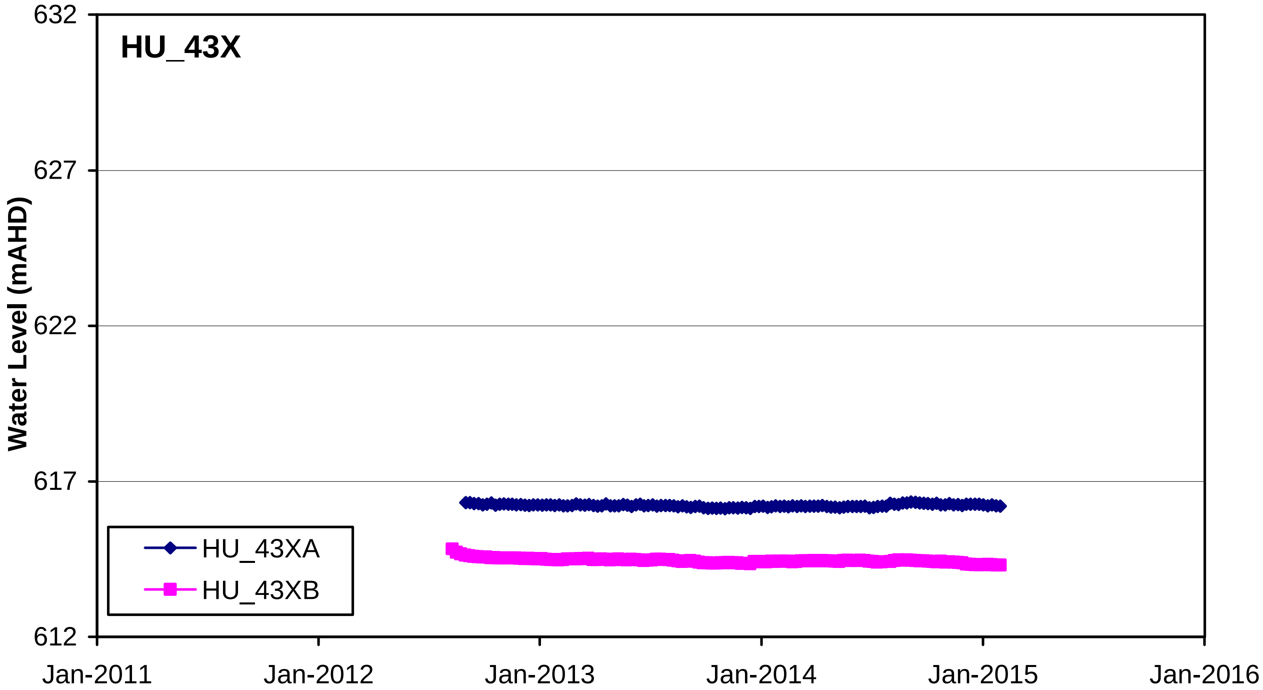

HU_32LD
Water Level (mAHD)
645
640
635
630
625
HU_32LDA
HU_32LDB
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016

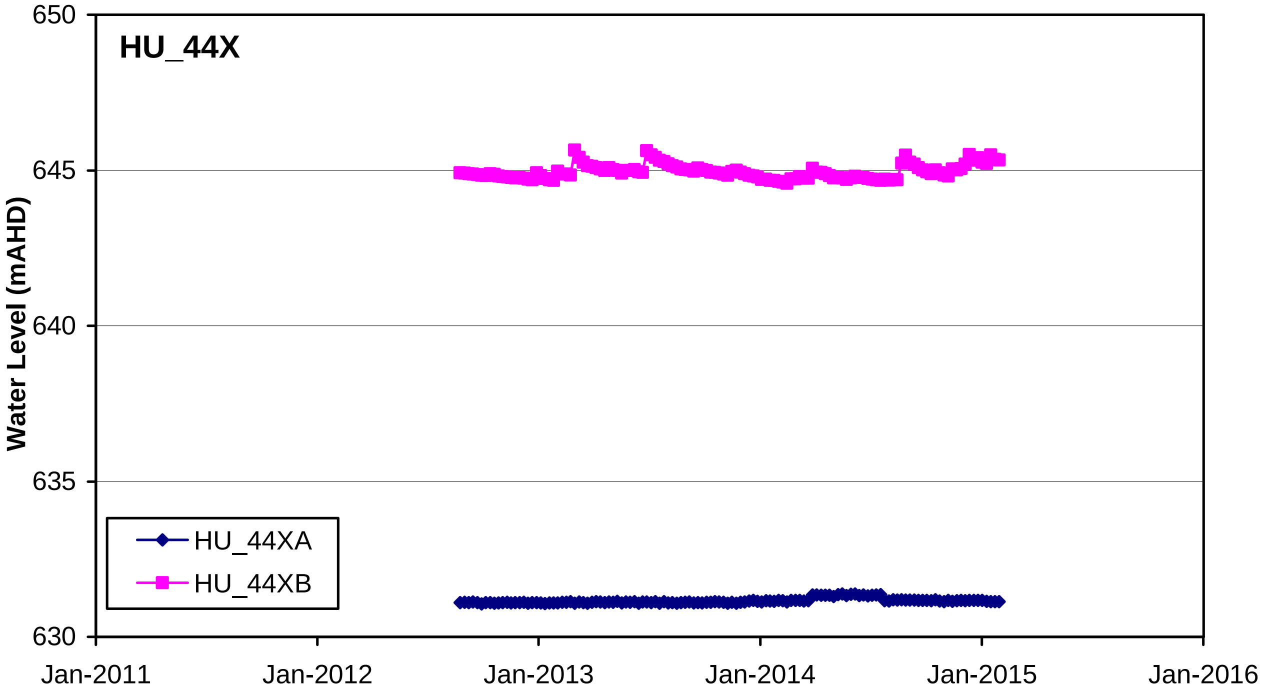

HU_35
Water Level (mAHD)
680
675
670
665
660
655
650
645
640
635
630
HU_35A
HU_35B
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016

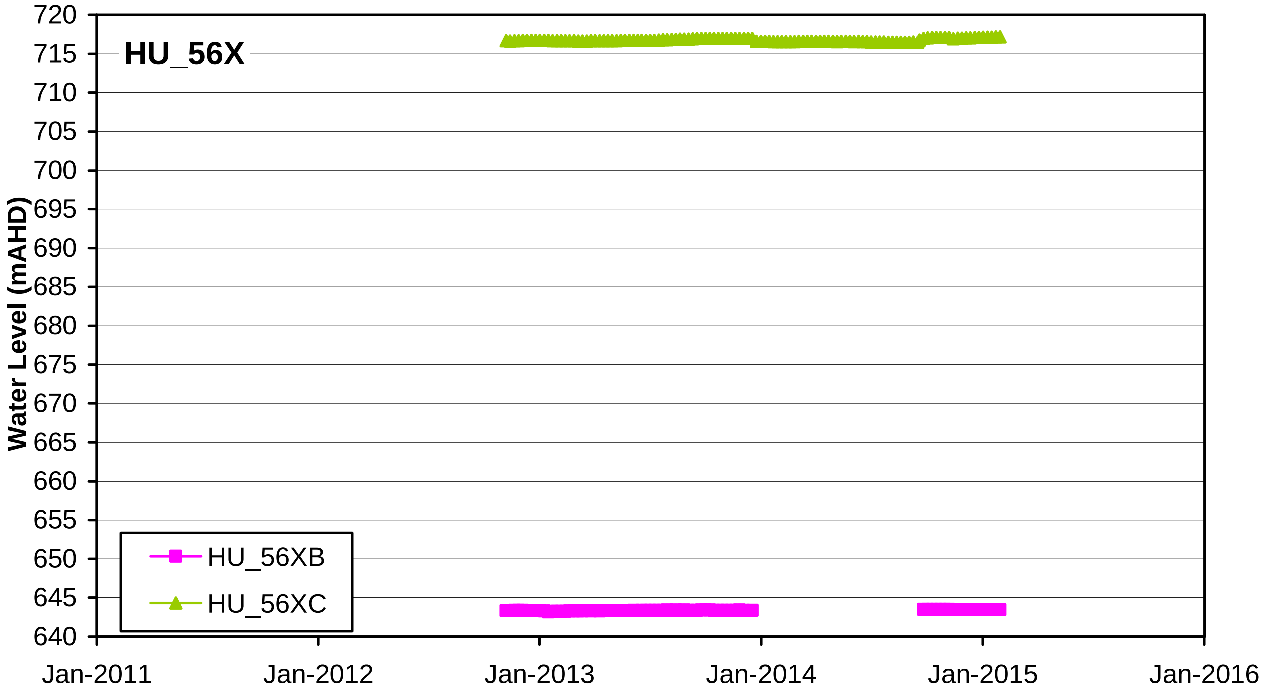

HU_37
Water Level (mAHD)
655
650
645
640
635
HU_37A
HU_37B
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016

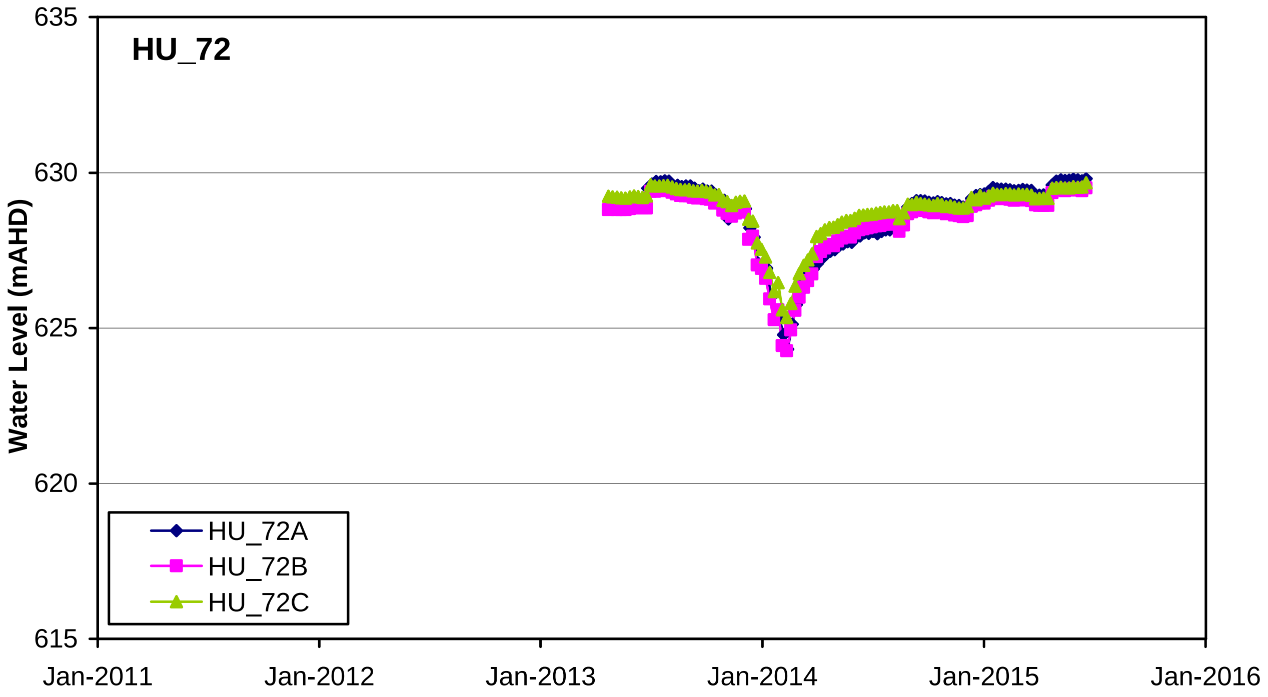

HU_38
Water Level (mAHD)
645
640
635
630
625
HU_38A
HU_38B
HU_38C
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016

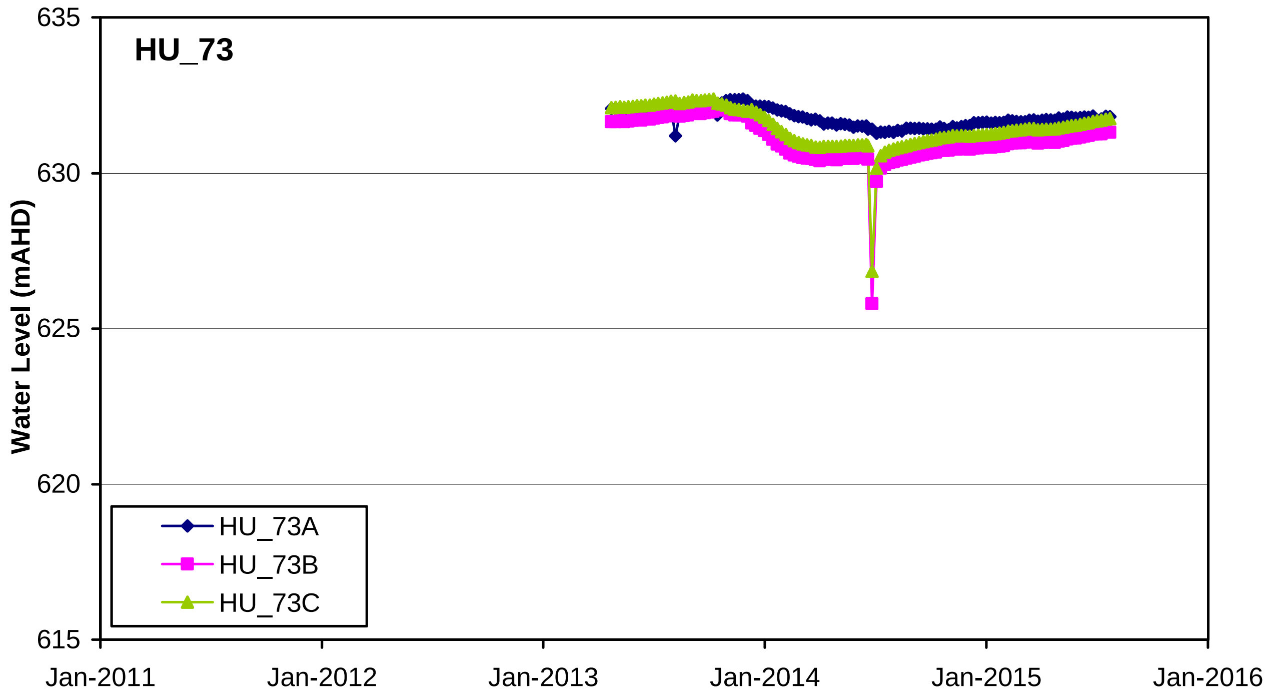

HU_42
Water Level (mAHD)
625
620
615
610
605
HU_42A
HU_42C
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016

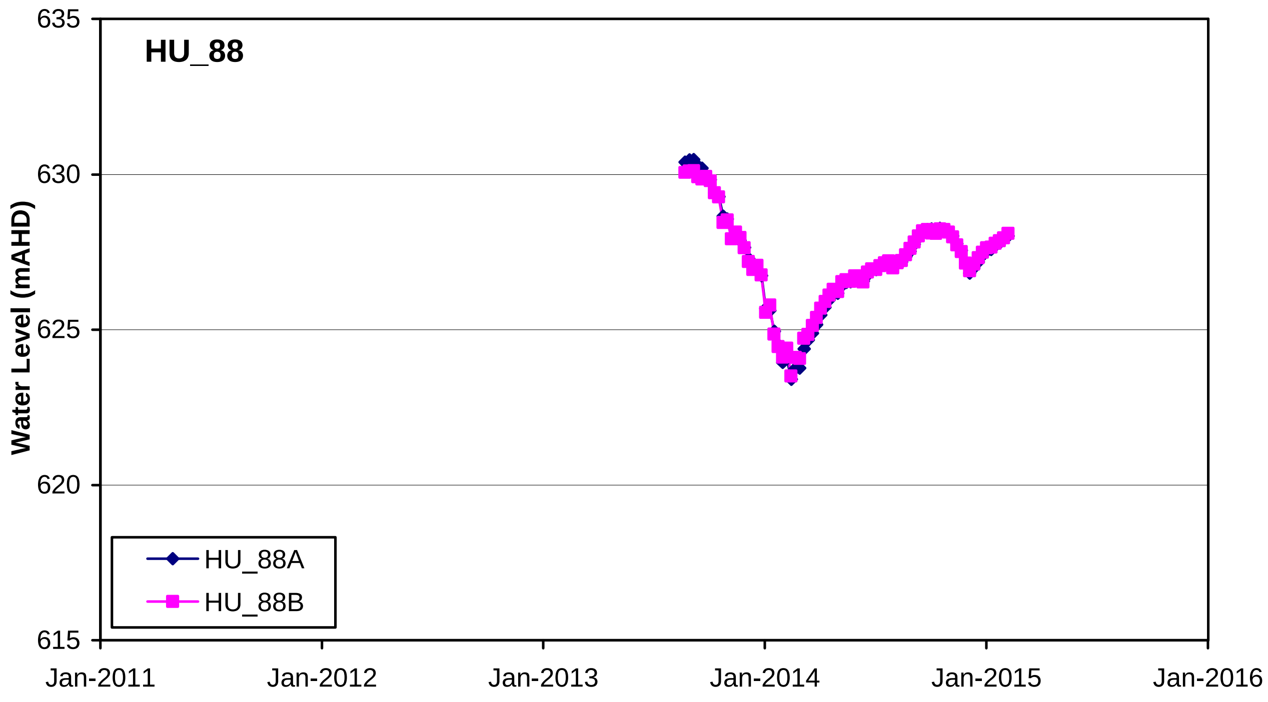

HU_43X
Water Level (mAHD)
632
627
622
617
612
HU_43XA
HU_43XB
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016

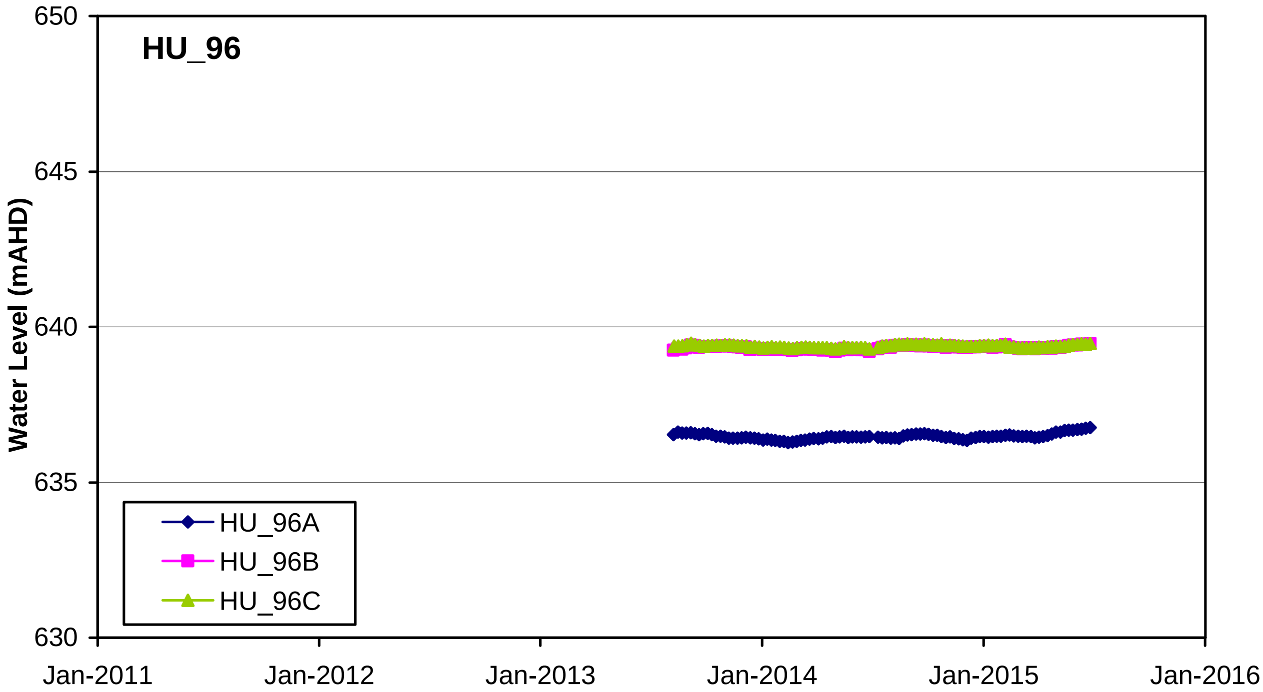

HU_44X
Water Level (mAHD)
650
645
640
635
630
HU_44XA
HU_44XB
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016


HU_56X
Water Level (mAHD)
720
715
710
705
700
695
690
685
680
675
670
665
660
655
650
645
640
HU_56XB
HU_56XC
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016

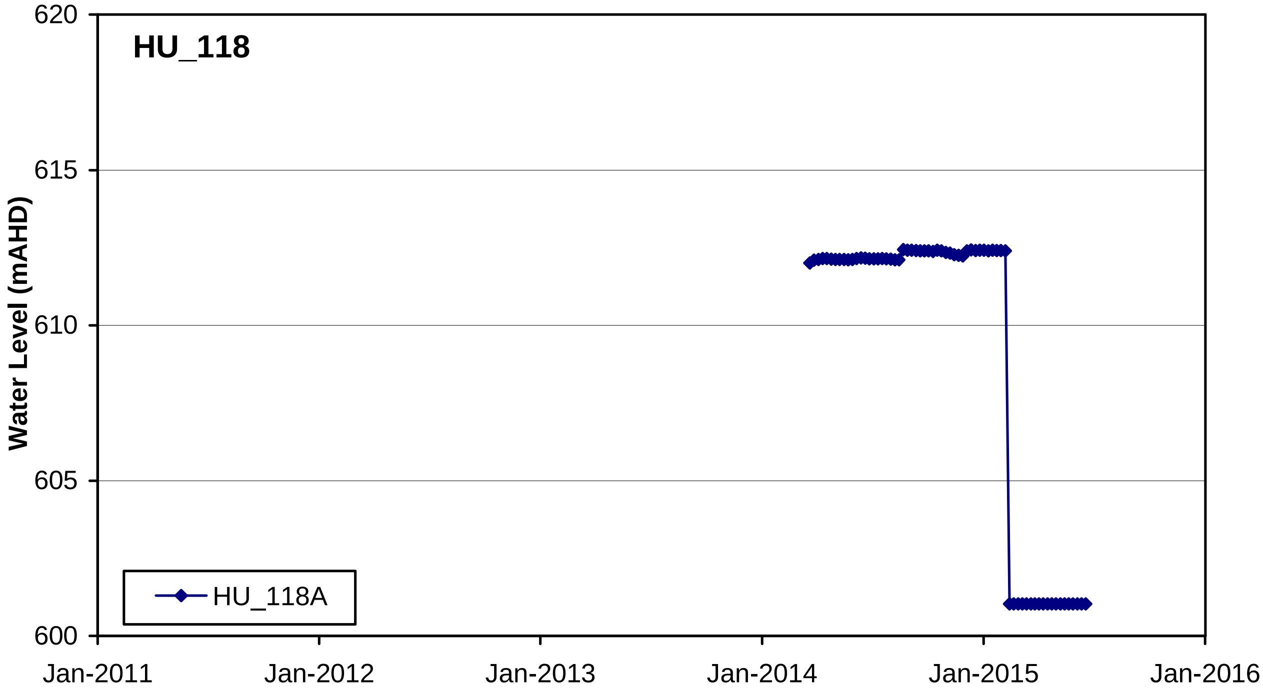

HU_72
Water Level (mAHD)
635
630
625
620
615
HU_72A
HU_72B
HU_72C
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016


HU_73
Water Level (mAHD)
635
630
625
620
615
HU_73A
HU_73B
HU_73C
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016

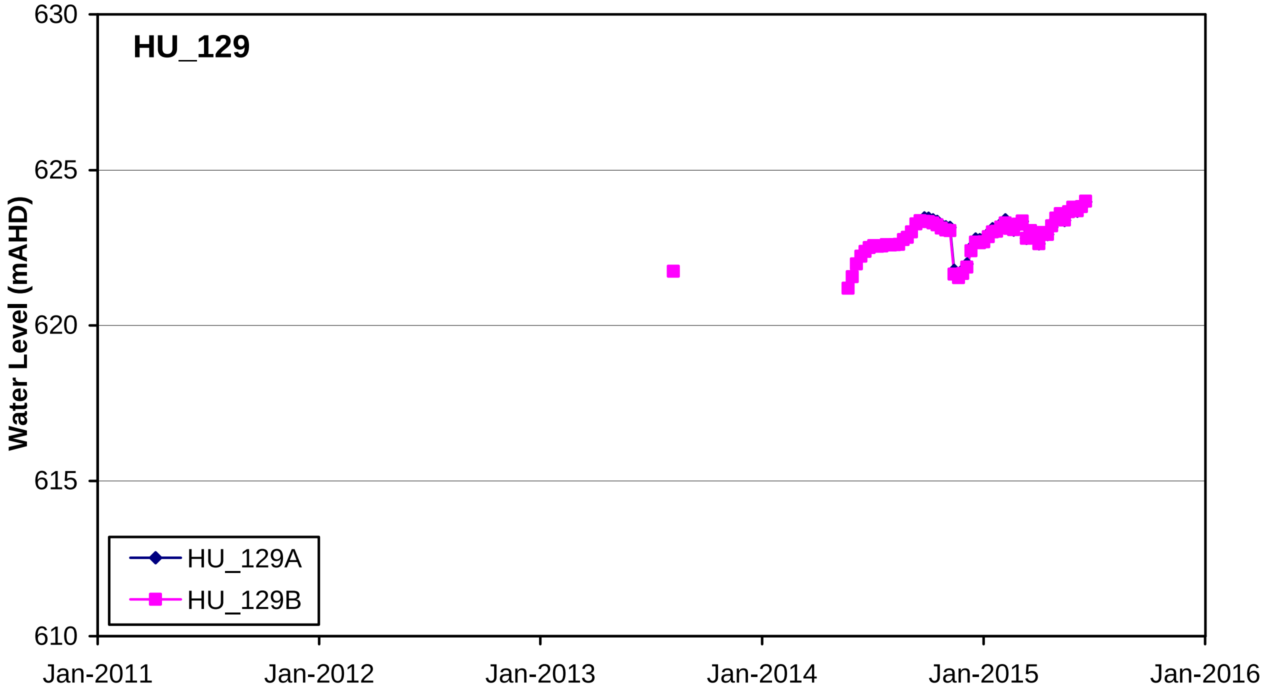

HU_88
Water Level (mAHD)
635
630
625
620
615
HU_88A
HU_88B
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016



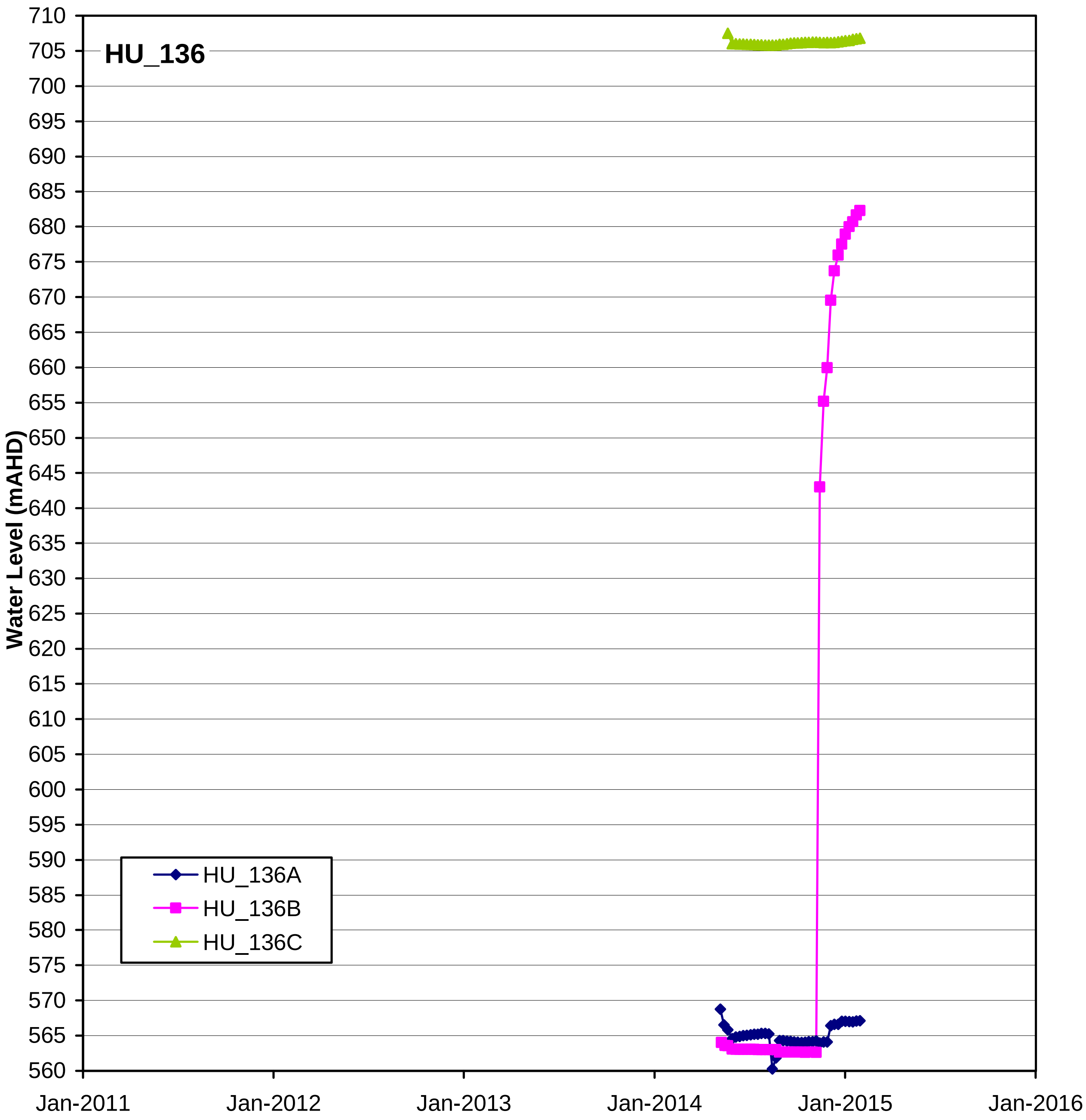
HU_96
Water Level (mAHD)
650
645
640
635
630
HU_96A
HU_96B
HU_96C
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016

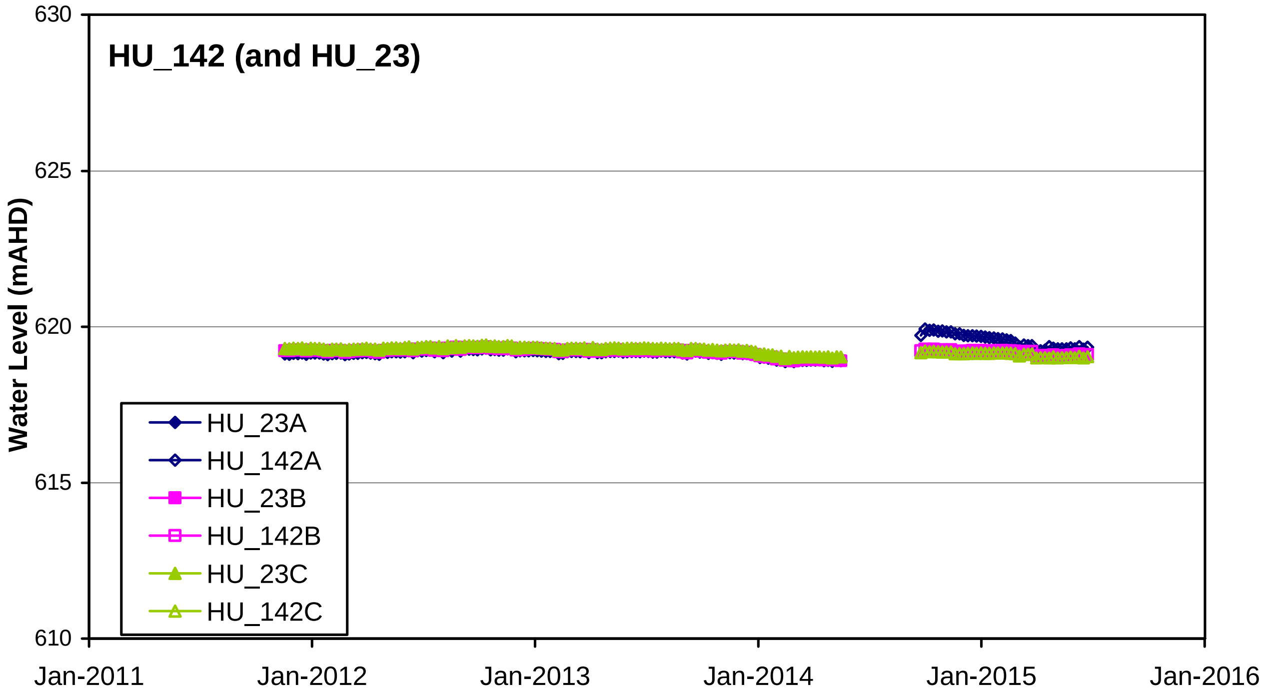


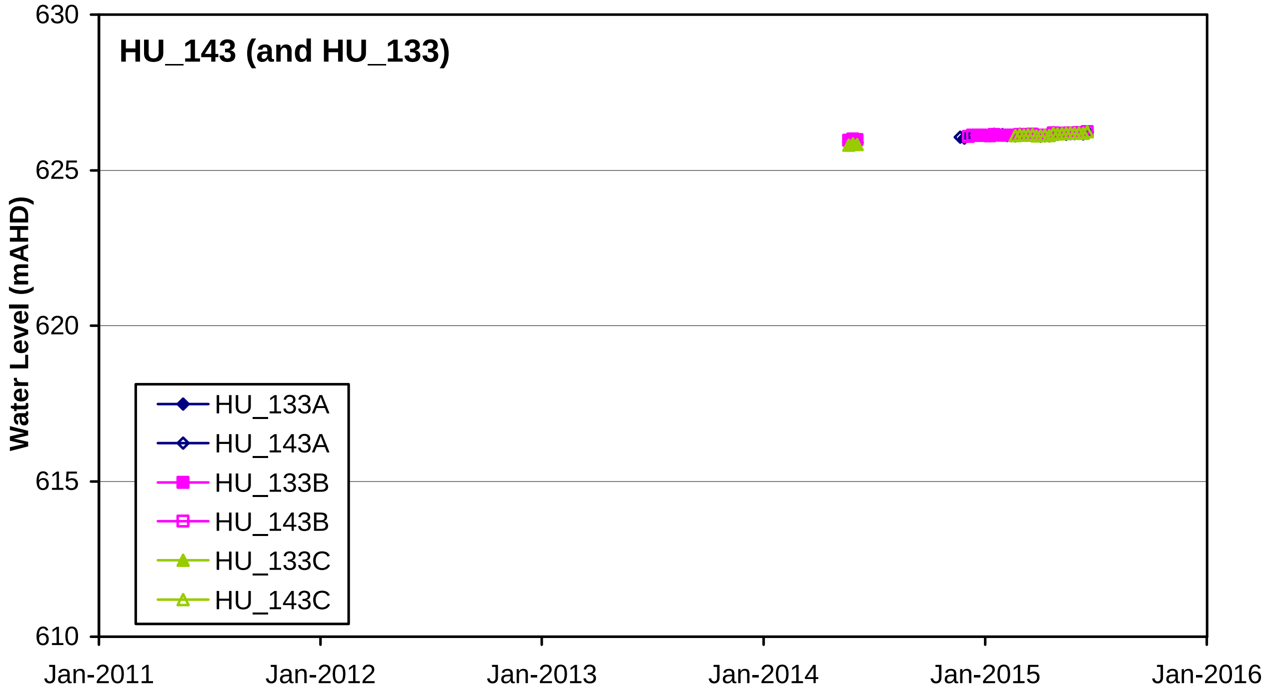
HU_118
Water Level (mAHD)
620
615
610
605
600
HU_118A
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016

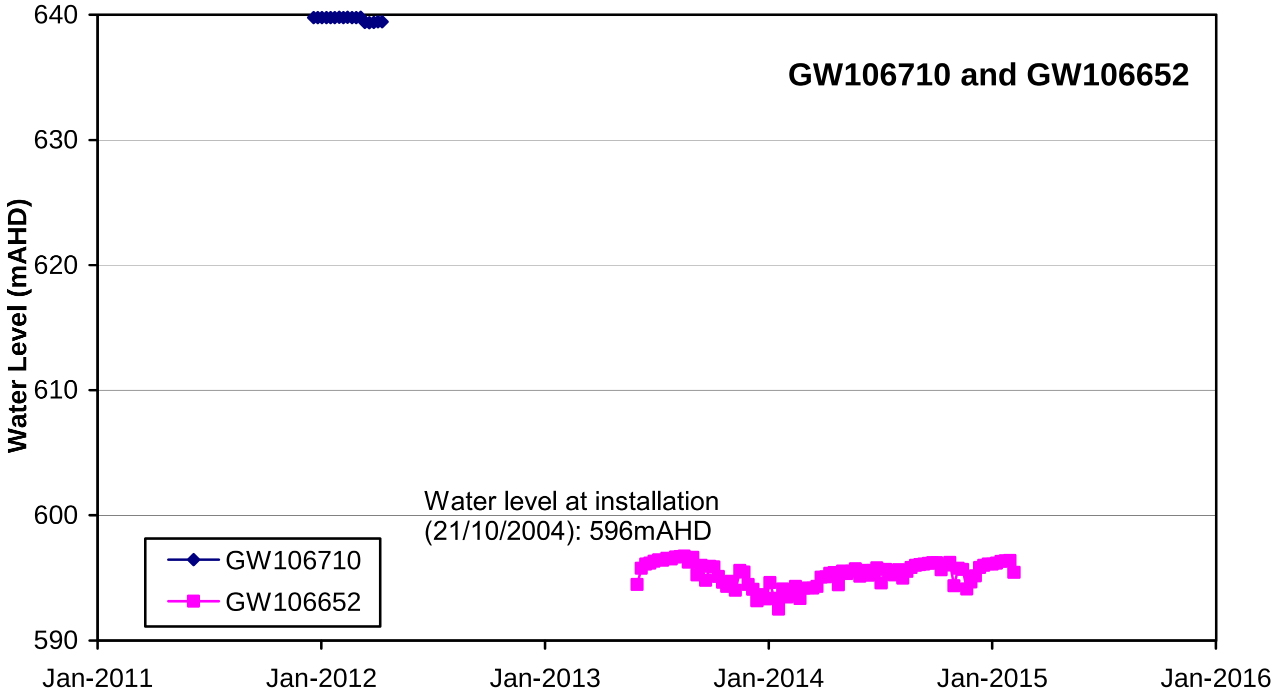


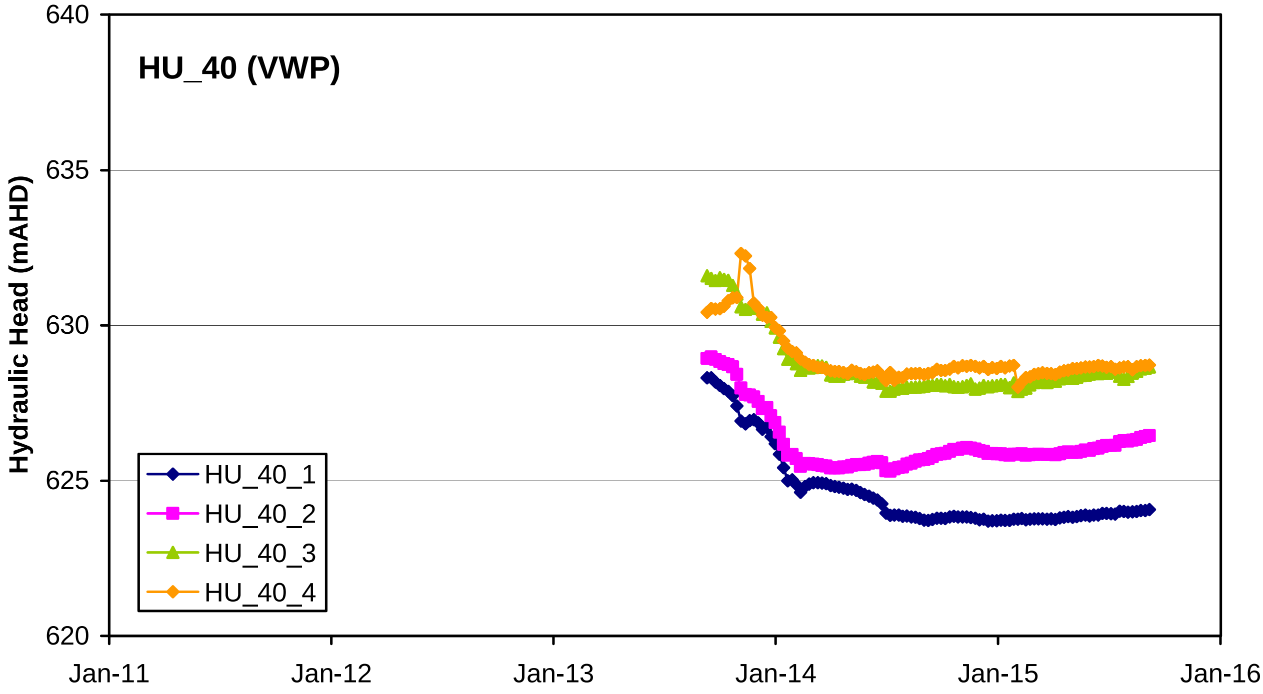
HU_129
Water Level (mAHD)
630
625
620
615
610
HU_129A
HU_129B
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016

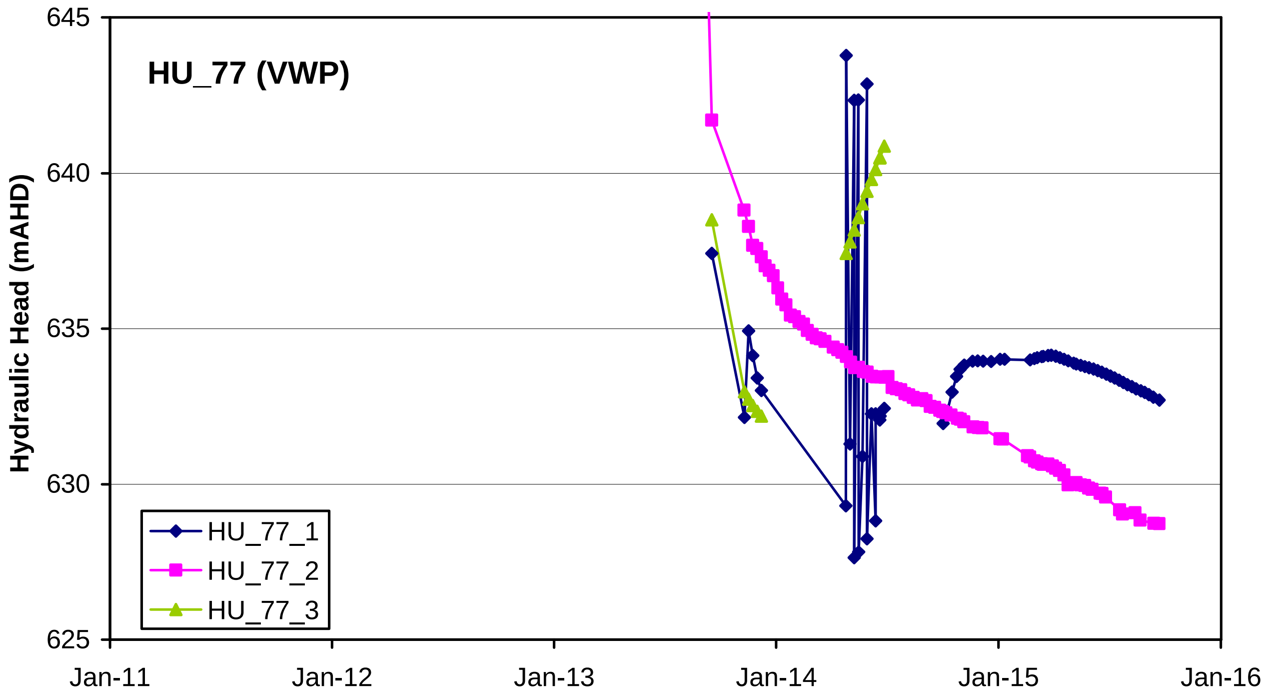

HU_136
Water Level (mAHD)
710
705
700
695
690
685
680
675
670
665
660
655
650
645
640
635
630
625
620
615
610
605
600
595
590
585
580
575
570
565
560
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016
HU_136A
HU_136B
HU_136C

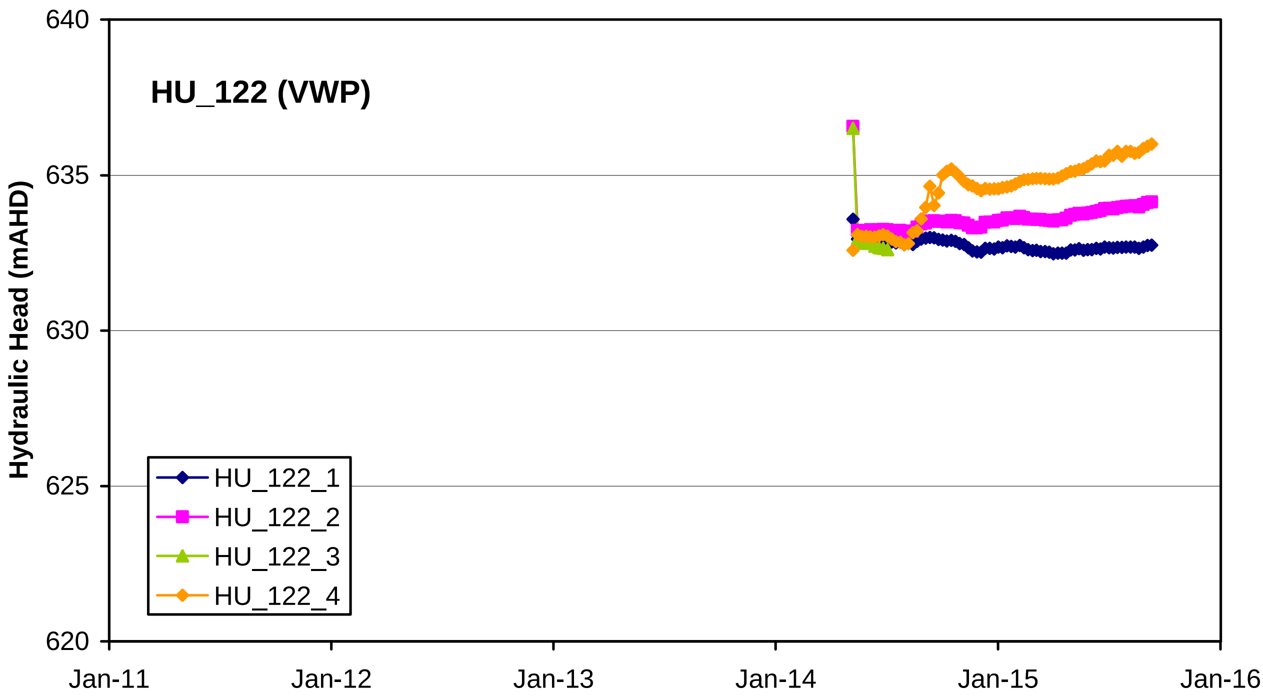

HU_142 (and HU_23)
Water Level (mAHD)
630
625
620
615
610
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016
HU_23A
HU_142A
HU_23B
HU_142B
HU_23C
HU_142C

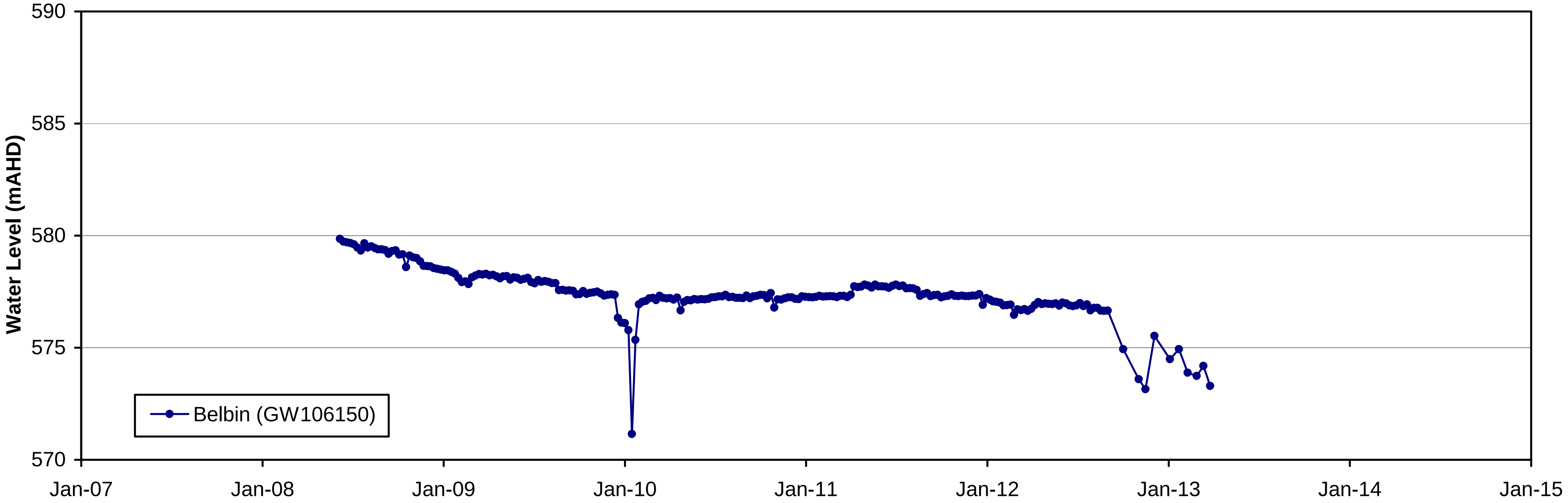

HU_143 (and HU_133)
Water Level (mAHD)
630
625
620
615
610
HU_133A
HU_143A
HU_133B
HU_143B
HU_133C
HU_143C
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016


GW106710 and GW106652
Water Level (mAHD)
640
630
620
610
600
590
Water level at installation
(21/10/2004): 596mAHD
GW106710
GW106652
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016

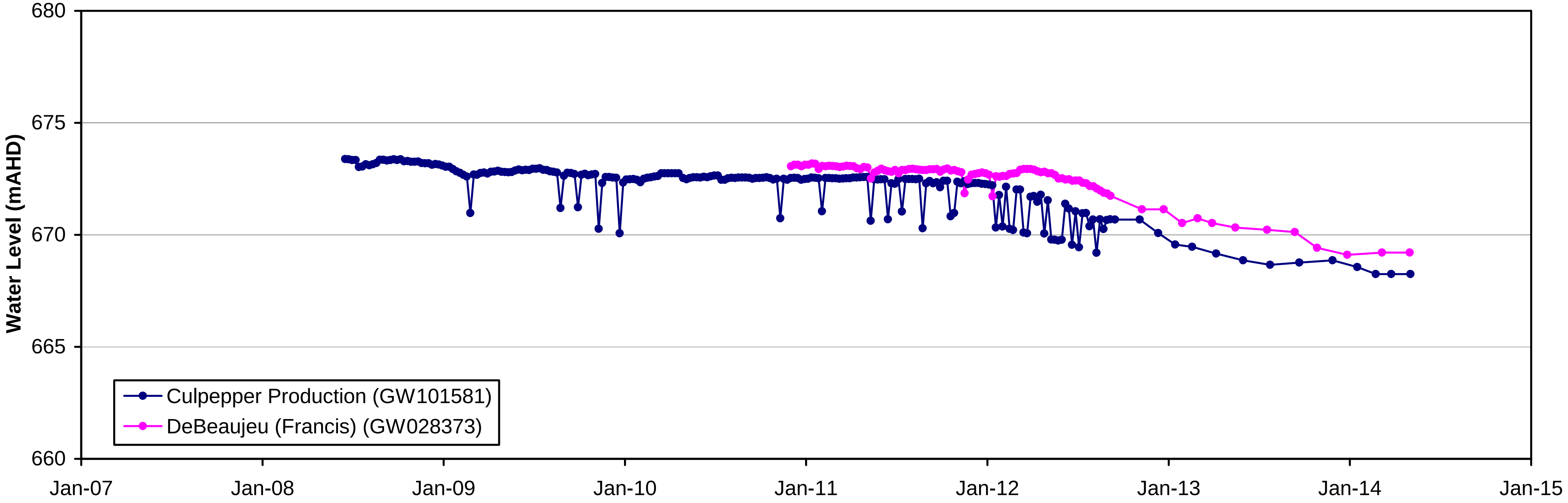

HU_40 (VWP)
Hydraulic Head (mAHD)
640
635
630
625
620
Jan-11
Jan-12
Jan-13
Jan-14
Jan-15
Jan-16
HU_40_1
HU_40_2
HU_40_3
HU_40_4


HU_77 (VWP)
Hydraulic Head (mAHD)
645
640
635
630
625
Jan-11
Jan-12
Jan-13
Jan-14
Jan-15
Jan-16
HU_77_1
HU_77_2
HU_77_3

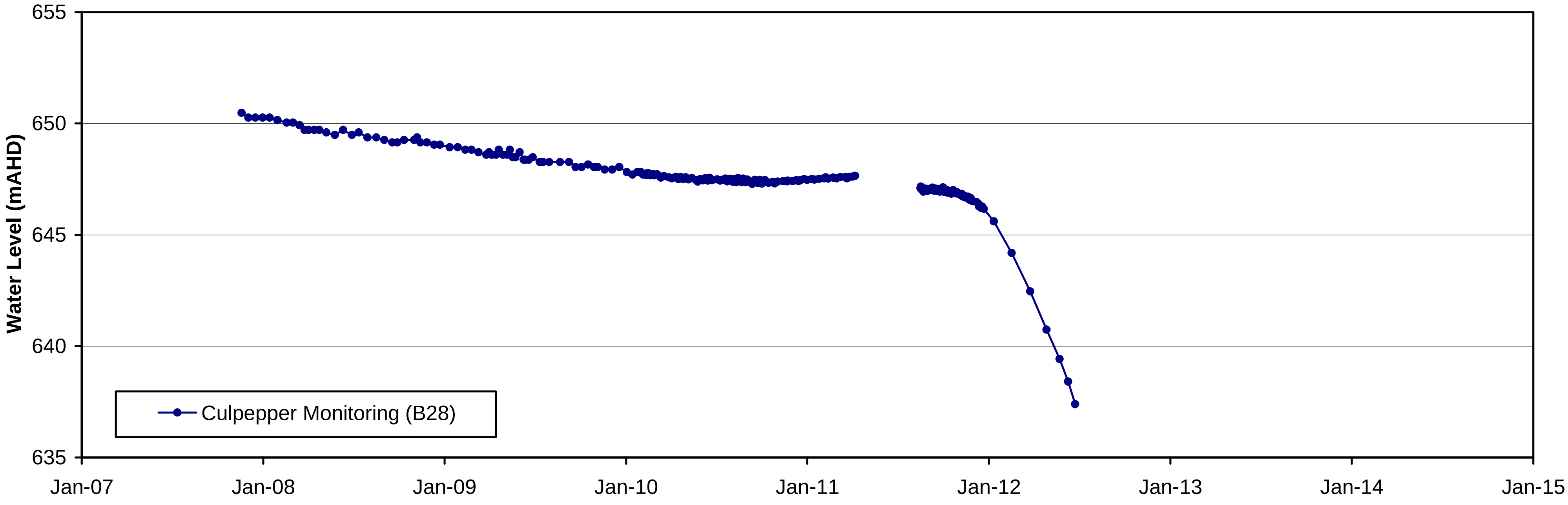

HU_122 (VWP)
Hydraulic Head (mAHD)
640
635
630
625
620
Jan-11
Jan-12
Jan-13
Jan-14
Jan-15
Jan-16
HU_122_1
HU_122_2
HU_122_3
HU_122_4



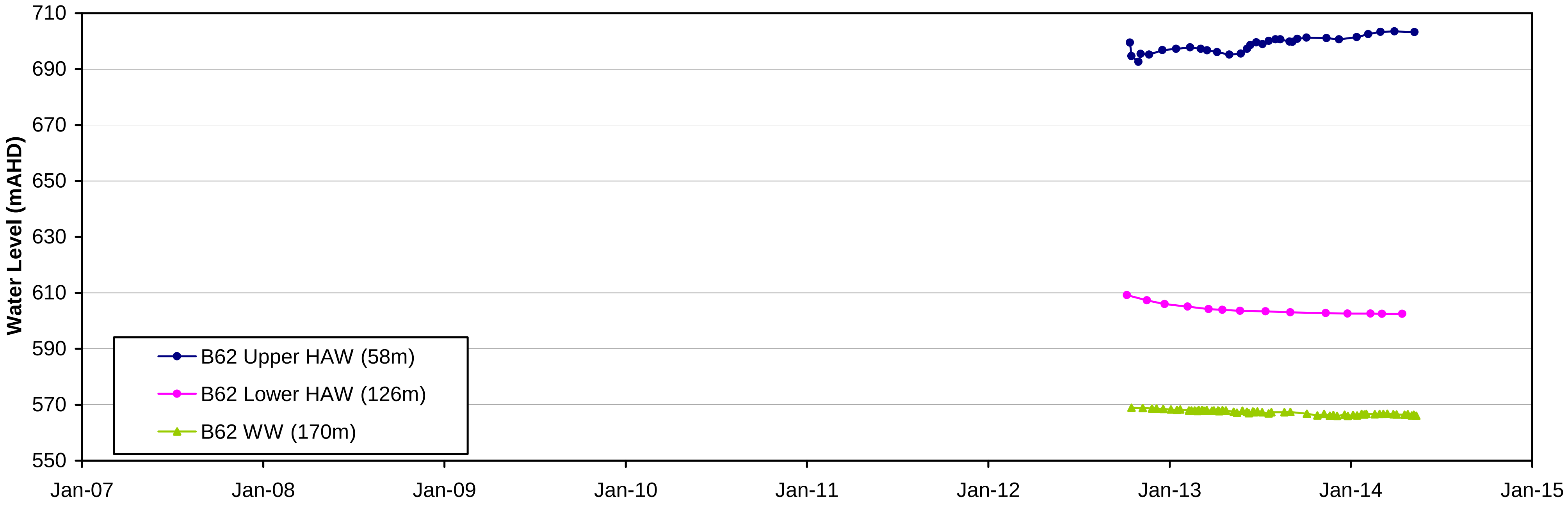
Water Level (mAHD)
590
585
580
575
570
Belbin (GW106150)
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11
Jan-12
Jan-13
Jan-14
Jan-15



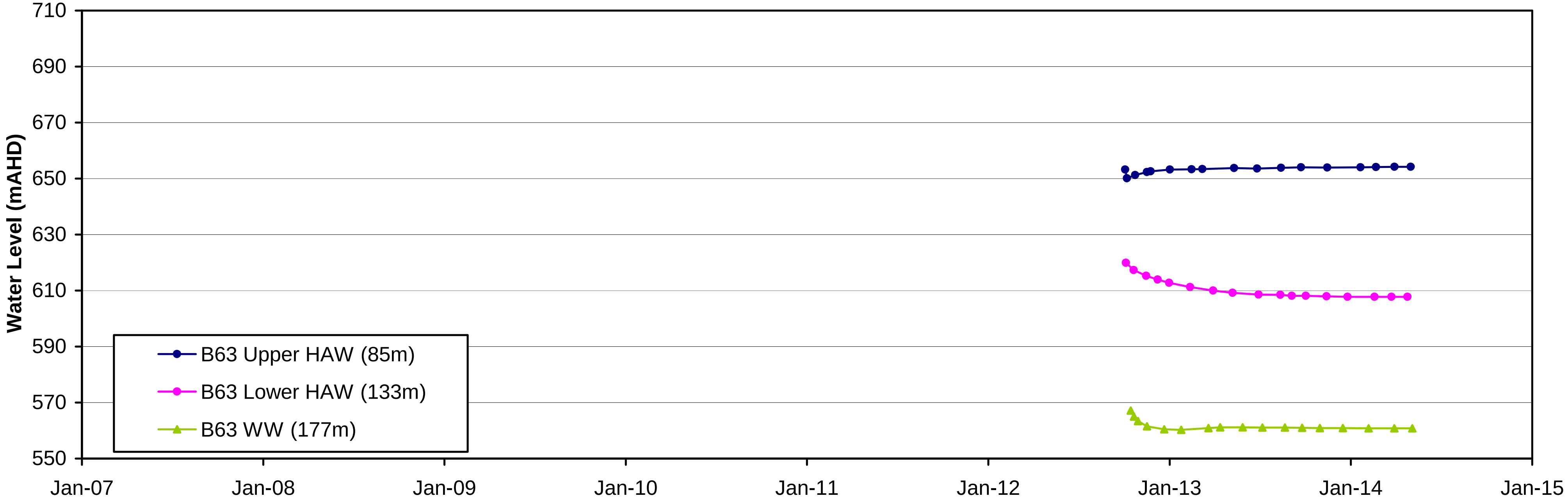
Water Level (mAHD)
680
675
670
665
660
Culpepper Production (GW101581)
DeBeaujeu (Francis) (GW028373)
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11
Jan-12
Jan-13
Jan-14
Jan-15



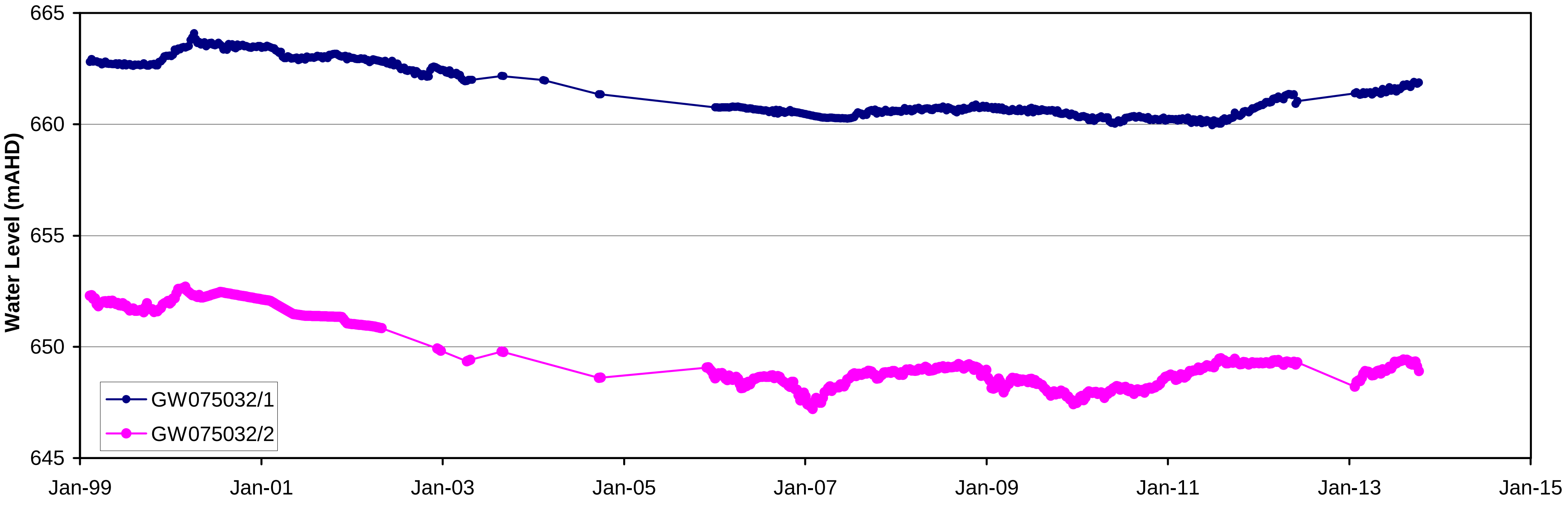
655
650
645
640
635
Water Level (mAHD)
Culpepper Monitoring (B28)
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11
Jan-12
Jan-13
Jan-14
Jan-15

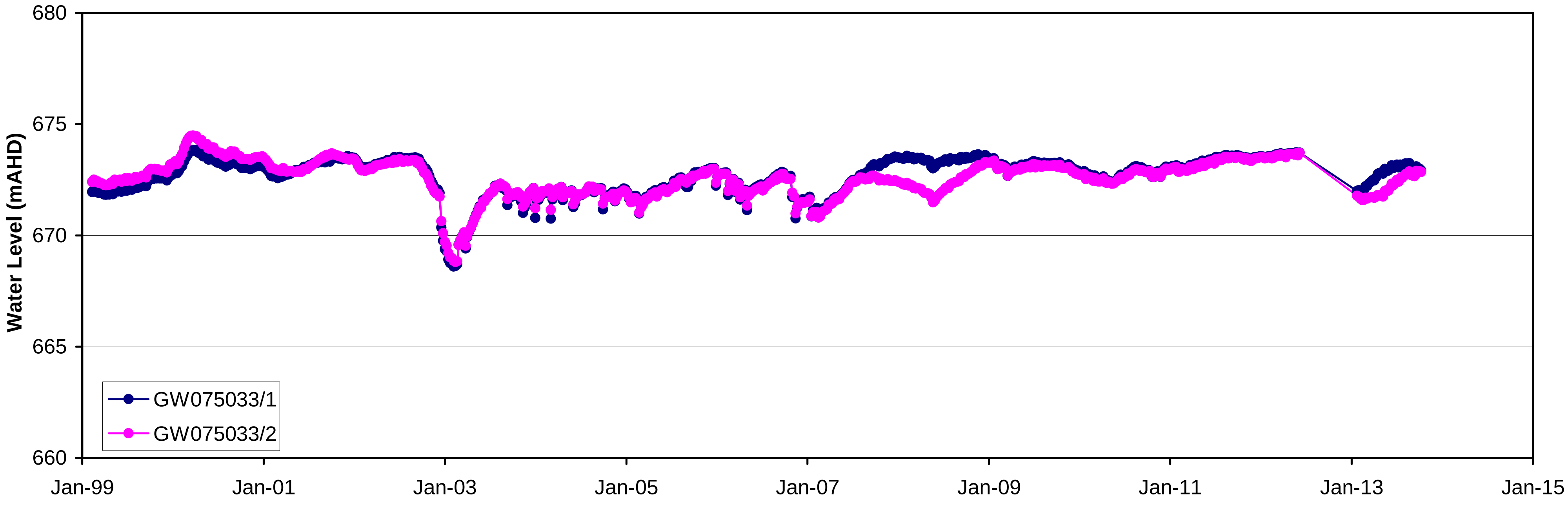


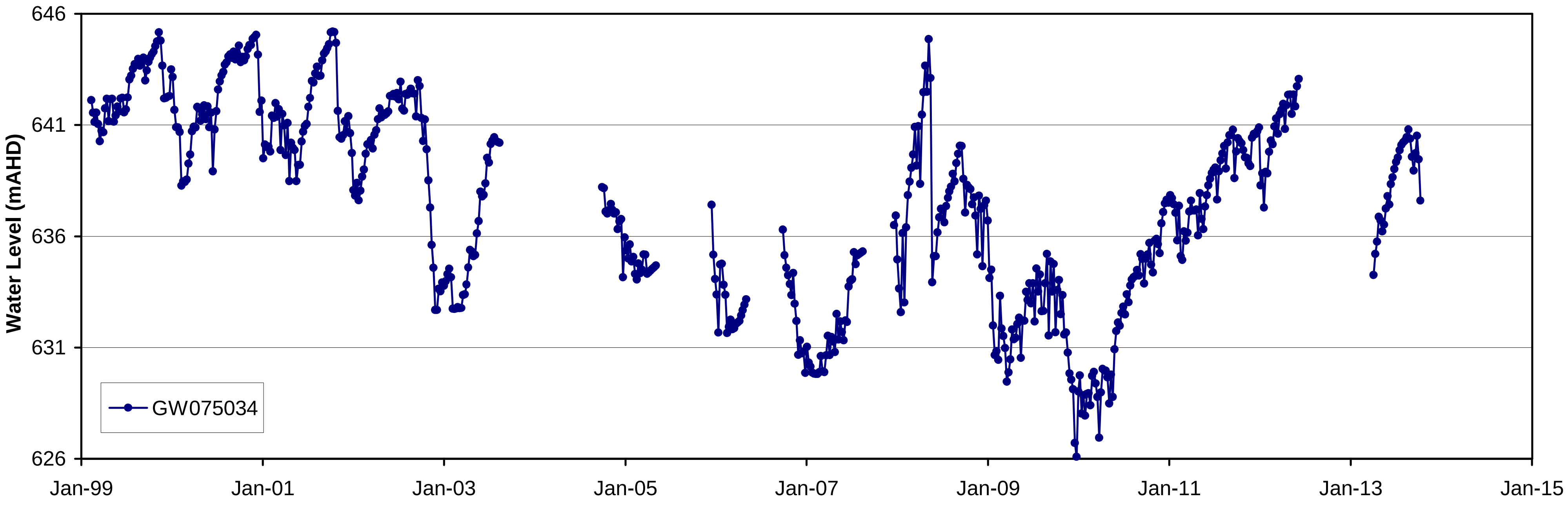
710
690
670
650
630
610
590
570
550
Water Level (mAHD)
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11
Jan-12
Jan-13
Jan-14
Jan-15
B62 Upper HAW (58m)
B62 Lower HAW (126m)
B62 WW (170m)



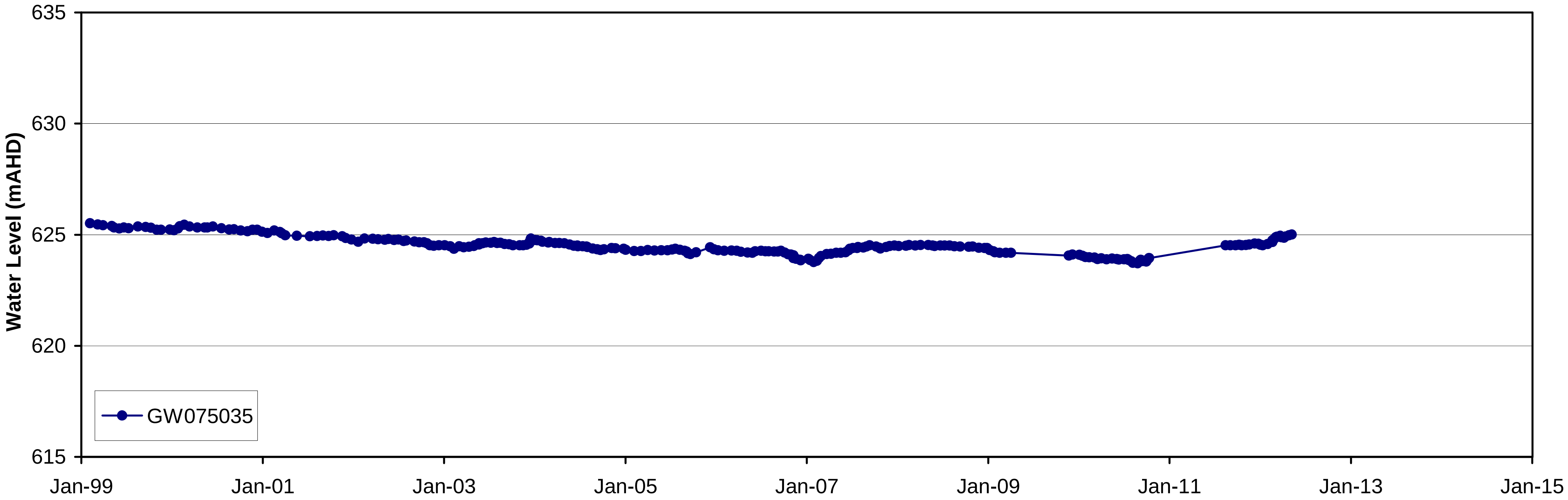
710
690
670
650
630
610
590
570
550
Water Level (mAHD)
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11
Jan-12
Jan-13
Jan-14
Jan-15
B63 Upper HAW (85m)
B63 Lower HAW (133m)
B63 WW (177m)


Water Level (mAHD)
665
660
655
650
645
GW075032/1
GW075032/2
Jan-99
Jan-01
Jan-03
Jan-05
Jan-07
Jan-09
Jan-11
Jan-13
Jan-15

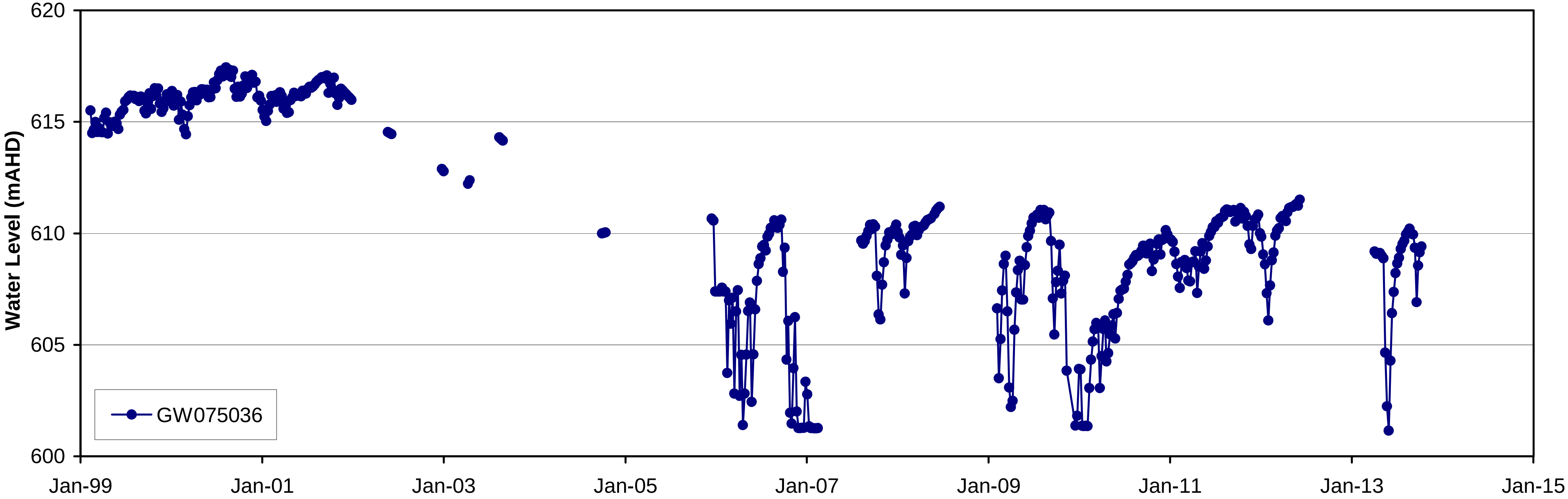

Water Level (mAHD)
680
675
670
665
660
GW075033/1
GW075033/2
Jan-99
Jan-01
Jan-03
Jan-05
Jan-07
Jan-09
Jan-11
Jan-13
Jan-15

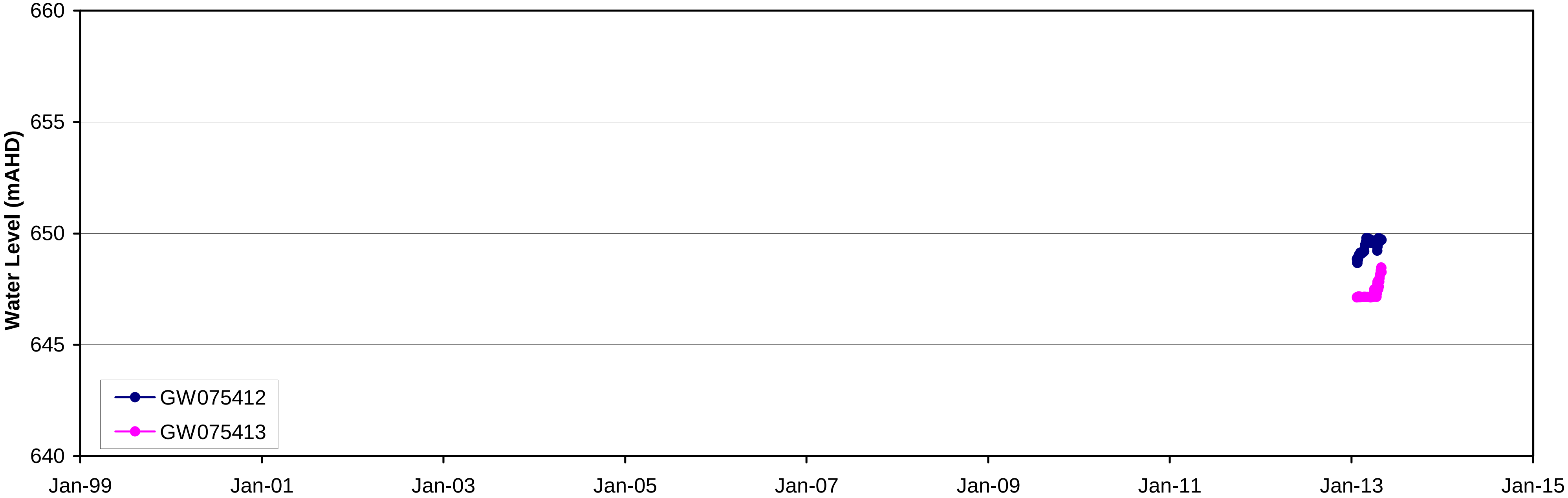


646
641
636
631
626
Water Level (mAHD)
GW075034
Jan-99
Jan-01
Jan-03
Jan-05
Jan-07
Jan-09
Jan-11
Jan-13
Jan-15

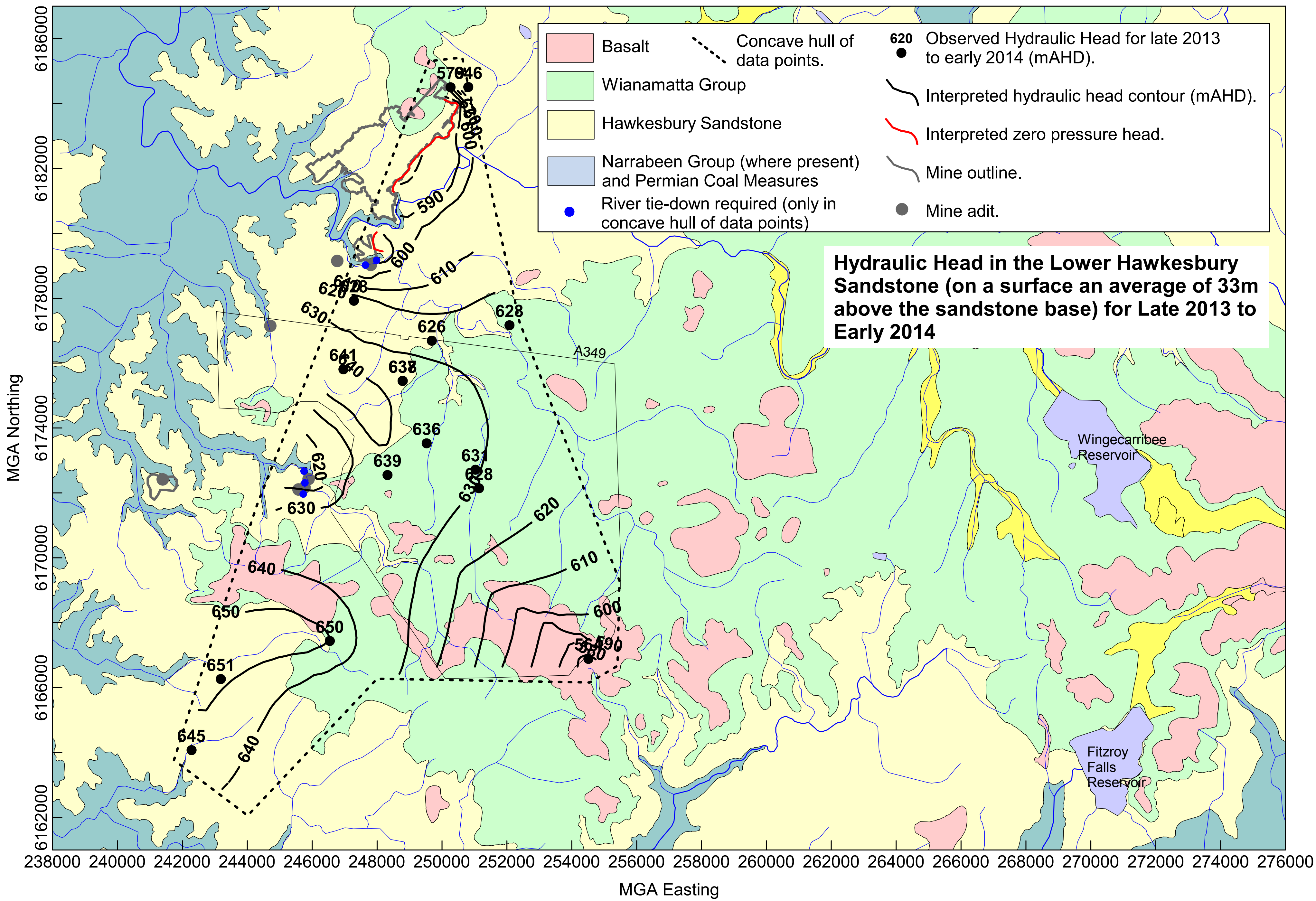


635
630
625
620
615
Water Level (mAHD)
GW075035
Jan-99
Jan-01
Jan-03
Jan-05
Jan-07
Jan-09
Jan-11
Jan-13
Jan-15

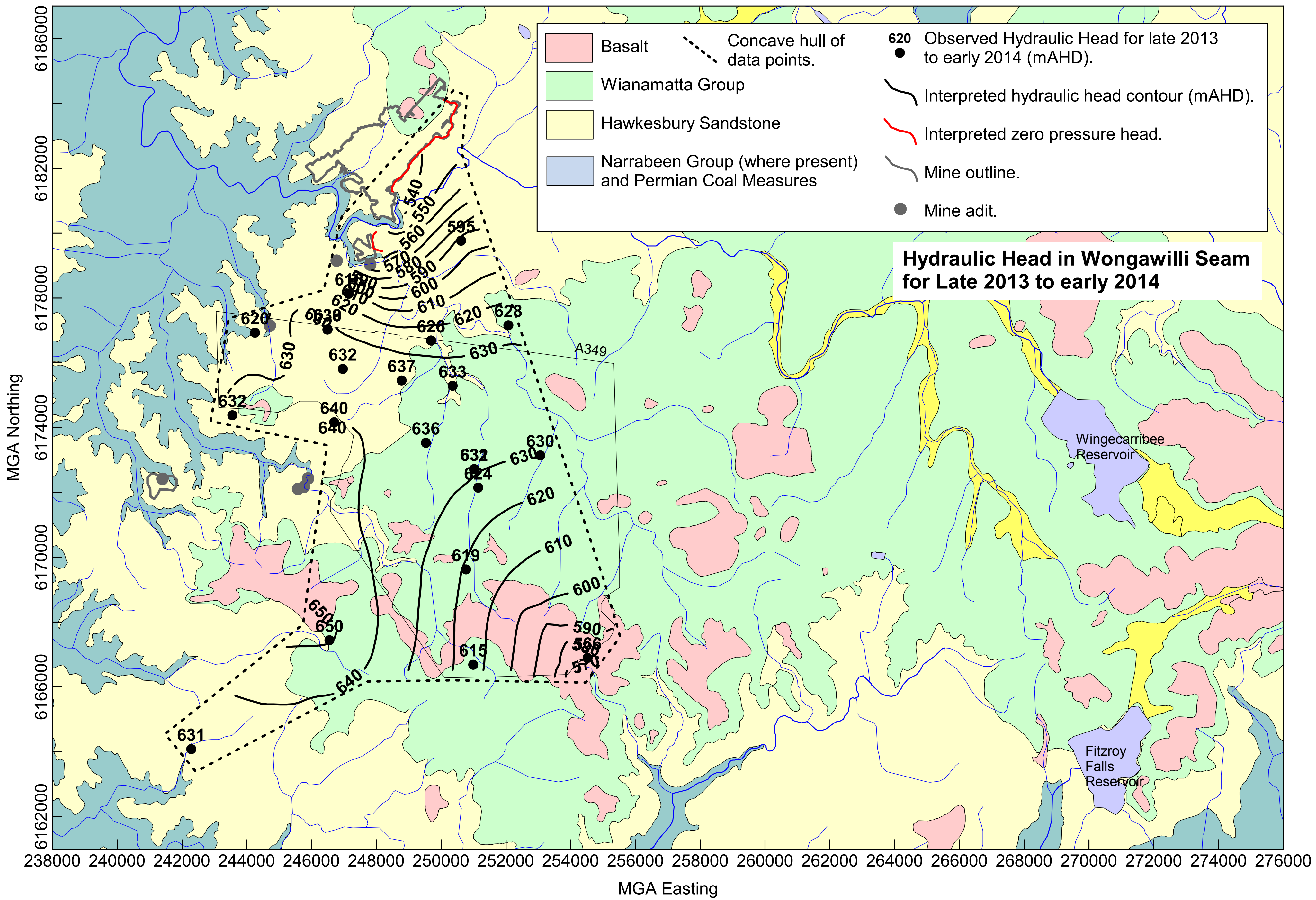

620
615
610
605
600
Water Level (mAHD)
GW075036
Jan-99
Jan-01
Jan-03
Jan-05
Jan-07
Jan-09
Jan-11
Jan-13
Jan-15


660
655
650
645
640
Water Level (mAHD)
GW075412
GW075413
Jan-99
Jan-01
Jan-03
Jan-05
Jan-07
Jan-09
Jan-11
Jan-13
Jan-15

Appendix E - Hydraulic Head Surfaces



Basalt
Wianamatta Group
Hawkesbury Sandstone
Narrabeen Group (where present) and Permian Coal Measures
River tie-down required (only in concave hull of data points)
Concave hull of data points.
620 Observed Hydraulic Head for late 2013 to early 2014 (mAHD).
Interpreted hydraulic head contour (mAHD).
Interpreted zero pressure head.
Mine outline.
Mine adit.
Hydraulic Head in the Lower Hawkesbury Sandstone (on a surface an average of 33m above the sandstone base) for Late 2013 to Early 2014
Wingecarribee Reservoir
Fitzroy Falls Reservoir
A349
MGA Northing
MGA Easting
238000 240000 242000 244000 246000 248000 250000 252000 254000 256000 258000 260000 262000 264000 266000 268000 270000 272000 274000 276000
6162000 6166000 6170000 6174000 6178000 6182000 6186000



Basalt
Wianamatta Group
Hawkesbury Sandstone
Narrabeen Group (where present) and Permian Coal Measures
Concave hull of data points.
620 Observed Hydraulic Head for late 2013 to early 2014 (mAHD).
Interpreted hydraulic head contour (mAHD).
Interpreted zero pressure head.
Mine outline.
Mine adit.
Hydraulic Head in Wongawilli Seam for Late 2013 to early 2014
Wingecarribee Reservoir
Fitzroy Falls Reservoir
A349
MGA Northing
MGA Easting

Appendix F - Hydraulic Head Data for the Southeastern Basalt Body

DATABASE OF WATER LEVELS IN AND AROUND THE SOUTHEASTERN BASALT BODY

Bore	Easting (MGA)	Northing (MGA)	Network	Stratum	Ground Elevation* (mAHD)	Water Level (mAHD)	Probable date of water level measurement	Pressure Head (m)	Height above base of HAW (m)
GW011262	252352	6166970	Private	Basalt	723	719	1-Dec-55	5	170
GW014121	252487	6166696	Private	Basalt	724	716	1-Dec-56	14	158
GW014491	253454	6166753	Private	Basalt	730	721	1-Nov-56	7	180
GW015061	251024	6166459	Private	Basalt	702	701	1-Dec-56	12	134
GW050251	252889	6166923	Private	Basalt top (weathered)	733	728	1-Feb-79	9	180
GW066761	253508	6166662	Private	Basalt	725	721	16-Oct-92	7	180
GW066764	254253	6166435	Private	Basalt	712	698	Unknown	5	167
GW066769	254252	6166466	Private	Basalt	711	704	Unknown	9	170
GW066770	254362	6166160	Private	Basalt	710	700	Unknown	12	162
GW067521	253702	6168715	Private	Basalt	683	665	28-Jan-92	9	137
GW069007	254188	6166419	Private	Basalt	712	702	4-Nov-91	13	163
GW069118	253610	6166800	Private	Basalt	727	709	25-Feb-91	6	171
GW072154	253249	6166401	Private	Basalt	717	707	17-Jan-94	10	157
GW072273	253044	6166546	Private	Basalt (weathered)	724	720	31-Jan-92	11	168
GW072416	252451	6166806	Private	Basalt	723	716	24-Nov-94	8	165
GW100256	254259	6166306	Private	Basalt (weathered)	712	704	10-Aug-93	11	166
GW100257	254231	6166339	Private	Basalt / Sandstone	712	701	12-Aug-93	13	162
GW101324	254223	6166588	Private	Basalt	712	705	26-Sep-95	4	175
GW101421	254321	6165789	Private	Basalt	712	703	13-Mar-96	14	159
GW102401	254158	6166186	Private	Basalt / Shale	719	705	20-Dec-96	32	145
GW102621	254577	6166721	Private	Basalt	716	703	11-Dec-98	8	172
GW102622	254626	6166784	Private	Basalt	719	707	13-Nov-98	20	165
GW102623	254576	6166752	Private	Basalt	716	705	15-Nov-98	12	171
GW102624	254548	6166844	Private	Basalt	719	708	18-Nov-99	6	179
GW102964	253499	6166812	Private	Basalt	730	715	1-Jan-56	4	178
GW104193	255989	6167862	Private	Basalt	686	680	13-Feb-02	15	164
GW104198	252443	6166728	Private	Basalt base	724	713	5-Feb-02	13	156
GW105097	253767	6167150	Private	Basalt / Sandstone	727	567	31-Oct-03	37	1
GW106103	253879	6167685	Private	Basalt base	717	690	27-Feb-04	20	143
GW107625	252749	6166539	Private	Basalt	723	716	15-Nov-05	12	161
GW108271	254281	6167270	Private	Basalt base	717	702	26-Aug-06	47	132
GW100720	253419	6166882	Private	HAW below Basalt	735	572	20-Oct-96	24	14
GW102694	253410	6168417	Private	HAW below Basalt	707	618	1-Sep-99	44	48
GW102757	251971	6167918	Private	HAW below Basalt	716	617	5-May-99	55	19

Bore	Easting (MGA)	Northing (MGA)	Network	Stratum	Ground Elevation* (mAHD)	Water Level (mAHD)	Probable date of water level measurement	Pressure Head (m)	Height above base of HAW (m)
GW104727	252108	6169089	Private	HAW below Basalt	720	619	25-Mar-03	37	47
GW104917	255641	6168126	Private	HAW below Basalt	676	611	28-Nov-02	64	43
GW105093	252884	6165950	Private	HAW Base / Top ICM	702	576	19-Nov-03	25	4
GW105308	250384	6167628	Private	HAW below Basalt	713	630	1-Mar-02	47	31
GW105950	254257	6167973	Private	HAW Base / Top ICM	684	612	1-Jan-04	53	39
GW110529	251309	6166226	Private	HAW Base / Top ICM	705	585	29-Oct-09	34	-3
H136A	254521	6166894	Hume	WW	718	566	22-May-14	47	-4
H136B	254517	6166890	Hume	HAW	718	564	22-May-14	7	34
H136C	254513	6166887	Hume	RB	718	708	22-May-14	44	140
H42A	250988	6166688	Hume	WW	702	615	23-Mar-14	70	-7
H42C	250985	6166678	Hume	HAW	702	613	21-Aug-14	54	7

* Approximate for private bores (estimated from overplotting with digitial elevation model).

APPENDIX F – HUME COAL PROJECT EIS GROUNDWATER ASSESSMENT VOLUME 2: MODELLING AND IMPACT ASSESSMENT (COFFEY 2016B)

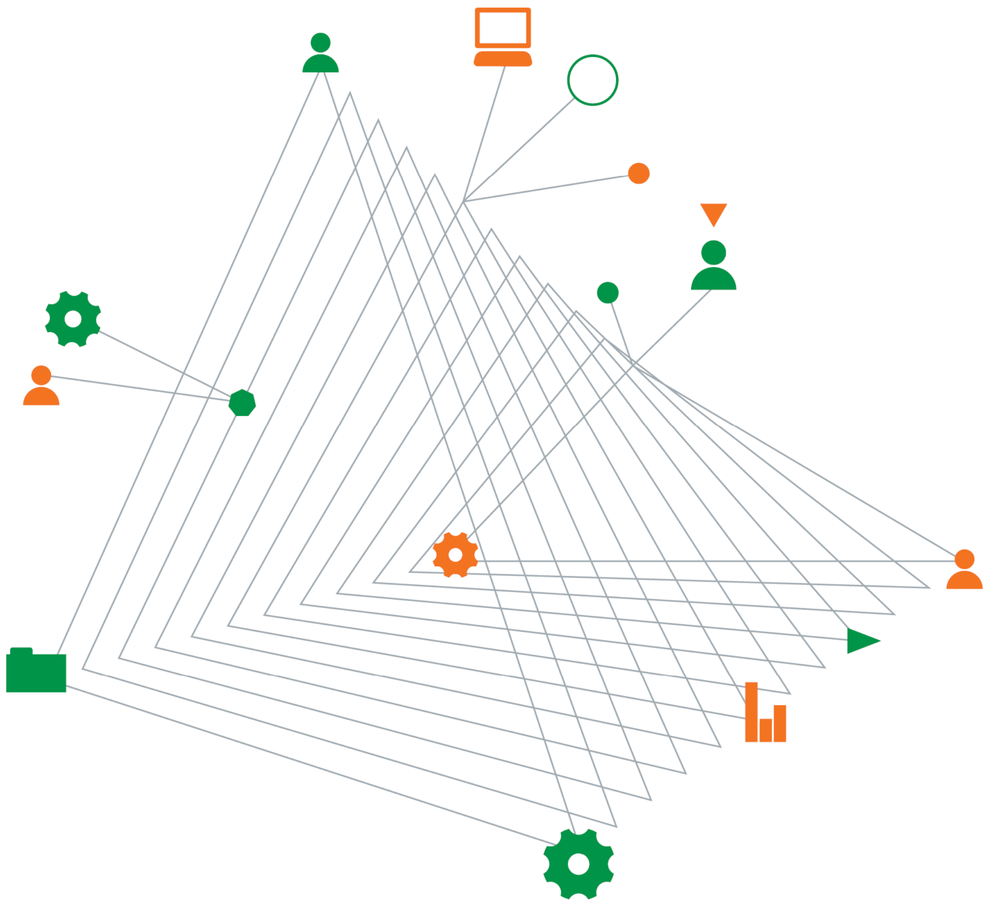
coffey
A TETRA TECH COMPANY

Hume Coal Pty Limited

Hume Coal Project

Groundwater Assessment Volume 2: Numerical Modelling and Impact Assessment

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
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17 November 2016

Document authorisation

Our ref: GEOTLCOV25281AB-ACB

For and on behalf of Coffey

Paul Tammetta
Associate Subsurface Hydrologist

Quality Information

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Distribution

Report Status	No. of copies	Format	Distributed to	Date
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2nd Draft	1	PDF	Hume Coal Pty Limited	9 Jun 2016
Final	1	PDF	Hume Coal Pty Limited	17 Nov 2016

Table of Contents

Tables

Figures

Drawings

Appendices

Executive Summary

A regional numerical groundwater flow model was developed for the Hume Coal Project. Model calibration was successful in reproducing shallow groundwater discharges (stream baseflow), deep groundwater discharges (discharge to the Berrima mine void), and hydraulic heads, and has adhered strongly to the observed hydraulic conductivity distribution.

The combination of observations from the pumping tests undertaken by Hume, with shallow and deep discharge observations, allows the calibrated Kv distribution to be applicable to an appropriate scale and is considered to have a high level of reliability, including reliable representation of the effects of the high density of open bores present in the area, and the tectonic activity that has occurred in the area.

This has reduced the uncertainty in model outputs. The model is considered to be acceptably calibrated and fit for its purpose in simulating the groundwater system with application of the magnitude of the stress defined by the Hume mine schedule.

The model was subsequently used in a predictive capacity to assess impacts from Hume mining operations using the Pine Feather layout and method. Model predictive simulation results are as follows:

- The total volume of groundwater inflow that reports to the sump is calculated as 8.4 GL during the time the effects of mining are active in the groundwater system. The maximum inflow rate to the sump is 2.7 ML/day (1000 ML/year) in year 17 of mining.
- The total volume of groundwater inflow that reports to the void is 24.3 GL during the time the effects of mining are active in the groundwater system. The maximum inflow rate to the void is 5.1 ML/day (1860 ML/year) in year 15 of mining.
- The drawdown footprint achieves a maximum size at about 17 years since the start of mining. The zone of highest drawdown in the footprint migrates according to worked areas. At 17 years, the 2 m differential drawdown* contour at the water table extends a maximum of about 2 km past the southeast corner of the mine footprint. The duration of differential drawdown of the water table varies between about 15 years and 60 years. Recovery of the water table over most of the area, to 2 m differential drawdown, is largely complete within about 60 years after the start of Hume mining.
- Maximum total drawdown of the water table greater than 2 m occurs at several locations where there are shallow water levels. These areas have been provided to the ecology team to consider potential impacts to ecosystems that may be present at these locations.
- No direct leakage from the Wingecarribee River, induced by Hume operations, is calculated by the model. Model results indicate that 98% of the total inflow to the Hume mine workings is satisfied by interception of baseflow to streams, and release of groundwater storage from media. 2% of the inflow is satisfied by leakage from Medway Reservoir (a total leakage of approximately 804 ML over 22 years, or an overall average over the period of approximately 0.1 ML/day). Baseflow interception induced by Hume operations is largest for Medway Rivulet. Baseflow analysis of flow observations from Medway Rivulet suggests the average baseflow measured at these gauges (over the monitoring period) is about 3 times larger than the calculated future maximum baseflow interception.
- Of the 117 private bores identified as residing in the potential drawdown zone, 99 bores are assessed as being subject to a differential drawdown of 2 m or more. The overall average proportion of the maximum total drawdown that is caused by Hume operations is 87%. Groundwater extraction by private users accounts for the remaining 13%. The duration of the period for each bore where differential drawdown is greater than 2 m ranges between 2 months and 65 years, with an average of 34 years. The majority of these bores have recovered back to 2

m differential drawdown by 60 years since the start of mining. Five of these bores are likely to be intersected by mining because they penetrate the mined zone.

* Differential drawdown is calculated as the difference between drawdowns from the active Hume mining scenario (which gives the total drawdown) and a null scenario where the Hume operation is inactive (giving a null case drawdown). The differential drawdown is thus that drawdown due only to the Hume operation.

1. Introduction

This is the second of two volumes 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 groundwater users due to the 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 on the groundwater system and on private water bores from mining. This volume presents numerical model development, calibration, and predictive simulations and results.

An analysis of a substantial database of observations compiled from data provided by Hume and published sources, was undertaken to support development of the hydrogeological conceptual model and subsequent numerical model development and calibration. That analysis is reported in Volume 1. This volume should be read in conjunction with Volume 1.

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 proposes to use 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.

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 1.1, is approximately 5,051 hectares (ha). Surface disturbance will mainly be restricted to the surface infrastructure areas shown in Figure 1.2, 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.

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 1.1). 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 1.1). 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 1.1).

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.

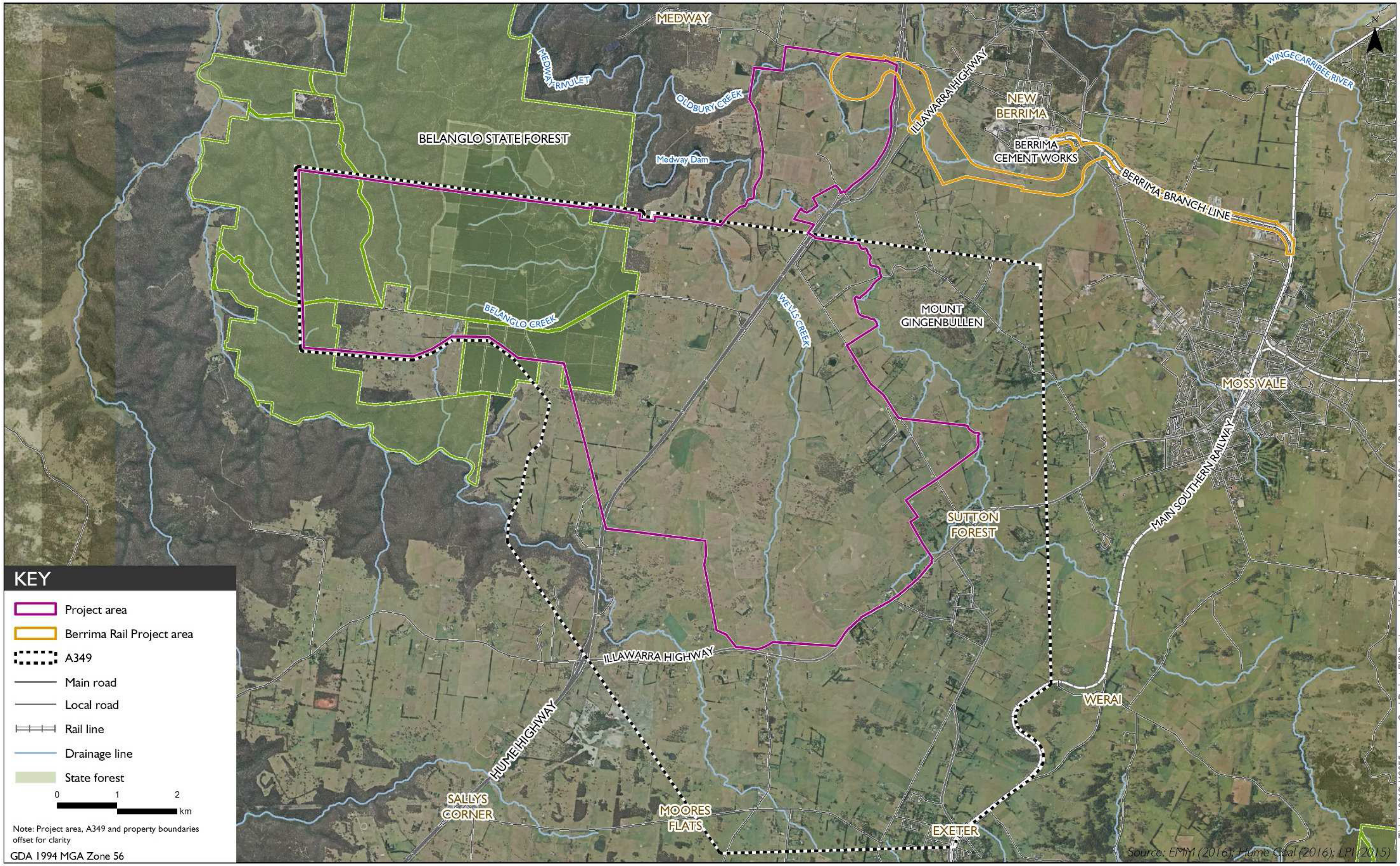


Figure 1.1. Local context

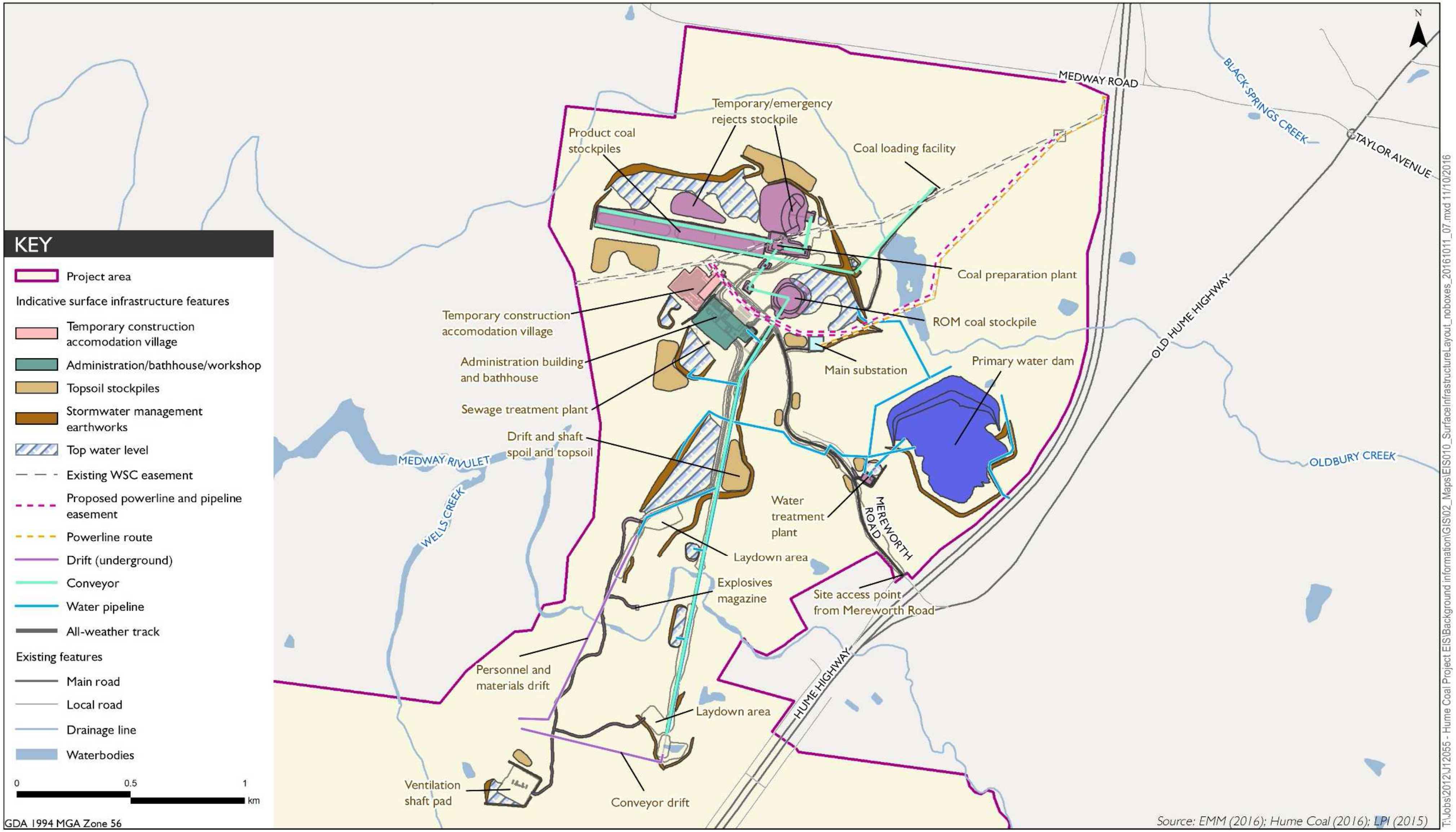


Figure 1.2. Indicative surface infrastructure layo ut.

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. 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 impacts 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 on a localised zone of Hawkesbury Sandstone bounded by Medway Rivulet and the Wingecarribee River. The mine worked the Wongawilli Seam and ceased 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. Proposed mining

Hume will undertake a first workings mining layout and method. 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. Each panel is separated from the next by unmined coal. 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 2.1 is a detail of two panels for reference in the following discussion.

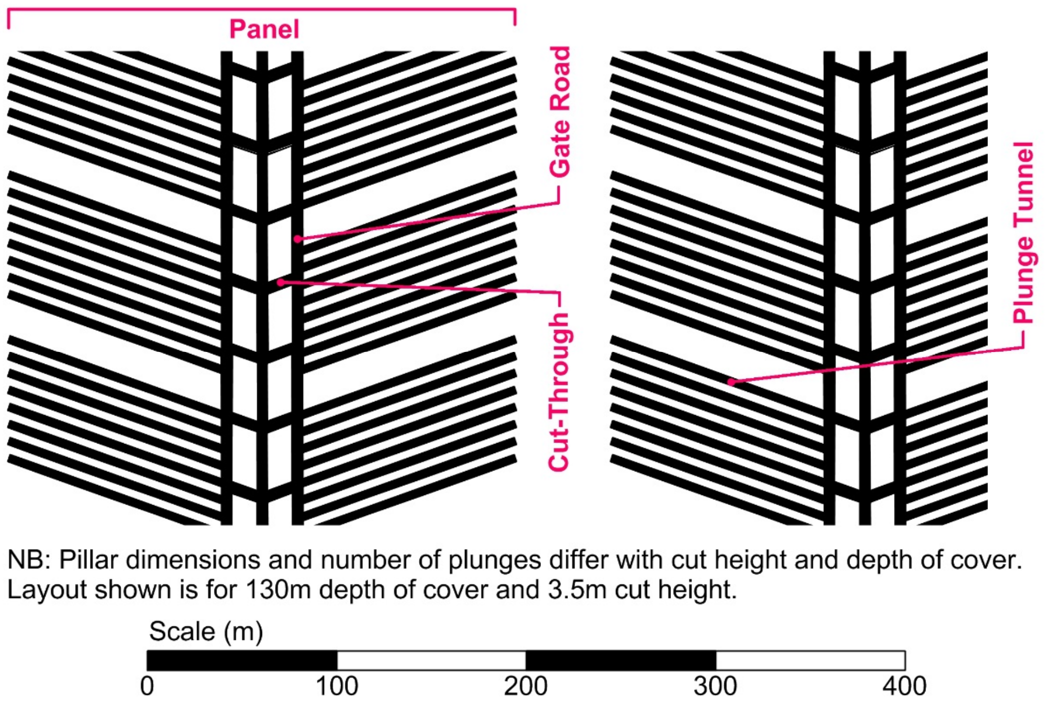


Figure 2.1. Detail of mine openings for the first workings mining method. Black areas indicate removed coal. Refer to Table 1 for panel dimensions and other information.

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. The mining method is non-caving, with additional workings comprising plunges (tunnels) that are driven off the gate roads. These openings are separated by pillars that are designed not to fail post-mining. This results in openings remaining open post-mining, without caving (goaf is not created). Relaxation in the immediate roof over the openings is generally limited to less than 3 m into the overlying roof.

Figure 2.2 shows the panel layout to be used for the Hume mine, and made the subject of predictive simulations. Panel and headings names are also shown. Mining comprises 54 panels, four main headings (three of which have flanking plunges attached directly to them), two shafts, and one sump.

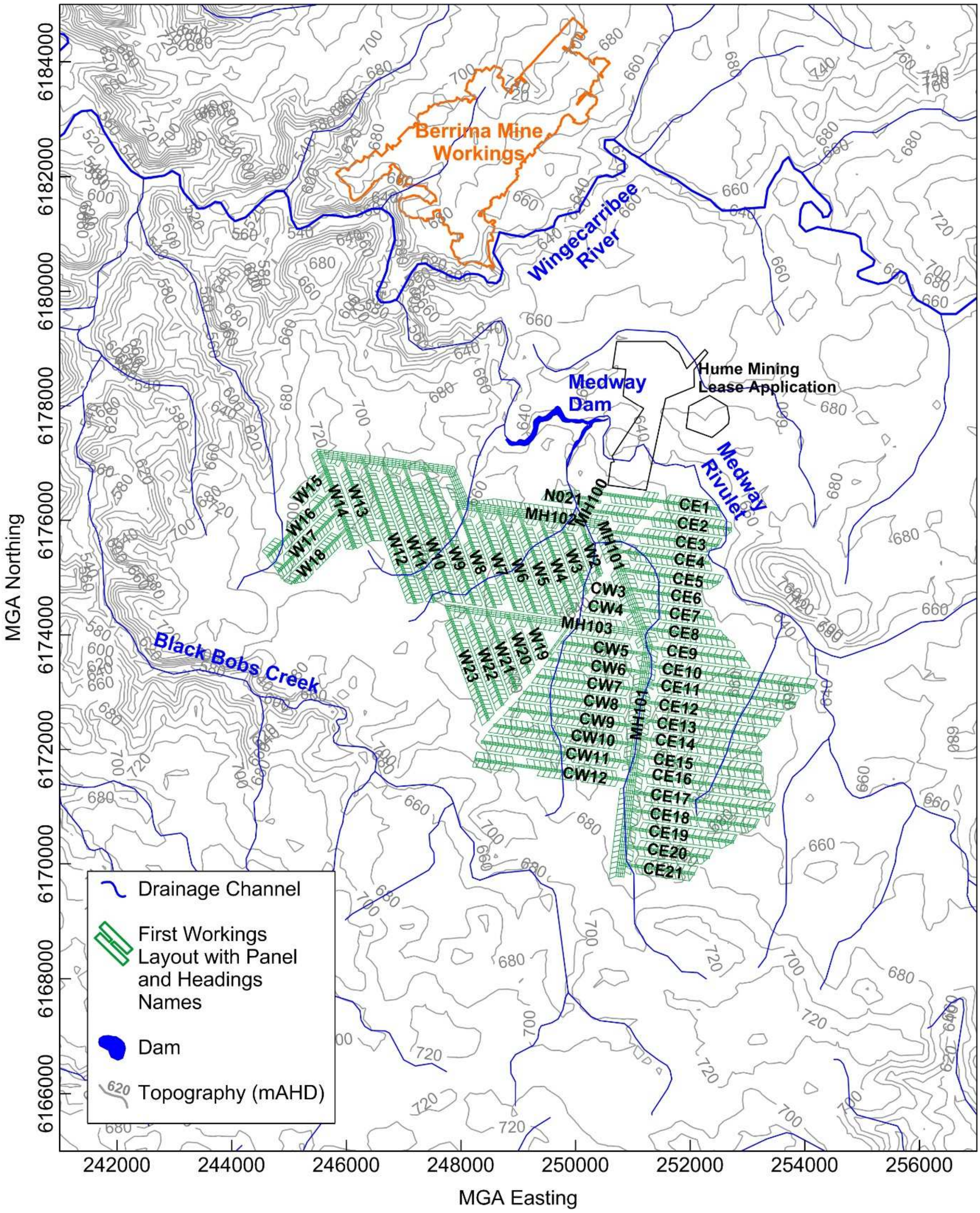


Figure 2.2. Hume mine panel layout used in predictive simulations.

Table 1 lists salient features of the mine layout. Appendix A provides tables listing mined volumes on a panel and annual basis, a plan showing the variation of mining height over the mined area, and the mining schedule. The schedule illustrates the direction of mining.

Table 1. Hume first workings mining method characteristics.

Maximum Mining Height (m)	3.5
Typical Panel Width (m)	270
Inter-panel Distance (m)	50
Calculated Height of Desaturation (H) (m above working section roof)	2
Total extracted coal volume (ML) *	32666
Mine Life (years)	19
Method Details	Non-Caving. Spine of 3 gate roads along panel centreline. 120 m tunnels (plunges) extending from gate roads.

* 1000 m^3 = 1 ML.

Rock and coal fragments left over from washing and processing of coal (tailings) are combined with mine water to form a mixed slurry. Disposal of the slurry is known as co-disposal. For the Hume mine, co-disposal will be made to the underground voids.

Several groundwater drawdown mitigation measures have been modelled, comprising backfilling of the mined void with co-disposed tailings, sealing individual panels as they are mined (using bulkheads rated to withstand equilibrated hydraulic heads), and injection of mine inflow back into the void through the bulkheads (should excess water be available). These measures are designed to reduce the total groundwater drainage into the workings and thereby reduce drawdown in the overburden.

3. Model development

A regional groundwater flow numerical model has been developed to simulate underground mining in the Hume lease. The model was developed using MODFLOW-SURFACT Version 3, distributed by Hydrogeologic, Inc. (Virginia, USA). It is an advanced version of the standard USGS MODFLOW algorithm and is able to simulate variably saturated flow. The software can accommodate unsaturated zones at depth. MODFLOW-SURFACT is operated within the Visual Modflow (Version 2009) pre- and post-processing environment, developed by Schlumberger Water Services.

3.1. Layers and grid

The active model area (the model domain) is shown in Drawing 1. It covers 752 km^2. Its boundary follows natural features and has been selected so that the hydraulic heads in the model are controlled by rainfall recharge and groundwater sinks at the extremities of the model area (in conjunction with interior boundary conditions such as the mines and drainage channels). This eliminates difficulties associated with the uncertainty in, and control of, groundwater fluxes to or from constant head cells or general head boundaries on the boundary of the model area. An exception is Wingecarribee Reservoir (on the eastern model boundary) which is considered valid to simulate using a local constant head condition in the top model layer (see below).

The model grid comprises 15 layers (two of which are inactive) with 379 columns and 425 rows. Cell dimensions are 50 m x 50 m over the Hume lease, expanding to 50 m x 100 m over the Berrima lease, then to 200 m x 200 m over the remaining area. The finer grid is placed where detail is required during model calibration and predictive simulations.

13 model layers are used to represent hydraulic contrasts between hydrostratigraphic units, maintain adequate depth resolution, and permit modelling of behavioural changes arising from deformation. These layers and their average thicknesses are listed in Table 2.

Based on the assessment of hydraulic heads in the southeastern basalt body (see Volume 1), the Robertson Basalt is not explicitly simulated in the main model. A large vertical hydraulic head gradient is present between the basalt and underlying media, and a desaturated zone is interpreted to occur underneath most of the Wianamatta Group (WG) underlying the basalt. The basalt was therefore modelled separately (Appendix H). The basalt is conceptualised as a stable source of recharge to the WG and its presence is incorporated in the recharge rate for the WG underlying the basalt. This greatly facilitates the functioning of the model and reduces the requirement to estimate further parameters for which observations are not available.

Structure contours for the model layers were created by first resolving six key horizons in detail (bases of the Tertiary Basalt, Wianamatta Group, Hawkesbury Sandstone, Wongawilli Seam, Illawarra Coal Measures (ICM), and Shoalhaven Group). Additional structure contours for other layers (for example, subdivision of the Hawkesbury Sandstone) were developed from these six fundamental surfaces using constant offsets or proportioned thicknesses.

The Hawkesbury Sandstone is represented by six layers to facilitate the development of hydraulic head profiles in proximity, and allow the effects of deformation to be incorporated. The bottom two layers for the Hawkesbury Sandstone (Layers 6 and 7) are to accommodate roof relaxation from mining where the interburden or plies above the working section are absent.

Layer 8 represents sediment dominant lithologies, and contains the Wongawilli Seam R ply (WWR Ply).

Table 2. Model layer thicknesses.

Stratum	Model Layer	Average Layer Thickness (m)
Wianamatta Group	1	55 (where present)
Hawkesbury Sandstone	2	53 (where overlain by WG). Reduces from this average, to nil (from edge of WG to limit of sandstone)
	3	30
	4	34
	5	7
	6	2
	7	2
Interburden (Narrabeen Group, WWR Ply, and Farmborough Claystone)	8	4*
Wongawilli Seam above mined section	9	2*
	10	2*
Wongawilli Seam mined section	11	3.5
Illawarra Coal Measures	12	19 (min. 2, max. 49)
Shoalhaven Group	13	120

* Hume lease area. Not present everywhere (minimum model layer thickness is 0.1 m).

The Mt Gingenbullen intrusion (see Drawing 1) occurs on the northeastern lease boundary. A detailed analysis of the potential role of intrusions has been undertaken in Volume 1. Given the observed extents of disturbed zones in the Berrima lease area, and observations made at other coal mines, the intrusion is not explicitly modelled (see Volume 1).

A discussion on the Cement Works Fault is provided in Volume 1. Available hydraulic head observations show no perturbation due to this fault. Given the large change in displacement over a relatively short distance, and comparison to the magnetic intensity field, the fault has not been explicitly modelled since, in the absence of intersection, and due to its relatively localised nature, its ability to influence the evolution of the hydraulic head field from Hume mining operations is considered limited.

Hydraulic parameters for rock are defined according to depth below ground. 15 parameter zones have been used to discretise the decrease in hydraulic conductivity (K) and storativity with depth. Anisotropy in the K field is modelled for the vertical direction.

Figure 3.1 shows a cross section of the model layering (along Row 242, MGA Northing 6174000) through the mine lease from west to east. The finer grid over the Hume mine area and coarser grid to the east can be seen.

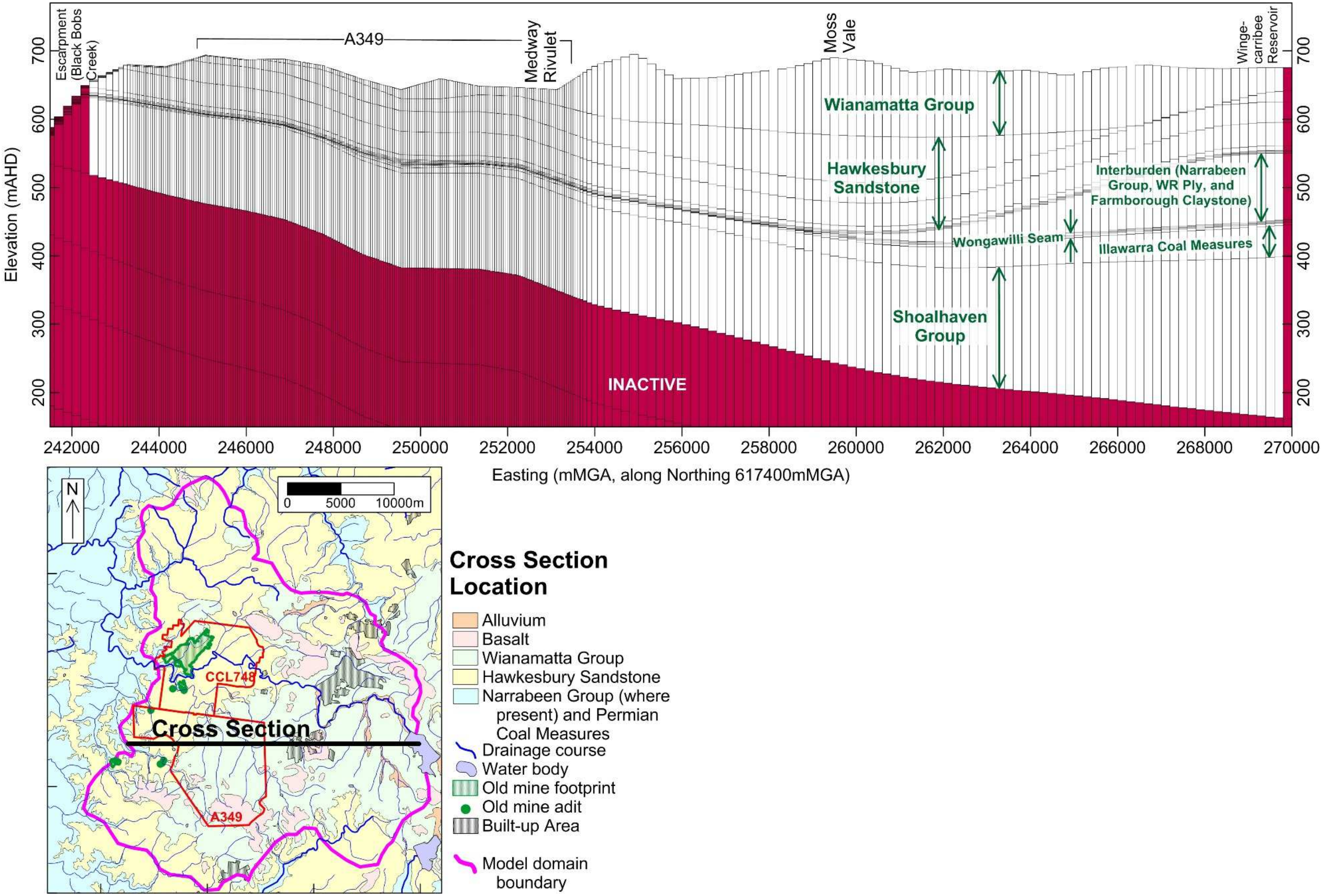


Figure 3.1. Model cross section illustrating model layering and grid along Row 242.

3.2. Boundary conditions

All layers were designated as variable type layers (a layer that will allow both unconfined and confined behaviour).

The model boundary has been selected sufficiently distant from the mine area to significantly reduce the potential for flow normal to the boundary occurring due to stresses imposed at the mine. The boundary conditions at the extremity of the model area consist of:

- No-flow at topographic divides.
- Discharge zones at drainage channels.
- Local constant head at Wingecarribee Reservoir.
- Discharge zones at escarpments.

Escarpments are treated as a line of drain cells to simulate consumption of groundwater at the escarpment by seepage and evapotranspiration. The western escarpment (limit of the Illawarra Coal Measures) approaches the proposed workings in some areas. Interpretation of observed hydraulic heads indicates drawdown decreases rapidly below the mined coal seam (see Figure 6.1 of Volume 1); a behaviour observed at virtually all mines in stratified sedimentary systems (where Kv is smaller than Kh). Drawdown from the proposed Hume mine can only migrate west of the western escarpment through the Shoalhaven Group.

Wingecarribee Reservoir provides a strong, reasonably constant hydraulic control in the upper model layer. Vertical gradients at Government piezometer GW075033 are negligible and reservoir water levels are reasonably constant.

3.2.1. Rivers and creeks

The Wingecarribee River was simulated using the River package, due to its quasi-permanent nature and proximity to the proposed mine. This allows two-way transfer of water between the channel and the subsurface. Two groups of river cells are used (for 50 m x 50 m cells and 50 m x 100 m cells) to allow the use of a single notional vertical K (Kv) of 0.1 m/day for the notional riverbed material. This is considered reasonable and moderately high, providing strong hydraulic connection between water in the channel and groundwater in the underlying media.

Medway Dam, an in-stream storage on Medway Rivulet, was also simulated using the River Package. No information was available for the base of the dam. Riverbed conductance was set to 25 m^2/day for 50 m x 50 m cells, based on simulation of leakage from Avon and Cordeaux dams in the Dendrobium mine area (HC 2010, Coffey 2012). It assumes the presence of residual soil at the dam base. For this cell size, and a soil thickness of 2 m at the dam base, Kv of the soil is 0.02 m/day. This is high for soils of WG origin and is considered conservative.

Remaining drainage channels were simulated using the Drain package due to their ephemeral nature, or distance from the imposed stresses. Flow monitoring for streams on the mine lease indicate these drainage channels are ephemeral. Drain conductance was set to a high value of 1000 m^2/day, allowing the media hydraulic properties to control leakage to the channels. Elevations for the inverts of these and other channels over the model domain are based on digital elevation information available from the Australian Government, checked against LiDAR topographic survey data for the Hume Lease.

3.2.2. Reservoirs

Wingecarribee reservoir, on the eastern model boundary, was simulated with a local constant head condition in the top model layer. Analysis of its water levels indicates a minimal change with time, with virtual equilibrium over the last several years. Water may exchange with the subsurface in either direction. The reservoir storage capacity is considered large compared to any changes in groundwater exchange rates caused by mining, so that the specified head is approximated as invariant with changes in groundwater exchange. The water level elevation was held invariant at 676 m AHD for all simulations.

3.2.3. Rainfall recharge and evapotranspiration

Rainfall recharge was applied as a constant percentage of incident rainfall recorded at Moss Vale (Bureau of Meteorology (BOM) Station 68045) over quarterly periods. The average long-term annual rainfall for the mine lease is estimated as 957 mm, similar to the average rainfall at Moss Vale. Rainfall recharge is applied to the topmost active cell in each vertical column. Net recharge to the saturated zone from irrigation is considered minor in comparison to rainfall recharge and is therefore not considered separately in the model.

Evapotranspiration (ET) was applied over the entire domain with a maximum rate of 3 mm/day and extinction depth of 1.5 m, based on land surface types and proportions.

3.2.4. Unconsolidated sediments

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, and would discharge to the 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.

Leakage from the alluvium into the mine void is therefore considered a small component of the total inflow, with rock providing the majority of the inflow. For the current study the assumption is made that the contribution to mine inflow (or to dewatered rock) from unconsolidated sediments is negligible compared to rock, based on the site geology and borehole logs (see Volume 1).

Major pumping is not known to occur from the alluvium, and it is not considered by the NSW DPI to be a separate groundwater source in the relevant water sharing plan.

3.2.5. Mine workings

Height of drainage above non-caving workings

The first workings mining method to be adopted by Hume is non-caving. Some parts of the existing Berrima and Loch Catherine voids, are also non-caving workings where the height of deformation is nominally 2 m into the roof. The deformation height is also the adopted height of groundwater drainage. This type of mining was extensively practised prior to the advent of mechanisation but is rarely undertaken now. It is the preferred mining method for the Hume project as it significantly minimises groundwater impacts compared to full extraction mining.

Deformation (dilation) from 1st workings consists of enlargement of defect apertures and minor cracking in the roof above mine openings, extending upwards a maximum of approximately 3 m above the roof of the working section, depending on road width, horizontal stress magnitudes, roof rock strength, and rock bolting (or other support) strategy. This is based on typical published measurements from extensometers placed in headings roofs (see for example Sweby 1997, Whittles 1999, and British Coal Corporation 1996). Dilation typically extends approximately 2 m into the roof for common 1st workings mine plans. Extensional strains in the overburden are significantly smaller, and extend a shorter vertical distance, than full extraction mining.

The anticipated roof bolting strategy for the proposed PF mine layout is as follows:

- Bolting of gate roads at a density of between 4 x 1.8 m bolts per 1.5 m, up to 6 x 2.1 m bolts per 1 m. The most likely scenario would be 4 x 1.8 m bolts per 1 m.
- Gate road intersections may have higher bolt densities, with 4 x 4 m flexi bolts common practice, or alternatively, moving from a 4-bolt pattern to a 6-bolt pattern through the intersection and for 10 m either side.

The bolted interval is the most likely region of the roof to experience deformation, however current roof bolt installation practice is for installation under pre-tension of between 5 t and 10 t which assists in closing roof delaminations. For resin-encapsulated bolts, the resin backpressure may create additional fracturing in some cases, however the roof support system for the Hume mine plan has been designed to avoid these effects.

A 3 m relaxation height is considered to be excessively conservative if applied over the entire mine footprint, since:

- The mine roof will act more stiffly in some areas, particularly in the shallower areas of the mine (for example, less than 150 m overburden thickness).
- First workings recovery is approximately 35%, which will have the effect of increasing pillar stiffness.

To estimate a reasonable relaxation height, a sensitivity analysis was undertaken with the model, prior to predictive simulation, to assess the change in mine inflows for relaxation heights of 2 m and 4 m. This was applied over an area representative of the typical extent of an actively draining area at an instant in time. This analysis is reported in the sensitivity section. Results indicate an increase in inflow of 4.3% between 2 m and 4 m relaxation heights. Observational databases indicate a relaxation height of less than 2.5 m is common for first working mines. Given the small change in inflow between 2 m and 4 m heights, and the design of the Hume mine plan, the most representative relaxation height applicable over a large area of non-caving workings is considered to be 2 m, and this was adopted for predictive simulations.

Height of drainage above caved workings

Parts of the existing Berrima and Loch Catherine voids are full extraction workings where caving has occurred. These comprise panels of extracted 1st workings pillars. Heights of desaturation (H) above full extraction panels are calculated according to the equation of Tammetta (2013) for longwall panels. Local and international observations indicate H for pillar extraction panels is between 50% and 60% of H for a longwall panel with equivalent geometry (Tammetta 2013). 60% is used in this work.

For calibration purposes H above the Berrima and Loch Catherine voids was first calculated for individual panels. Figure 3.2 shows the full extraction panels for the Berrima and Loch Catherine voids, and their calculated H. Refer to Drawing 1 for the locations of these mines with respect to each other. These are old workings with variable panel shapes. To simplify calibration, an average H of 53 m above the roof of the working section was adopted for the full extraction panels for these voids, based on the general similarity in H amongst the panels (see Figure 3.2). 1st workings areas of the Berrima void are given a relaxation height of 2 m above the working section roof.

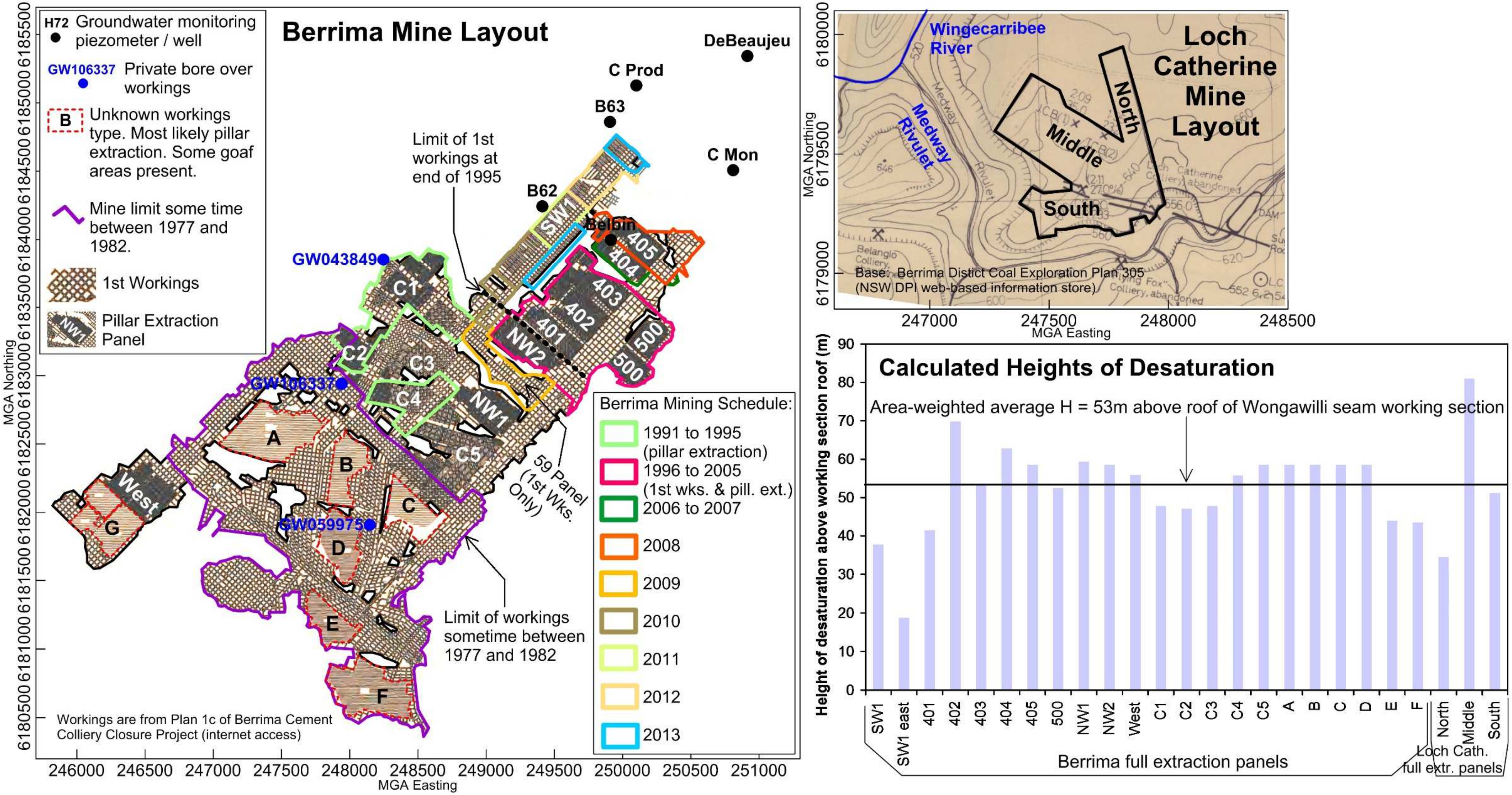


Figure 3.2. Full extraction panels for Berrima and Loch Catherine mines, and calculated heights of desaturation.

Model implementation

The creation of mine openings, and the associated ground deformation, creates a compressional zone (the pressure arch and abutments; Booth 1986) around the deformed zone due to changes in the stress field caused by deformation. Figure 3.3 illustrates the warping of vertical and horizontal stress vectors around both full extraction panels and 1st workings openings. For non-caving first workings no goaf occurs (because pillars do not fail) and stress perturbations occur over a smaller area (compared to caving systems).

For mining techniques that involve full extraction, caving creates a complex change in the K field, with increases and decreases in pre-mining K occurring (Tammetta 2015). Figure 3.3 shows interpreted areas of K reduction, assuming flanking of workings by other same-type workings, based on Tammetta (2015). Changes in the K field occur over a significantly smaller zone for non-caving mine openings. Detailed spatial simulation of the resulting K field would require micro-discretisation, untenable for a regional model with numerous panels or non-caving mine openings. For a regional model, the resulting K field imparted by the stress concentration zone around an opening is incorporated using the conductance of drains used to simulate mine openings and the overlying drained zones. This also avoids the problem of estimation of post-mining K in the drained zone (where desaturation occurs and estimation of K via calibration is not possible).

H is estimated a-priori for full extraction (caved) and non-caving workings, and drains are used to simulate drainage in each layer intersected by the deformed zone (the collapsed zone for full extraction, and the relaxation zone for non-caving workings). H for non-caving workings is a few metres whereas H for full extraction panels is comparable to the panel width (depending on panel geometry and overburden thickness).

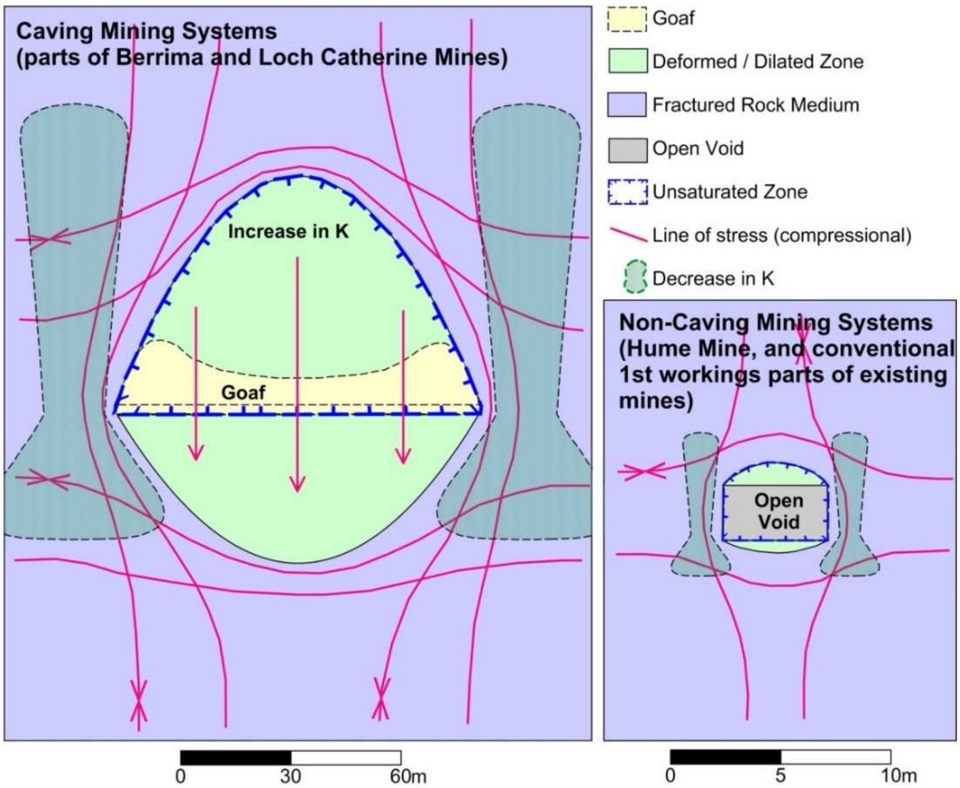


Figure 3.3. Conceptualisation of the perturbation of stress trajectories and changes in K in fractured media caused by underground mining.

Potential changes in hydraulic conductivity above the relaxed zone

An assessment of mine subsidence (MA 2015) used the work of Ditton and Frith (2003) to assess the likely maximum localised values of horizontal strain (compressive and tensile) in the Hawkesbury Sandstone in the mine lease. Results are predictive horizontal strains above the workings of 0.01% and 0.018%, using two different methods of calculation. An upper threshold of 0.02% was used for assessment of impacts. Results in MA (2015) indicate that predicted extensional strains for the first workings method, above the relaxed zone adopted in the model, will be insufficient to activate movement of defect apertures, since the relaxation will be consumed by elastic expansion of the matrix, with negligible change in defect aperture. These results support the modelling assumption of nil change in the hydraulic conductivity field above the relaxed zone in the Hume Mine.

Berrima Mine

A review of available literature provided useful observations made during the course of mining at the Berrima Colliery, for use in model implementation. A summary is provided below.

Panels mined near the end of mine life generally comprised five gate roads driven at 5.5 m width and 2.3 m height. Pillar dimensions varied from 37.5 m to 45 m centres. Development and extraction of runouts on the left panel side was undertaken concurrently with panel development. The right runouts were extracted on retreat but were sometimes split on advance. Full extraction of pillars occurred after splitting, at 25 m centres (once parallel to the cut-through).

Mining conditions were generally good with minimal roof support required. Roof bolting was undertaken at 2 m spacing with 2 roof bolts per row at 3 m spacing (1.25 m from each rib wall). Spacing was decreased when passing through sections of soft roof.

3.2.6. Pumping from private bores

The model simulates pumping from the following private water bores located in the model domain:

- 83 high extraction bores with associated aquifer access licences. These bores are generally used for irrigation or other industrial purposes. The combined level of entitlement is 14.5 ML/day (5300 ML/year).
- 299 bores approved for stock and/or domestic use.

No metering of actual usage is known to be undertaken by regulatory agencies for the area. Pumping was therefore a variable. Stock / domestic bores were assigned a constant pumping rate of 3 ML/year (0.008 ML/day) (Lowe et al 2009, SAMDBNRMB undated). The total pumping rate for high-extraction bores was varied slightly during calibration, with the optimal rate found to be 14.1 ML/day, or 97% of the allocation. This rate most probably takes into account pumping from unlicensed bores, and / or possible pumping in excess of allocation at licensed bores.

For bores whose hydraulic interval penetrates multiple model layers, pumping is partitioned according to the transmissivity of the layer compared to the transmissivity of the total penetrated interval. This means pumping rates may decrease should one or more intersected layers dry during the course of the simulation.

4. Model calibration

Given the age of the Berrima and Loch Catherine mines, model calibration was undertaken in two stages as follows:

- Stage 1: Mining at Berrima finished recently but had been active between 1926 and 2011. The first stage of calibration comprised a transient simulation simulating a notional period of 32 years, as an approximation for the evolving hydraulic head field due to mining effects between 1926 and 2011, to obtain a reasonable starting head distribution for the point in time at the beginning of the main calibration period (January 2011). The modelled January 2011 hydraulic head distribution is used as the starting hydraulic head field for the main transient calibration.
- Stage 2: Transient calibration over the main calibration period (1 January 2011 to 31 December 2014), covering mining of the last stages of the Berrima workings.

Observations for the period 1 January 2015 up to the dates of observation availability in mid 2015 (ranging between March and July), as at the time of calibration, were reserved for the verification phase. Parameter change was performed manually.

4.1. Calibration targets

Calibration targets comprised:

- Hydrographs of hydraulic head from the Berrima and Hume monitoring networks (Parsons Brinckerhoff 2015). Target hydrographs were selected according to the following criteria:
  - Characterisation of mining-induced drawdown.
  - Longer monitoring periods.
  - Smaller screen intervals.

  The calibration hydraulic head dataset comprised hydrographs covering intervals of between 1 and 3 years at 49 points in the subsurface, at 23 locations. The calibration target piezometers and their locations are listed in Appendix B. Appendix B also lists piezometers not used for calibration and the reasons for their exclusion. There is evidence that water levels at the DeBeaujeu and Culpepper monitoring bores are influenced by Berrima mining. These bores, while having long hydraulic intervals, were retained as the best available monitoring points for characterisation of mining-induced drawdown at distance from the Berrima workings.
- Observed shallow groundwater discharges (estimated baseflow to drainage channels).
- Observed deep groundwater discharges (estimated discharge to the Berrima mine void).
- The observed K distribution for moderate observation scales (similar to the model discretisation).

4.2. Sources of uncertainty in hydraulic head calibration targets

Numerical simulation of regional groundwater systems requires calibration to observations. The reliability of results is generally a function of the reliability in observations, and the ability of the model to replicate these observations. In comparing modelled hydraulic heads from the discretised medium of a model domain to measured hydraulic heads from a natural continuum, the following sources of uncertainty are introduced, regardless of calibration quality:

- Accuracy of VWP data. The accuracy of VWP data is considered to be not better than ±10 m.

- Model layer thickness and the vertical position of a piezometer screen interval with respect to the model layer. Vertical hydraulic gradients in proximity to mining may be significant. Away from mining, smaller gradients are observed. In a finite difference numerical model, a layer will have only one head value per cell (an average value, applicable to the centre of the cell). Assuming a 50 m thick layer and a vertical hydraulic gradient of 0.5, with a measurement point located at either the top or the bottom of the layer, then if the model is perfectly replicating the system, the observed and modelled heads will differ by half of 25 m, or 12.5 m. This difference depends on several factors, the most significant of which are the layer thickness and the vertical hydraulic head gradient.
- The Berrima mine schedule. The mining schedule for Berrima is not known in detail, and generally only to a resolution of yearly blocks. An attempt has been made to replicate it based on typical mining practices and experience. Plans available in various publications show the extent of workings, and the mine footprint, at a few points in time. Coal extraction is assumed to have ceased in early 2013.
- Large screen intervals in bores. Observations from private bores DeBeajeu and C Prod are considered important targets for calibration however their screened intervals (greater than 40 m) span two or more model layers. A reasonable departure of modelled water levels from observed water levels is therefore expected for these bores, regardless of calibration quality.

4.3. Calibration results

Transient calibration was undertaken for the period 1 January 2011 to 31 December 2014 with monthly stress periods. Rainfall recharge was applied as a percentage of incident rainfall. Parameter change was performed manually. Verification was undertaken for the period 1 January 2015 to 27 August 2015. Hydraulic head observations were available up to July 2015 and Berrima discharge observations to August 2015.

Prior to calibration, it was suspected that subvertical groundwater flow barriers associated with the southern basalt bodies (see Volume 1) might be critical in replicating the hydraulic head field. These barriers were interpreted from analysis of the three-dimensional hydraulic head field, and airborne geophysical survey data. The calibration phase indicated that hydraulic head observations at southern piezometer nests (east to west) H56X, H37, H42, and H136 could not be replicated without inclusion of such barriers. Therefore, during the calibration phase, sub-vertical flow barriers were incorporated as follows (see Figure 4.1):

- Vertical barriers to groundwater flow offering significantly reduced K normal to their planes, but unimpeded K along their planes.
- 10 m thick with a fault core K of 0.001 m/day, based on observations from large scale barriers elsewhere.
- The barriers do not penetrate into the basalt.

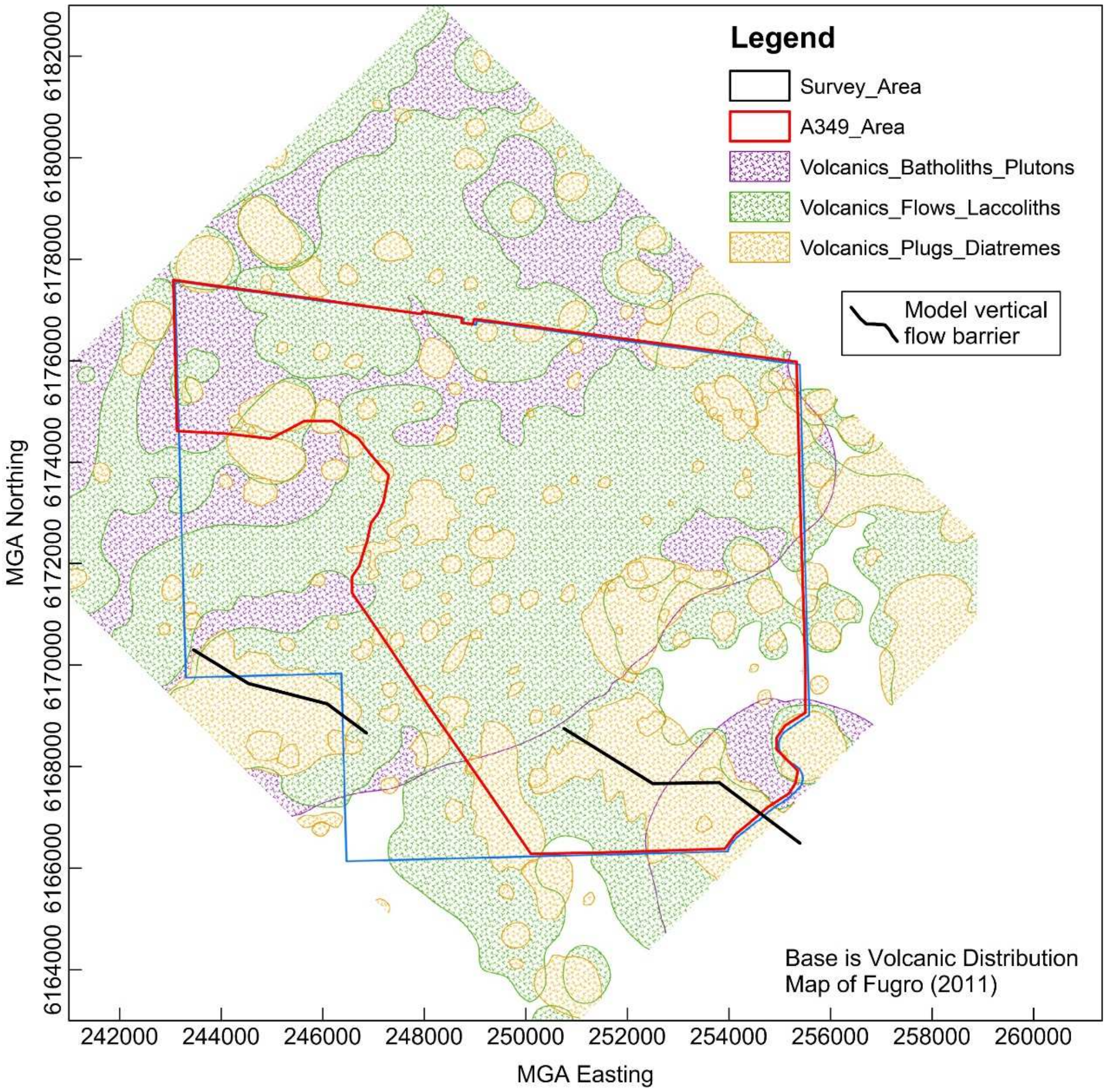


Figure 4.1. Modelled flow barriers incorporated during the calibration phase. The volcanic interpretation is after Fugro (2011).

4.3.1. Hydraulic heads

27 August 2015

Figure 4.2 shows modelled and observed hydraulic heads for the end of the verification period (modelled water levels for 27 August 2015, compared to actual observations ranging between April and June 2015). The normalised root-mean-squared (NRMS) error is 11.9 % and considered reasonable, given the VWP outliers B62_Upper and B63_WW, comparison of non-coincident modelled and observed water levels, and other factors. B62_Upper and B63_WW are poorly matched however these are VWPs and their reliability is lower than for standpipes. Residuals are reasonably normally distributed.

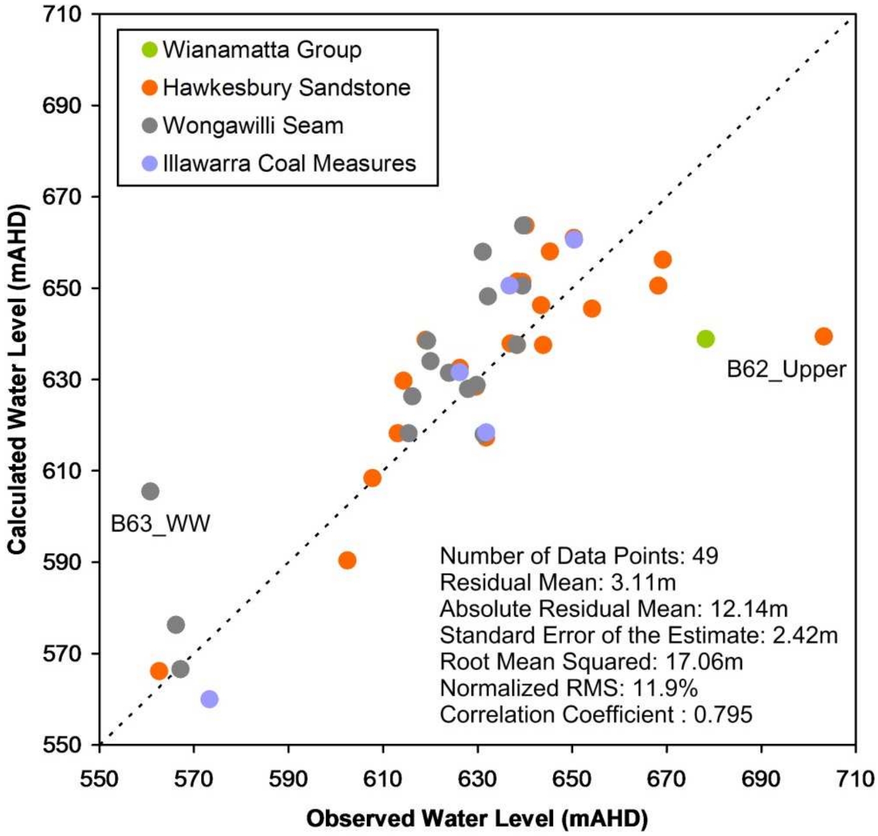


Figure 4.2. Comparison of last available observed water levels (March to July 2015) and model-calculated water levels for 27 August 2015.

The residual mean is 3.1 m, small compared to the total variation in head during the calibration (and predictive) phases, and a small proportion of the saturated thickness above the mined horizon. The offset will overestimate mine inflows by less than 5%. The offset is mainly due to:

- Uncertainty in stream invert elevations.
- Uncertainty in private pumping.

A proportion of modelled stream invert elevations are higher than actual, in the central model area. The digital elevation model (DEM) for the entire model domain was obtained from the Geoscience Australia web-based data service. This model was compared to detailed laser-based elevations (LiDAR, considered more accurate than the DEM) obtained by Hume for the mine lease. The comparison indicated good agreement but with a variation of about ±8 m AHD. The proportion of inverts that are higher than the LiDAR equivalents, combined with the defined drainage channel lines not occurring precisely over the minima in the DEM, have influenced the calibration results.

The mean residual for the seven Berrima network observations is smaller than overall, indicating the stronger control of the Wongawilli Seam hydraulic head condition in the mined zone on hydraulic heads surrounding the Berrima mine.

Figure 4.3 presents a north-south cross section of modelled hydraulic head through the Berrima mine for 27 August 2015, for comparison to the interpreted hydraulic head cross section for late 2013 / early 2014 (also shown). Recognising the offset of the modelled cross-section down hydraulic gradient, and the difference in times, the replication of the vertical hydraulic head distribution is considered reasonable. The model calculates saturation to be present above partial extraction (1st workings) areas of the Berrima, and the absence of saturation above full extraction areas.

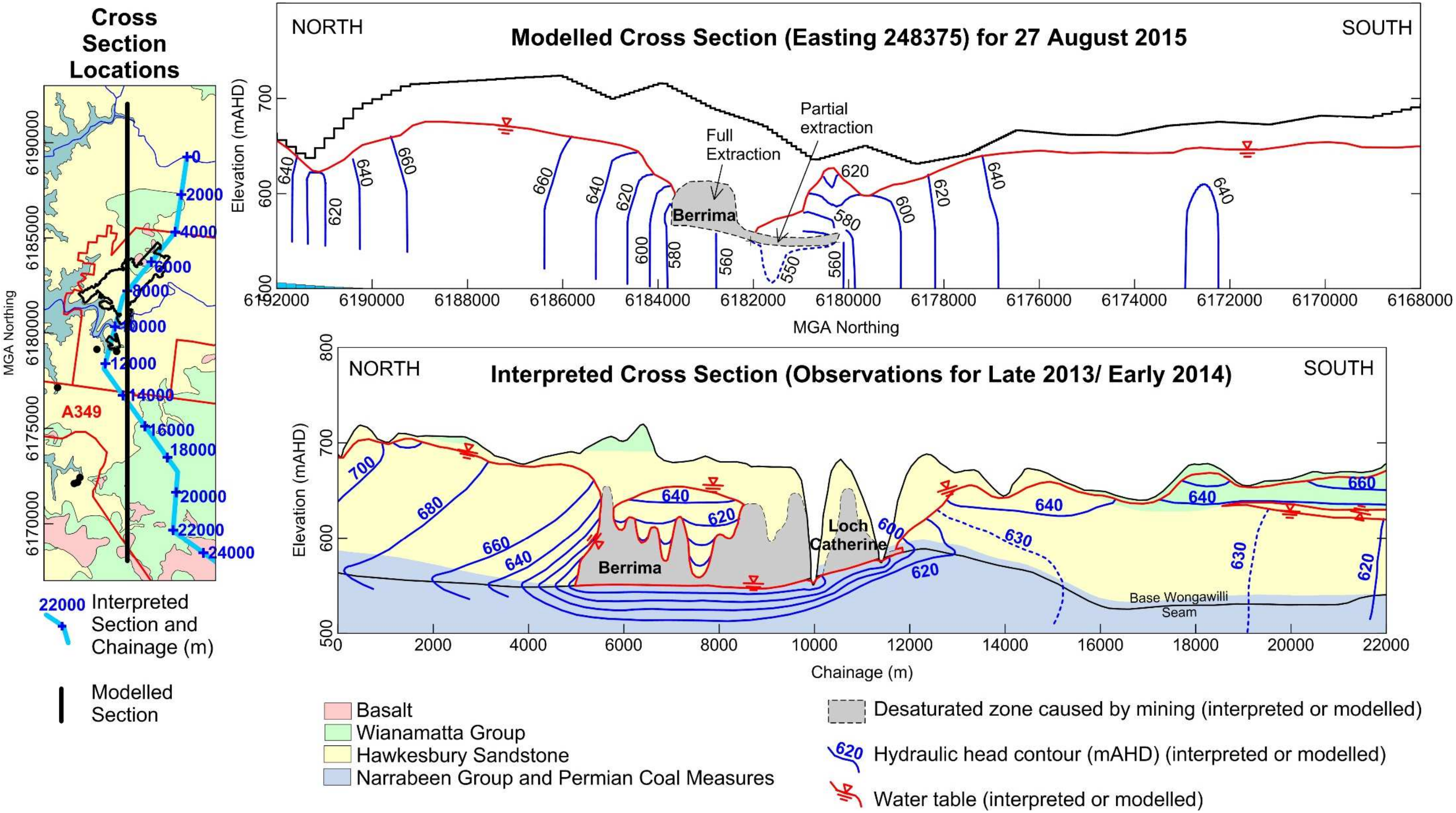


Figure 4.3. Modelled hydraulic heads along a north-south cross section through Berrima mine for 27 August 2015, compared with interpreted hydraulic heads for late 2013 / early 2014 along a nearby cross section.

Figure 4.4 shows the modelled water table for 27 August 2015, representative of conditions prior to mining at the proposed Hume mine. Flow along the water table surface is from outcrop sandstone areas along the western boundary (rainfall recharge to sandstone), and Wingecarribee reservoir on the eastern boundary (reservoir leakage), to drainage channels to the south, northeast, and west. The lower reaches of Wingecarribee River and Medway Rivulet are groundwater discharge areas.

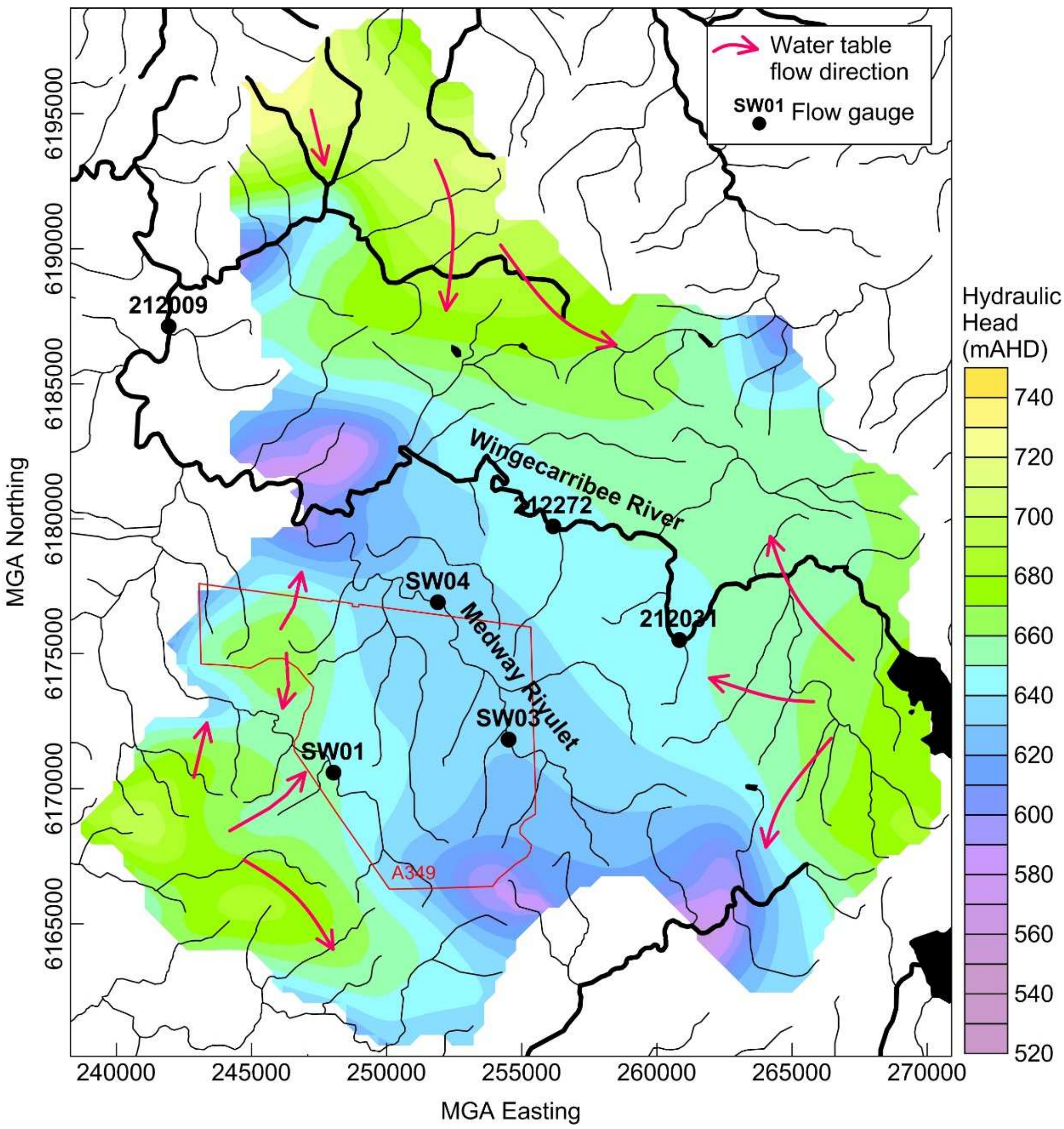


Figure 4.4. Modelled water table for 27 August 2015.

Hydrographs

Appendix B presents modelled and observed hydrographs of hydraulic head. Observed heads are reasonably reproduced overall. Drawdown from Berrima mining (seen at B62, B63, DeBeaujeu, and C Prod) is also reasonably reproduced. B62_Upper and B63_WW are poorly matched, however the other four observation datasets for B62 and B63 are reasonably matched.

4.3.2. Hydraulic properties

Calibrated media properties are listed in Table 3.

Table 3. Calibrated media properties.

Stratum	Model Layer	Average Depth to Base in Hume Lease (mbgl)	Kh[a] (m/day)	Kv[b] (m/day)	Specific storage (m^{-1})	Specific yield	Kv/Kh
Wianamatta Group	1	30	1	0.01	1×10^{-6}	0.01	0.01
Hawkesbury Sandstone	2	56	0.6	0.001	1×10^{-6}	0.01	0.0017
	3	86	0.05	0.003	7×10^{-7}	0.008	0.06
	4	120	0.03	0.0005	7×10^{-7}	0.008	0.017
	5	127	0.01	0.0005	7×10^{-7}	0.005	0.05
	6	129	0.005	0.001	5×10^{-7}	0.005	0.2
	7	131	0.005	0.001	5×10^{-7}	0.003	0.2
Interburden*	8	133	0.005	0.001	5×10^{-7}	0.003	0.2
Wongawilli Seam above mined section	9	135	0.005	0.001	5×10^{-7}	0.003	0.2
	10	137	0.005	0.001	5×10^{-7}	0.003	0.2
Wongawilli Seam mined section	11	140	0.005	0.001	5×10^{-7}	0.003	0.2
Illawarra Coal Measures	12	160	0.0001	0.0001	5×10^{-7}	0.003	1
Shoalhaven Group	13	250	0.0001	0.0001	5×10^{-7}	0.003	1

a. Kh denotes lateral hydraulic conductivity (K). b. Kv denotes vertical K. mbgl denotes metres below ground level. * Narrabeen Group, WWR Ply, and Farmborough Claystone.

Figure 4.5 compares calibrated and observed K (refer to Volume 1 for a discussion of K measurements). Large-scale measurements of K are mostly representative of the lateral component of the K tensor (except where specifically analysed for Kv, where measurements allow). The calibrated Kh distribution is considered to reasonably represent K observations. Large scale Kv for the Hume area is heavily affected by its tectonic history and associated intrusive activity, and the high density of private open water bores. The calibrated Kv distribution is considered a reasonable replication of the large scale Kv distribution in the subsurface. It is supported by calibration to shallow and deep groundwater discharges, and important large scale Kv estimates from the two long-term pump tests undertaken by Hume on the mine lease in 2014. These three datasets are independent of each other.

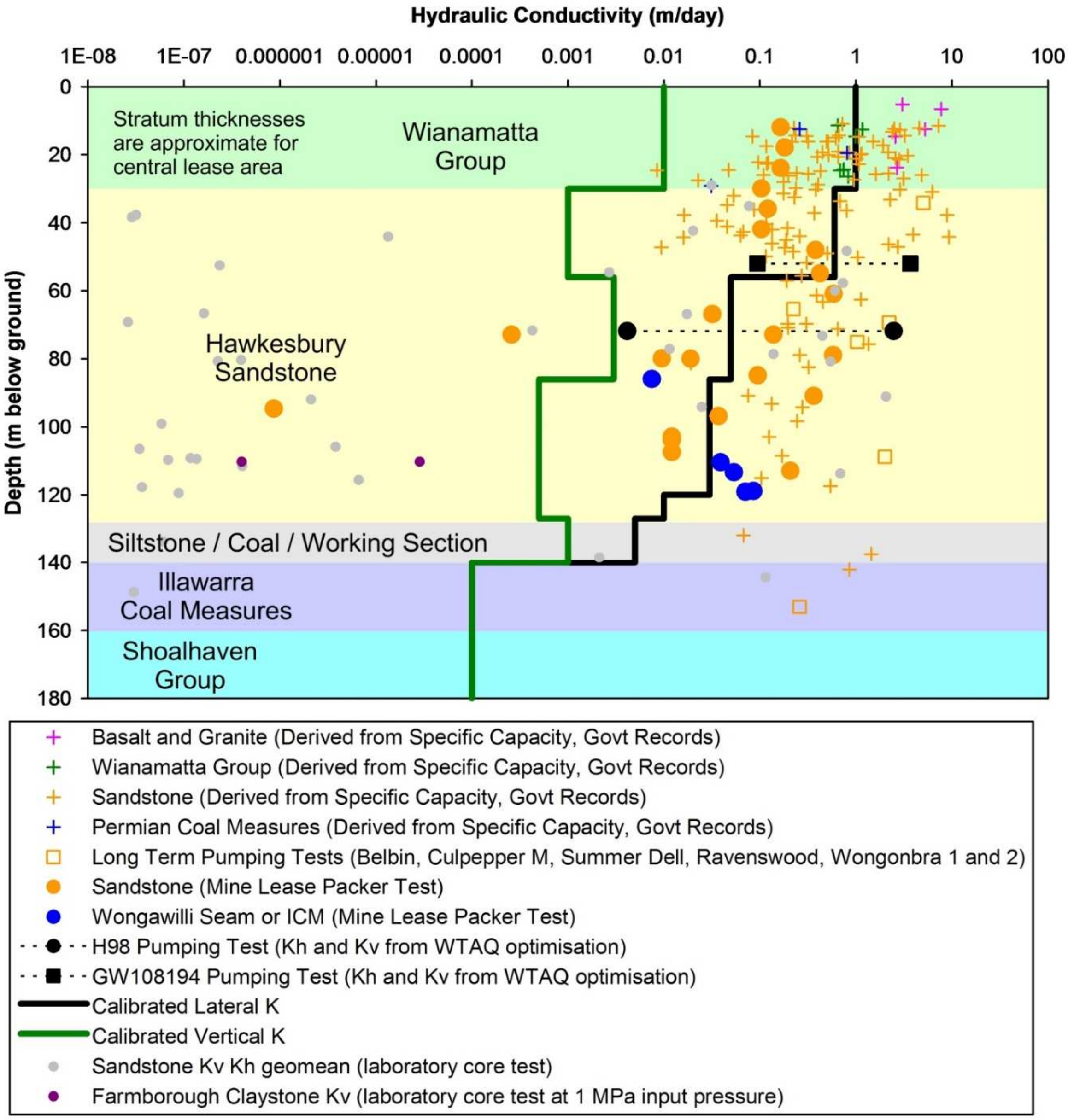


Figure 4.5. Comparison of calibrated and observed hydraulic conductivity.

Berrima Mine drain conductance

The calibrated drain conductance for Berrima mine workings is 0.1 m^2/day (for 50 m x 100 m cells). For 50 m x 50 m cells (the cell size over the Hume mine footprint), the equivalent conductance is 0.05 m^2/day (see the discussion in the Predictive Simulation section below).

For the case of numerical simulation of development headings for proposed mining in Area 3B in the Dendrobium mine lease (Coffey 2012), a drain conductance of 0.1 m^2/day was calibrated for a depth of around 300 m, for 50 m x 50 m cells. For this model also, hydraulic heads, K, and flows (shallow and deep) were simultaneously reasonably replicated. The similarity between calibrated conductances at Berrima and Dendrobium indicates that the application of the calibrated conductance for predictive simulation of the Hume mine is reasonable.

4.3.3. Recharge and discharge

Recharge

The mine lease and model domain have estimated area-weighted long-term average annual rainfalls of 957 mm and 949 mm respectively. The actual rainfall applied to the model domain over the simulation period (Moss Vale) was 4.81 m, slightly above average. The calibrated rainfall recharge rate is 1.8% of incident rainfall.

Shallow discharge

78% of the catchment for flow gauge 212009 (or 467 km^2) occurs within the model domain. The estimated baseflow at this gauge is 1.5% of average annual rainfall over the catchment. Assuming this rate is applicable over the calibration period, the estimated baseflow to the intersected part of the catchment would be about 18 ML/day. The modelled baseflow to the Wingecarribee River and its tributaries in the model domain was 12 ML/day at the end of the simulation period. The model does not simulate basalt; when an estimate for the basalt baseflow component (between 30% and 40%) is removed from the observationally-based estimate, the modelled baseflow is considered to compare favourably with it.

Deep discharge

Figure 4.6 shows the observed discharge from the Berrima mine void and the modelled inflow over the calibration period. The adopted observation dataset for Berrima Mine inflow is discussed in Volume 1. The observed discharge from the void is assumed to be a reasonable representation of the discharge to the void from surrounding media.

David (2015) reports that the most accurate period of discharge readings is April to November 2014. Modelled inflows are considered to accurately replicate observed discharge over this period. Modelled inflows slightly overestimate other less reliable measurements. Some overestimation by the model is likely to be due partly to calculation of H (the vertical extent of desaturation) for pillar extraction panels as 60% of their longwall equivalents; 55% is likely to be a better representation in this case (see Tammetta 2013). Modelled inflows are considered to accurately match the observation dataset.

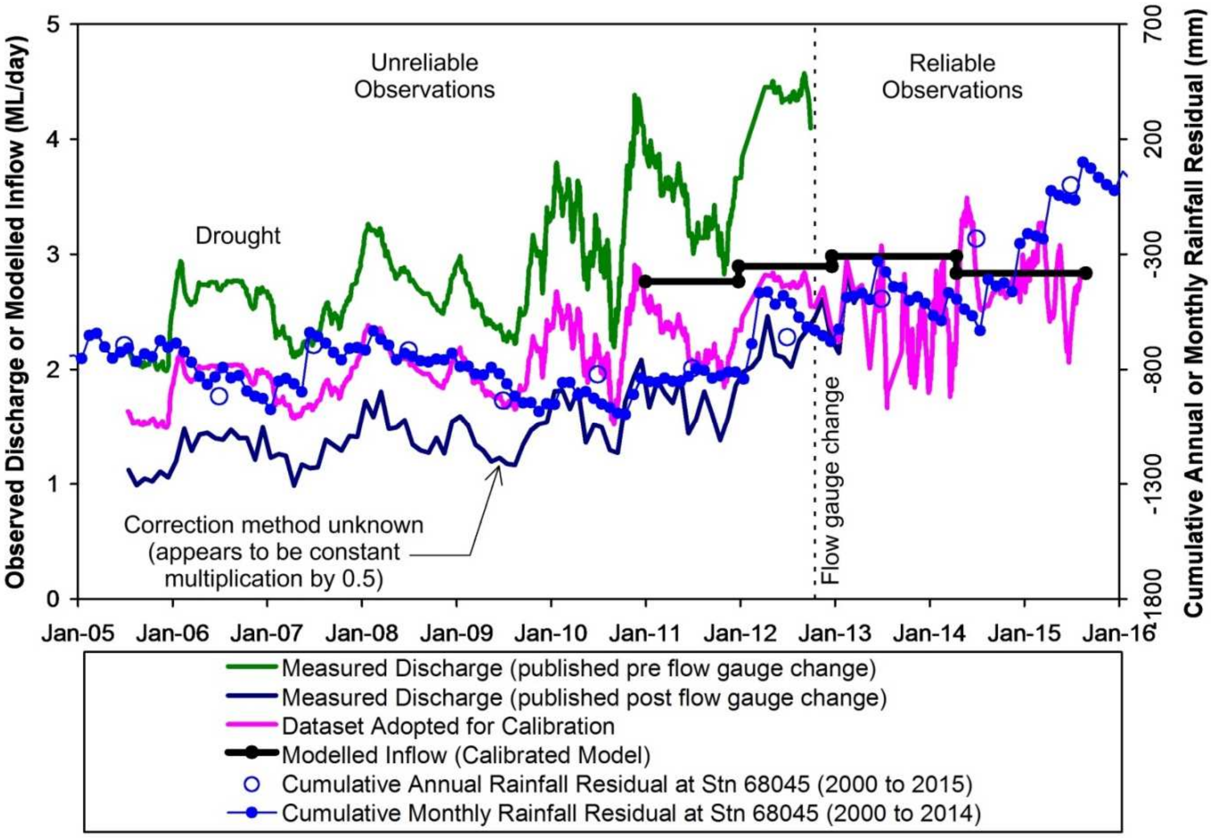


Figure 4.6. Observed discharge from, and calibrated inflows to, the Berrima mine void over the calibration and verification periods combined.

4.3.4. Flow budget

The modelled average flow budget for the domain over the calibration and verification periods combined (1 January 2011 to 27 August 2015) is listed in Table 4. The flow budget discrepancy is considered reasonable.

Table 4. Modelled average flow budget over the calibration and verification periods combined.

IN (ML/day)		OUT (ML/day)	
Rainfall Recharge	37.5	Baseflow to Wingecarribee River	11.9
Release from Media Storage	12.2	Baseflow to other Rivers and Creeks	10.3
Leakage from Reservoirs	2.3	Berrima Mine Inflow (to river)	2.9
Leakage from Medway Dam	0.5	Loch Catherine Mine Inflow (to river)	0.5
		Inflow to Other Mines (to rivers)	0.7
		Private Pumping	14.6
		Evapotranspiration	14.2
TOTAL	52.7	TOTAL	54.9
Discrepancy: -2.2 ML/day (-4.1%)			

4.3.5. Model fitness for purpose

The hydrogeological conceptual model and numerical groundwater model have been developed based on the following four crucial, large, and totally independent observation datasets:

- Hydraulic heads.
- Hydraulic conductivity.
- Shallow groundwater discharge (baseflow to streams).
- Deep groundwater discharge (drainage to the existing Berrima mine void).

The numerical model is simultaneously reasonably replicating all four datasets, which considerably reduces uncertainty in outputs, and has allowed a reliable estimation of the Kv versus depth distribution (fundamental for predictive simulation of deep discharges). The model Kv distribution also accords with a 5^{th} group of critical observations: Kv estimated from the long-term pumping tests undertaken by Hume on the mine lease in 2014. Calibrated storage parameters accord with several observations in the database. The model is therefore considered fit for estimating impacts from proposed mining in the Hume lease area, and is considered to provide a reliable basis for predictive simulation.

The model is expected to conform to approximately 70% of the criteria for Class 3 models, with remaining aspects of the model conforming to Class 2 criteria, according to the classification system in the Australian Groundwater Modelling Guidelines (Barnett et al 2012).

For the Class 3 model criterion that predictive “stresses are not more than 2 times greater than those included in calibration”, the quantity to be used in defining the stress is not explicitly stated in the guidelines. However, most of the examples used to define stress in the guidelines are fluxes (for example, rainfall recharge or pumping). The document defines stress as a process that leads to the removal or addition of water from or to a groundwater system. Using a spatial extent criterion, the model calibrated herein would conform to the Class 2 criterion for predictive stress magnitude. However, using a flux criterion, predictive modelling indicates that the predictive stress (the Hume mine) generates about 6 ML/day, compared to around 3 ML/day for the main calibration stress (the Berrima mine). With the inclusion of the Loch Catherine mine, and other mines, the model would conform to the Class 3 predictive stress magnitude criterion.

5. Predictive simulation

The calibrated model has been used as the basis for a predictive model that simulates mining in the Hume Lease area. The predictive model is used for impact assessment.

5.1. Model settings

The following settings have remained unchanged from the calibration model:

- Subsurface media geometry and hydraulic parameters.
- Rainfall recharge applied at 1.8% of the area-weighted long-term annual average rainfall of 949 mm for the model domain, without variation).
- Wingecarribee reservoir water level (676 m AHD).
- Kv of 0.1 m/day for the Wingecarribee River.
- Riverbed conductance of 25 m^2/day (for 50 m x 50 m cells) for Medway Dam.
- Existing mine workings (extent and drain conductance), passively draining to rivers. It is understood the owners of Berrima Colliery are considering sealing the discharge adit. It is not known if this will occur.
- Drain and river invert elevations, and other imposed boundary conditions at the model extremities.

Hume mining occurs in 50 m x 50 m cells. The calibrated mine drain conductance for the Berrima mine applies to 50 m x 100 m cells. Under the assumption that the major part of the induced flow field is vertical (with the conductance parameter behaving similarly to a riverbed conductance) the drain conductance for Hume mine workings is set to 0.05 m^2/day. This also assumes similar stress distributions around mine openings for the existing Berrima and proposed Hume workings. This parameter is the subject of a sensitivity analysis (see section 5.2.2).

The starting hydraulic head field for predictive simulations is the modelled hydraulic head distribution of 27 August 2015, obtained from the calibration model. Proposed mining comprises the main change to the calibration model to create the predictive model; implementation is discussed below.

5.2. Pumping from Hume-owned bores

There are several Hume-owned bores which will be used during mining. These bores are listed in Table 5. The total volume of entitlement that is expected to be available for these bores is 962 ML/year. In predictive simulations, allocations for these bores are used for mining, with farming activities utilising any unused allocation. The predictive scenario pumping schedule for these bores is as follows:

- GW108194 and GW108195 are never pumped.
- The remaining five bores are pumped at full annual entitlement, less the volume required to cover total mine take (inflow to the sump and inflow to the void), while mine take is less than the entitlement.
- The pumped water is used first for water balance deficit satisfaction, then for irrigation. The pumped amount reduces as mine take increases, and is extinguished when mine take reaches 962 ML/year.
- When mine take is higher than the total Hume entitlement, bores are not pumped.

Table 5. Private bores passing to Hume ownership prior to mining.

Bore Number	Easting (mMGA)	Northing (mMGA)	Licence Number	Allocation (ML/year)	Licensed Purpose	Use during mining
GW053331	251462	6177338	10CA111696	488	Domestic / stock / irrigation	Pumping at maximum licensed rate, except when allocation is applied to mine inflow.
GW031686	251953	6178061				
GW059306	252123	6178404				
GW057908	250955	6176276	10CA111712	179	Domestic / stock / irrigation	
GW106491	249802	6173568	10CA112150	100	Irrigation	
Assumed future purchase				75	To be confirmed	
GW108195	250939	6172001	10CA112196	120	Irrigation	No Pumping
GW108194	251005	6172692				
GW025588	252124	6178343	10WA109649	N/A	Stock	Minor pumping
GW031684	253137	6178647	10WA109694	N/A	Domestic	
GW031685	252179	6178221	10WA109707	N/A	Domestic	
GW031687	252013	6178679	10WA109708	N/A	Domestic	
GW109084	250446	6170161	10WA111035	N/A	Stock / domestic	

5.2.1. Mine water balance

Calculation of an approximate mine water balance was required for the predictive simulation. The mine water balance deficit is satisfied by

- Pumping from Hume bores; and /or
- Withdrawal of water from recovering mine voids.

Pumping from Hume bores is available only in early years, since their allocation is required to cover increasing mine take as mining progresses.

Changes in bore pumping (both Hume and private bores) and withdrawal from recovering voids caused changes in mine inflows and therefore changes in the water balance deficit and mine take amounts. This therefore required an iterative simulation process.

Table 6 lists the components comprising mine water inputs and demands, and the resulting deficit, using results from the final simulation run (further discussed below in the results section).

Table 6. Mine water inputs and demands (using optimised results).

Mining Year	IN (ML/year)		OUT (ML/year)								Net Water Balance (ML/year)
	Ground runoff + pond rain-on less pond evaporation A	Ground-water Inflow to mine sump	Net CHPP process water demand B	Tailings makeup water demand D	Product coal handling demand C	ROM coal stockpile demand C	Underground Operations		MIA demand C	Bathhouse, crib rooms, etc B	
							ROM coal added water D	Ventilation loss D			
1	125	127	6	0	110	28.1	13	30	5	14	46
2	125	181	27	166	110	28.5	58	49	16	14	-162
3	125	282	47	257	111	28.7	96	49	20	14	-216
4	125	326	54	220	112	29.5	86	49	36	14	-150
5	125	331	81	296	113	29.8	96	49	41	14	-264
6	125	332	94	355	112	29.5	105	49	39	14	-341
7	125	595	81	367	112	29.6	107	49	43	14	-83
8	125	373	58	392	113	29.7	107	49	43	14	-308
9	125	434	59	382	113	29.7	113	49	44	14	-245
10	125	389	65	261	113	29.8	98	49	46	14	-162
11	125	428	60	284	113	30	93	49	46	14	-135
12	125	457	69	283	113	29.9	100	49	44	14	-120
13	125	492	77	364	113	29.9	112	49	46	14	-188
14	125	409	75	471	113	29.7	112	49	45	14	-375
15	125	425	71	553	112	29.6	103	49	42	14	-424
16	125	489	65	310	112	29.6	88	49	41	14	-95
17	125	985	76	293	113	29.8	105	49	44	14	386
18	125	792	47	254	112	29.5	87	49	38	14	287
19	125	513	24	110	111	28.8	39	49	20	14	242

A. Long-term runoff coefficient 0.2. Average rainfall 0.957 m/year. Ground: area 735110 m^2; net accession 0.191 m/year. Water: area: 202900 m^2; net accession -0.078 m/year.
B. Specified by Hume.
C. Parsons Brinckerhoff. 2015. Hume Coal Project - Stage 1 (Preliminary) Water Balance Report. Report 2200538A-WAT-REP-001 Rev2, prepared for Hume Coal. September.
D. "HUM1652-373 Water Balance Spreadsheet mdb060516.xlsx" received 7 May 2016 from Palaris.

Withdrawal from recovering voids is undertaken only when bulkheads are established at the entries to the respective panels. Specific voids were targeted, comprising panels sealed during mining years 3 to 7, as follows:

- Panels W6 to W8.
- Panels W9 and W10.
- Panels W11 to W13.
- Panels W14 to W18.

Deficits and mine take beyond year 7 were satisfied by withdrawal from panels W14 to W18.

Initial withdrawal from voids would be carried out by pumping water from behind the bulkhead (through pipes and valves in the bulkheads, or from bores penetrating the voids and sealed throughout overburden media). Once panels W14 to W18 are sealed, withdrawal from them would be undertaken using permanent bores penetrating those voids and sealed throughout overburden media.

5.3. Proposed mining

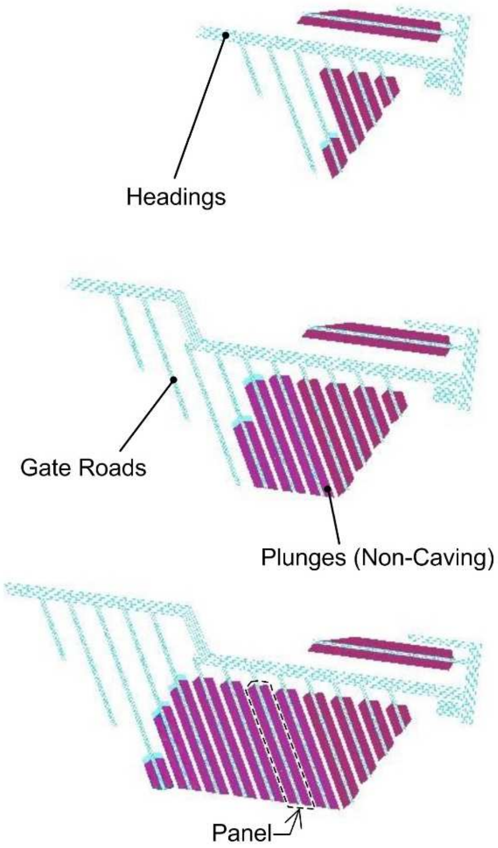
Mining occurs for a period of 19 years (nominally 2021 to 2039 inclusive). Approximately 50 Mt will be mined. Table 7 lists the yearly mining schedule and other information discussed below.

Mining advance is simulated by activation of drains when a part of the seam is mined. The drain elevation is set to 0.1 m above the mined floor level. The drain condition is imposed in any layer intersected by the drained zone above a panel or mine opening. The model simulates development of main headings and panel gate roads prior to secondary extraction. Figure 5.1 illustrates the typical progress of mining for the first workings method. The majority of changes in media hydraulic properties occur in the drained zone, but since this zone is maintained in a dewatered state, these changes do not significantly impact the functioning of the model. Changes in media properties above the drained zone are considered negligible for non-caving methods, and the overall vertical K field between ground surface and the top of the relaxed zone does not change.

Figure 5.2 illustrates the adopted heights of desaturation with respect to model layering.

Table 7. Yearly mined volume and co-disposed tailings emplaced.

Calendar Year	Mining Year	Run-of-Mine Coal (Mt)	Mined Volume (m^3)	Co-Disposed Tailings Emplaced (m^3)
2021	1	0.38	247980	0
2022	2	1.69	1102692	345471
2023	3	2.82	1839725	534062
2024	4	2.54	1665325	456877
2025	5	2.82	1841464	613792
2026	6	3.08	1994056	737812
2027	7	3.15	2045160	762305
2028	8	3.16	2040342	813945
2029	9	3.31	2154903	794062
2030	10	2.87	1888687	542602
2031	11	2.73	1772364	589989
2032	12	2.95	1915615	587177
2033	13	3.28	2132458	756667
2034	14	3.29	2102426	978965
2035	15	3.04	1853594	1148742
2036	16	2.59	1671060	644259
2037	17	3.08	2013607	609421
2038	18	2.55	1640445	526792
2039	19	1.14	743896	227761
2040				75316
TOTAL		50.48	32665796	11746020
Total co-disposed tailings volume as a proportion of total mined volume				0.36



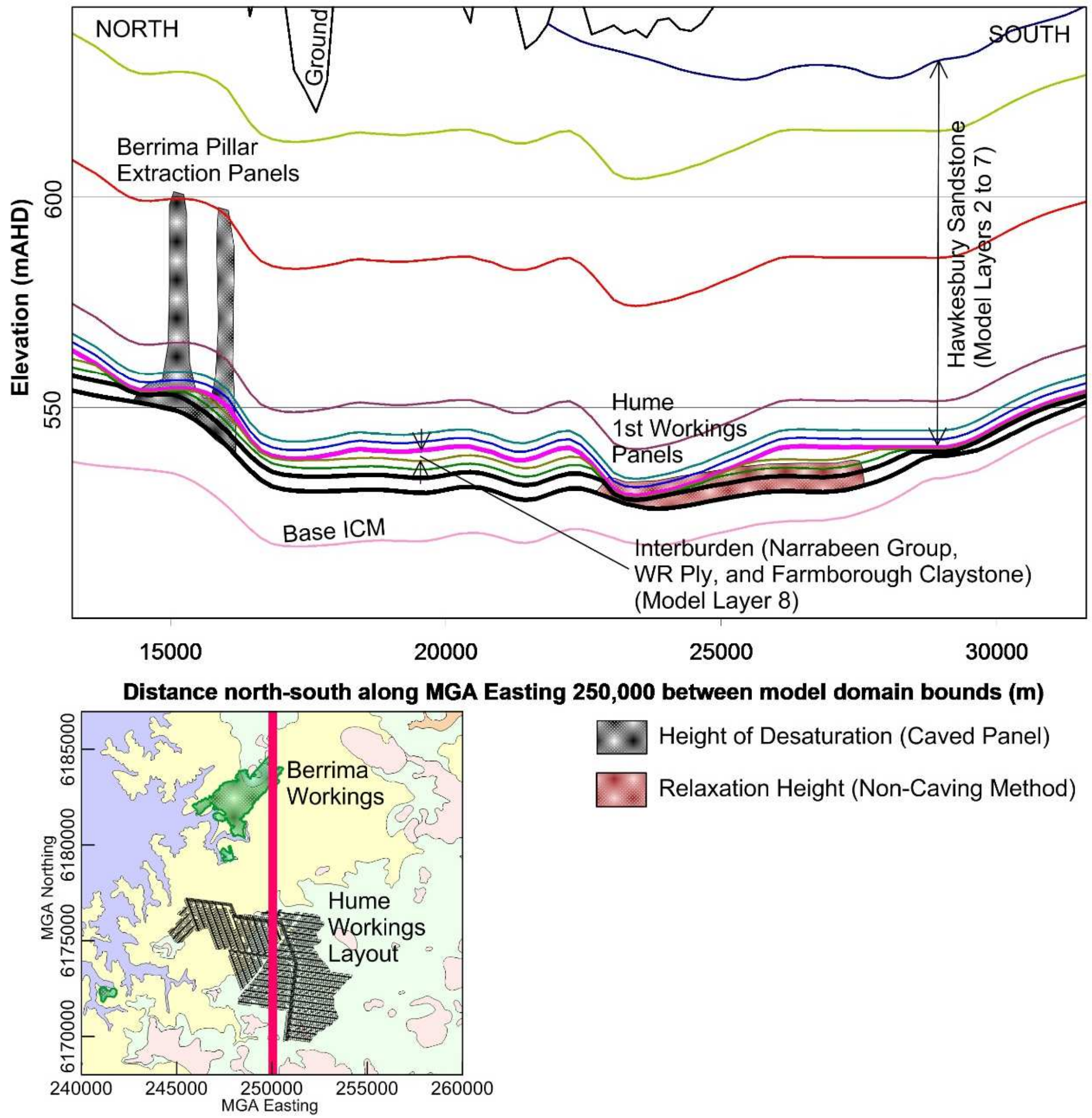


Figure 5.1. Evolution of headings and workings for the Pine Feather method over three instants in time (time moves forward from top to bottom).

Figure 5.2. Interrelationship between model layering and adopted heights of desaturation above workings types.

5.3.1. Mitigation measures

The following three groundwater mitigation measures for the Hume mine were simulated:

- Sealing individual panels as they are mined, using bulkheads rated to withstand equilibrated hydraulic heads. Bulkheads are water-tight seals placed in panel gate roads at their juncture with main headings, when the panel is complete. They are also placed at the start of main headings when the headings are no longer required.
- Backfilling of the mined void with co-disposed tailings. In its final state (following extraction of decanted water) it is non-draining (it neither accepts nor releases water, and is inert with respect to groundwater fluxes). The decanted water is not included in co-disposed tailings volumes used in numerical simulation.
- Injection of mine water back into the void through the bulkheads, should excess water be available. Bulkheads will be constructed to provide a seal capable of withstanding the applied water pressures at post-mining equilibration of the hydraulic head field. Injection would be carried out through access pipes built into the bulkheads.

These measures operate during mining. Mine water balance calculations undertaken during iterative predictive simulation indicate that negligible water was available for bulkhead injection.

Panels are sealed about one week after completion. Co-disposal of tailings begins prior to this, following extraction in plunges; it lags the workings area by about 200 m. Co-disposed tailings emplacement is estimated to fill approximately 36% of the total mine void space. Main headings are sealed after the block of panels serviced by them is completed.

During mining, active void dewatering is not undertaken where water pools downdip of the workings area. Figure 5.3 conceptualises the fate of groundwater inflow to the mine void depending on the direction of mining with respect to the dip of a panel. Appendix C presents a plan of estimated inflow areas where pumping will not be required, based on mined seam structure contours and mine layout. Inflow to these zones contributes to void refilling. The mining rate is faster than the encroachment of the beach (formed by the mine pool) in these situations.

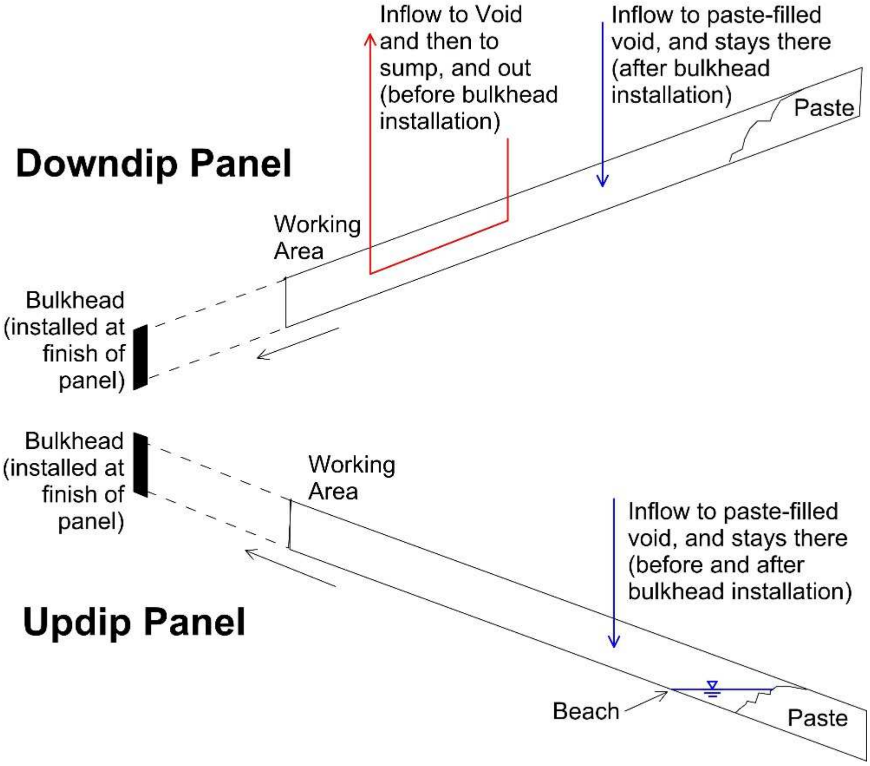


Figure 5.3. Conceptualisation of the fate of groundwater inflow to the workings, depending on panel dip with respect to mining direction.

Model implementation

Model implementation of the mitigation measures and post-mining water level recovery is carried out in a simplified way to reduce uncertainties.

During mining, drainage into the mined void is carried out using the drain mechanism (see above). To simulate the mitigation measures, the drain cells for a panel are active only for the time required for the total drained water to be equivalent in volume to the remaining void of that panel after injection behind the bulkheads and co-disposed tailings emplacement. The remaining void is calculated from a-priori schedules of injection behind bulkheads and co-disposed tailings emplacement (listed in Table 7). Predictive simulation was undertaken in an iterative fashion until the modelled total water exiting the drains for a panel was within 1% of the remaining mined volume for that panel (that is, with co-disposed tailings emplacement and injection volumes removed), and taking account of water withdrawn to satisfy water deficits. This methodology is illustrated in Figure 5.4.

This approximation circumvents the difficulty inherent in using a Darcian flow algorithm (flow in a resistive medium by the action of a potential energy field) to simulate a void that fills by hydrodynamic processes. Since the vast majority of the remaining mined volume is present in the roadways (rather than the roof), and the K field above the drained zone undergoes negligible change, and H penetrates only 2 m into the roof, the approximation negligibly impacts the head differential applied to the drained zone during recovery, and negligibly impacts the post-mining hydraulic head field above the relaxed zone (see Figure 5.4). The post-mining storage capacity in the model in the void zone is less than 1% of the actual storage capacity, which results in the void zone being filled quasi-instantaneously relative to the time-scale of recovery, and negligibly impacts recovery times. The lateral hydraulic head gradient in the mined seam is also small in the fully recovered state, as it would be in the actual state.

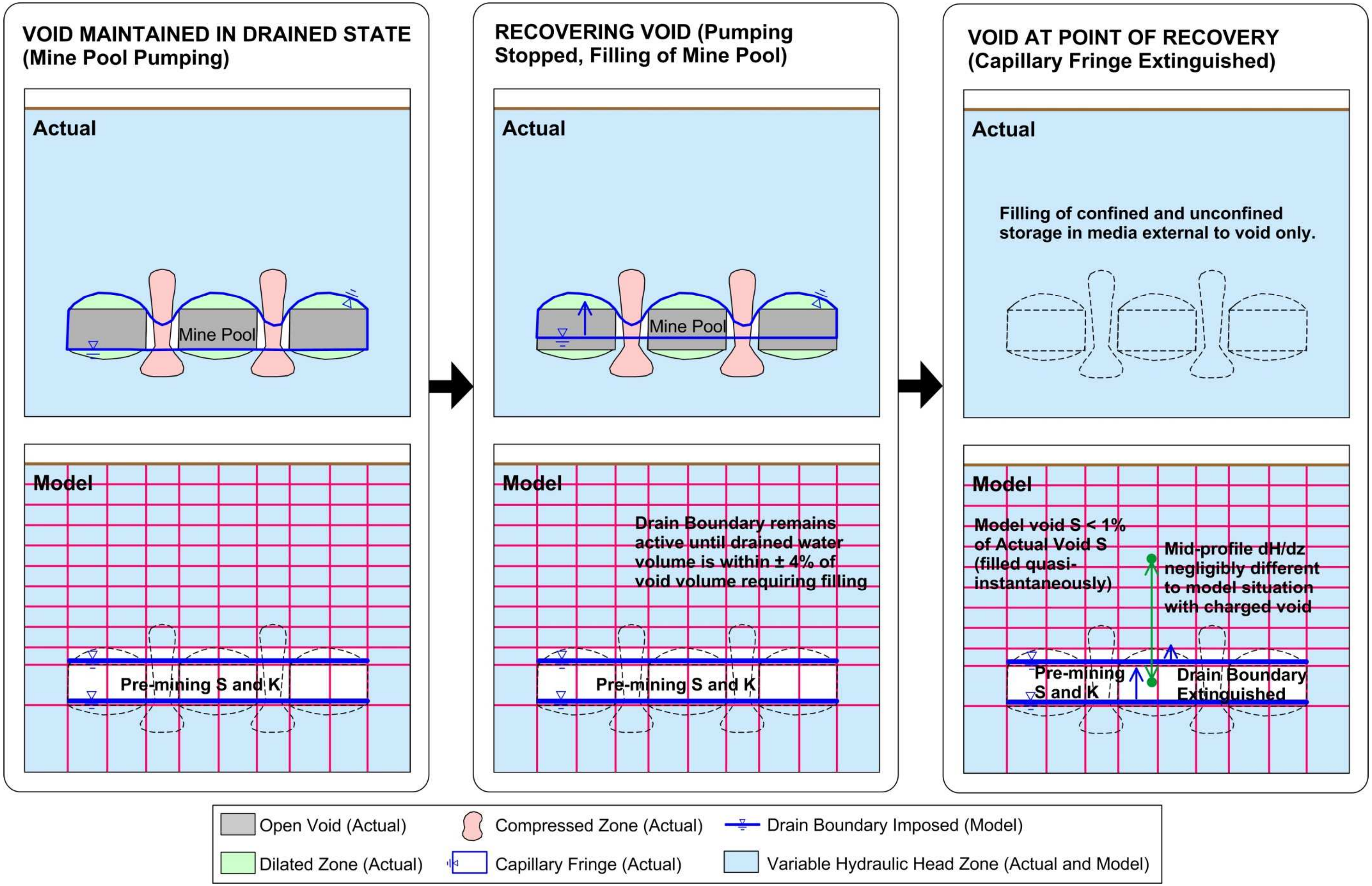


Figure 5.4. Methodology used in the numerical model to simulate mine drainage and post-mining recovery.

5.3.2. Modelled scenarios

Predictive simulation was undertaken for a period of 100 years for the most probable future scenario. Predictive model simulation years and mining schedule years are equivalent. The future scenario comprises:

- Use of the first workings mining method and layout.
- Average rainfall.
- Co-disposed tailings emplacement filling 36% of the mined void.

Three sensitivity simulations were also undertaken. Modelled scenarios are listed in Table 8. Run 1 comprises the simulation used for predictive impact assessment.

The sensitivity runs were undertaken for a scenario excluding bulkhead injection, considered to be more sensitive to the changes specified in Table 8.

Table 8. Simulated future scenarios

Run Identifier	Details	Purpose
1	First workings method BASE CASE Co-disposed tailings void filling proportion 36%. Injection behind panel bulkheads active. Average rainfall.	Impact Assessment
Null	Identical to Run 1 except no Hume mining.	Differential Impact Calculation
S1	Relaxation Height: 2 m and 4 m.	Sensitivity Analysis
S2	Kv: Calibrated and x 3 down the profile, for layers 1 to 5 (WG and HAW)	
S3	Hume Mine Drain Conductance: 0.05 and 0.1 m^2/day.	

6. Predictive results

9 iterations were required to reduce the total water balance error for the mine, and its interaction with the mine take, to 0.009 (0.9%). The mine water balance is in deficit for 15 of the 19 mining years (years 2 to 16 inclusive). Negligible amounts were available for reinjection behind bulkheads.

6.1. Inflows to mine workings

Figure 6.1 shows the modelled inflows to the mine workings. Inflow to the active mine area (the sump) ceases after year 19, when pumping within the mine ceases. Inflow behind the sealed bulkheads (mine void) ceases at the end of year 22 following the start of mining (3 years after cessation of mining), beyond which groundwater recharge is consumed by media storage around the void (recovery of elastic storage and recovery at the water table). The time of overall maximum impact for groundwater storage release and drawdowns (discussed below) is at approximately 17 years since the start of mining.

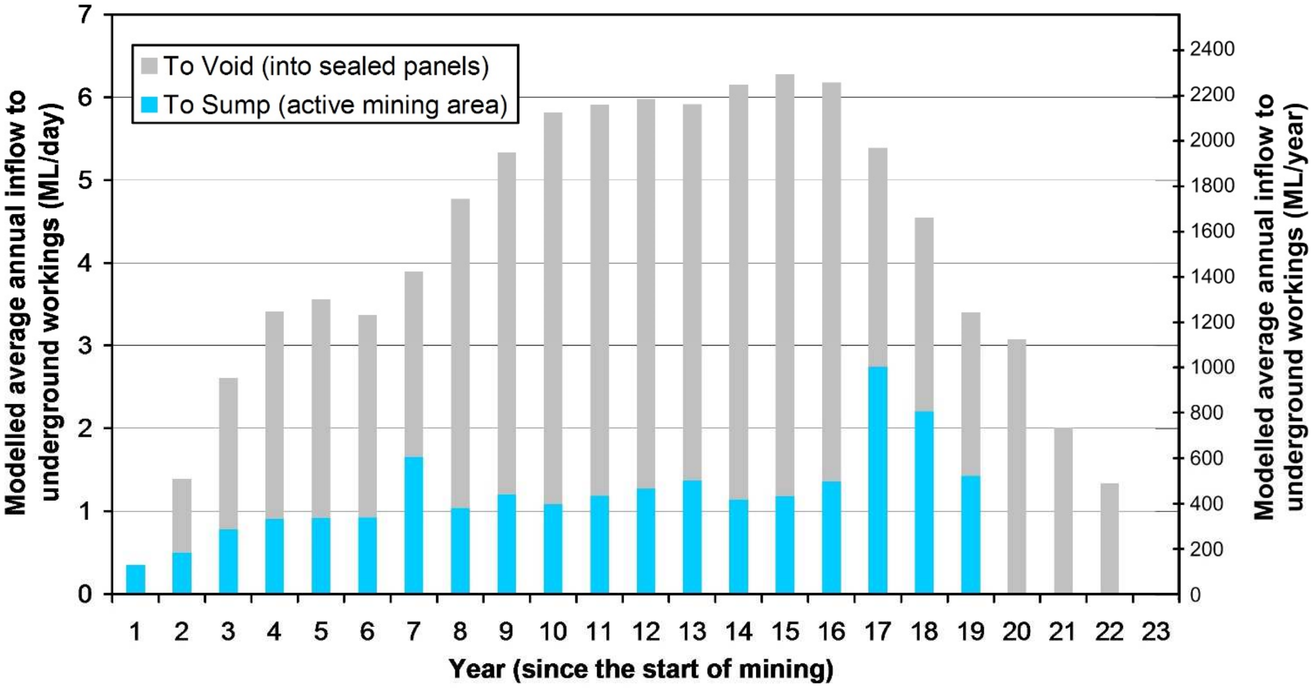


Figure 6.1. Modelled inflows to the mine void for the active mining case.

Table 9 lists maximum inflows and total accounts.

Table 9. Maximum flow rates and total accounts during the period of active stress induced by the mine.

Maximum Rates over the Period of Active Stress*		
Mine Inflow Component	**GL/year**	**ML/day**
Sump	1.00	2.74
Void	1.86	5.10
Total	2.29	6.28
Total Accounts over the Period of Active Stress		
Component	**Total (GL)**	
Mined Volume	32.7	
Inflow to Mine Void (Modelled) (3.3 GL pumped out to satisfy mine water demand deficit)	24.3	
Co-disposed tailings Volume (36% of Mined Volume)	11.7	
Injected Volume (Modelled)	nil	
Inflow To Mine Sump (Modelled)	8.4	

* The time to reach maximum is not necessarily coincident for each item.

6.2. Flow budget

The modelled average flow budget for the domain over the period of mine inflow (mining, and simulation, years 1 to 22 inclusive) is listed in Table 10 for the case where Hume mining is active. The flow budget discrepancy is considered reasonable. The increased leakage from reservoirs from 2015 (0.2 ML/day) is mostly due to private pumping.

Table 10. Modelled average flow budget over the period of mine inflow (mining and simulation years 1 to 22 inclusive) for the case of active Hume mining.

IN (ML/day)		OUT (ML/day)	
Rainfall Recharge	34.9	Baseflow to Wingecarribee River	10.2
Release from Media Storage	7.4	Baseflow to other Rivers and Creeks	10.9
Leakage from Reservoirs	2.4	Berrima Mine Inflow (to river)	2.5
Leakage from Medway Dam	0.6	Loch Catherine Mine Inflow (to river)	0.4
		Inflow to Other Mines (to rivers)	0.6
		Private Pumping	11.0
		Hume Mine Inflow	2.6
		Evapotranspiration	10.4
TOTAL	45.4	TOTAL	48.6
Discrepancy: -3.2 ML/day (-6.8 %)			

Comparison to the null case indicates that at 17 years since the start of mining, baseflow interception of overlying streams makes up approximately 23% of the total inflow.

The water balance deficit is satisfied by pumping from the following voids:

- Panels W6 to W8: 6% of deficit.
- Panels W9 and W10: 17% of deficit.

- Panels W11 to W13: 25% of deficit.
- Panels W14 to W18: 52% of deficit.

The modelled average flow budget for the domain over simulation years 1 to 22 inclusive for the null case (Hume mining is not active) is listed in Table 11. The flow budget discrepancy is considered reasonable.

Table 11. Modelled average flow budget over simulation years 1 to 22 inclusive for the null case (Hume mining is inactive).

IN (ML/day)		OUT (ML/day)	
Rainfall Recharge	34.9	Baseflow to Wingecarribee River	9.0
Release from Media Storage	6.4	Baseflow to other Rivers and Creeks	11.2
Leakage from Reservoirs	2.4	Berrima Mine Inflow (to river)	2.5
Leakage from Medway Dam	0.5	Loch Catherine Mine Inflow (to river)	0.4
		Inflow to Other Mines (to rivers)	0.6
		Private Pumping	13.0
		Hume Mine Inflow	0.0
		Evapotranspiration	10.3
TOTAL	44.3	TOTAL	47.0
Discrepancy: -2.8 ML/day (-6.0 %)			

6.3. Drawdown

Changes to the hydraulic head field from Hume mining operations are discussed as the following:

- Total drawdown (cumulative; includes Hume and other users). This is the drawdown from the beginning of the simulation period, for the scenario where all stresses in the model are operating, including the Hume mining operation, the draining mine void at Berrima, and private pumping. This is the active Hume mining scenario. The total drawdown is thus the cumulative drawdown due to all stresses.
- Differential drawdown (Hume only; excludes other users). This drawdown is calculated as the difference between drawdowns from the active Hume mining scenario (which gives the total drawdown) and the null scenario where the Hume operation is inactive (giving a null case drawdown). The differential drawdown is thus that drawdown due only to the Hume operation.

6.3.1. Temporal drawdown

Apart from private bores (discussed below), temporal drawdown has been obtained at the following 16 virtual monitoring piezometer locations (shown in Figure 6.2):

- Locations G1 to G11: Drawdown at potential groundwater dependent ecosystem (GDE) areas.
- Locations A1 to A5: Drawdown over the Hume mine footprint, and along a line extending away from it in a southeasterly direction.

Actual piezometers are not used since they are not precisely located at required horizons, and many will be eliminated by mining with time. For virtual piezometer locations, the uppermost virtual piezometer provides the modelled water table elevation, since it is located in the layer where the water table resides (the model provides a single hydraulic head value for a single layer).

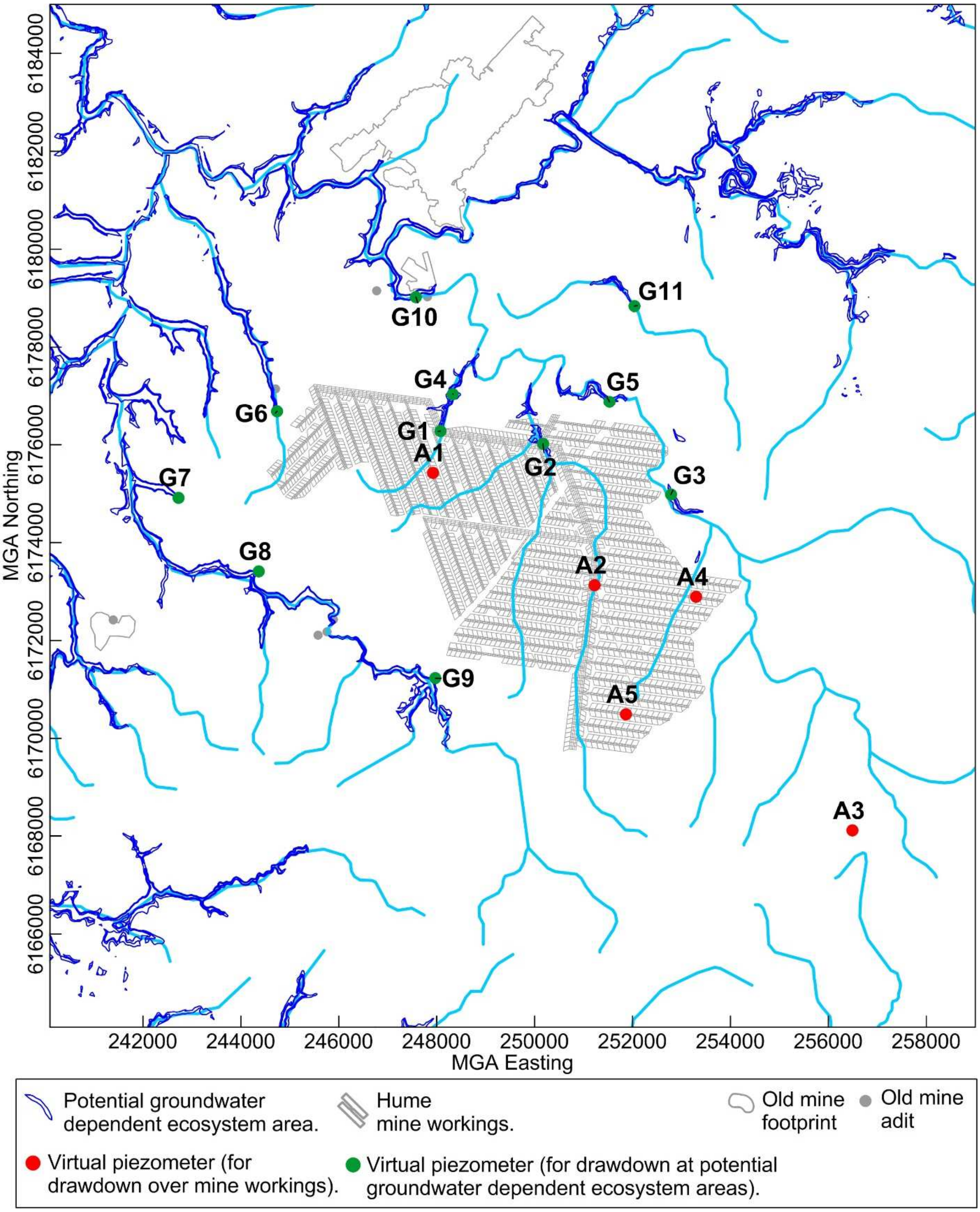


Figure 6.2. Locations of virtual piezometers used for obtaining hydraulic head and drawdown information at specific locations.

Figure 6.3 shows the modelled differential drawdown over the main headings (piezometer nest A2) and over the southern part of the workings (piezometer nest A5), showing the vertical hydraulic head gradient that is generated by the mine in overlying strata. Virtual piezometer A2 is located over the main headings and this is the more impacted area of the mine as the mains remain open throughout mining.

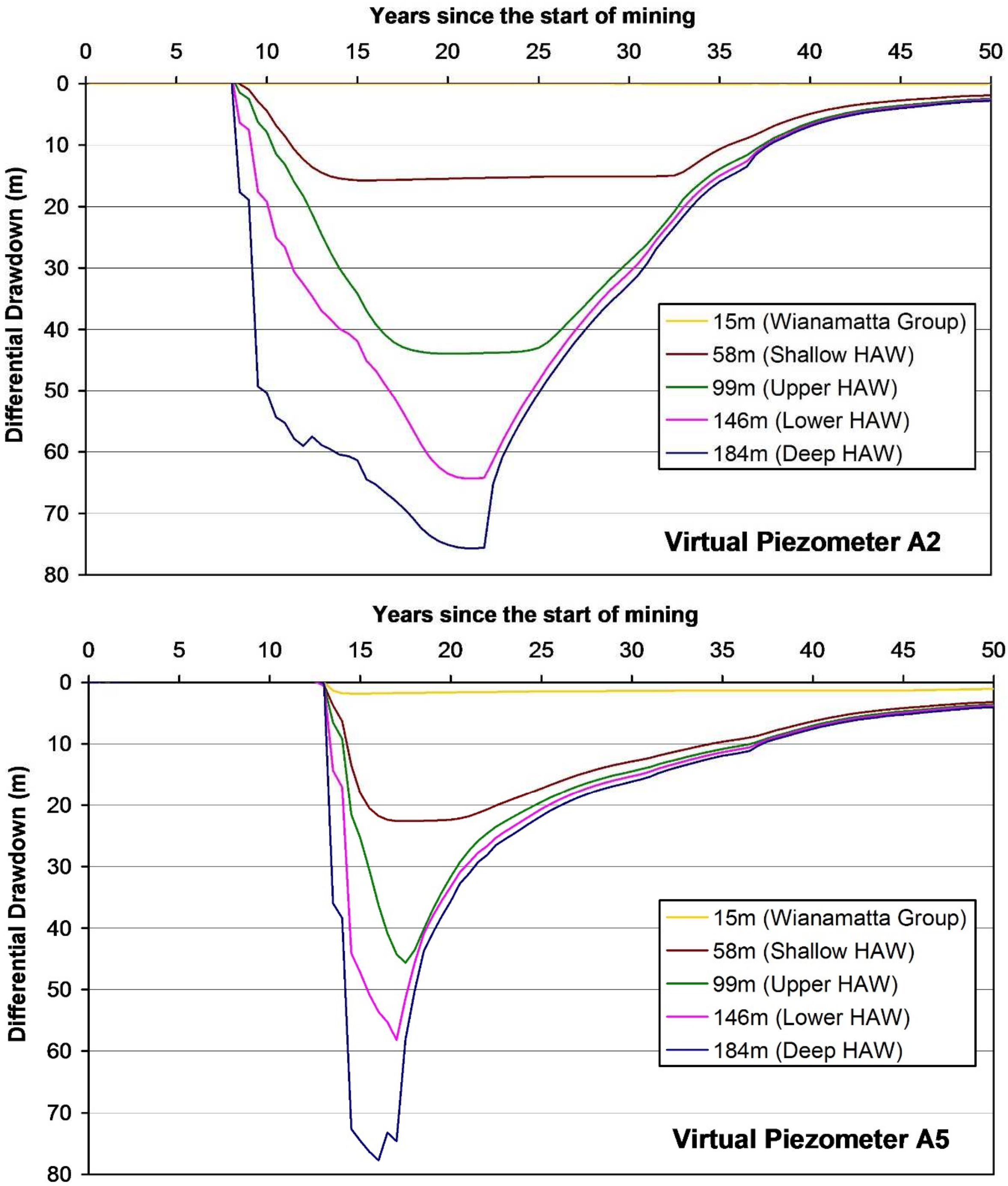


Figure 6.3. Differential drawdown at virtual piezometer nests A2 and A5.

Table 12 lists the modelled maximum total and differential drawdowns at the water table at each of the virtual piezometer nests, and the proportion of the total drawdown caused by Hume operations.

Table 12. Maximum drawdown of the water table at virtual piezometer nests.

Piezometer Nest*	Location Relative to Mine Footprint	Maximum Drawdown (m)		Proportion of Total Drawdown caused by Hume operations (%)
		Total	Differential	
A1	Inside	25.28	22.84	90
A2	Inside	0.22	0.02	11
A3	Outside	8.05	0.88	11
A4	Inside	9.02	5.35	59
A5	Inside	6.06	1.82	30
G1	Inside	23.21	20.95	90
G2	Inside	0.18	0.00	2
G3	Inside	5.02	2.51	50
G4	Outside	20.31	18.14	89
G5	Outside	0.31	0.01	2
G6	Outside	6.63	3.57	54
G7	Outside	5.00	1.44	29
G8	Outside	4.61	1.50	33
G9	Outside	7.09	4.89	69

* Nil differential drawdown calculated at G10 and G11 at the water table.

Nil differential drawdown was calculated at G10 and G11 at the water table. The maximum differential drawdown of the water table reaches to 25.3 m (at A1) at locations inside the mine footprint and to 20.3 m (at G4) at locations outside the mine footprint. Hume operations account for the majority of the total drawdown inside the mine footprint.

Maximum total drawdown of the water table greater than 2 m, of which a component is due to Hume mining, occurs at all virtual piezometer locations except A2, G2, G5, G10, and G11. Significant drawdown of the water table at potential GDE locations has the potential to affect groundwater dependent ecosystems that may be present.

Appendix D provides total and differential drawdowns for the water table and the base of the Hawkesbury Sandstone for the virtual piezometers. The modelled differential drawdown at G10 and G11 was nil for all horizons.

Figure 6.4 shows modelled differential drawdown of the water table at the virtual piezometer nests. Drawdowns follow relatively complex trends that result from a combination of mitigation measures active during mining, and the ground surface elevation with respect to lithological horizon structure contours. Hydrographs indicate that the overall time instant of maximum impact to the groundwater system (in conjunction with drainage to the mine void; see Figure 6.1) is at about 17 years since the start of mining (2 years before the end of mining).

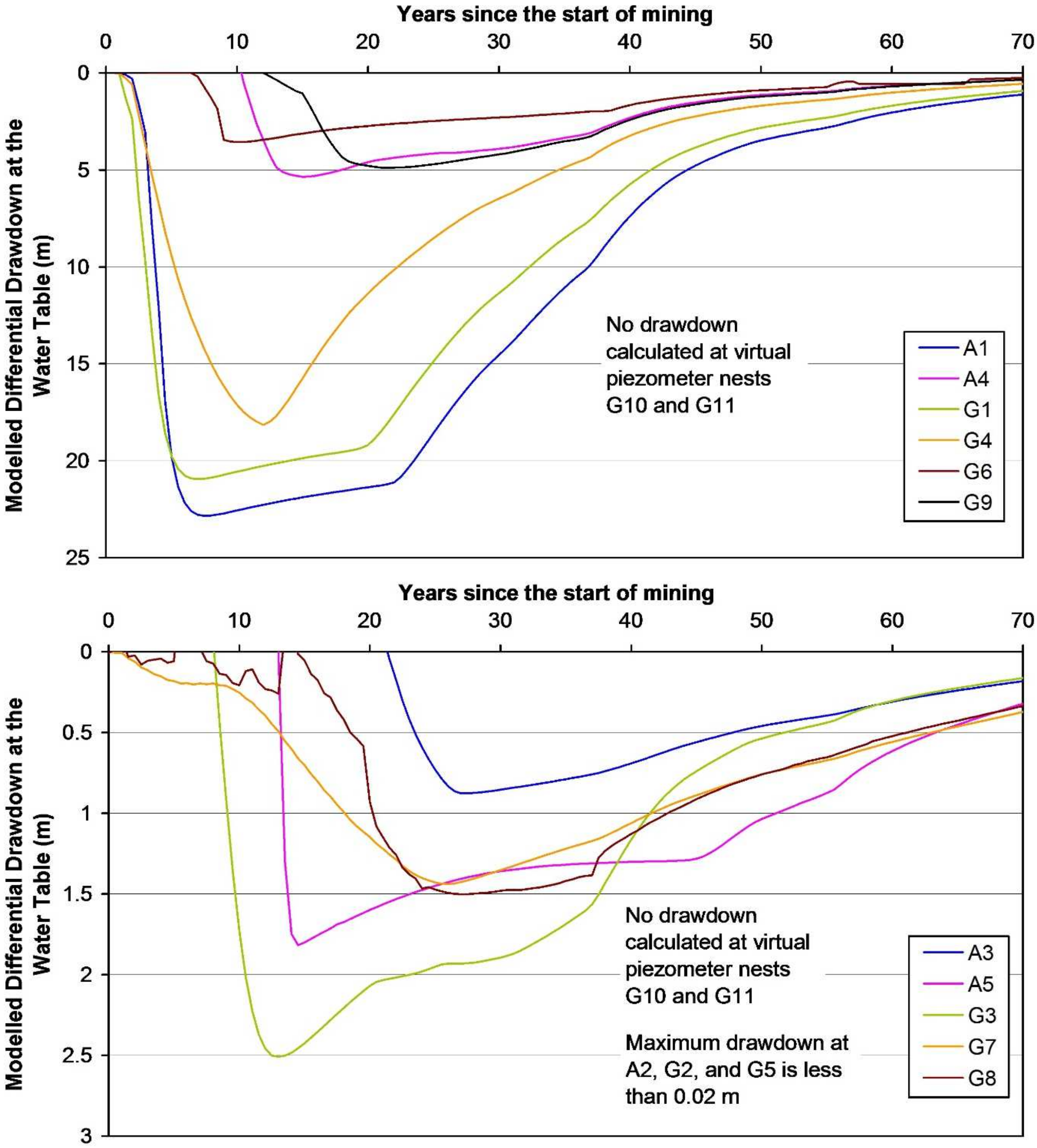


Figure 6.4. Differential drawdown of the water table at virtual piezometer nests.

Recovery time

Recovery of drawdown is presented for differential drawdowns. Total drawdown does not recover to less than 2 m at several virtual locations, due to the effects of private pumping and continued drainage at the Berrima void.

Figure 6.5 shows the duration of time for which differential drawdown of the water table is 2 m or greater, at the virtual piezometer locations. This situation occurs only at seven of the 16 virtual piezometer locations.

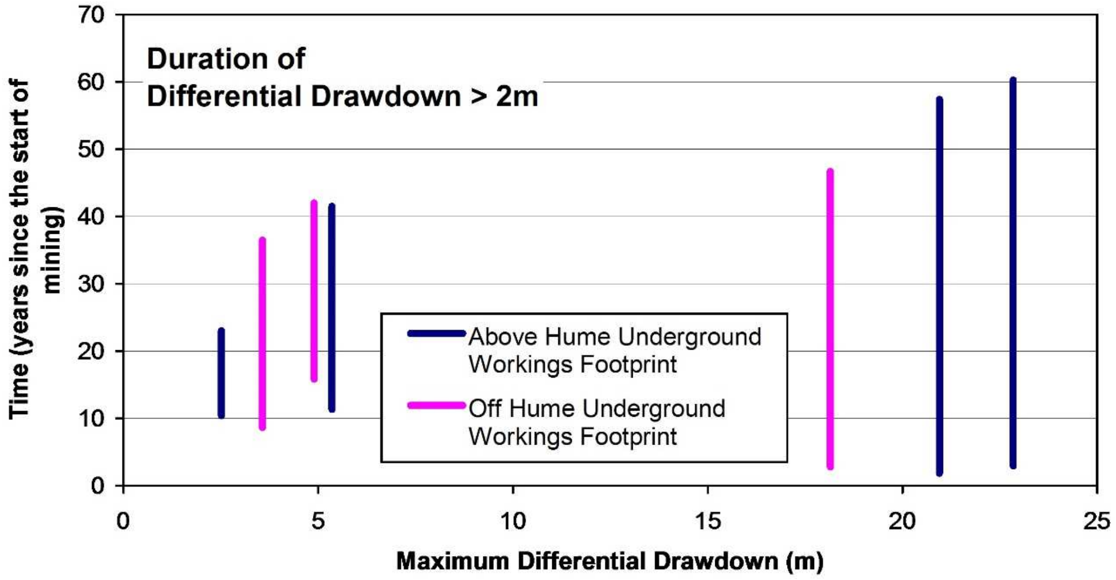


Figure 6.5. Duration of time for which differential drawdown of the water table is 2 m or greater, at virtual piezometer locations.

Differential drawdowns greater than 2 m occur for longer times over the workings footprint. The duration varies between about 15 years and 60 years. Recovery of the water table over most of the area, to 2 m differential drawdown, is largely complete within about 60 years since the start of mining.

6.3.2. Spatial drawdown

Water table

Figures 6.6 and 6.7 show the differential drawdown of the water table at 17 and 30 years since the start of mining, respectively. Contours of total drawdown of the water table for these times are shown in Appendix E.

Contours for differential drawdown of the water table form a complex pattern that results from a combination of mitigation measures active during mining, and the ground surface elevation with respect to lithological horizon structure contours. At 17 years, a maximum differential drawdown of about 45 m occurs in a small localised area over the western footprint.

The drawdown extent expands to the east, due to the recharge influx at the western sandstone extremity and the effect of the regional easterly stratigraphic dip on the K field. At 17 and 30 years the 2 m differential drawdown contour extends about 2 km and 4 km respectively past the southeast corner of the mine footprint.

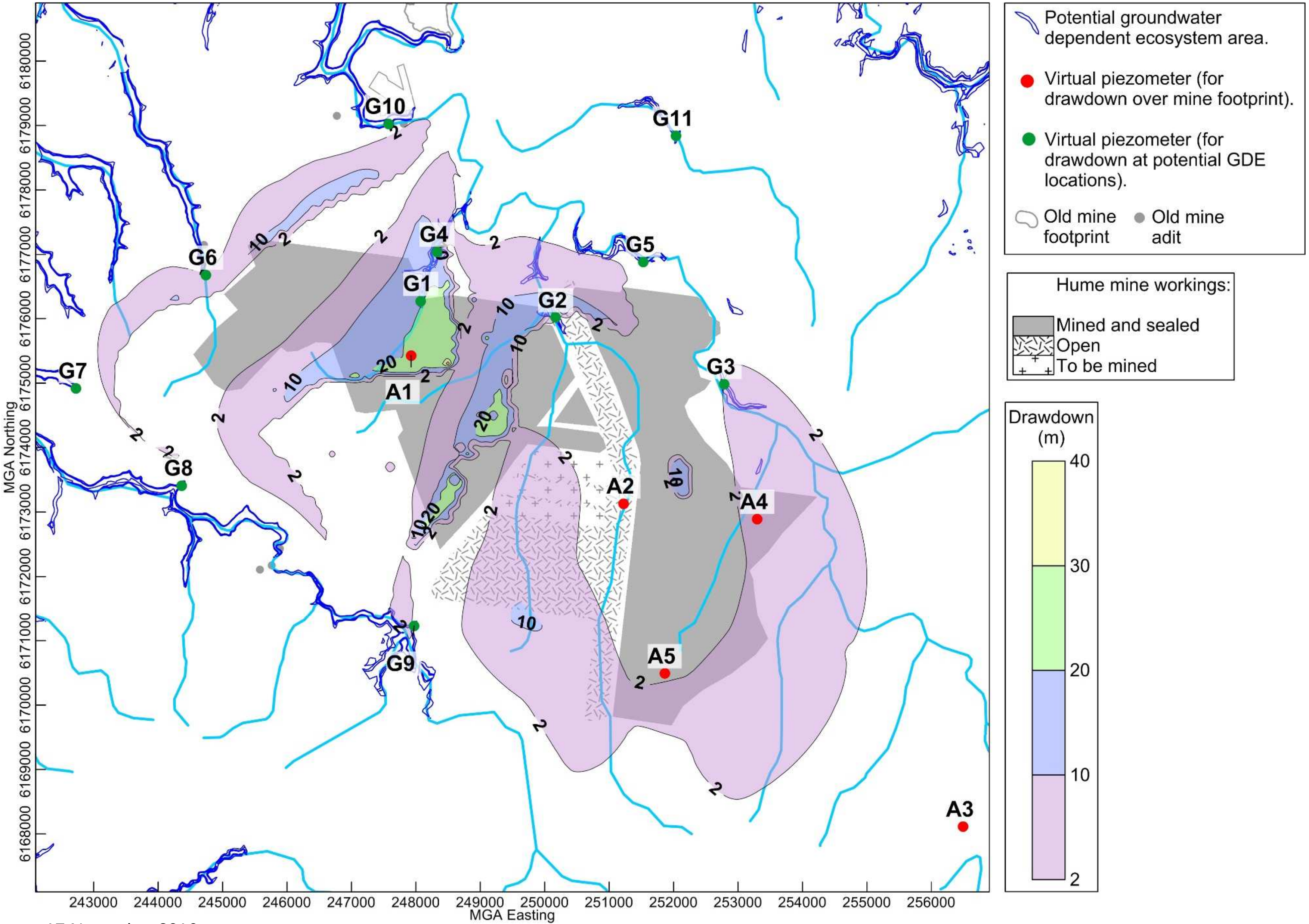


Figure 6.6. Differential drawdown of the water table at 17 years since the start of mining.

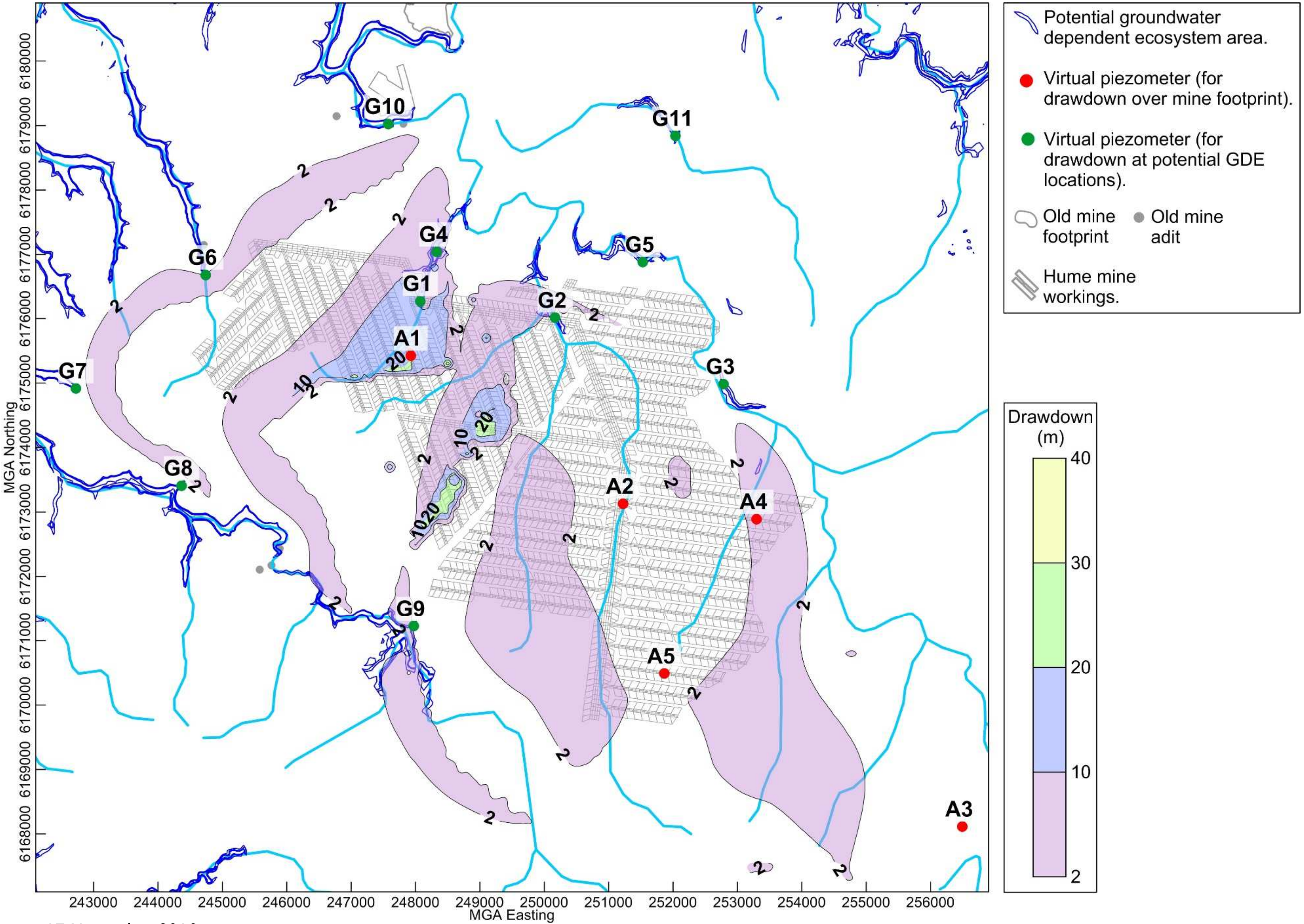


Figure 6.7. Differential drawdown of the water table at 30 years since the start of mining.

Cross Section

Figure 6.8 shows a north-south cross-section of modelled total head, pressure head, and total drawdown through the mine footprint. The total hydraulic head illustrates quasi-horizontal contours above the workings that indicate downward vertical hydraulic head gradients. Gradients can achieve values greater than one for short periods following emplacement of a void. The duration for gradients greater than one depends on recharge and discharge fluxes, and the hydraulic characteristics of the media. Pressure head contours illustrate decreases in pressure moving down through the profile over the workings.

Drawdown contours show the shape of the drawdown envelope, and the increase in drawdown moving down through the profile over the mine footprint. The shape of the drawdown contours is typical for depressurisation induced in a horizontally stratified resistive medium by drainage at depth.

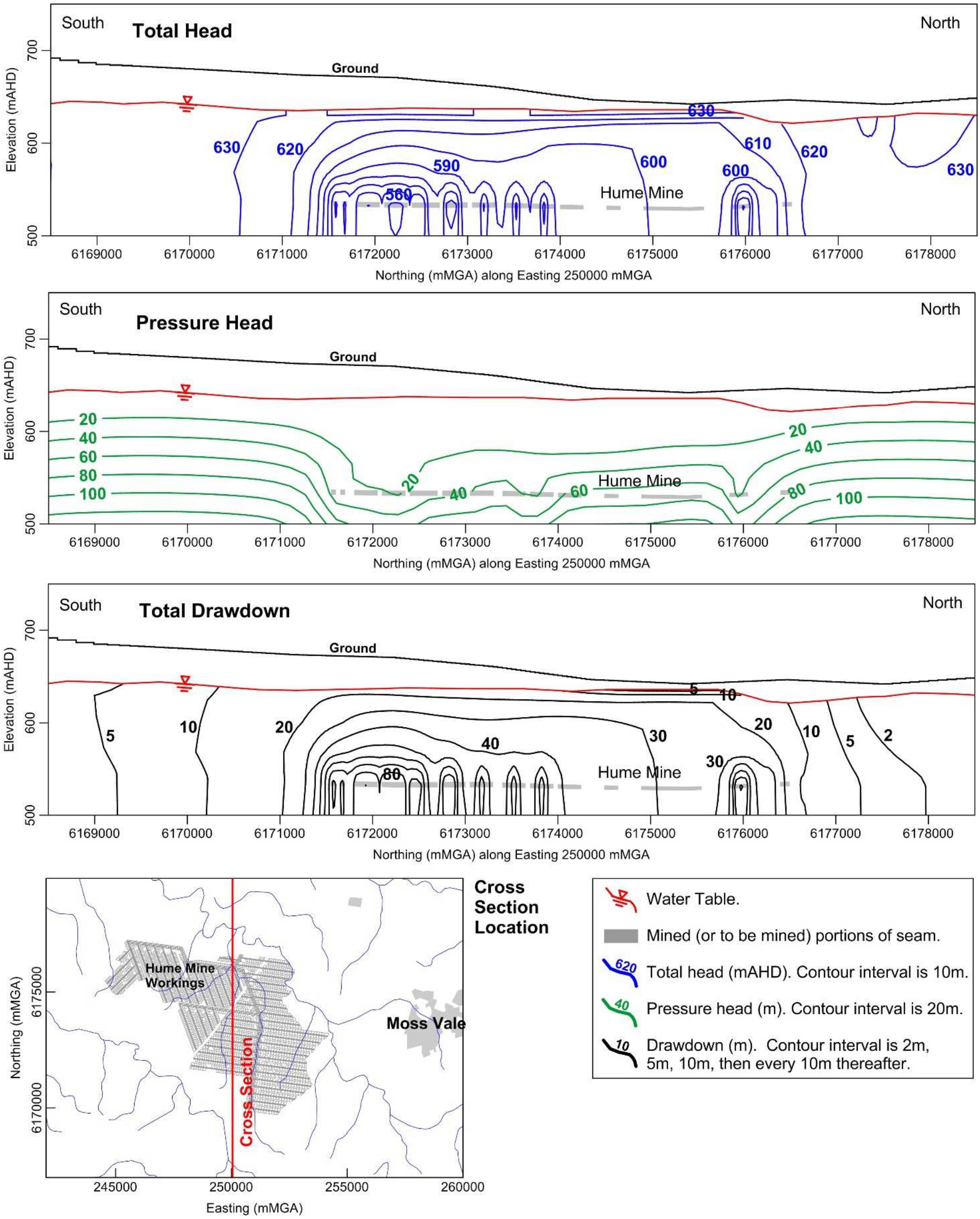


Figure 6.8. Modelled total head, pressure head, and total drawdown (depressurisation) along a north-south cross section at 17 years since the start of mining.

7. Impact assessment

7.1. Water sources

Under the AIP the NSW Government requires mines to consider how their water take may impact upon adjacent and connected water sources. The Water Sharing Plans for the Greater Metropolitan Region (DPI 2011a, 2011b), outline the delineation of both groundwater and surface water sources in this area. Table 13 lists the sources that overlie and are adjacent to the Hume area and Figure 7.1 shows the zones defining these sources.

For the assessment of surface water for the Hume project, the Lower Wingecarribee River and Medway Rivulet surface water zones have been further divided into smaller catchments.

Table 13. Water source zones and numbering adopted in the model

<table>
<tr><th>Source Type</th><th>Source Zone</th><th>Hosting Groundwater Source Zone</th></tr>
<tr><td rowspan="3">Ground-water</td><td>Nepean Management Zone 1 (NMZ1)</td><td rowspan="3">N/A</td></tr>
<tr><td>Nepean Management Zone 2 (NMZ2)</td></tr>
<tr><td>Sydney Basin South (SBS)</td></tr>
<tr><td rowspan="6">Surface Water</td><td>Upper Wingecarribee River</td><td>NMZ1</td></tr>
<tr><td>Lower Wingecarribee River in groundwater zone NMZ1
Lower Wingecarribee River in groundwater zone NMZ2
Black Bobs Creek
Longacre Creek</td><td>NMZ1
NMZ2
NMZ1
NMZ1</td></tr>
<tr><td>Medway Rivulet
Oldbury Creek
Belanglo Creek
Wells Creek
Wells Creek Tributary</td><td>NMZ1</td></tr>
<tr><td>Lower Wollondilly River</td><td>NMZ1</td></tr>
<tr><td>Nattai River in groundwater zone NMZ1
Nattai River in groundwater zone NMZ2</td><td>NMZ1
NMZ2</td></tr>
<tr><td>Bundanoon Creek</td><td>SBS</td></tr>
</table>

Estimation of water drawn from streams and from media storage, within the various source zones, requires these components to be disaggregated for each groundwater source. A surface water source may straddle two or more groundwater sources, in which case the surface water source needs to be disaggregated into the relevant groundwater source areas.

In the current work, release from groundwater storage is decomposed into:

- Storage release that is normally baseflow, but is reduced by mining (referred to as intercepted baseflow).
- Storage release that is caused by mining.

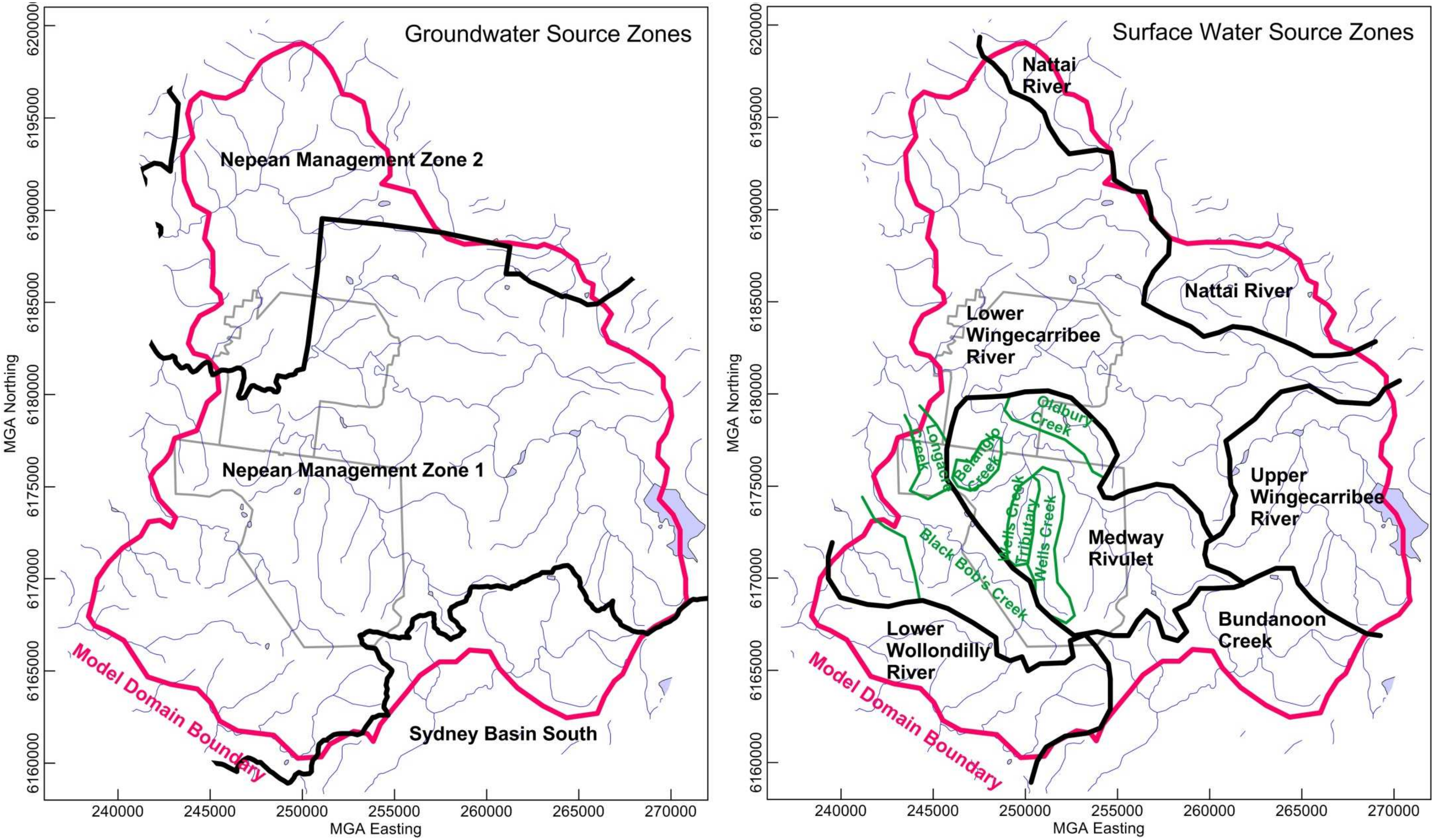


Figure 7.1. Groundwater and surface water sources and zones.

DPI (2011a) defines water of surface water sources as that water:

- occurring naturally on the surface of the ground within the boundaries of the water sources as shown on the DPI (2011a) Plan Map, and
- in rivers, lakes, estuaries and wetlands within the boundaries of these water sources as shown on the DPI (2011a) Plan Map.

This definition excludes water contained in coastal sands, any fractured rocks or porous rocks, the area below the mangrove limit, any alluvial sediments, or the Kangaroo River, Mooney Mooney Creek, and Mangrove Creek water sources.

7.1.1. Model results

No loss from the surface water body residing in the Wingecarribee River channel was calculated by the model. Model results indicate that 98% of the total inflow to the Hume mine workings is satisfied by interception of baseflow to streams, and release of groundwater storage from media. 2% of the inflow is satisfied by leakage from Medway Reservoir (a total leakage of approximately 804 ML over 22 years, or an overall average over the period of approximately 0.1 ML/day).

Intercepted baseflow and released storage are regenerated by rainfall recharge direct to the media. The loss from Medway Reservoir is regenerated by rainfall recharge direct to the media, and the portion of surface runoff from the catchment that collects and remains stationary in the reservoir. The overall modelled source / sink discrepancy is -1.3%.

Table 14 lists the maximum intercepted baseflow induced by the Hume Mine for each surface water source in the model domain. Table 15 lists the maximum flow emanating from media storage induced by the Hume Mine for each groundwater source in the model domain.

Table 14. Induced maximum intercepted baseflow for surface water sources in the model domain.

Surface Water Source	Maximum rate of baseflow interception induced by the Hume Mine (ML/day)		Time to Maximum rate (years since the start of mining)
Upper Wingecarribee River		N/A*	
Lower Wingecarribee River (whole source)		0.849	13
Lower Wingecarribee River excluding Black Bobs and Longacre Creeks.	0.800		17
Black Bobs Creek	N/A*		
Longacre Creek	0.311		13
Medway Rivulet (whole source)		0.927	11
Medway Rivulet excluding Oldbury, Belanglo, and Wells Creeks, and Wells Creek Tributary.	0.841		11
Oldbury Creek	0.002		11
Belangalo Creek	0.017		9.5
Wells Creek	0.075		1.5
Wells Creek Tributary	0.033		1.5
Lower Wollondilly River		0.050	26
Nattai River		N/A*	
Bundanoon Creek		0.024	28

* Nil baseflow interception calculated.

Table 15. Induced maximum groundwater flow losses (release from media storage) for groundwater sources in the model domain.

Groundwater Source	Maximum rate of release from groundwater storage induced by the Hume Mine* (ML/day)	Time to Maximum rate (years since the start of mining)
Nepean Management Zone 1 (NMZ1)	5.206	15
Nepean Management Zone 2 (NMZ2)	0.003	2
Sydney Basin South (SBS)	0.042	25

* Intercepted baseflow is not included (it is reported in Table 14).

Baseflow interception is a maximum for Medway Rivulet (0.9 ML/day at 11 years since the start of mining). The average total flow at flow gauge SW04 over the period of monitoring is 51.8 ML/day, with an average estimated baseflow of 3.3 ML/day. Insufficient data were available for SW04 to undertake an assessment of annual baseflow proportion versus rainfall. These functions usually have an element of curvature (see Volume 1), however a linear relation can be used for a reasonably small interval around the data collection condition. The average baseflow during average rainfall would be about 3 ML/day, about triple the maximum intercepted baseflow calculated by the model.

These results suggest the drainage channels in the Medway Rivulet catchment are likely to be able to sustain the loss in baseflow over a large range of climate conditions, without impacting other users of the Medway Rivulet water supply.

Six-monthly accounts as calculated by the model for intercepted baseflow and groundwater storage release due to Hume operations are listed in Appendix F.

7.2. Drawdown in private bores

Registered private bores within a 9 km radius of the mine footprint centroid were extracted from the NSW DPI groundwater database in December 2015. This identified 363 private bores (excluding Hume monitoring piezometers and two abandoned bores). Predictive simulation provided the extent of the 2 m differential drawdown (drawdown due only to Hume operations) contour for model layers. Private bores were selected for impact analysis according to the following criteria:

- Bores located inside the 2 m differential drawdown contour for the mined seam at 17 years, and outside the contour to the southeast. The seam is where the largest drawdowns in any hydrostratigraphic unit are developed, and the time of such drawdown in the seam is at 17 years since the start of mining.
- Bores located inside the 2 m differential drawdown contour for the water table at 17 years and outside the contour to the southeast. Inclusion of bores outside the contour takes account of the migrating drawdown of the water table following Year 17.

These criteria ensure that calculated differential drawdowns of 2 m or more are captured. The drawdown footprint generally contracts moving upward, except to the southeast where some migration in a southeasterly direction occurs (see Figure 6.6). These criteria define the potential impact zone for private bores from Hume operations. The model calculates differential drawdowns of less than 2 m outside these criteria.

117 private bores were identified as residing in the potential drawdown zone. Available bore logs suggest 116 bores are completed in Triassic and Permian media of the Sydney Basin and one is completed in basalt (GW106103). For bores that are located in the area of outcrop of the basalt body, the majority of those that are screened in basalt are located south of the major subvertical hydraulic

barrier under the basalt body (see Volume 1), where the basalt thickness is significantly greater than north of the feature.

Table 1 in Appendix G lists the private bores and relevant information as obtained from government records, or as estimated. Map 1 in Appendix G shows bore locations. Drawdown in the basalt bore was assessed using a separate model as discussed below.

The lithology log for bore GW067521 lists basalt as the intersected stratum, however it is interpreted to be in shale of the Wianamatta Group (WG) based on the following:

- The elevation of the logged basalt is grossly inconsistent with structure contours for the base of the basalt developed from nearby bores. The latter indicate termination of the basalt along a line similar to current published geology maps.
- The bore is located north of the basalt limit as shown on current geological maps.
- Dark grey to black shale of the WG is known to have been mistaken for basalt in lithology logs for other registered bores in the Sydney Basin.

The drawdown at each bore was calculated as the transmissivity-weighted average of drawdown in each model layer intersected by the bore hydraulic interval (the interval over which water in the bore communicates with the external medium).

7.2.1. Drawdown in the basalt bore

Due to the method of emplacement, basalt bodies host a palaeosol horizon at the interface with underlying media that has been significantly heat affected and may typically be highly weathered. This horizon is typically of significantly lower K than surrounding media, and usually acts to retard vertical drainage from the basalt body to underlying media. If several lava flow events comprise the basalt body, palaeosol horizons may also be dispersed throughout the basalt sequence, imparting a strong vertical anisotropy to the basalt body.

Hydraulic head observations for the basalt bodies in the Hume area indicate negligible vertical hydraulic head gradients in the basalt, suggesting the body was emplaced over a relatively short period. There is a large vertical hydraulic head gradient between the basalt bodies and underlying media, suggesting the palaeosol horizon at the base of the basalt retards vertical drainage.

To assess drawdown impacts to the private bore in basalt (GW106103) due to mining, a separate numerical model, targeting a smaller area than the main model, was developed. The conceptualisation of the system upon which the model is based is as interpreted in Coffey (2016). Use of a separate model greatly facilitates characterisation of Kv of the retarding layer underlying the basalt, which is the main parameter upon which drawdown in the basalt body depends. Appendix H provides information regarding the basalt model.

7.2.2. Model results

Drawdowns are discussed as both of the following:

- Total drawdown (cumulative; includes Hume and other users): The drawdown actually developed at the bore for the active Hume mining scenario. This is the drawdown which must be used to assess the functioning of the bore following impacts.
- Differential drawdown (Hume only; excludes other users): The drawdown caused only by Hume operations. It is calculated as the difference between a null case (all processes operating, except for Hume operations) and the active Hume mining scenario. It is used to calculate the proportion of total drawdown at a private bore that is caused by Hume operations only.

Total drawdowns have only been used to assess whether any bores go dry, and to calculate the proportion of total drawdown caused by Hume operations. A large number of total drawdown hydrographs also do not recover to within 2 m of pre-mining water levels (that is, the effects of private pumping and drainage at Berrima, in the absence of Hume operations, causes drawdowns in excess of 2 m by the end of the simulated period).

Of the 117 private bores identified as residing in the potential drawdown zone, 99 bores are assessed as being subject to a differential drawdown of 2 m or more. Table 2 in Appendix G lists the maximum total and differential drawdown developed at each private bore, and the times required to achieve these maximums. This table also provides the times (in years since the start of mining) when 2 m differential drawdown first occurs at a private bore, and when the differential drawdown recovers back to 2 m. Appendix G also shows total and differential drawdown hydrographs for each bore for reference.

Figure 7.2 shows a histogram of the maximum differential drawdown at private bores. 18 bores have a maximum differential drawdown of 2m or less. The overall average proportion of the maximum total drawdown that is caused by Hume operations is 87%.

The drawdown developed at each bore is heavily dependent on bore location (whether on the mine footprint or more distant) and bore hydraulic interval (and particularly the proportion of shallower media intersected). At a given location, shallower media undergo smaller drawdowns than deeper media.

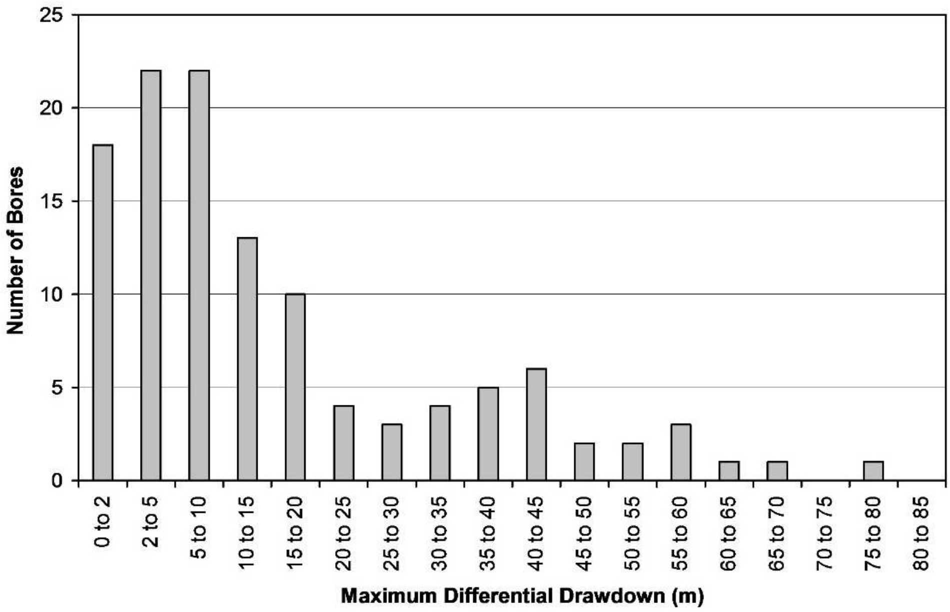


Figure 7.2. Histogram of maximum differential drawdown in private bores.

Figure 7.3 provides a spatial summary of the modelled maximum differential drawdown (for bores where it is 2m or greater), at the private bores, and bore screened strata. Also shown is the time to maximum differential drawdown (in years since the start of mining, for clarity). Year 1 of mining is provisionally 2021. Larger drawdowns generally occur over the mine footprint.

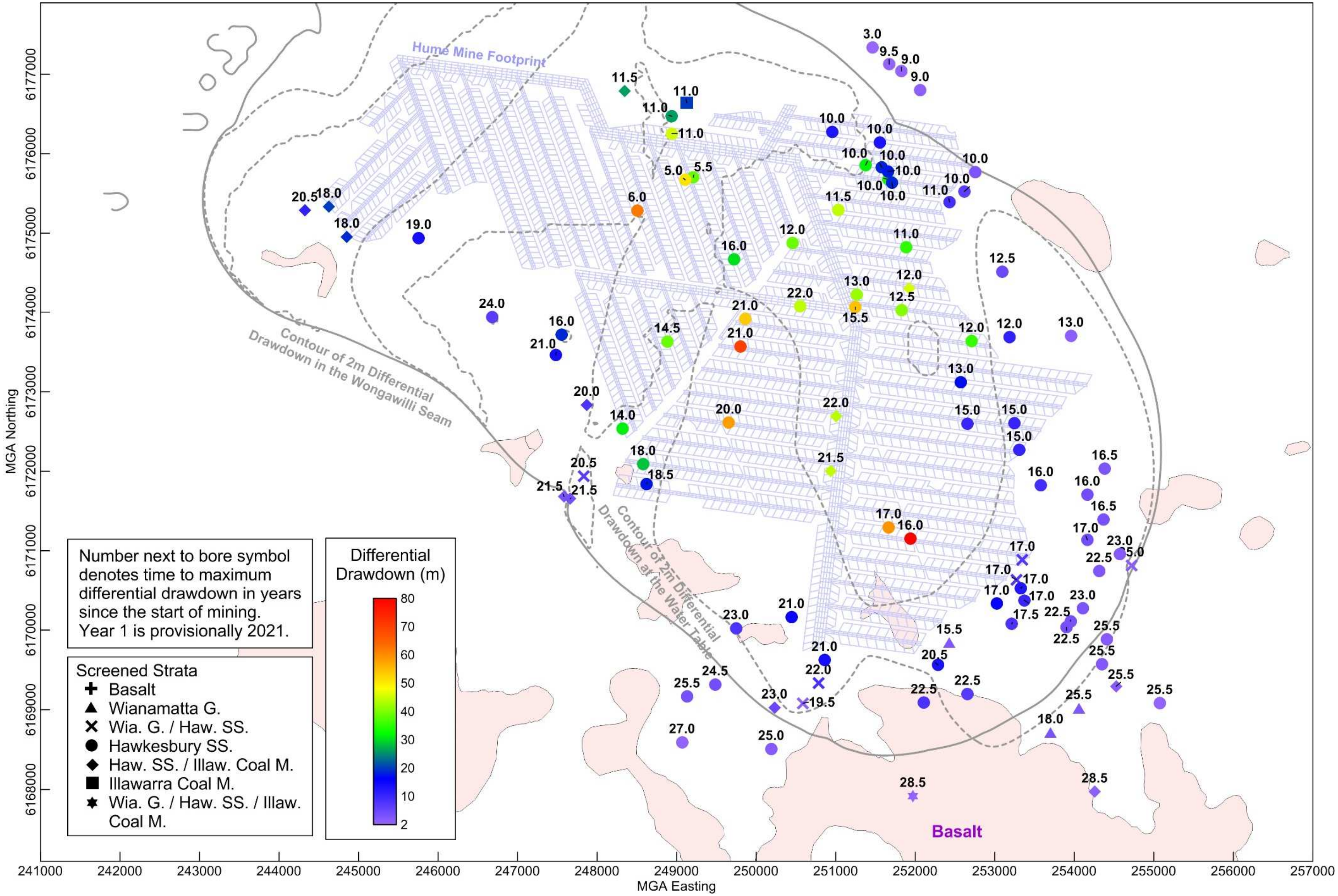


Figure 7.3. Spatial distribution of modelled maximum differential drawdown at private bores (and the time to maximum differential drawdown) and private bore screened strata.

Figure 7.4 shows the duration of the period for each bore where differential drawdown is greater than 2 m. The start and end of each period is given as years since the start of mining. Durations of these periods range between 2 months and 65 years, with an average of 34 years. The majority of private bores have recovered to less than 2 m differential drawdown by 60 years since the start of mining.

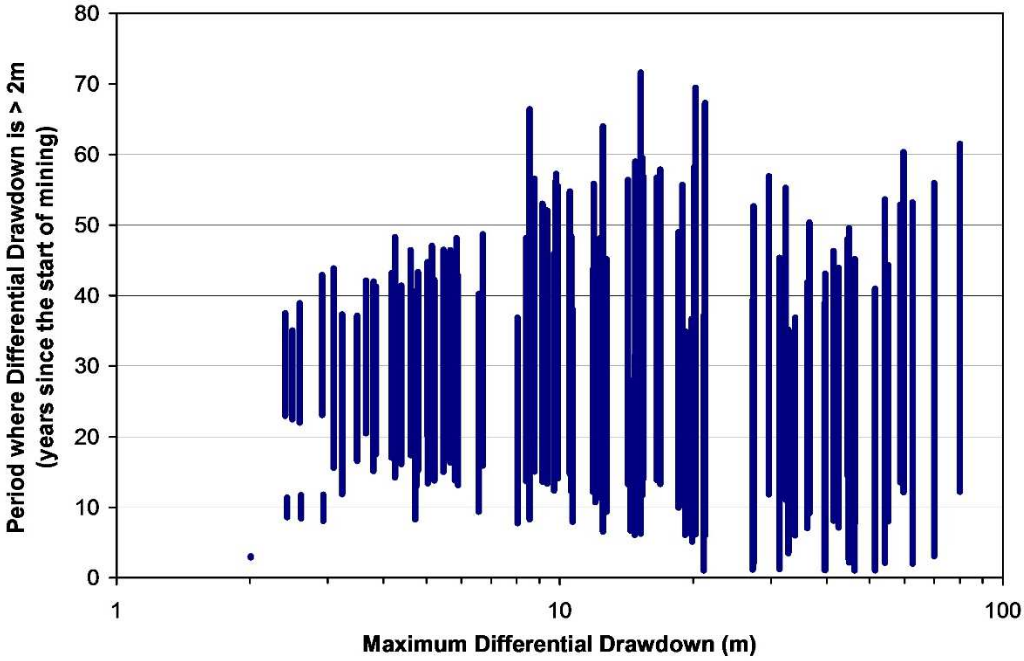


Figure 7.4. Duration of the period for each private bore where differential drawdown is greater than 2m.

Table 16 provides a summary of bores that may require replacement during mining, due to the nature of the impact. They are identified on Map 1 in Appendix G. Impacts include potential structural impacts which the groundwater models cannot simulate. Of these bores, five are likely to be intersected by mining.

In developing a threshold for the maximum distance between the base of a bore and the roof of the mined section, within which there may be structural impact, provision was made as follows:

- A mined section height of 3.5 m above the floor of the Wongawilli seam.
- A relaxation zone of 2 m with an additional 2 m for uncertainty.
- An error of ±8 m in relating the adopted digital elevation model to true ground level, and to bore logs.
- An error of ±2 m for bore depth in incorporating government database roundoff error and measurement error.

Table 16. Private water bores that may require replacement during mining.

Bore	Impact	Proportion of total drawdown due to Hume operations at start and end of dry period (%)	
GW106710	Over mine footprint and penetrates to within 14 m of working section roof (allowance for uncertainty). May be drained by mining.	N/A	
GW107535			
GW110236			
GW108195	Over mine footprint and penetrates to within 4 m of working section roof. May be drained by mining.		
GW052538	Over mine footprint and penetrates to working section roof or below. Likely to be intersected by mining during Year 7.		
GW072672	Over mine footprint and penetrates to working section roof or below. Likely to be intersected by mining during Year 8.		
GW102588	Over mine footprint and penetrates to working section roof or below. Likely to be intersected by mining during Year 7.		
GW104745	Over mine footprint and penetrates to working section roof or below. Likely to be intersected by mining during Year 8.		
GW108194	Over mine footprint and penetrates to working section roof or below. Likely to be intersected by mining during Year 10.		
GW023322	Goes dry approximately for the period 13 to 15 years since the start of mining.	99	99
GW026136	Goes dry approximately for the period 13 to 27 years since the start of mining.	93	94
GW032319	Goes dry approximately for the period 9 to 11 years since the start of mining.	98	99
GW035590	Goes dry approximately for the period 16 to 33 years since the start of mining.	57	68
GW047157	Goes dry approximately for the period 4 to 6 years since the start of mining.	99	99
GW048345	Goes dry approximately for the period 10 to 13 years since the start of mining.	95	97
GW064613	Goes dry approximately for the period 2 to 13 years since the start of mining.	98	99
GW066798	Goes dry approximately for the period 8 to 12 years since the start of mining.	96	99
GW104486	Goes dry approximately for the period 10 to 17 years since the start of mining.	91	95
GW106489	Goes dry approximately for the period 18 to 22 years since the start of mining.	95	96
GW106491	Goes dry approximately for the period 18 to 24 years since the start of mining.	96	97
GW108825	Goes dry approximately for the period 8 to 12 years since the start of mining.	94	92
GW037851	Water column* reduces to < 4 m	N/A	
GW067305			
GW067319			
GW068965			
GW105744			

* The distance between the base of the bore and the bore water level.

8. Parameter sensitivity analysis

Results of the three parameter sensitivity runs (see Table 8) are as follows:

- Relaxation height of 2 m and 4 m. These heights were applied over an area representative of the typical extent of an actively draining area at an instant in time (about 11 km^2). Results indicated an increase in inflow of 4.3%.
- Kv distributions as follows:
  - The calibrated Kv distribution (listed in Table 3).
  - Calibrated Kv of model layers 1 to 5 (see Table 3) multiplied by 3. These layers comprise the Wianamatta Group and Hawkesbury Sandstone between the water table and the mine workings.

  The higher Kv case produces an overall 28% increase in mine inflow. Inflows are considered sensitive to the Kv distribution, in comparison to other parameters.
- Hume mine drain conductance of 0.05 m^2/day (calibrated) and 0.1 m^2/day. Only a comparatively small change in inflows occurs between these cases.

The results of the sensitivity analysis indicate that the Kv distribution is one of the most important parameters for the simulations. This parameter is one of the most difficult to characterise. For the model reported herein, this parameter has been reasonably resolved by calibration to the following three crucial and completely independent sets of observations:

- Shallow groundwater discharges (stream baseflow).
- Deep groundwater discharges (Berrima mine inflow).
- Kv estimated from the two long-term pumping tests undertaken by Hume in 2014. Both tests were conducted with multiple observation piezometers down the depth profile, and drawdowns were assessed taking into account partial penetration and vertical anisotropy.

The combination of observations from the pumping tests undertaken by Hume, with shallow and deep discharge observations, allows the calibrated Kv distribution to be applicable to an appropriate scale and is considered to have a high level of reliability, including reliable representation of the effects of the high density of open bores present in the area, and the tectonic activity that has occurred in the area.

9. Conclusions

A regional numerical groundwater flow model has been developed for the Hume Coal Project. Model calibration has been successful in reproducing shallow groundwater discharges (stream baseflow), deep groundwater discharges (discharge to the Berrima mine void), and hydraulic heads, and has adhered strongly to the observed hydraulic conductivity distribution.

The combination of observations from the pumping tests undertaken by Hume, with shallow and deep discharge observations, allows the calibrated Kv distribution to be applicable to an appropriate scale and is considered to have a high level of reliability, including reliable representation of the effects of the high density of open bores present in the area, and the increased hydraulic conductivity imparted by tectonic activity that has occurred in the area.

This has reduced the uncertainty in model outputs. The model is considered to be acceptably calibrated and fit for its purpose in simulating the groundwater system with application of the magnitude stress defined by the Hume mine schedule.

The model was subsequently used in a predictive capacity to assess impacts from Hume mining operations using the Pine Feather layout and mining method. Model predictive simulation results are as follows:

- The total volume of groundwater inflow that reports to the sump is calculated as 8.4 GL during the time the effects of mining are active in the groundwater system. The maximum inflow rate to the sump is 2.7 ML/day (1000 ML/year) in year 17 of mining.
- The total volume of groundwater inflow that reports to the void is 24.3 GL during the time the effects of mining are active in the groundwater system. The maximum inflow rate to the void is 5.1 ML/day (1860 ML/year) in year 15 of mining.
- The drawdown footprint achieves a maximum size at about 17 years since the start of mining. The zone of highest drawdown in the footprint migrates according to worked areas. At 17 years, the 2 m differential drawdown contour of the water table extends a maximum of about 2 km past the southeast corner of the mine footprint. The duration of differential drawdown of the water table varies between about 15 years and 60 years. Recovery of the water table over most of the area, to 2 m differential drawdown, is largely complete within about 60 years after the start of mining.
- Maximum total drawdown of the water table greater than 2 m occurs at several locations where there are shallow water levels. These areas have been provided to the ecology team to consider potential influence on ecosystems that may be present at these locations.
- No direct leakage from the Wingecarribee River, induced by Hume operations, is calculated by the model. Model results indicate that 98% of the total inflow to the Hume mine workings is satisfied by interception of baseflow to streams, and release of groundwater storage from media. 2% of the inflow is satisfied by leakage from Medway Reservoir (a total leakage of approximately 804 ML over 22 years, or an overall average over the period of approximately 0.1 ML/day). Baseflow interception induced by Hume operations is largest for Medway Rivulet. Baseflow analysis of flow observations from Medway Rivulet suggests the average baseflow measured at these gauges (over the monitoring period) is about 3 times larger than the calculated future maximum baseflow interception.
- Of the 117 private bores identified as residing in the potential drawdown zone, 99 bores are assessed as being subject to a differential drawdown of 2 m or more. The overall average proportion of the maximum total drawdown that is caused by Hume operations is 87%. Groundwater extraction by private users accounts for the remaining 13%. The duration of the period for each bore where differential drawdown is greater than 2 m ranges between 2 months and 65 years, with an average of 34 years. The majority of these bores have recovered back to 2

m differential drawdown by 60 years since the start of mining. Five of these bores are likely to be intersected by mining because they penetrate the mined zone.

10. Limitations

Modelling is a useful tool to simulate complex subsurface media and to predict water balances and water levels when groundwater stresses are applied. In fractured media with large mining stresses, the modelling results will not exactly represent conditions on a local scale but are more representative on a medium to regional scale. Actual observations made in the future, during Hume mine operation, may differ from predictions made herein.

Model results also do not take into account disturbance of significant but unknown extraordinary defects or extraordinary structural features (those occurring as significant outliers of the typical defect population), which can extend the drained zone associated with the workings, as estimated herein, via the creation of extreme permeability pathways extending beyond the estimated drained zones.

Model results should be reviewed following 12 months of mine operation. Should predictions differ significantly from observations, model recalibration may be necessary.

11. References

Anderson MP and Woessner WW. 1992. Applied Groundwater Modelling: Simulation of Flow and Advective Transport. Academic Press, San Diego. 381 p.

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. June.

British Coal Corporation. 1996. Development of geotechnical design software for roadways and support systems. Report EUR 14271 EN (Contract No 7220-AB/818) prepared for European Commission (Directorate-General XVII, Energy), Technical coal research, Mining operations.

Coffey Geotechnics Pty Ltd. 2012. Groundwater Study, Area 3B Dendrobium Coal Mine, Numerical Modelling. Report GEOTLCOV24507AA-AB2 prepared for BHP Billiton. October.

David K. 2015. Hydrogeological assessment for the closure of Berrima Colliery. Report KD2015/5 prepared for Boral Cement Limited. August.

Ditton S and Frith R. 2003. Influence of Overburden Lithology on Subsidence and Sub-Surface Fracturing on Groundwater. Final Project Report, ACARP Project C10023.

EMM. 2016. Hume Coal Project Environmental Impact Assessment.

Heritage Computing (HC). 2010. Local area groundwater modelling of alternative Area 3A longwall panel lengths. Report HC2010/16 for Illawarra Coal Holdings Pty Limited. October.

Lowe L, Vardon M, Etchells T, Malano H, and Nathan R. 2009. Estimating unmetered stock and domestic water use. 18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July. http://mssanz.org.au/modsim09

Mine Advice Pty Ltd. 2015. Initial Analysis of Overburden Movements Associated with Long-Term Stable Remnant Pillar Layouts used with the Pine Feather Method at Hume. Draft Letter Report. 10 August 2015.

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.

NSW Department of Primary Industries (DPI). 2011a. Water Sharing Plan, Greater Metropolitan Region, Unregulated River Water Sources: Guide. July.

NSW Department of Primary Industries (DPI). 2011b. Water Sharing Plan, Greater Metropolitan Region, Groundwater Sources: Background document. July.

NSW Department of Land and Water Conservation. 1999. Farm Dams Assessment Guide.

Parsons Brinckerhoff. 2015. Water Fieldwork and Monitoring Report. Draft Report 2200539A-RES-REP-7812 RevA prepared for Hume Coal Pty Ltd. November.

South Australian Murray-Darling Basin Natural Resources Management Board (SAMDBNRMB). Undated. Estimates of Stock & Domestic Water Demand for the Eastern Mount Lofty Ranges Prescribed Water Resources Area.

Tammetta P. 2016. Estimation of the Change in Storage Capacity above Mined Longwall Panels. Groundwater, early view, January 2016, doi: 10.1111/gwat.12405.

Tammetta P. 2015. Estimation of the Change in Hydraulic Conductivity above Mined Longwall Panels. Groundwater, Volume 53, Issue 1, p. 122 to 129.

Tammetta P. 2013. Estimation of the Height of Complete Groundwater Drainage above Mined Longwall Panels. Ground Water, Volume 51, Number 5, p. 723 to 734.

Sweby G. 1997. Review the caving mechanisms around high extraction systems and determine the effect of the mechanisms on safety of the system. CSIR MiningTek research report COL 327. October.

Whittles DN. 1999. The application of rock mass classification principles to mine design. Doctoral dissertation, University of Nottingham, UK. November.

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Important information about your **Coffey** Report

As a client of Coffey you should know that site subsurface conditions cause more construction problems than any other factor. These notes have been prepared by Coffey to help you interpret and understand the limitations of your report.

Your report is based on project specific criteria

Your report has been developed on the basis of your unique project specific requirements as understood by Coffey and applies only to the site investigated. Project criteria typically include the general nature of the project; its size and configuration; the location of any structures on the site; other site improvements; the presence of underground utilities; and the additional risk imposed by scope-of-service limitations imposed by the client. Your report should not be used if there are any changes to the project without first asking Coffey to assess how factors that changed subsequent to the date of the report affect the report's recommendations. Coffey cannot accept responsibility for problems that may occur due to changed factors if they are not consulted.

Subsurface conditions can change

Subsurface conditions are created by natural processes and the activity of man. For example, water levels can vary with time, fill may be placed on a site and pollutants may migrate with time. Because a report is based on conditions which existed at the time of subsurface exploration, decisions should not be based on a report whose adequacy may have been affected by time. Consult Coffey to be advised how time may have impacted on the project.

Interpretation of factual data

Site assessment identifies actual subsurface conditions only at those points where samples are taken and when they are taken. Data derived from literature and external data source review, sampling and subsequent laboratory testing are interpreted by geologists, engineers or scientists to provide an opinion about overall site conditions, their likely impact on the proposed development and recommended actions. Actual conditions may differ from those inferred to exist, because no professional, no matter how qualified, can reveal what is hidden by earth, rock and time. The actual interface between materials may be far more gradual or abrupt than assumed based on the facts obtained. Nothing can be done to change the actual site conditions which exist, but steps can be taken to reduce the impact of unexpected conditions. For this reason, owners should retain the services of Coffey through the development stage, to identify variances, conduct additional tests if required, and recommend solutions to problems encountered on site.

Your report will only give preliminary recommendations

Your report is based on the assumption that the site conditions as revealed through selective point sampling are indicative of actual conditions throughout an area. This assumption cannot be substantiated until project implementation has commenced and therefore your report recommendations can only be regarded as preliminary. Only Coffey, who prepared the report, is fully familiar with the background information needed to assess whether or not the report's recommendations are valid and whether or not changes should be considered as the project develops. If another party undertakes the implementation of the recommendations of this report there is a risk that the report will be misinterpreted and Coffey cannot be held responsible for such misinterpretation.

Your report is prepared for specific purposes and persons

To avoid misuse of the information contained in your report it is recommended that you confer with Coffey before passing your report on to another party who may not be familiar with the background and the purpose of the report. Your report should not be applied to any project other than that originally specified at the time the report was issued.

Interpretation by other design professionals

Costly problems can occur when other design professionals develop their plans based on misinterpretations of a report. To help avoid misinterpretations, retain Coffey to work with other project design professionals who are affected by the report. Have Coffey explain the report implications to design professionals affected by them and then review plans and specifications produced to see how they incorporate the report findings.

Important information about your **Coffey** Report

Data should not be separated from the report*

The report as a whole presents the findings of the site assessment and the report should not be copied in part or altered in any way. Logs, figures, drawings, etc. are customarily included in our reports and are developed by scientists, engineers or geologists based on their interpretation of field logs (assembled by field personnel) and laboratory evaluation of field samples. These logs etc. should not under any circumstances be redrawn for inclusion in other documents or separated from the report in any way.

Geoenvironmental concerns are not at issue

Your report is not likely to relate any findings, conclusions, or recommendations about the potential for hazardous materials existing at the site unless specifically required to do so by the client. Specialist equipment, techniques, and personnel are used to perform a geoenvironmental assessment. Contamination can create major health, safety and environmental risks. If you have no information about the potential for your site to be contaminated or create an environmental hazard, you are advised to contact Coffey for information relating to geoenvironmental issues.

Rely on Coffey for additional assistance

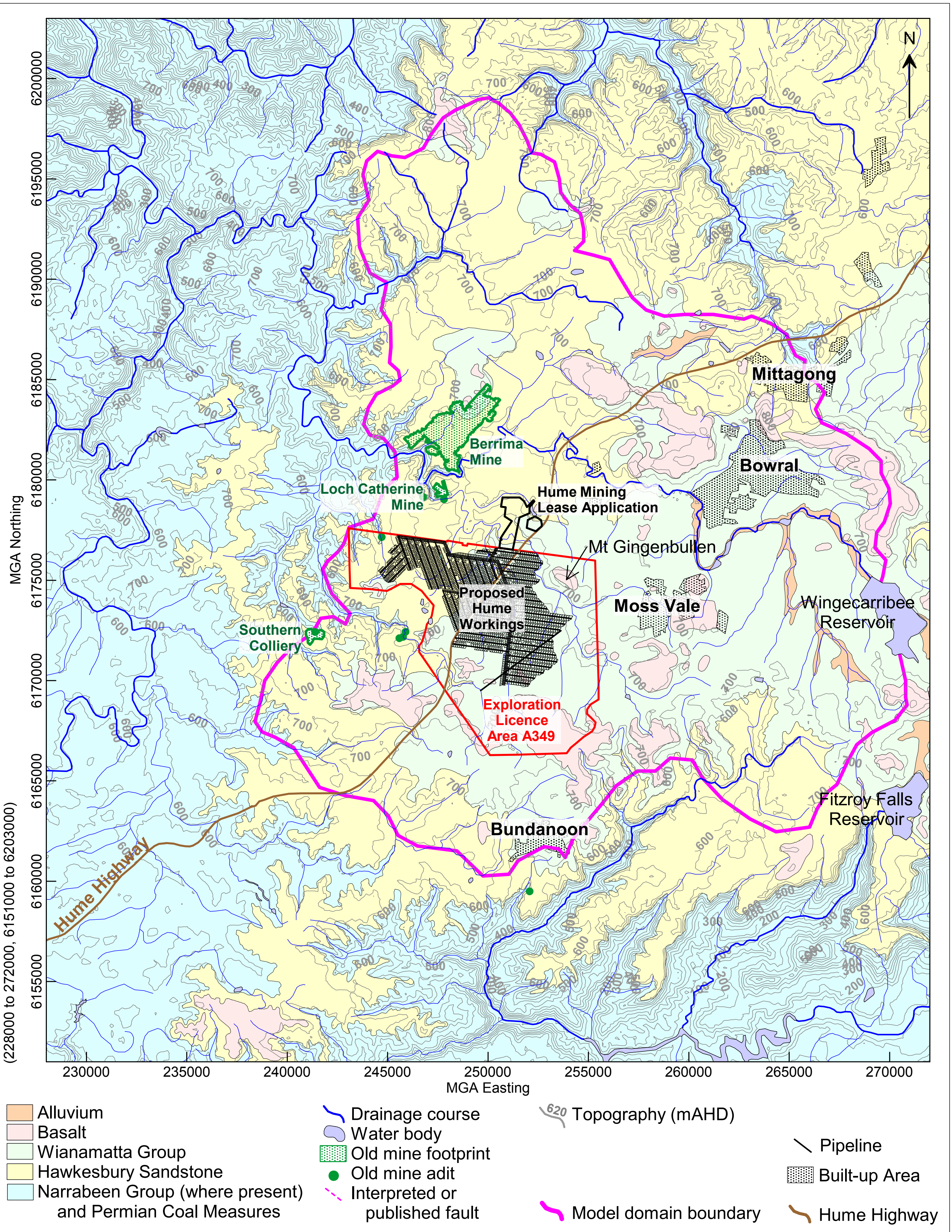
Coffey is familiar with a variety of techniques and approaches that can be used to help reduce risks for all parties to a project, from design to construction. It is common that not all approaches will be necessarily dealt with in your site assessment report due to concepts proposed at that time. As the project progresses through design towards construction, speak with Coffey to develop alternative approaches to problems that may be of genuine benefit both in time and cost.

Responsibility

Reporting relies on interpretation of factual information based on judgement and opinion and has a level of uncertainty attached to it, which is far less exact than the design disciplines. This has often resulted in claims being lodged against consultants, which are unfounded. To help prevent this problem, a number of clauses have been developed for use in contracts, reports and other documents. Responsibility clauses do not transfer appropriate liabilities from Coffey to other parties but are included to identify where Coffey's responsibilities begin and end. Their use is intended to help all parties involved to recognise their individual responsibilities. Read all documents from Coffey closely and do not hesitate to ask any questions you may have.

* For further information on this aspect reference should be made to "Guidelines for the Provision of Geotechnical information in Construction Contracts" published by the Institution of Engineers Australia, National headquarters, Canberra, 1987.

Drawings



drawn	PT	coffey A TETRA TECH COMPANY	client:	Hume Coal Pty Limited
approved	RJB		project:	Hume Coal Project Groundwater Assessment
date	30 Jun 2016			
scale	1:250,000		title:	**Regional Locality Plan**
original size	A4		project no: GEOTLCOV25281AB	figure no: **Drawing 1**

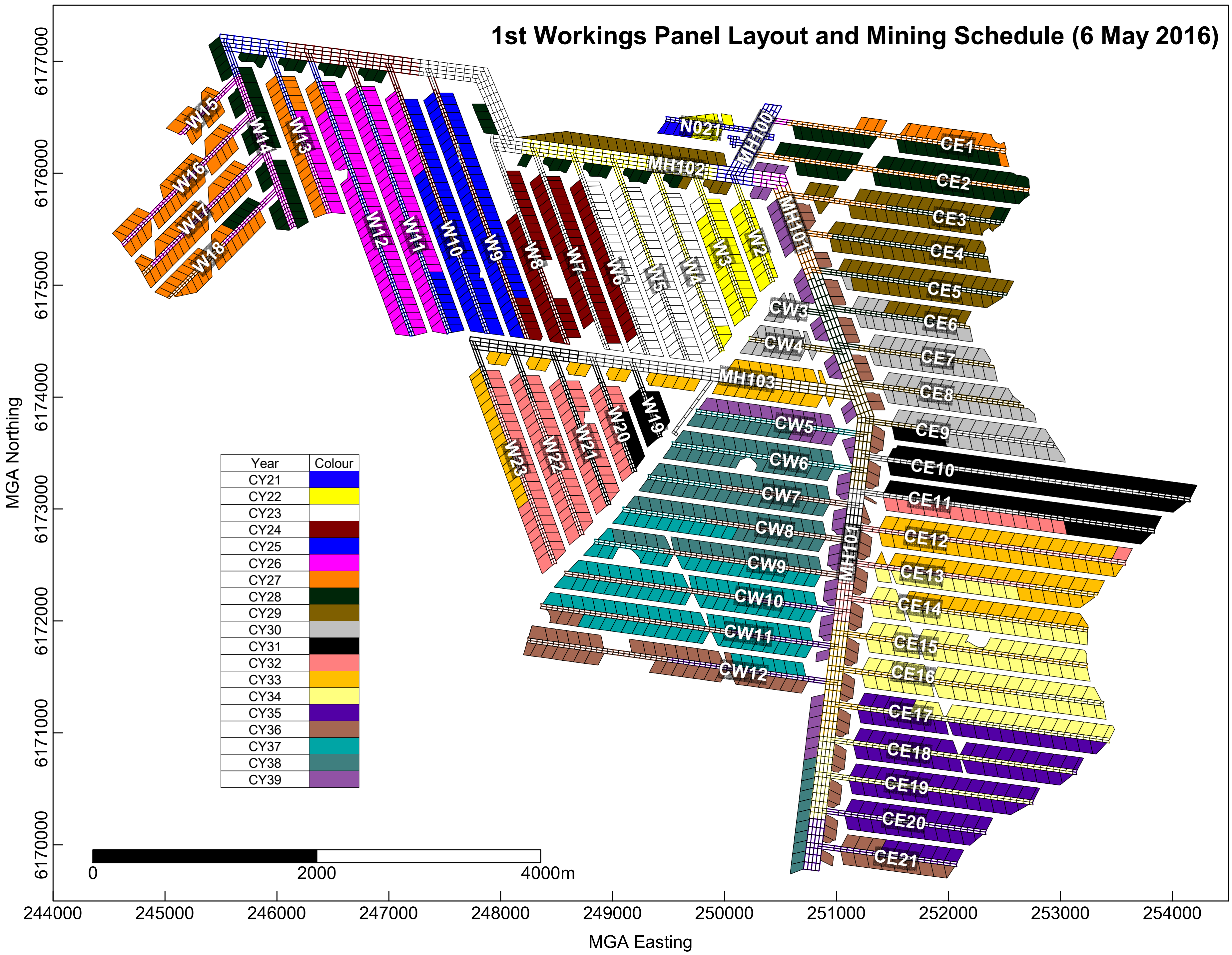
Appendix A - Hume Mining Schedule and Mining Heights

Production Volume by Panel / Heading

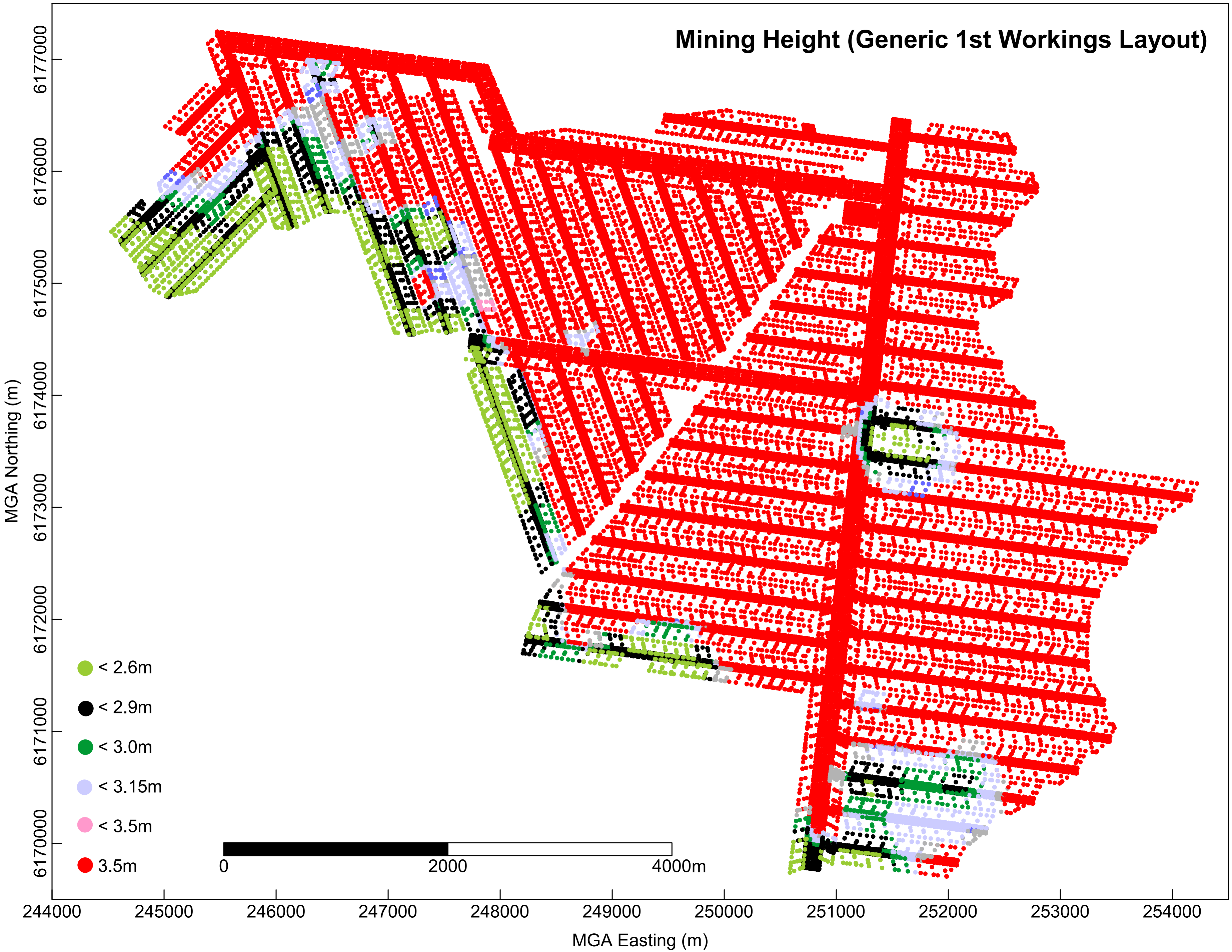
Panel or Heading	Start Date	Finish Date	Development (m^3)	Web Panel (m^3)	Total Void Volume (m^3)
N021	30/08/21	03/02/22	53000	112324	165324
CE001	11/12/26	17/04/28	141270	406099	547370
CE002	16/01/27	22/12/28	166886	574940	741826
CE003	11/09/27	09/07/29	128338	436958	565296
CE004	28/11/27	13/11/29	109862	414865	524727
CE005	15/02/28	13/01/30	112990	425862	538852
CE006	23/08/28	27/03/30	81445	300909	382355
CE007	18/12/28	29/05/30	87838	317630	405468
CE008	05/05/29	29/08/30	97408	359660	457068
CE009	02/11/29	30/01/31	99444	345500	444944
CE010	06/03/30	29/11/31	180104	640784	820888
CE011	15/07/30	27/03/32	169478	589618	759096
CE012	04/02/32	15/08/33	155942	538008	693950
CE013	19/06/32	08/03/34	141506	467821	609327
CE014	20/11/32	28/04/34	138995	460634	599629
CE015	13/03/33	20/09/34	140950	453273	594223
CE016	25/06/33	03/12/34	152838	507858	660696
CE017	30/11/33	25/05/35	155053	522297	677349
CE018	12/04/34	16/12/35	130759	443055	573814
CE019	22/05/34	03/07/35	100516	353978	454495
CE020	06/01/35	23/11/35	81320	271559	352879
CE021	15/04/35	21/03/36	65624	216580	282205
CW003	17/09/28	20/06/30	27115	44653	71767
CW004	29/01/29	25/08/30	50238	148636	198875
CW005	26/03/37	11/04/39	96382	335596	431978
CW006	20/03/37	07/11/38	108869	366418	475287
CW007	07/08/36	30/10/38	121112	446080	567191
CW008	26/07/36	04/06/38	133357	498474	631831
CW009	11/06/36	23/04/38	148291	513884	662175
CW010	17/09/35	25/10/37	162578	597347	759926
CW011	07/09/35	07/09/37	167544	609570	777114
CW012	01/07/35	11/02/37	154509	501831	656340
W002	11/01/22	22/07/22	64320	154808	219128
W003	04/03/22	16/01/23	90592	326586	417178
W004	14/05/22	05/07/23	117990	438896	556886
W005	16/08/22	04/12/23	128534	526146	654680
W006	18/12/22	17/04/24	128639	526733	655373
W007	24/04/23	26/07/24	123296	480552	603848
W008	05/08/23	27/09/24	126240	379480	505720
W009	23/12/23	28/10/25	176565	764067	940632
W010	03/05/24	24/02/26	162667	702219	864886
W011	01/12/24	20/10/26	160779	708405	869184
W012	03/01/25	23/01/27	153907	660482	814389
W013	12/10/25	02/05/27	91723	387584	479307
W014	18/11/25	09/08/28	144976	384351	529327
W015	21/03/26	21/03/27	47509	131872	179381
W016	10/05/26	03/09/27	102408	361532	463939
W017	20/06/26	13/10/27	86833	343298	430130
W018	29/09/26	29/01/28	73288	273653	346941
W019	26/02/31	14/07/31	43205	121872	165077
W020	21/03/31	17/03/32	65875	232148	298024
W021	20/05/31	08/08/32	91166	324085	415251
W022	03/11/31	22/12/32	108283	409721	518003
W023	11/11/31	23/03/33	109939	405264	515204
MH100	21/04/21	13/10/21	86773		86773
MH101	03/04/27	05/08/39	787191	1106498	1893689
MH102	13/10/21	31/08/39	701852	659579	1361431
MH102ext	05/03/23	30/06/23	14888		14888
MH103	09/06/29	06/10/33	311013	425330	736343
Shaft	19/08/21	29/08/21	5697		5697
Shaft2	29/05/30	15/07/30	25139		25139
Sump	19/09/21	22/10/21	15082		15082
TOTAL			8207931	24457865	32665796

Annual Production Mass and Volumes

Calendar Year	Mining Year	Total Run-Of-Mine Coal (Mt)	Total Void Volume (m^3)
2021	1	0.381	247980
2022	2	1.693	1102692
2023	3	2.819	1839725
2024	4	2.537	1665325
2025	5	2.824	1841464
2026	6	3.084	1994056
2027	7	3.147	2045160
2028	8	3.161	2040342
2029	9	3.314	2154903
2030	10	2.871	1888687
2031	11	2.726	1772364
2032	12	2.950	1915615
2033	13	3.282	2132458
2034	14	3.289	2102426
2035	15	3.041	1853594
2036	16	2.593	1671060
2037	17	3.081	2013607
2038	18	2.546	1640445
2039	19	1.141	743896
TOTAL		50.5	32665796



1st Workings Panel Layout and Mining Schedule (6 May 2016)
MGA Northing
MGA Easting
6177000
6176000
6175000
6174000
6173000
6172000
6171000
6170000
244000
245000
246000
247000
248000
249000
250000
251000
252000
253000
254000
0
2000
4000m
W15
W16
W17
W18
W14
W13
W12
W11
W10
W9
W8
W7
W6
W5
W4
W3
W2
N021
MH100
MH102
MH101
MH103
MH104
CE1
CE2
CE3
CE4
CE5
CE6
CE7
CE8
CE9
CE10
CE11
CE12
CE13
CE14
CE15
CE16
CE17
CE18
CE19
CE20
CE21
CW3
CW4
CW5
CW6
CW7
CW8
CW9
CW10
CW11
CW12
W19
W20
W21
W22
W23
Year
Colour
CY21
CY22
CY23
CY24
CY25
CY26
CY27
CY28
CY29
CY30
CY31
CY32
CY33
CY34
CY35
CY36
CY37
CY38
CY39


Mining Height (Generic 1st Workings Layout)
< 2.6m
< 2.9m
< 3.0m
< 3.15m
< 3.5m
3.5m
0
2000
4000m
MGA Northing (m)
MGA Easting (m)
6177000
6176000
6175000
6174000
6173000
6172000
6171000
6170000
244000
245000
246000
247000
248000
249000
250000
251000
252000
253000
254000

Appendix B - Hydraulic Head Targets and Calibrated Hydrographs

Table B1. Piezometers Used for Calibration Targets

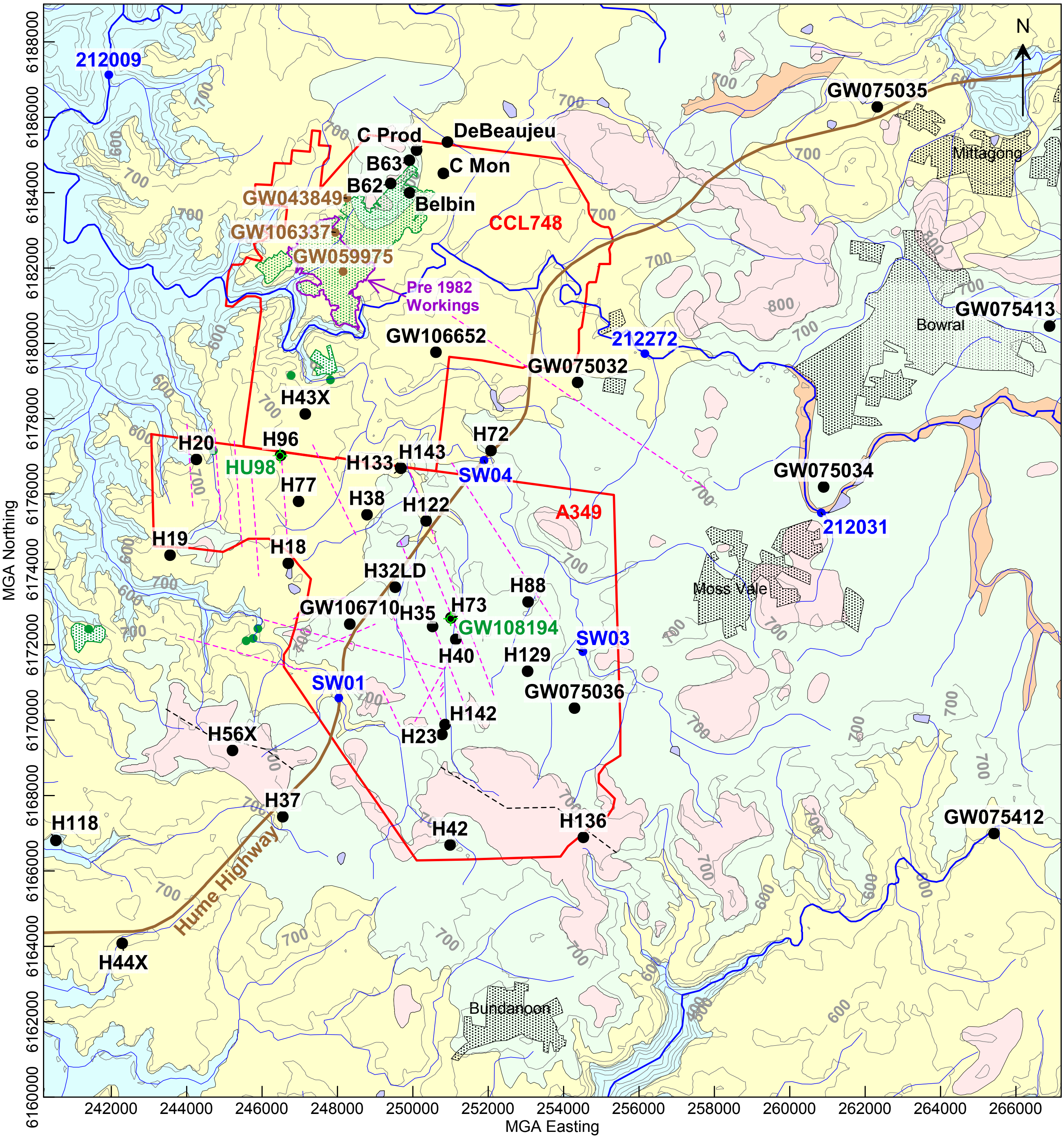
Monitoring Network	Piezometer	Easting (MGA)	Northing (MGA)	RL Ground (mAHD)	RL Casing (mAHD)	Drilled Depth (mbgl)	Screen (mbgl) From	Screen (mbgl) To	Sandpack (mbgl) From	Sandpack (mbgl) To	Screened Stratum	L (m)
Hume	H18A	246696	6174166	691.74	691.67	108	96	99	95	99	WW	4
	H18B	246695	6174159	691.97	691.89	114	75	88	73	88	HAW	15
	H19A	243557	6174381	720.65	720.55	108	100	103	100	103	WW	3
	H19B	243562	6174379	720.46	720.36	88	70	81	69	81	HAW	12
	H20B	244255	6176930	703.67	703.59	114	80	86	78	86	WW	8
	H35A	250523	6172486	681.43	682.16	152	53	77	50	78	HAW	28
	H35B	250531	6172487	680.84	681.52	35	15	34	14	35	WG	21
	H37A	246551	6167440	703.79	703.70	111	101	105	101	107	ICM	6
	H37B	246546	6167438	703.77	703.69	90	72	87	70	90	HAW	20
	H38A	248783	6175453	658.53	657.67	117	105	108	103	110	WW	7
	H38B	248788	6175452	658.44	658.33	78	74	77	72	78	HAW	6
	H38C	248793	6175452	658.31	658.17	63	55	62	52	63	HAW	11
	H42A	250988	6166688	702.50	702.43	173	156	159	153	161	WW	8
	H42C	250985	6166678	702.00	701.92	150	142	150	135	150	HAW	15
	H43XA	247147	6178127	692.04	691.96	111	95	101	93	103	WW	10
	H43XB	247152	6178133	691.77	691.69	87	77	86	75	87	HAW	12
	H44XA	242285	6164084	641.94	641.92	12	8	11	7	12	WW	5
	H44XB	242281	6164077	647.00	646.96	5	4	5	3.5	5	HAW	2
	H56XB	245225	6169198	735.45		140	132	140	130	140	HAW	10
	H72A	252074	6177157	640.12	640.05	129	124	128	121	129	WW	8
	H72B	252083	6177169	640.43	640.36	99	92	98	88	98	HAW	10
	H72C	252091	6177180	640.85	640.77	46	39	45	35	46	HAW	11
	H73A	251015	6172718	656.46	657.00	172	151	169	149	172	CM Lower	23
	H73B	251029	6172717	655.78	656.35	124	119	123	117	124	WW	7
	H73C	251035	6172717	655.50	656.13	86	79	85	77	86	HAW	9
	H88A	253059	6173144	655.44	655.37	156	143	146	141	148	WW	7
	H88B	253059	6173144	655.33	655.26	150	121	126	119	128	HAW	9
	H96A	246489	6177025	699.21	699.14	147	111	120	108	120	CM Lower	12
	H96B	246491	6177029	699.10	699.00	101	92	98	91	101	WW	10
	H96C	246494	6177045	683.00	682.94	89	69	87	67	89	HAW	22
	H129A	253042	6171301	679.10	679.04	177	166	170	165	171	WW	6
	H129B	253044	6171306	679.20	679.11	177	146	153	146	153	HAW	7
	H136A	254521	6166894	718.49	718.36	216	199	203	196	203	WW	7
	H136B	254517	6166890	718.52	718.40	168	157	168	155	168	HAW	13
	H142A(&H23A)*	250769	6169622	680.47	680.38	140	135	138	135	138	WW	3
	H142B(&H23B)*	250763	6169620	680.63	680.55	132	118	130	116	130	HAW	14
	H142C(&H23C)*	250755	6169617	680.76	680.69	100	84	97	82	97	HAW	15
	H143A(&H133A)*	249685	6176683	648.15	647.98	141	119	126	115	127	CM Lower	12
	H143B(&H133B)*	249688	6176688	648.17	648.04	113	108	113	108	113	WW	5
	H143C(&H133C)*	249690	6176694	648.03	647.94	84	80	83	77	84	HAW	7
Berrima	DeBeaujeu^	250915	6185343	678.00	678.00	50	7	50	Open hole		HAW	42
	Belbin^	249914	6183996		691.40	186	132	186	Open hole		ICM Lower	54
	Culpepper P^	250100	6185126		693.00	41		41	Open hole		HAW	< 41
	B62_Upper	249411	6184243	727.00	727.00	181	58	58	VWP	VWP	HAW	Point
	B62_Lower	249411	6184243	727.00	727.00	181	126	126	VWP	VWP	HAW	Point
	B62_WW	249411	6184243	727.00	727.00	181	170	170	VWP	VWP	WW	Point
	B63_Upper	249907	6184861	738.00	738.00	185	85	85	VWP	VWP	HAW	Point
	B63_Lower	249907	6184861	738.00	738.00	185	133	133	VWP	VWP	HAW	Point
	B63_WW	249907	6184861	738.00	738.00	185	177	177	VWP	VWP	WW	Point

HAW: Hawkesbury Sandstone. WW: Wongawilli Seam. WG: Wianamatta Group.
ICM: Illawarra Coal Measures. SS: Sandstone. Sh: Shale.
* Piezometer in brackets replaced with first one. Coords and completions are for replaced piezometer.
(green box) Strongly affected by subvertical barriers.
^ Registration Numbers: DeBeaujeu: GW028373; Belbin: GW106150; Culpepper P: GW101581.

Table B2. Piezometers Not Used for Calibration Targets

Monitoring Network	Piezometer	Easting (MGA)	Northing (MGA)	RL Ground (mAHD)	RL Casing (mAHD)	Drilled Depth (mbgl)	Screen (mbgl)		Sandpack (mbgl)		Screened Stratum	L (m)	Reason for Exclusion.
							From	To	From	To			
Hume	H20A	244258	6176920	703.25	703.18	80	71	77	71	77	HAW	6	Always dry.
	H32LDA	249532	6173533	646.60	646.78	152	108	114	106	117	WW	11	A and B in same hole, and long hydraulic interval.
	H32LDB	249532	6173533	646.60	646.73	152	57	88	54	89	HAW	35	
	H42B	250990	6166681	702.70		141	134	141	132	141	HAW	9	Collapsed (no data).
	H56XA	245214	6169199	735.38		150	143	144	141	146	WW	5	Unusable (no data).
	H56XC	245234	6169198	735.51		26	19	25	17	26	Basalt	9	Basalt not simulated.
	H118	240529	6166811	612.50		15	7	13	5	15	HAW	10	Appears to have failed.
	H136C	254513	6166887	718.51	718.40	60	52	59	50	60	Basalt	10	Basalt not simulated.
	H40_1	251140	6172143	656.51	656.51	129	120	120	VWP	VWP	WW	Point	Low resolution and accuracy.
	H40_2	251140	6172143	656.51	656.51	129	107	107	VWP	VWP	HAW	Point	
	H40_3	251140	6172143	656.51	656.51	129	81	81	VWP	VWP	HAW	Point	
	H40_4	251140	6172143	656.51	656.51	129	39	39	VWP	VWP	HAW	Point	
	H77_1	246966	6175811	689.74	689.74	98	87	87	VWP	VWP	WW	Point	Low resolution and accuracy.
	H77_2	246966	6175811	689.74	689.74	98	72	72	VWP	VWP	HAW	Point	
	H77_3	246966	6175811	689.74	689.74	98	58	58	VWP	VWP	HAW	Point	
	H122_1	250352	6175286	634.50	634.50	120	112	112	VWP	VWP	WW	Point	Low resolution and accuracy.
	H122_2	250352	6175286	634.50	634.50	120	86	86	VWP	VWP	HAW	Point	
	H122_3	250352	6175286	634.50	634.50	120	45	45	VWP	VWP	HAW	Point	
	H122_4	250352	6175286	634.50	634.50	120	15	15	VWP	VWP	HAW	Point	
	GW106652	250614	6179763	652.32	652.85	120	25	120	Open hole		HAW	95	Long hydraulic interval.
	GW106710	248326	6172551	672.39	672.70	115	64	108	Open hole		HAW	44	Long hydraulic interval.
Berrima	Culpepper M (B28)	250809	6184507		677.90	143		143	Open hole		HAW	> 100	Long hydraulic interval.
Government	G75032_1	254374	6178962	678.23	678.75	91	24	29	1	31	HAW	30	Long hydraulic intervals.
	G75032_2	254374	6178962	678.23	678.65	91	73	88	2	91	HAW	90	
	G75033_1	273474	6170523	692.96	693.58	101	30	35	1	36	SS	35	Long hydraulic intervals.
	G75033_2	273474	6170523	692.96	693.04	101	89	99	50	101	SS/Sh	51	
	G75034	260898	6176191	660.01	660.73	101	90	100	50	101	WG	51	Long hydraulic interval.
	G75035	262322	6186276	648.25	648.17	91	74	89	1	91	HAW	90	Long hydraulic interval.
	G75036	254286	6170323	660.24	660.87	100	73	84	2	85	SS	84	Long hydraulic interval.
	G75412	265421	6166998	650.07		70	52	64	44	70	SS	26	Far to southeast.
	G75413	266895	6180460	710.69		151	108	151	Open hole		WG	43	Open hole.

HAW: Hawkesbury Sandstone. WW: Wongawilli Seam. WG: Wianamatta Group.
ICM: Illawarra Coal Measures. SS: Sandstone. Sh: Shale.

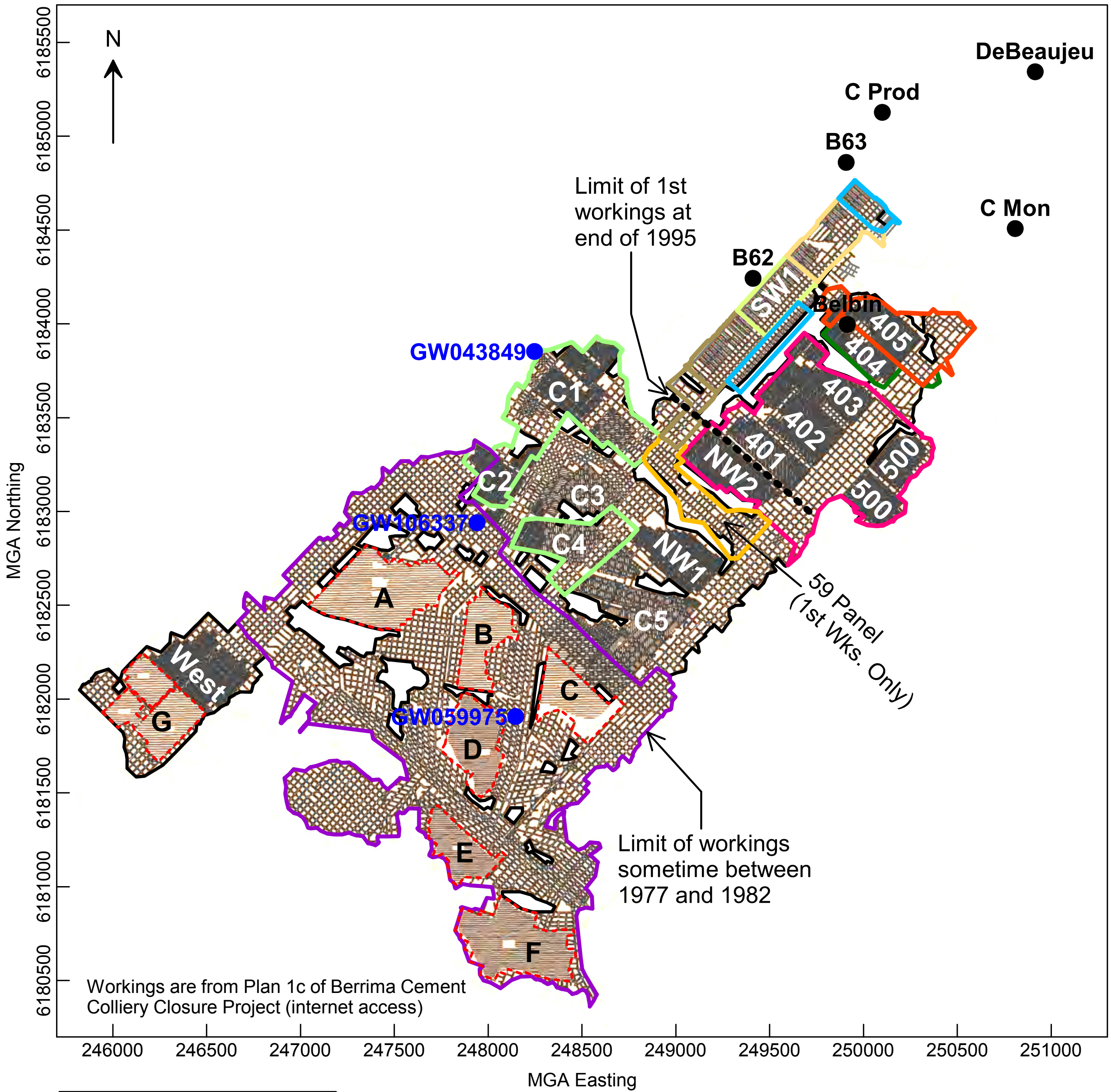


Subsurface flow barrier emplaced during model calibration.

- Alluvium
- Basalt
- Wianamatta Group
- Hawkesbury Sandstone
- Narrabeen Group (where present) and Permian Coal Measures
- Drainage course
- Water body
- Old mine footprint
- Old mine adit
- Interpreted or published fault
- GW106337 Hume pumping test bore
- 620 Topography (mAHD)
- H72 Groundwater monitoring piezometer / well
- GW106337 Private bore over workings
- SW01 Flow gauge
- Pipeline
- Built-up Area
- Hume Highway

drawn	PT	client:	Hume Coal Pty Limited
approved	RJB	project:	Hume Coal Project Groundwater Assessment
date	29 Jul 2016		
scale	1:150,000	title:	**Monitoring Piezometer and Well Locations**
original size	A4	project no: GEOTLCOV25281AB	figure no: **Figure B1**

coffey
A TETRA TECH COMPANY



Berrima Mining Schedule:

- 1991 to 1995 (pillar extraction)
- 1996 to 2005 (1st wks. & pill. ext.)
- 2006 to 2007
- 2008
- 2009
- 2010
- 2011
- 2012
- 2013

- H72 Groundwater monitoring piezometer / well
- GW106337 Private bore over workings
- B Unknown workings type. Most likely pillar extraction. Some goaf areas present.
- Mine limit some time between 1977 and 1982.
- 1st Workings
- Pillar Extraction Panel

drawn	PT	client:	Hume Coal Pty Limited
approved	RJB	project:	Hume Coal Project Groundwater Assessment
date	6 Jun 2016		
scale	1:35,000	title:	**Monitoring Piezometers/Wells (Berrima Mine)**
original size	A4	project no: GEOTLCOV25281AB	figure no: **Figure B2**

coffey
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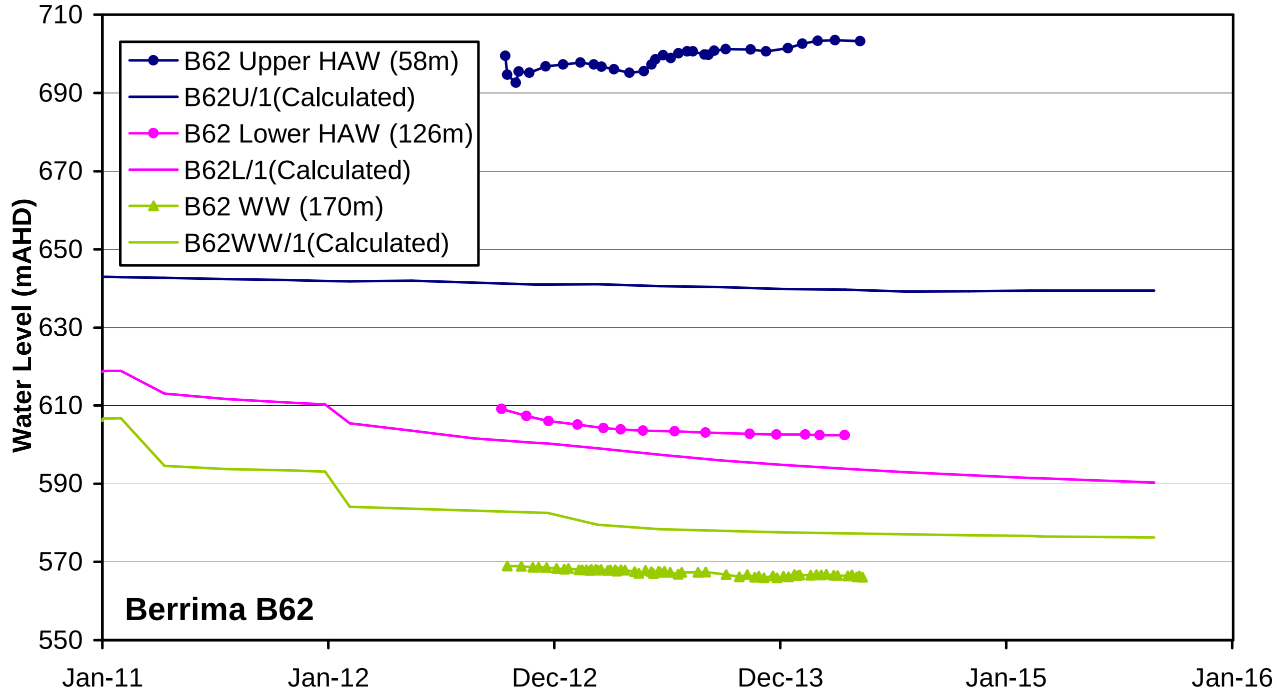
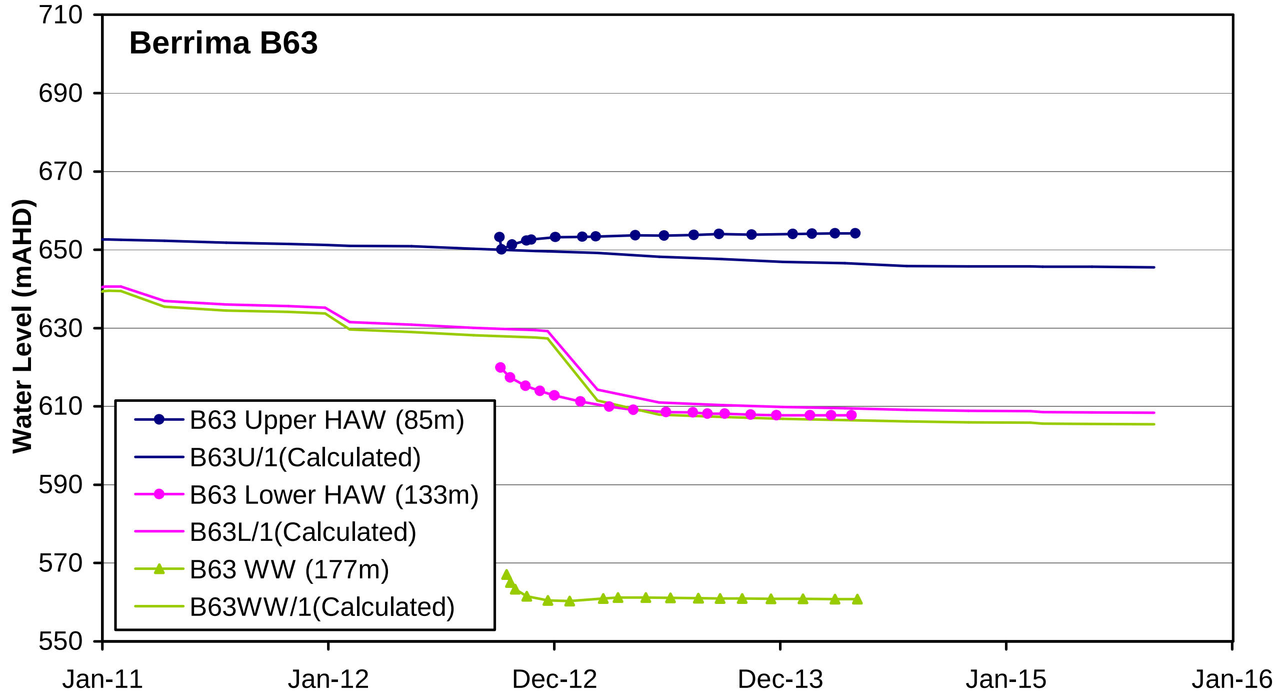
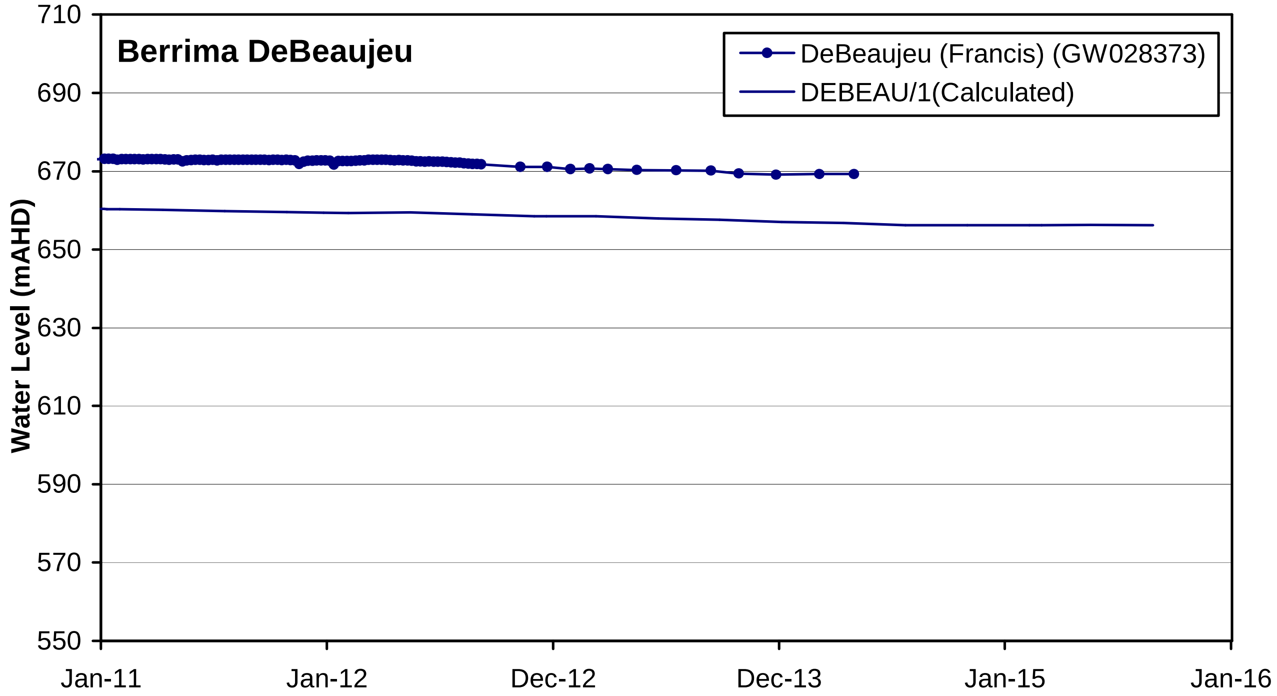
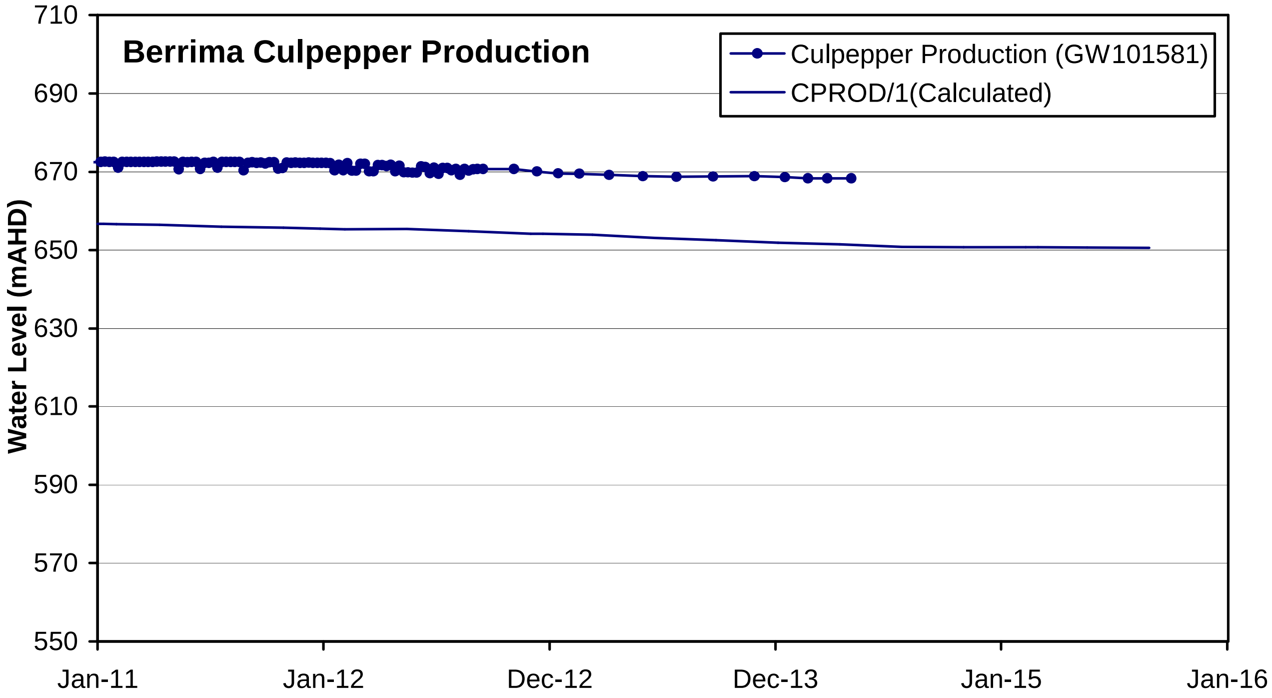
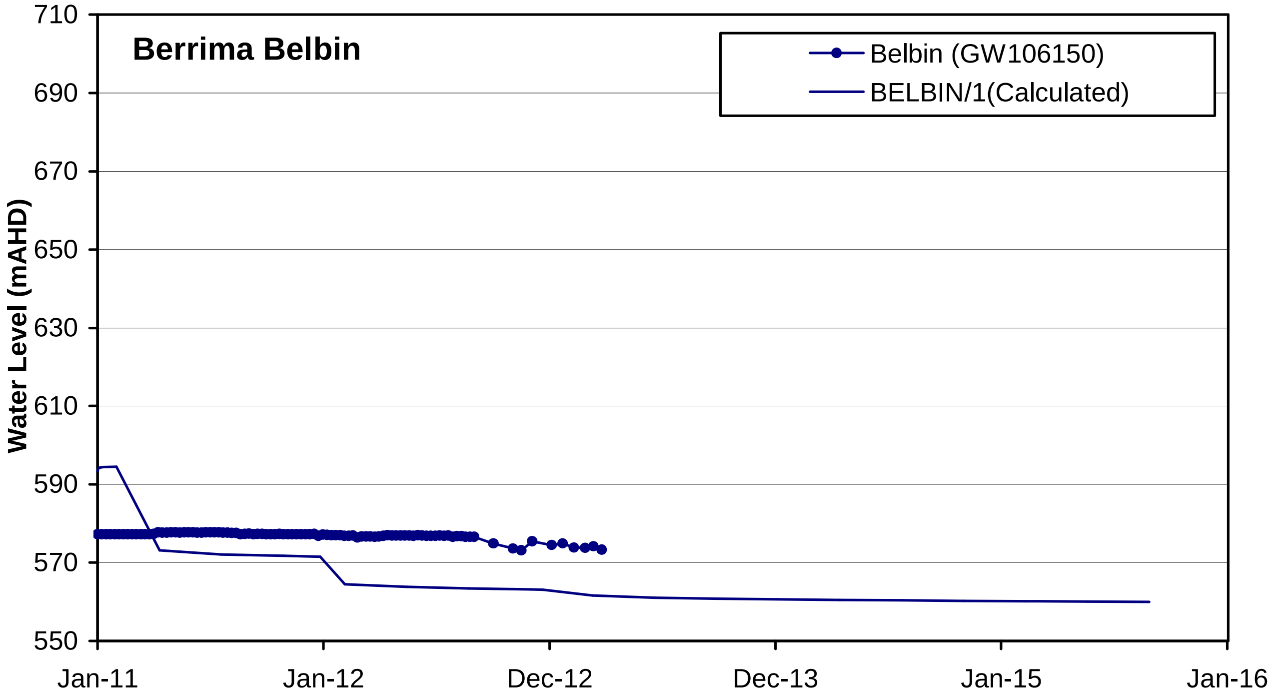
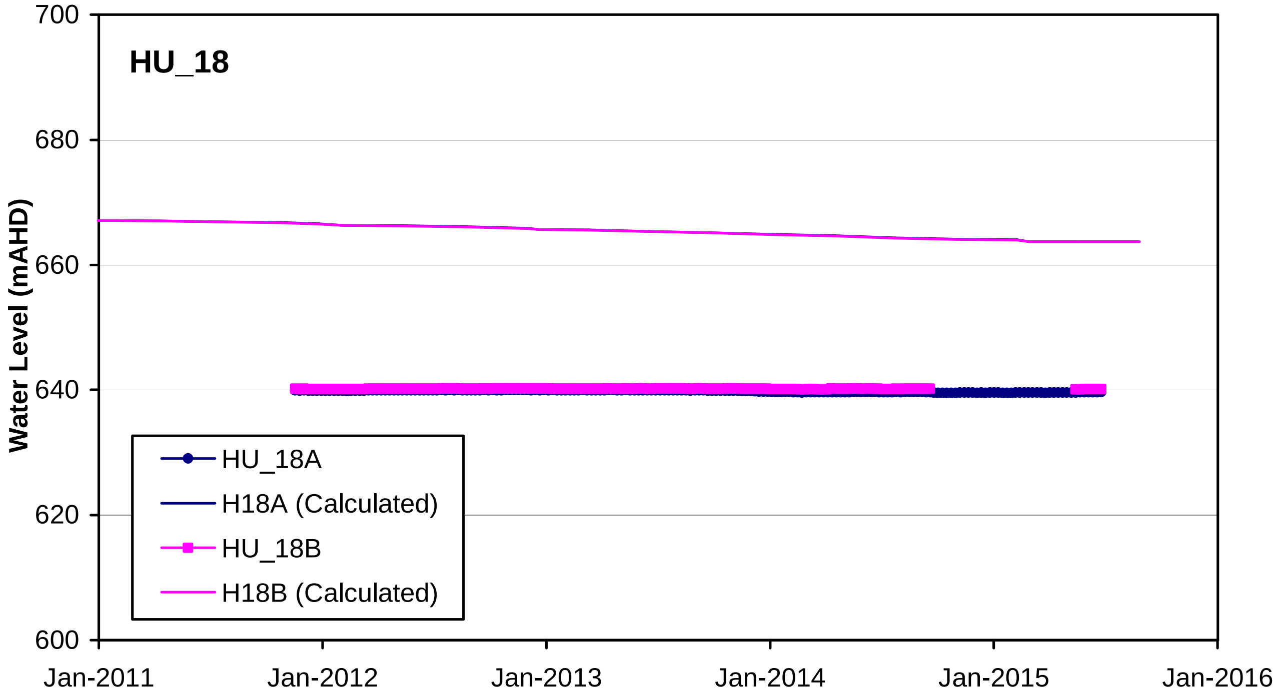

Berrima B62
B62 Upper HAW (58m)
B62U/1(Calculated)
B62 Lower HAW (126m)
B62L/1(Calculated)
B62 WW (170m)
B62WW/1(Calculated)
Water Level (mAHD)
710
690
670
650
630
610
590
570
550
Jan-11
Jan-12
Dec-12
Dec-13
Jan-15
Jan-16

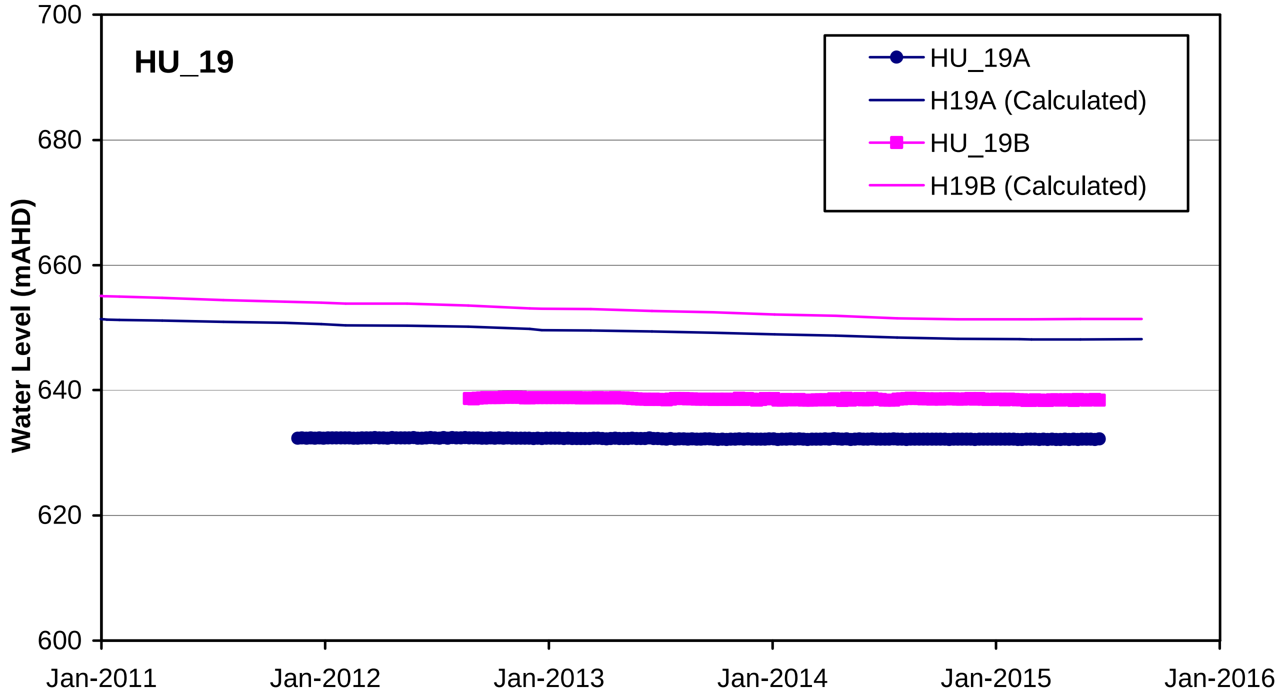

Berrima B63
B63 Upper HAW (85m)
B63U/1(Calculated)
B63 Lower HAW (133m)
B63L/1(Calculated)
B63 WW (177m)
B63WW/1(Calculated)
Water Level (mAHD)
710
690
670
650
630
610
590
570
550
Jan-11
Jan-12
Dec-12
Dec-13
Jan-15
Jan-16

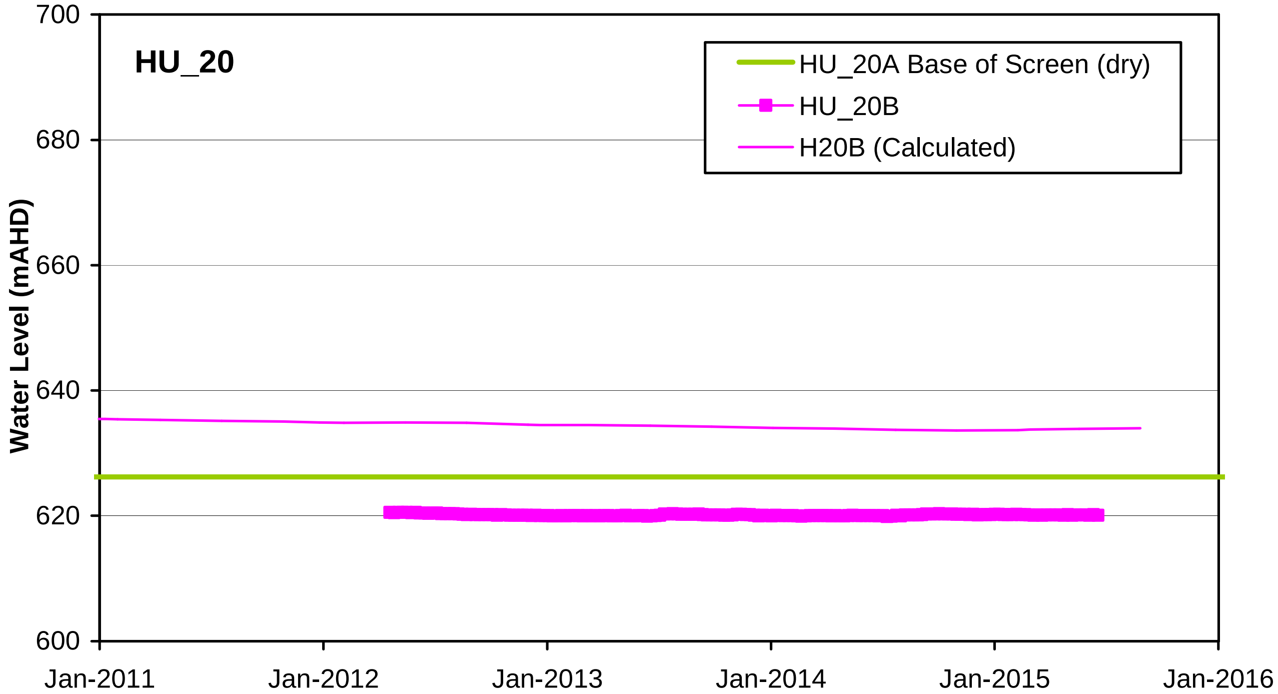

Berrima DeBeaujeu
DeBeaujeu (Francis) (GW028373)
DEBEAU/1(Calculated)
Water Level (mAHD)
710
690
670
650
630
610
590
570
550
Jan-11
Jan-12
Dec-12
Dec-13
Jan-15
Jan-16

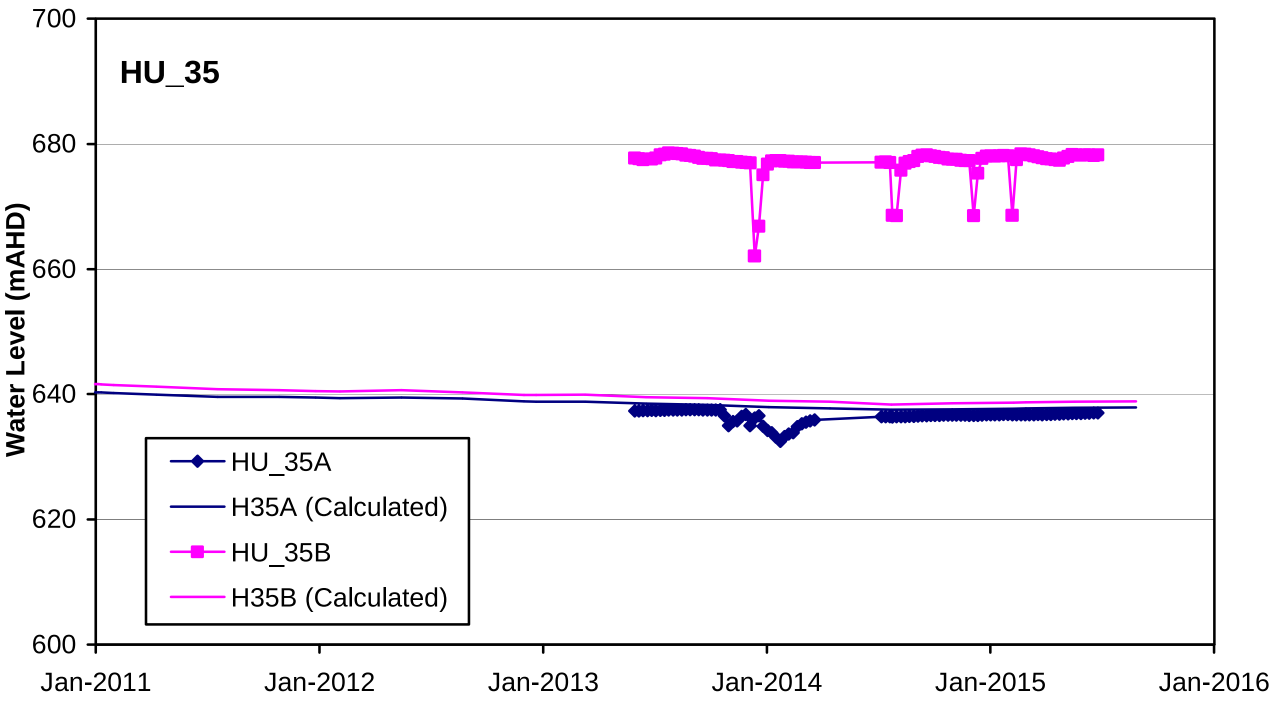

Berrima Culpepper Production
Culpepper Production (GW101581)
CPROD/1(Calculated)
Water Level (mAHD)
710
690
670
650
630
610
590
570
550
Jan-11
Jan-12
Dec-12
Dec-13
Jan-15
Jan-16

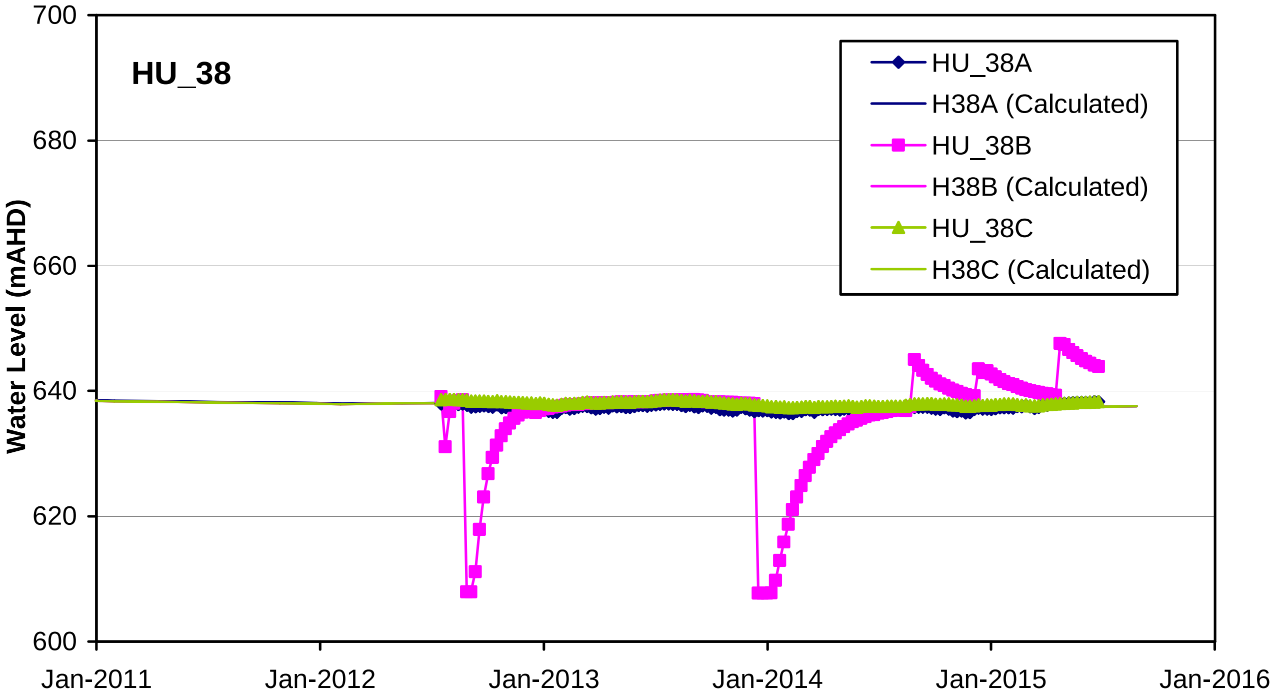

Berrima Belbin
Belbin (GW106150)
BELBIN/1(Calculated)
Water Level (mAHD)
710
690
670
650
630
610
590
570
550
Jan-11
Jan-12
Dec-12
Dec-13
Jan-15
Jan-16

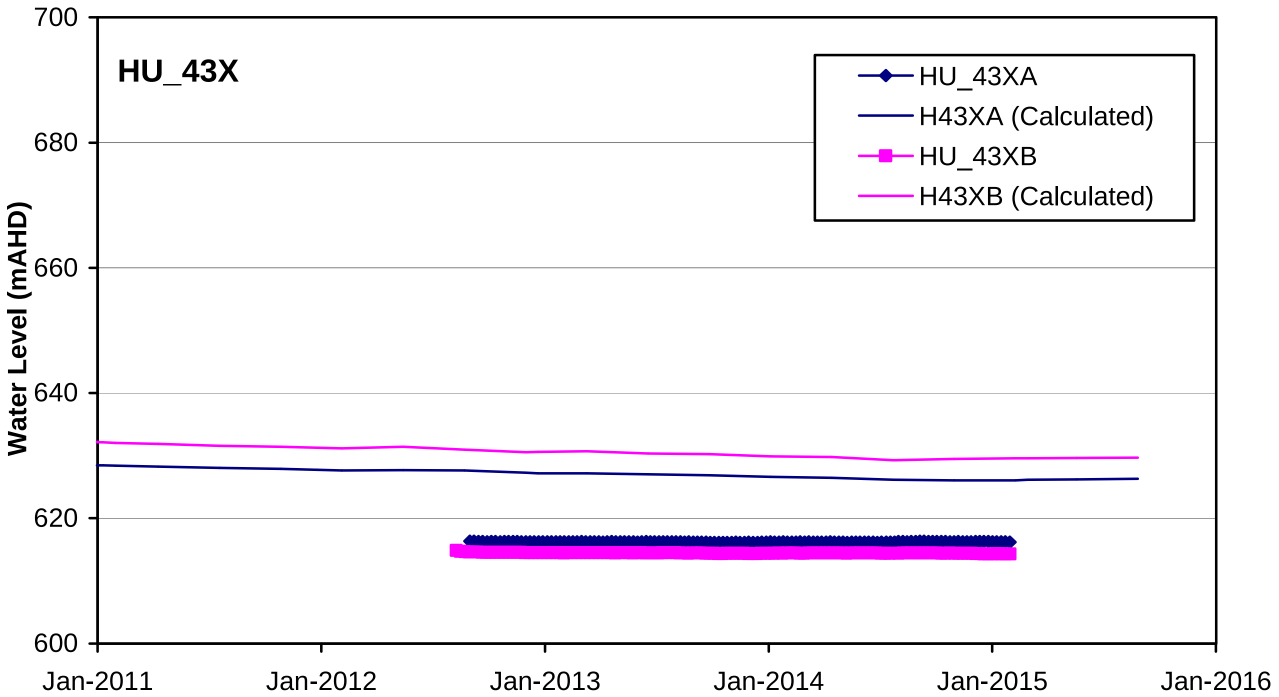

HU_18
Water Level (mAHD)
700
680
660
640
620
600
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016
HU_18A
H18A (Calculated)
HU_18B
H18B (Calculated)

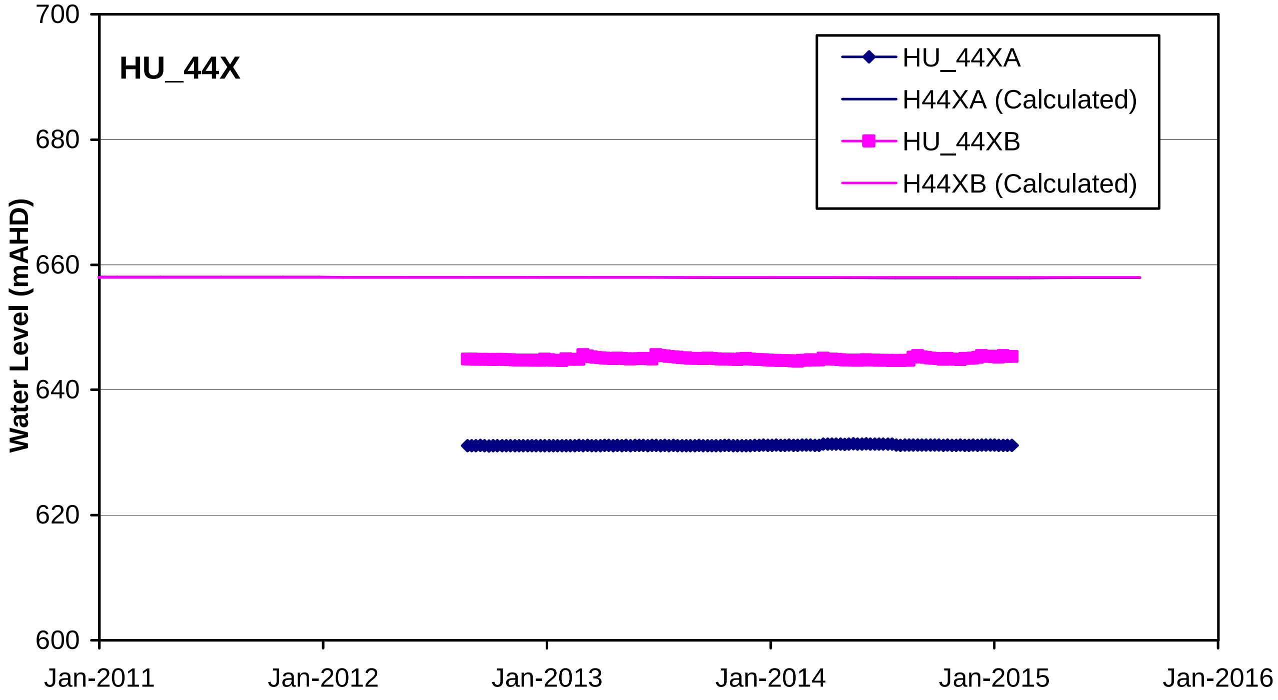

HU_19
Water Level (mAHD)
700
680
660
640
620
600
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016
HU_19A
H19A (Calculated)
HU_19B
H19B (Calculated)

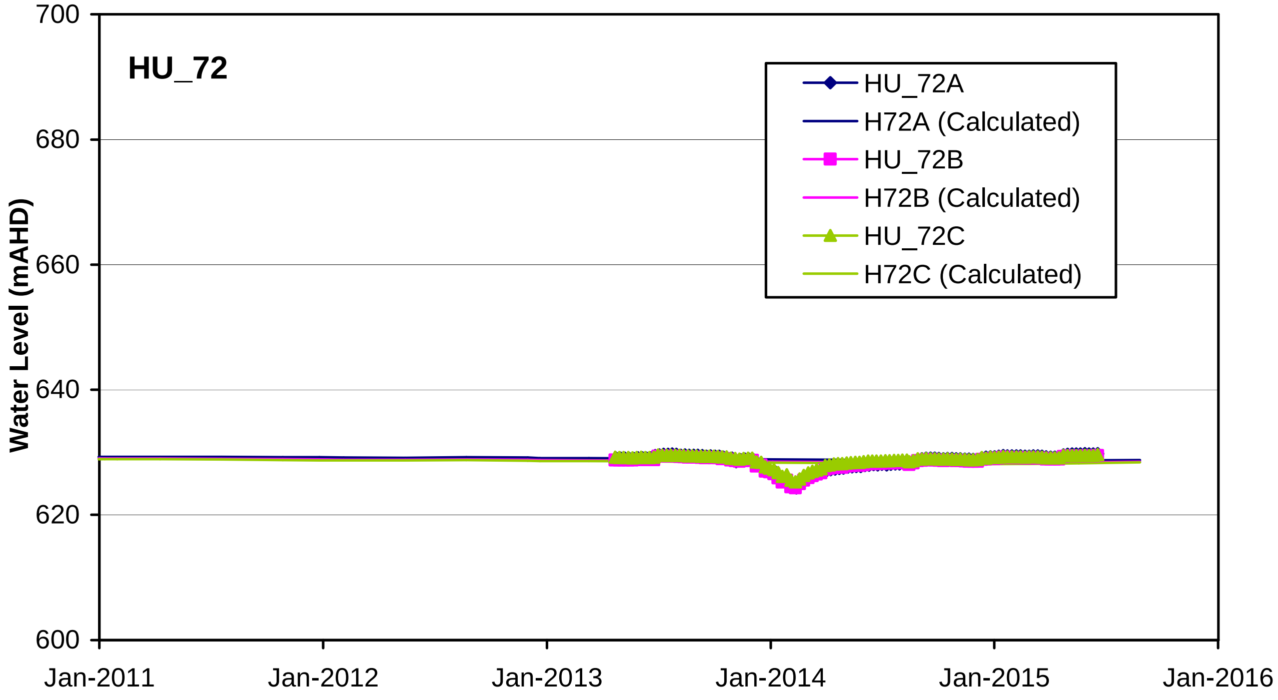

HU_20
Water Level (mAHD)
700
680
660
640
620
600
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016
HU_20A Base of Screen (dry)
HU_20B
H20B (Calculated)

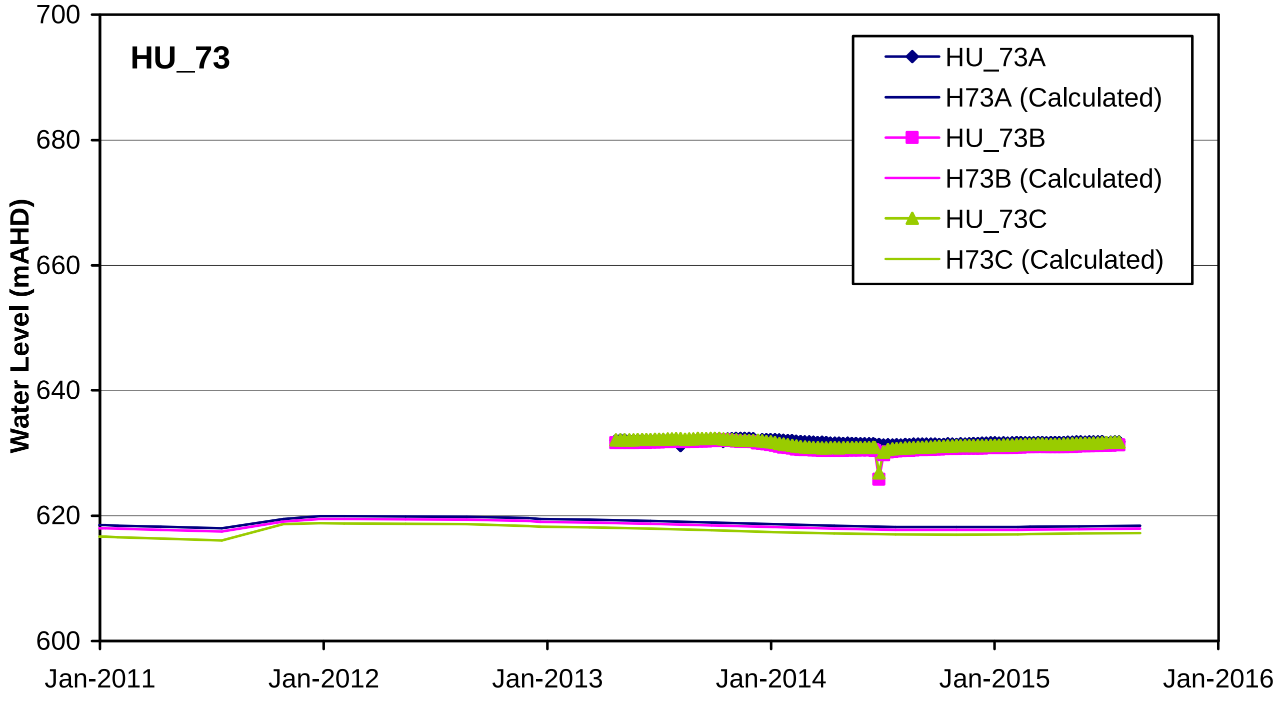

HU_35
Water Level (mAHD)
700
680
660
640
620
600
HU_35A
H35A (Calculated)
HU_35B
H35B (Calculated)
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016

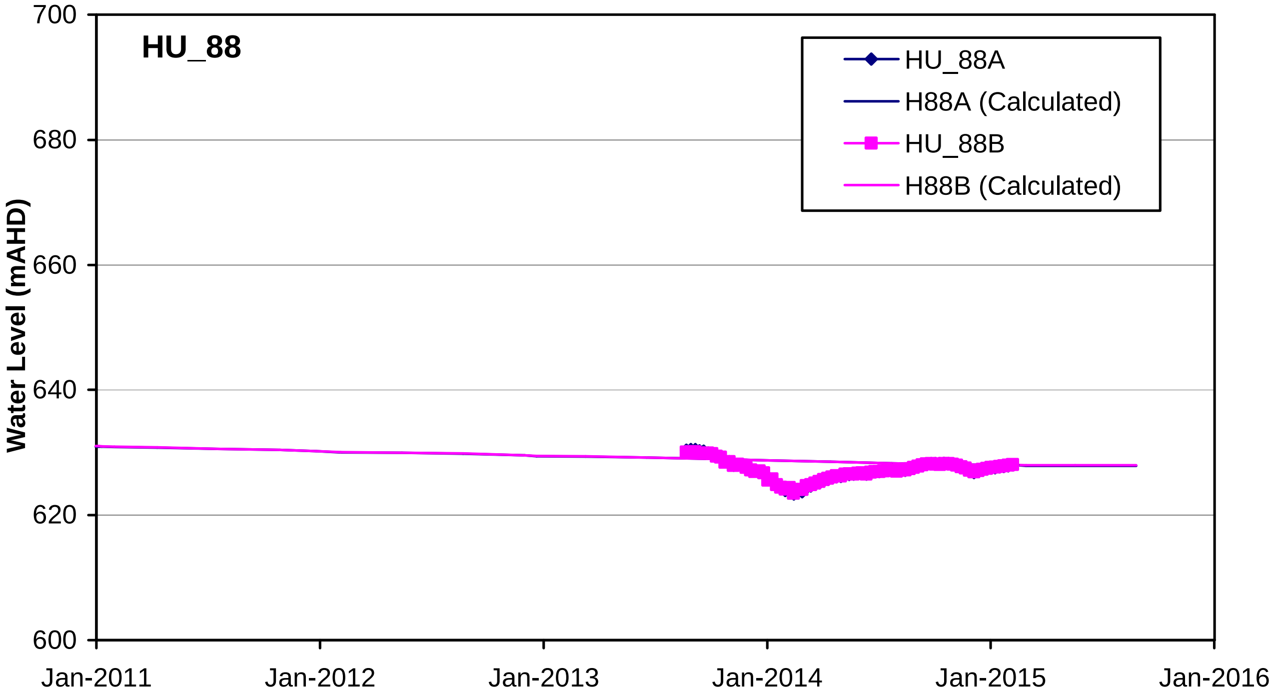

HU_38
Water Level (mAHD)
700
680
660
640
620
600
HU_38A
H38A (Calculated)
HU_38B
H38B (Calculated)
HU_38C
H38C (Calculated)
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016


HU_43X
Water Level (mAHD)
700
680
660
640
620
600
HU_43XA
H43XA (Calculated)
HU_43XB
H43XB (Calculated)
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016

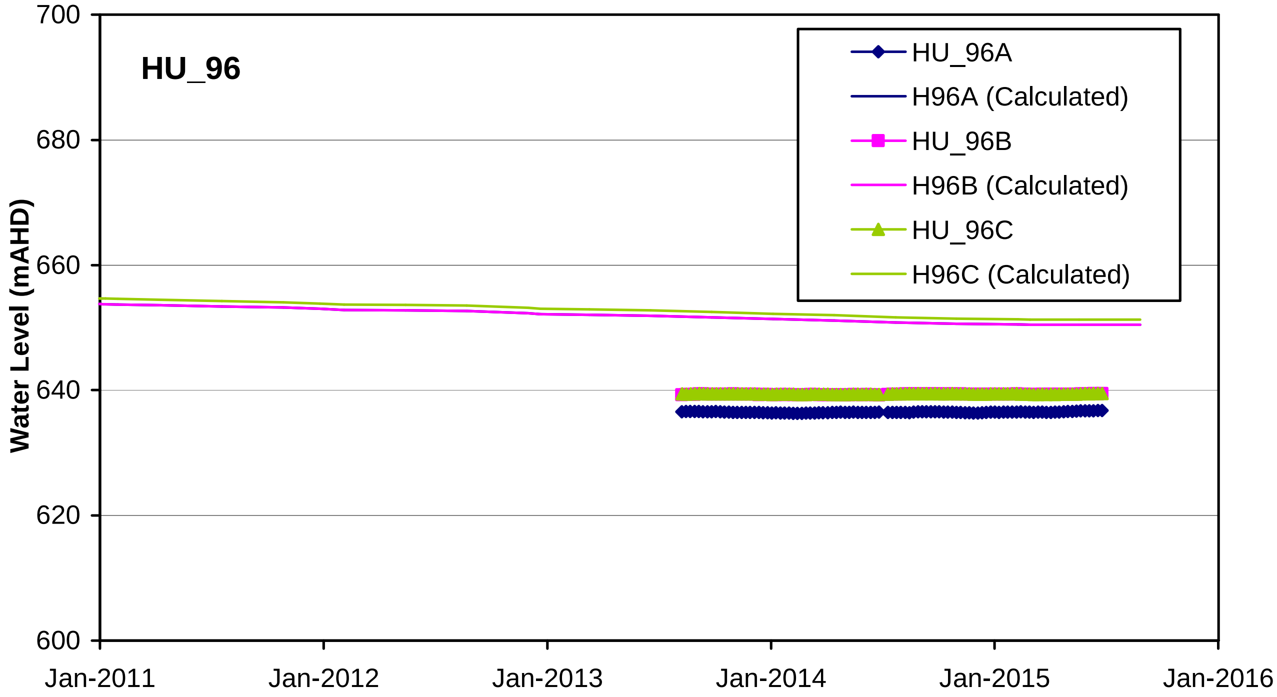

HU_44X
HU_44XA
H44XA (Calculated)
HU_44XB
H44XB (Calculated)
Water Level (mAHD)
700
680
660
640
620
600
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016


HU_72
HU_72A
H72A (Calculated)
HU_72B
H72B (Calculated)
HU_72C
H72C (Calculated)
Water Level (mAHD)
700
680
660
640
620
600
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016

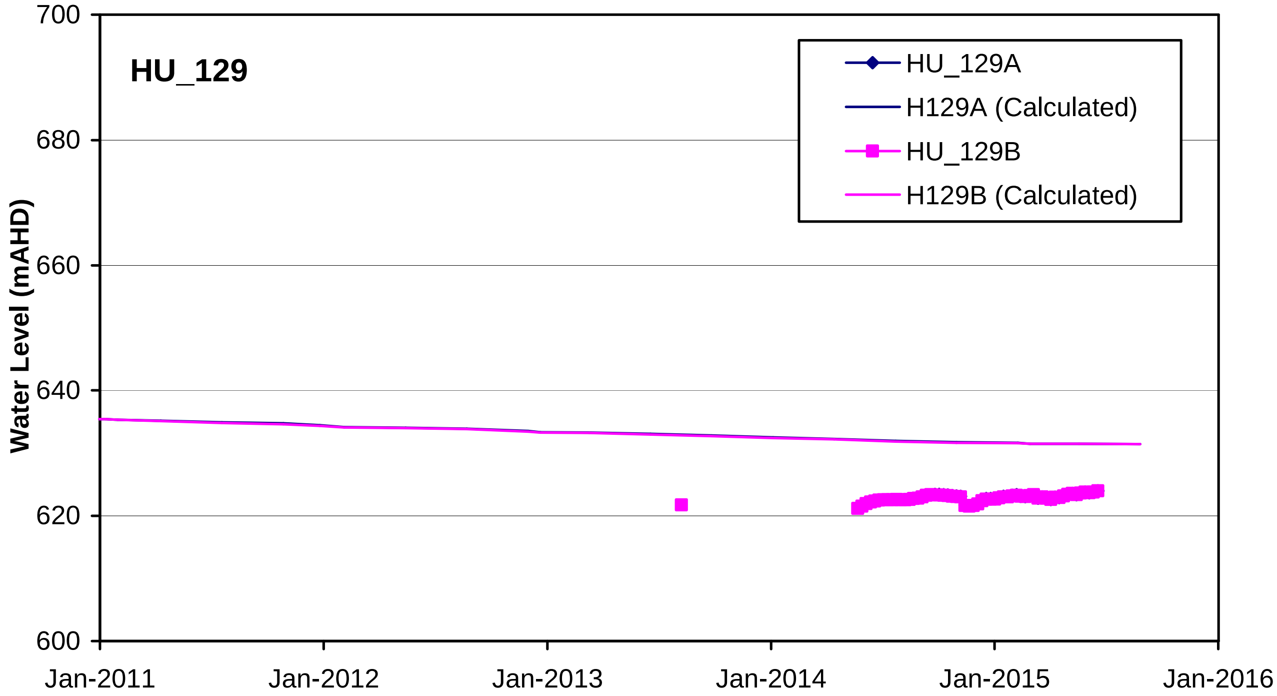

HU_73
HU_73A
H73A (Calculated)
HU_73B
H73B (Calculated)
HU_73C
H73C (Calculated)
Water Level (mAHD)
700
680
660
640
620
600
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016



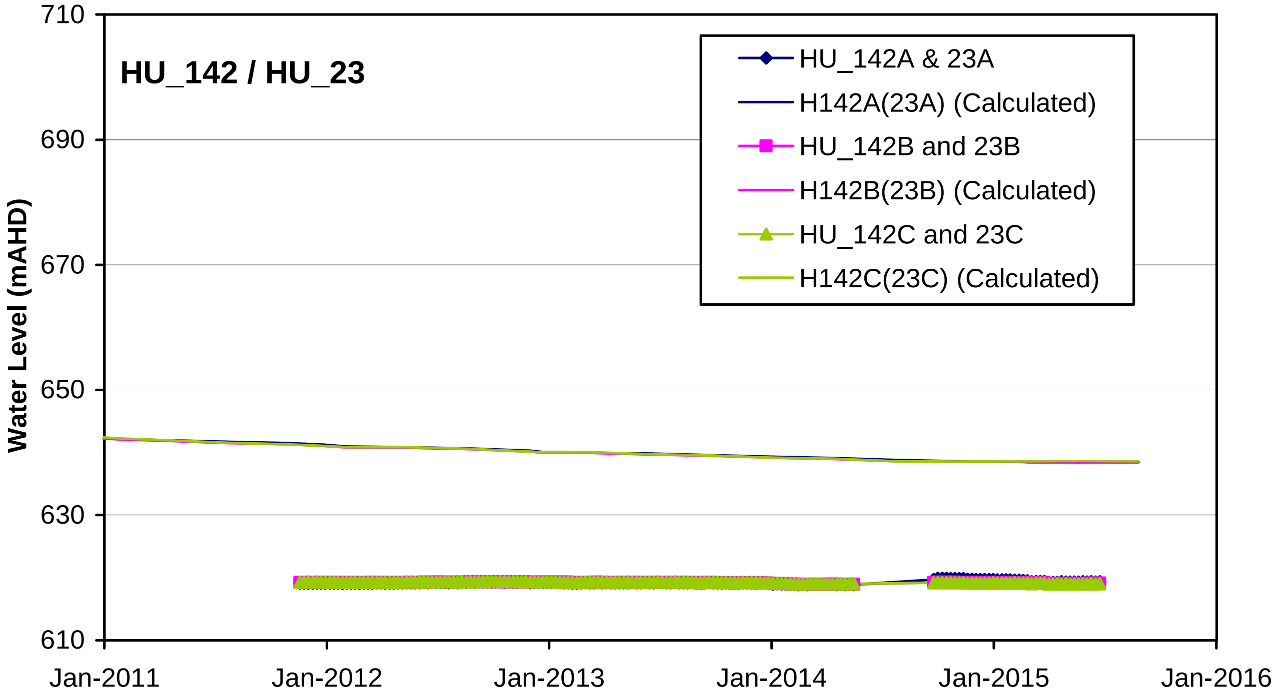
HU_88
HU_88A
H88A (Calculated)
HU_88B
H88B (Calculated)
Water Level (mAHD)
700
680
660
640
620
600
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016

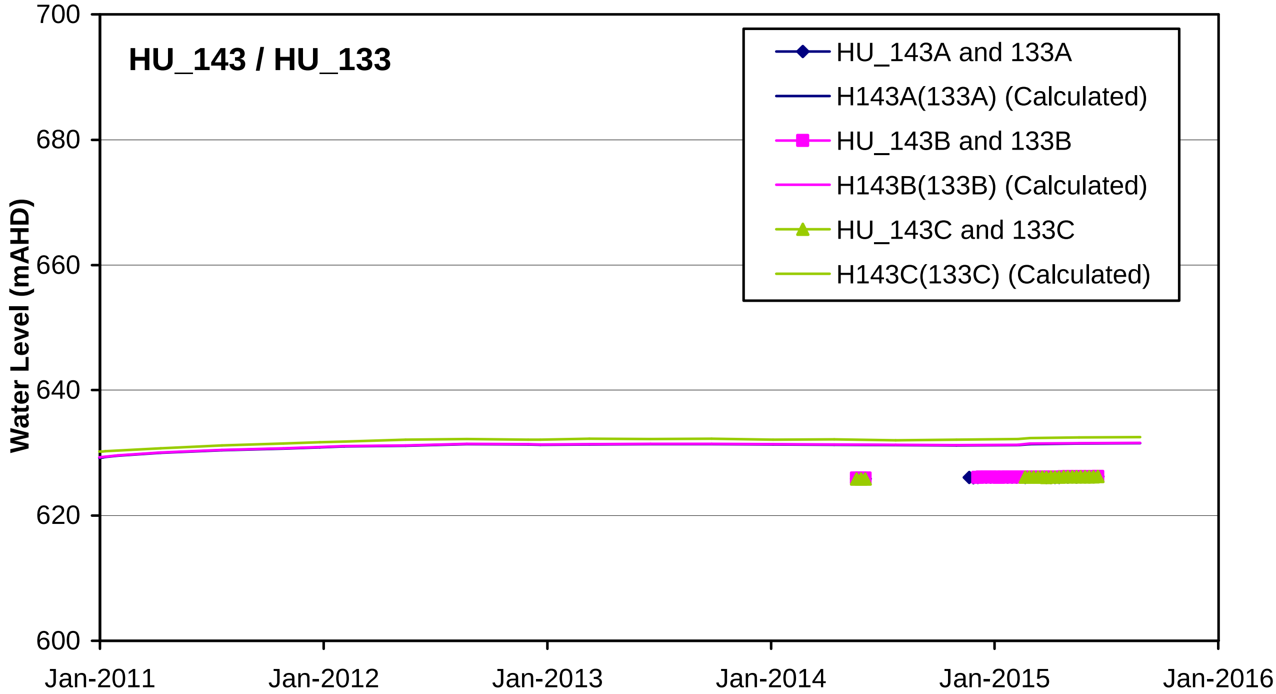


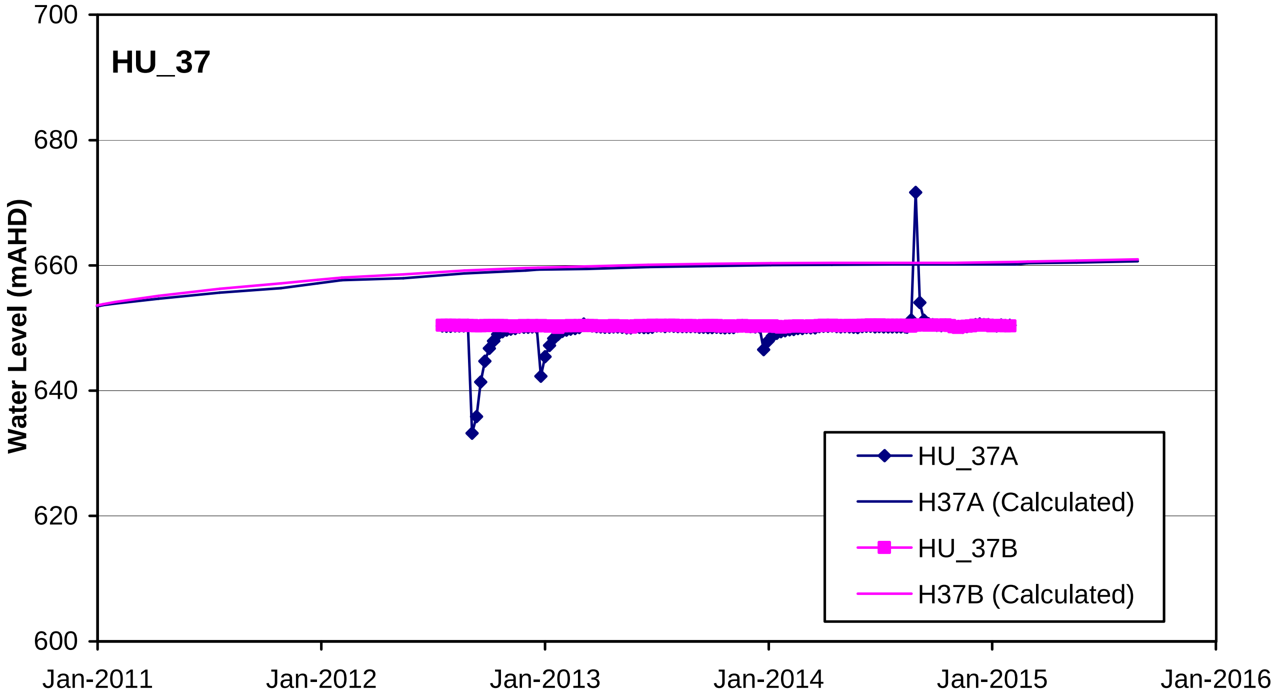
HU_96
HU_96A
H96A (Calculated)
HU_96B
H96B (Calculated)
HU_96C
H96C (Calculated)
Water Level (mAHD)
700
680
660
640
620
600
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016

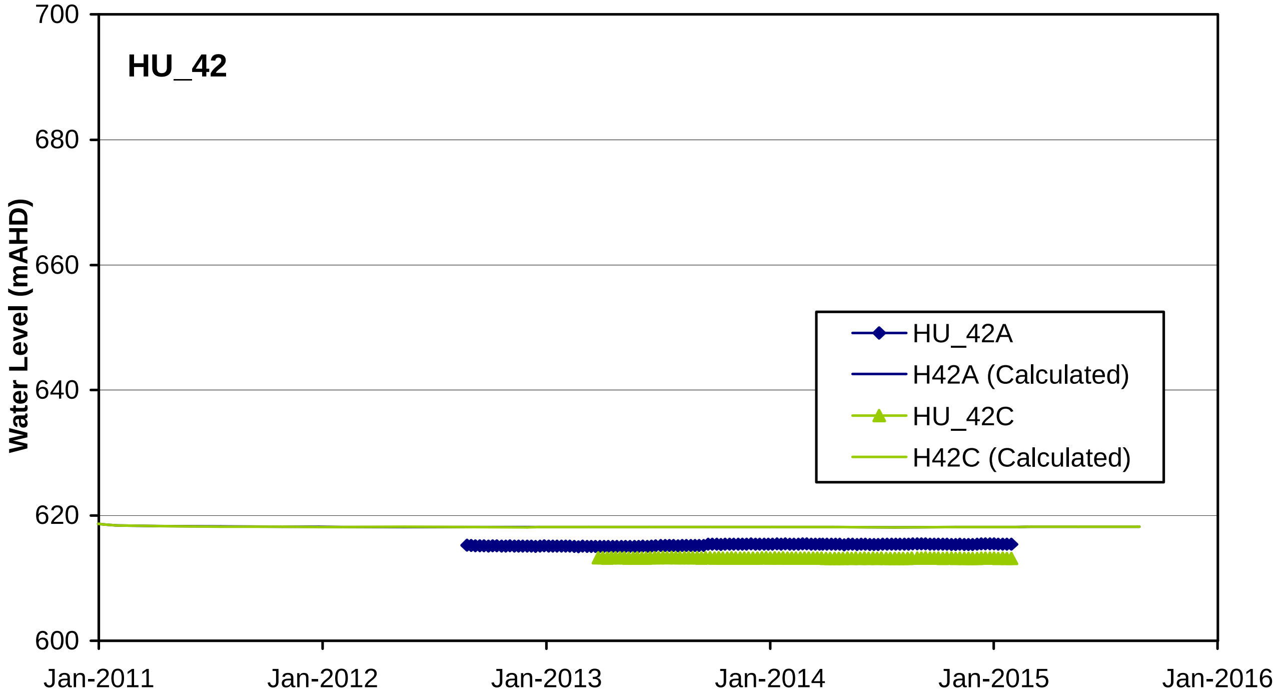


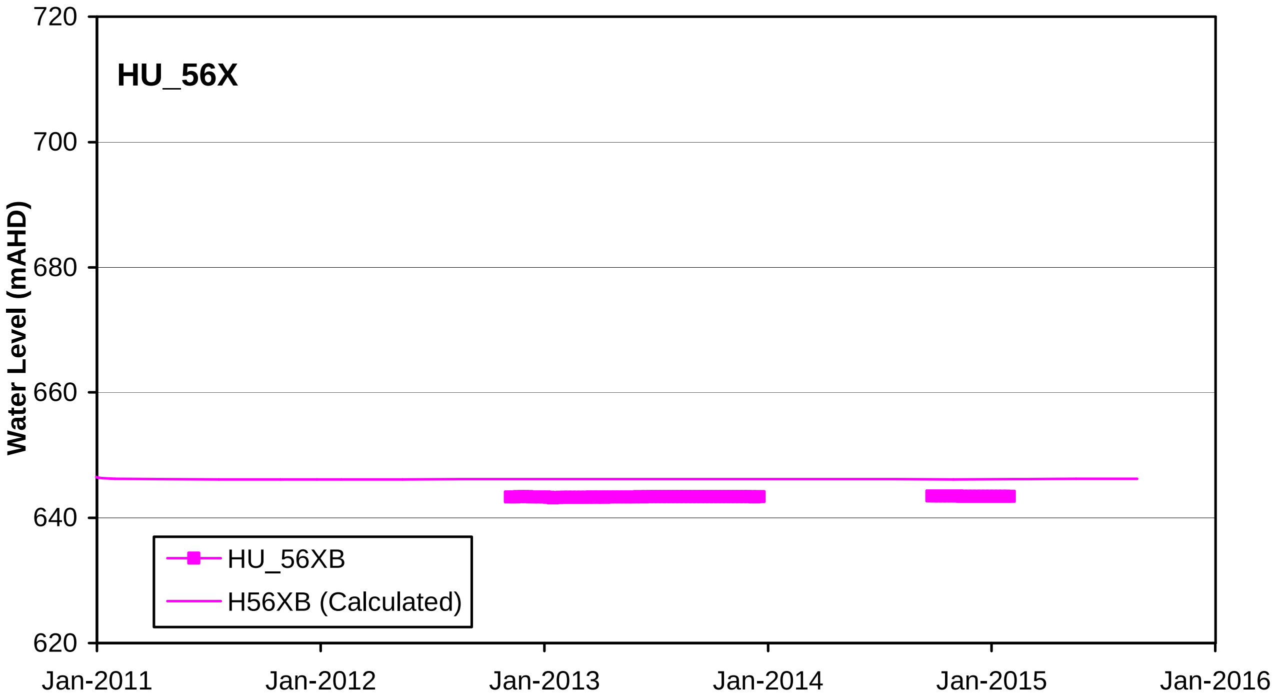
HU_129
HU_129A
H129A (Calculated)
HU_129B
H129B (Calculated)
Water Level (mAHD)
700
680
660
640
620
600
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016

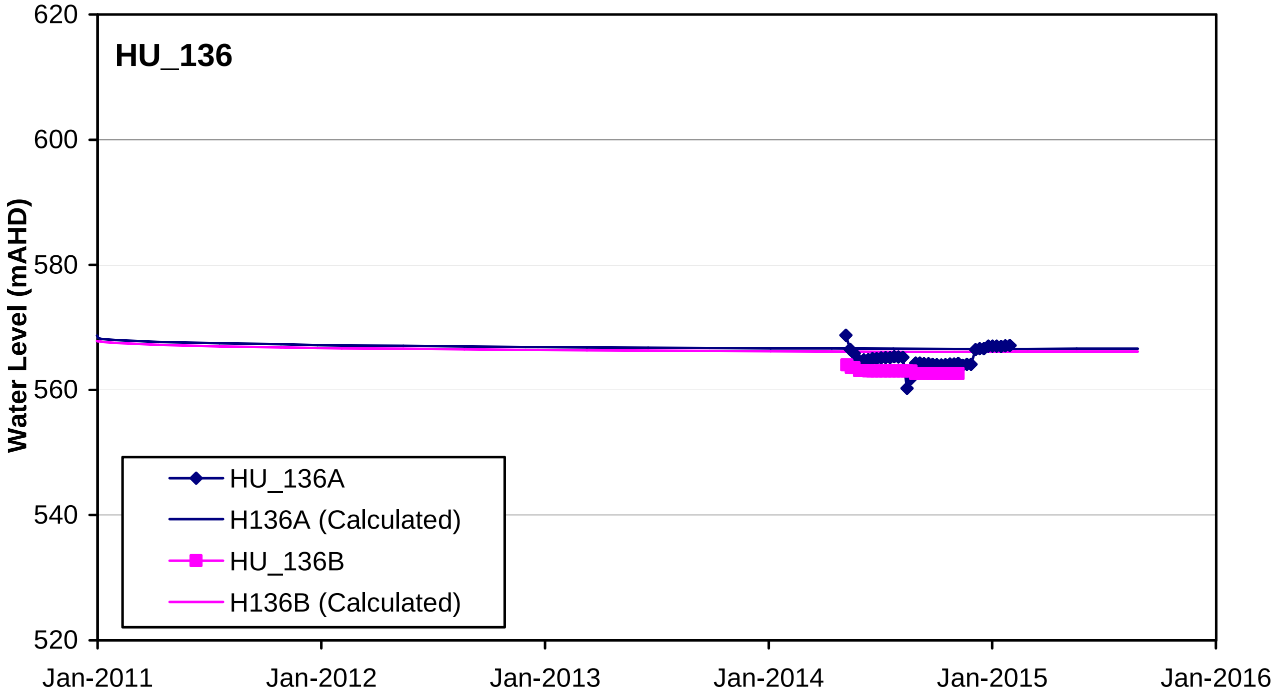

HU_142 / HU_23
HU_142A & 23A
H142A(23A) (Calculated)
HU_142B and 23B
H142B(23B) (Calculated)
HU_142C and 23C
H142C(23C) (Calculated)
Water Level (mAHD)
710
690
670
650
630
610
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016


HU_143 / HU_133
HU_143A and 133A
H143A(133A) (Calculated)
HU_143B and 133B
H143B(133B) (Calculated)
HU_143C and 133C
H143C(133C) (Calculated)
Water Level (mAHD)
700
680
660
640
620
600
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016


HU_37
Water Level (mAHD)
700
680
660
640
620
600
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016
HU_37A
H37A (Calculated)
HU_37B
H37B (Calculated)

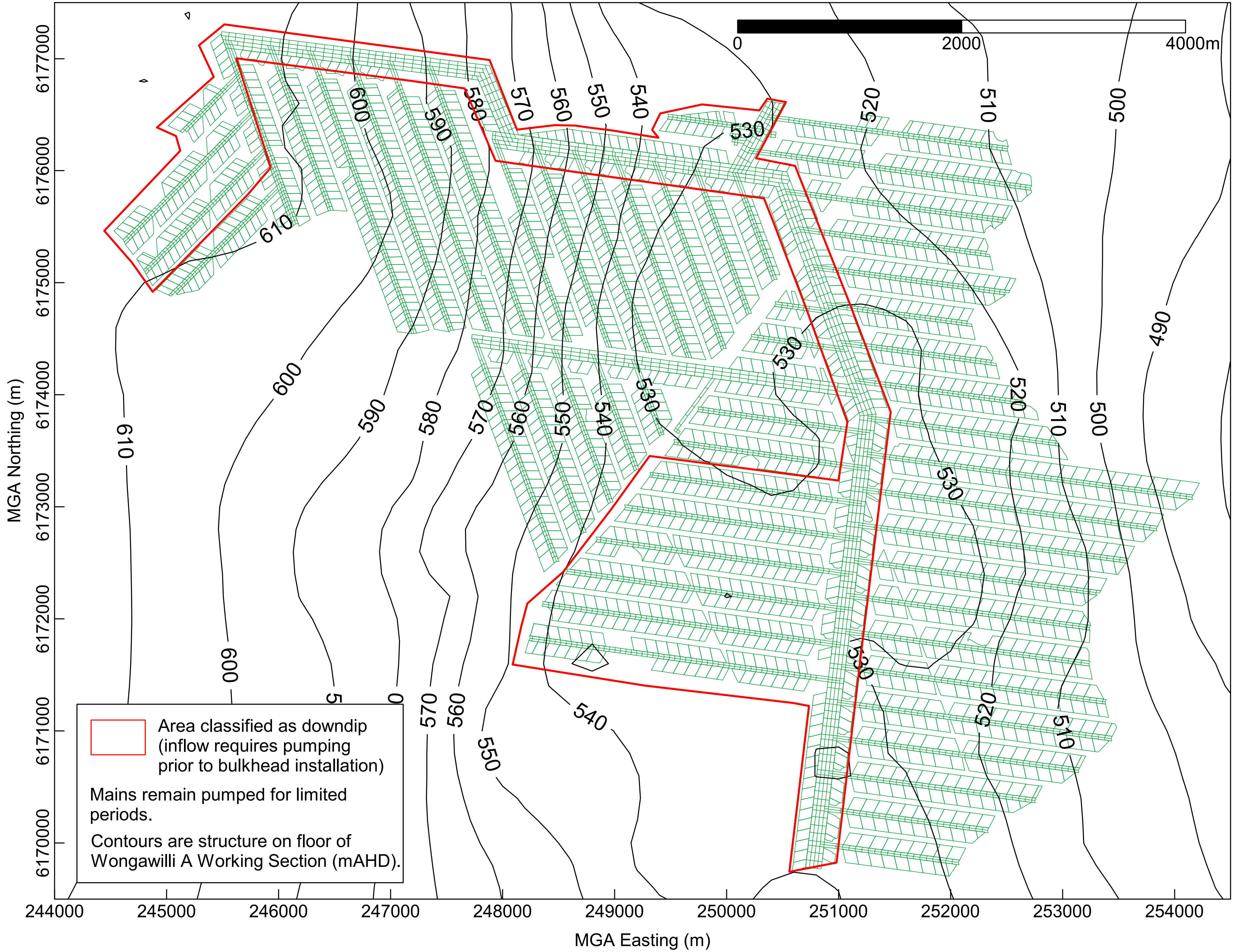

HU_42
Water Level (mAHD)
700
680
660
640
620
600
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016
HU_42A
H42A (Calculated)
HU_42C
H42C (Calculated)


HU_56X
Water Level (mAHD)
720
700
680
660
640
620
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016
HU_56XB
H56XB (Calculated)


HU_136
Water Level (mAHD)
620
600
580
560
540
520
Jan-2011
Jan-2012
Jan-2013
Jan-2014
Jan-2015
Jan-2016
HU_136A
H136A (Calculated)
HU_136B
H136B (Calculated)

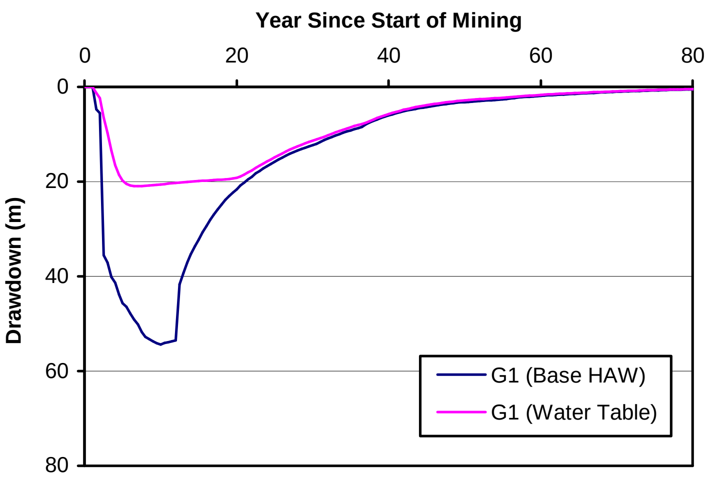
Appendix C - Downdip and Updip Panel Areas

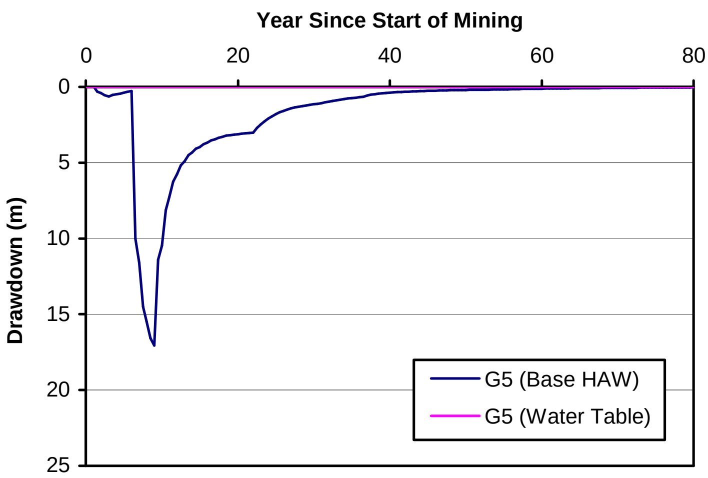
Downdip and Updip Panel Areas (1st Workings Layout 06.05.2016)

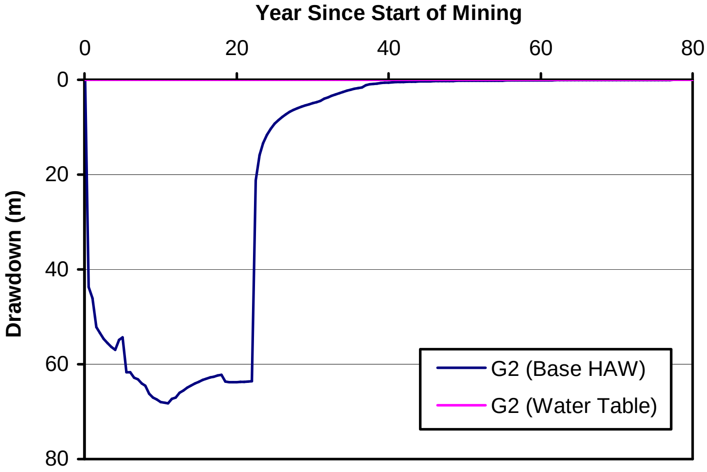


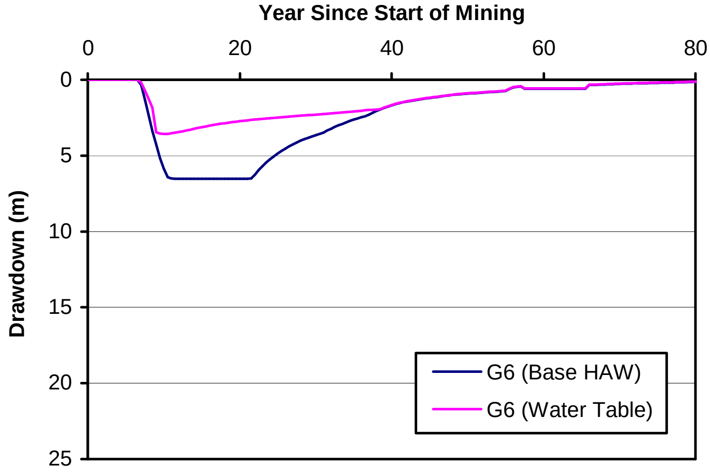
Appendix D - Total and Differential Drawdown of the Water Table and at the Base of the Hawkesbury Sandstone at Virtual Piezometers

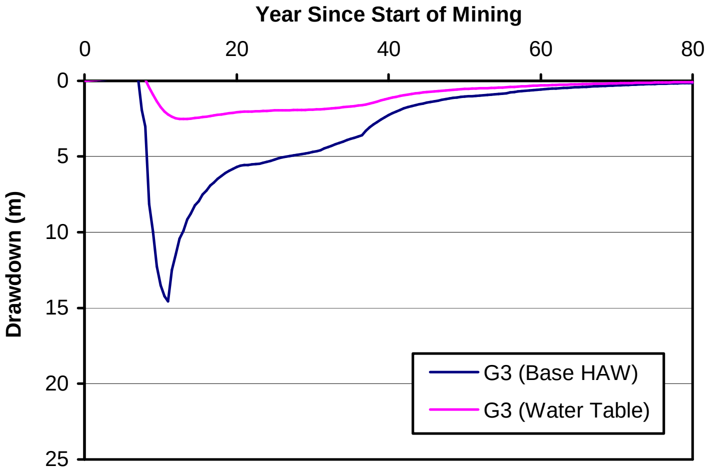
DIFFERENTIAL DRAWDOWN

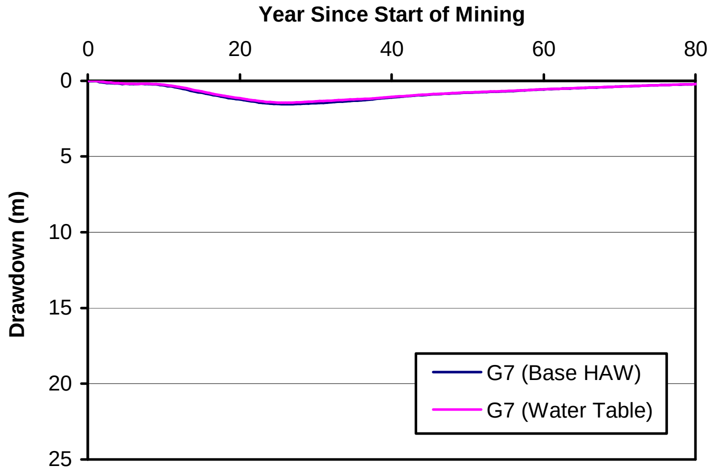


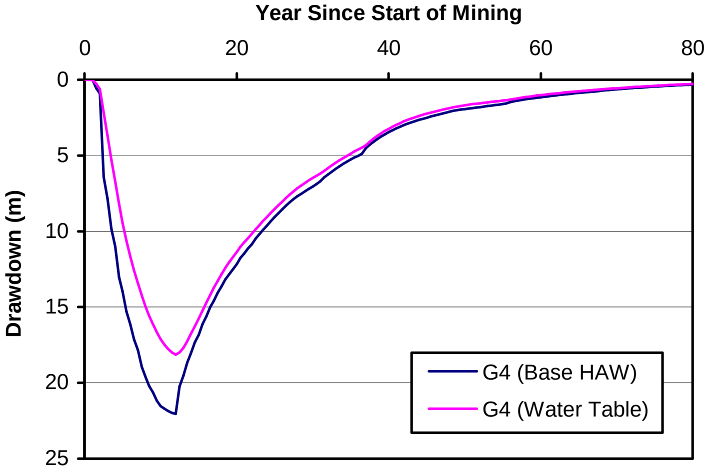


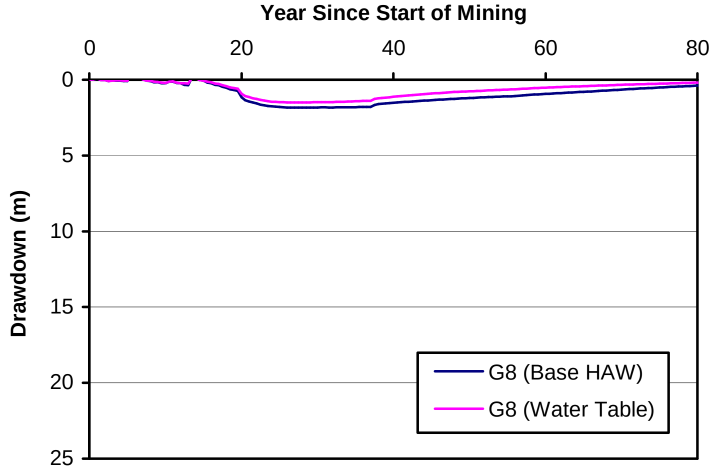




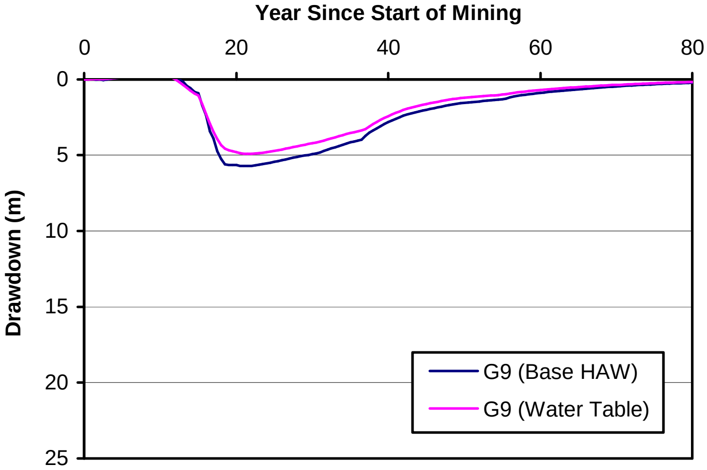


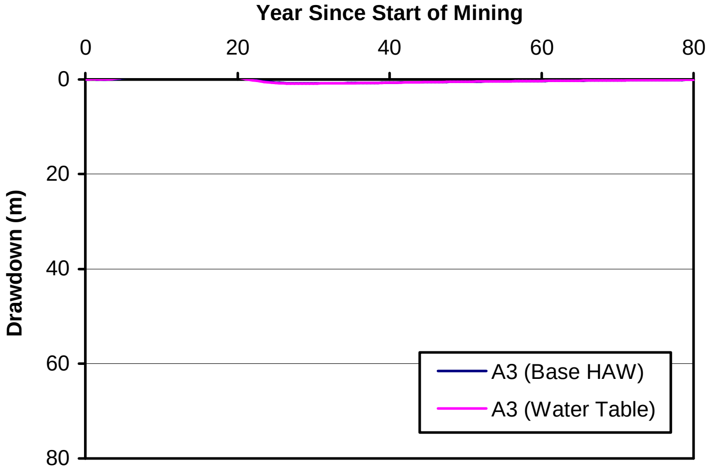




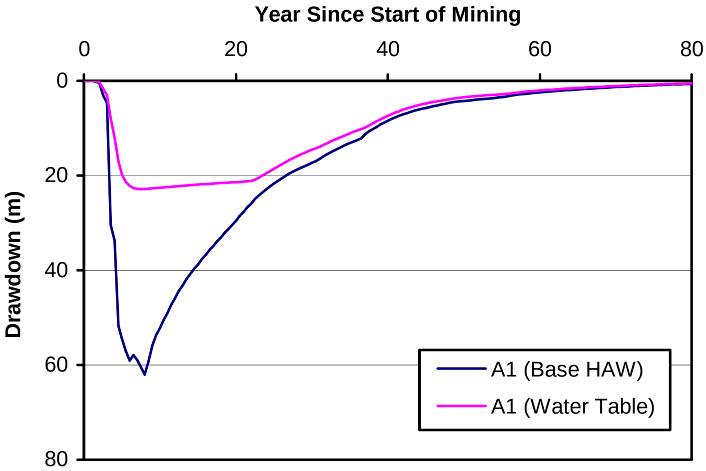


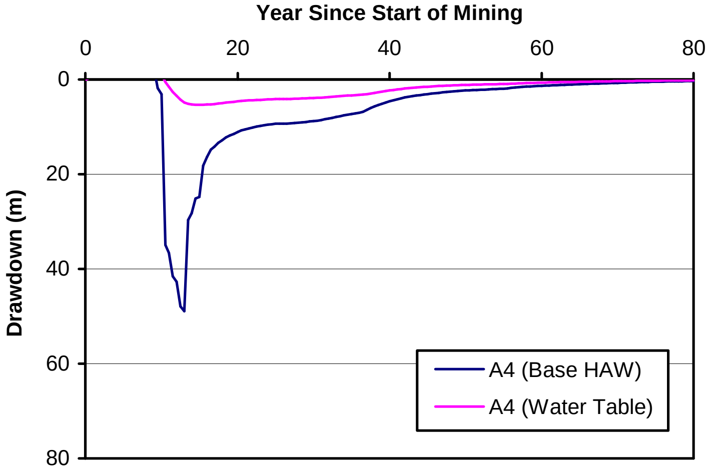
DIFFERENTIAL DRAWDOWN

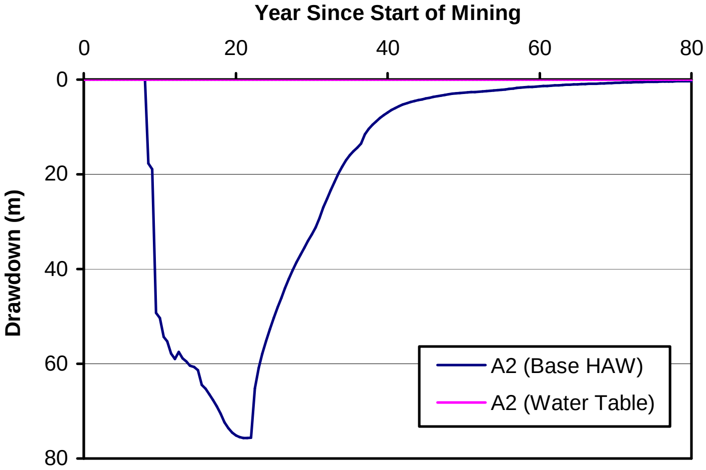


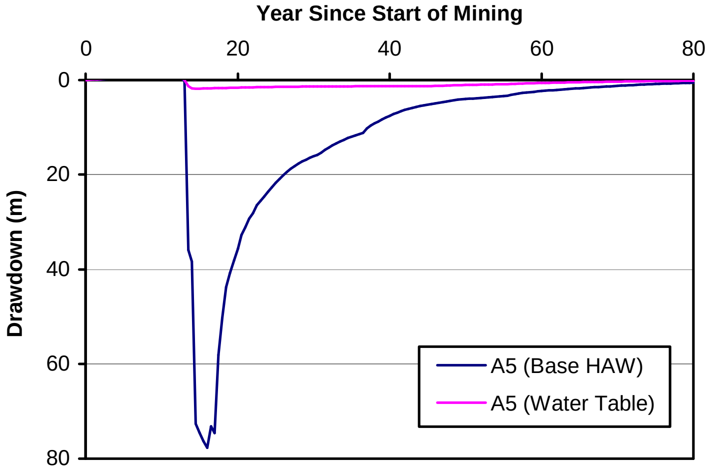


Nil drawdown calculated at G10 and G11

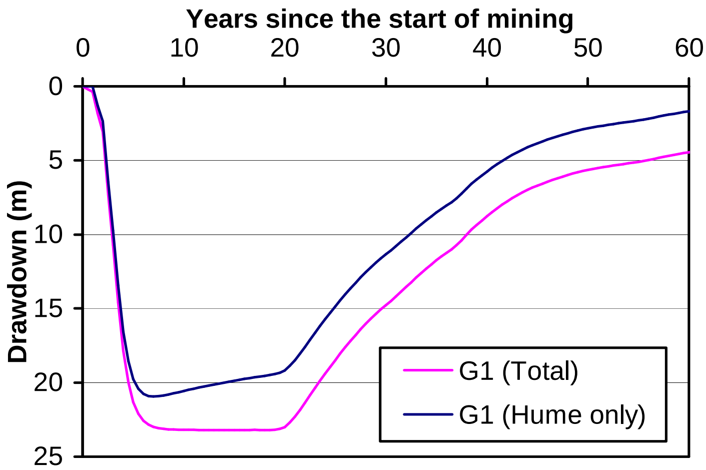


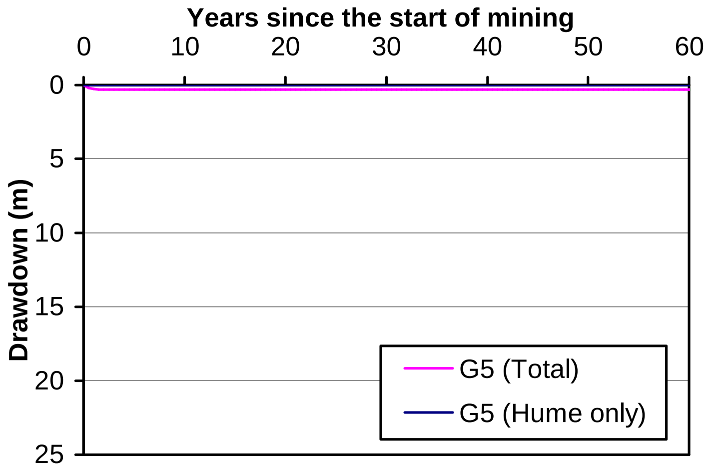


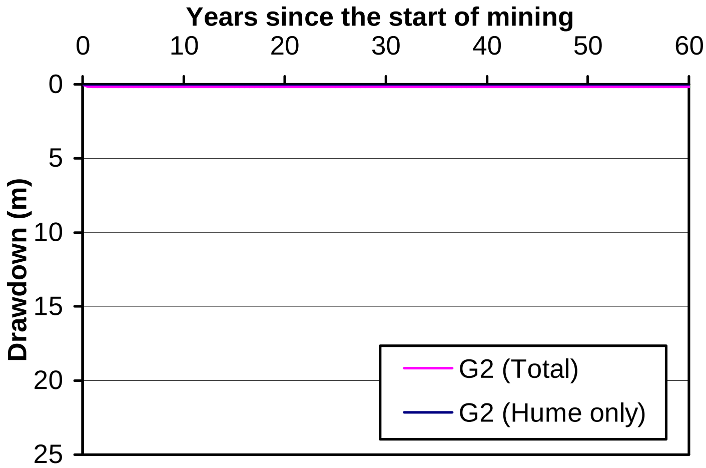


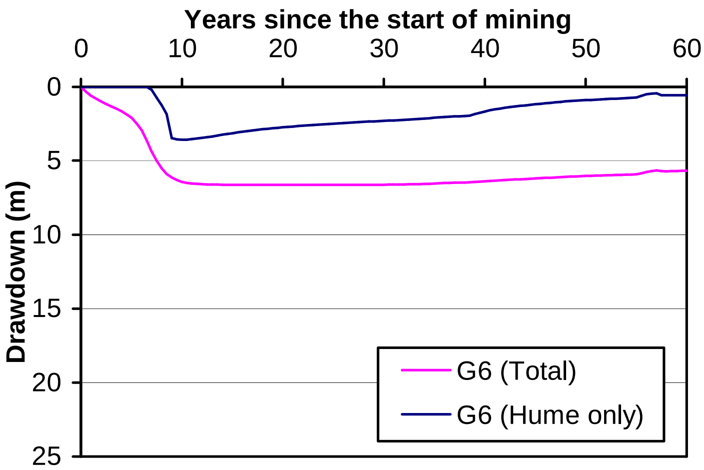


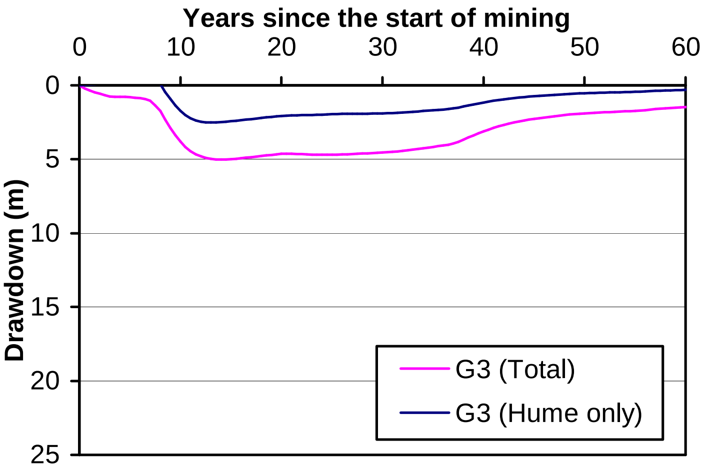
TOTAL AND DIFFERENTIAL DRAWDOWN (WATER TABLE)

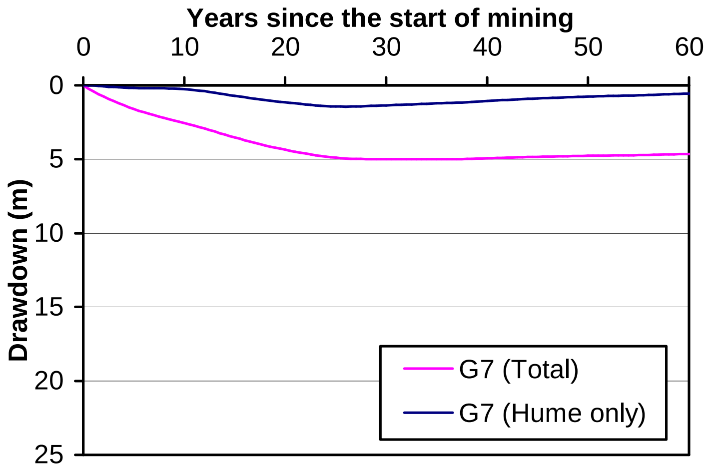


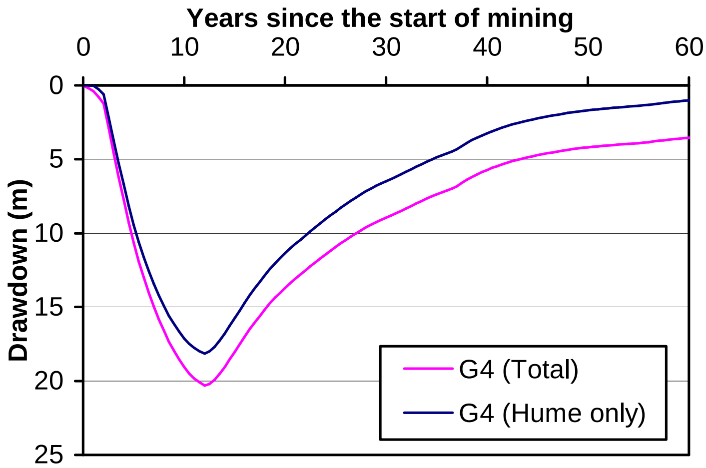


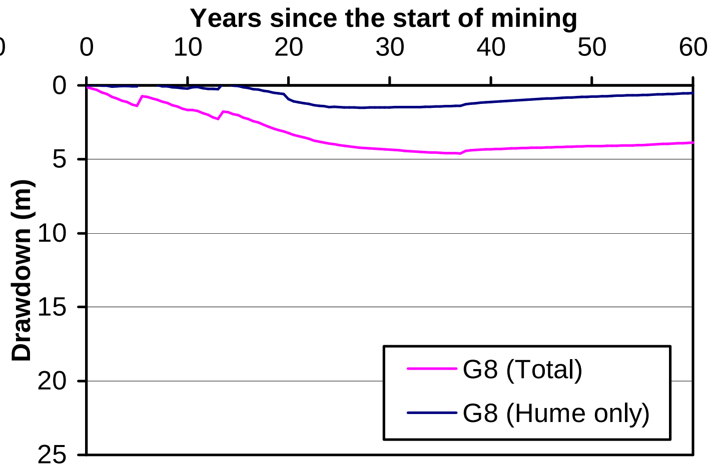




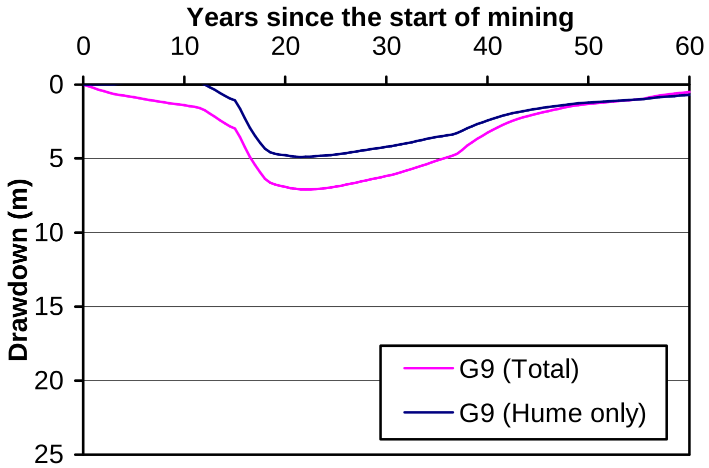




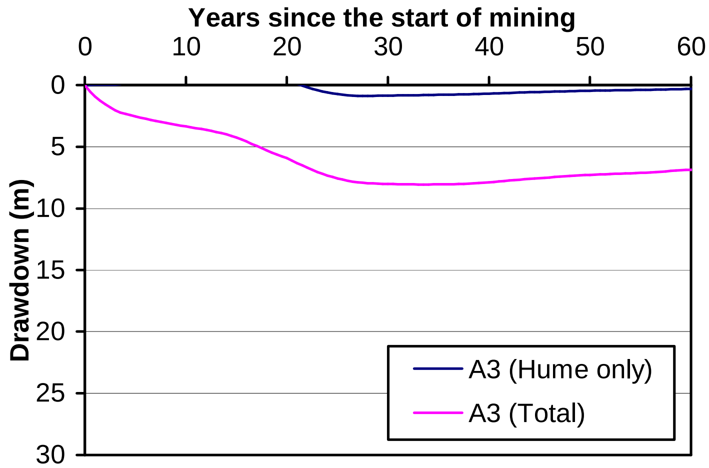


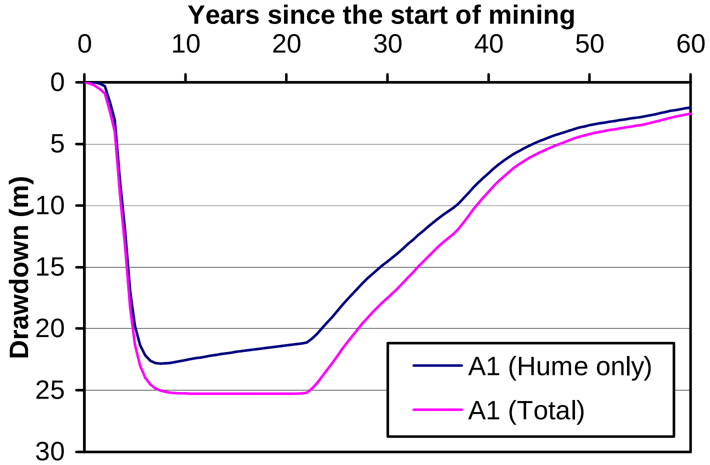


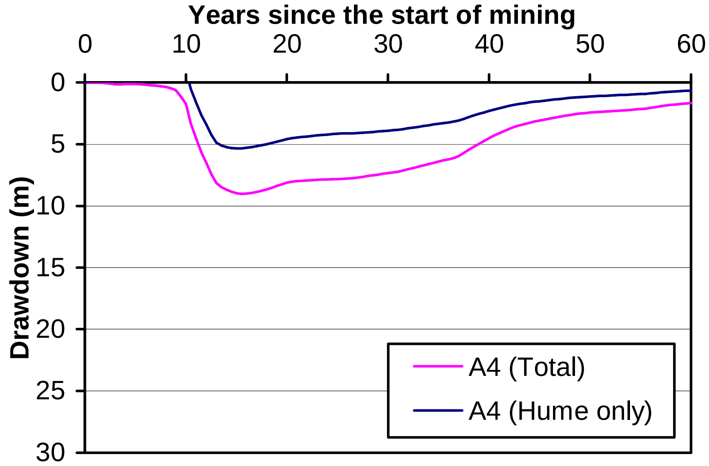
TOTAL AND DIFFERENTIAL DRAWDOWN (WATER TABLE)

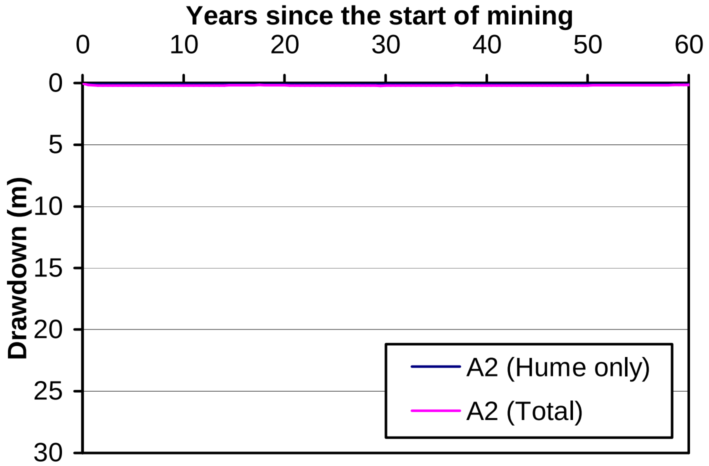


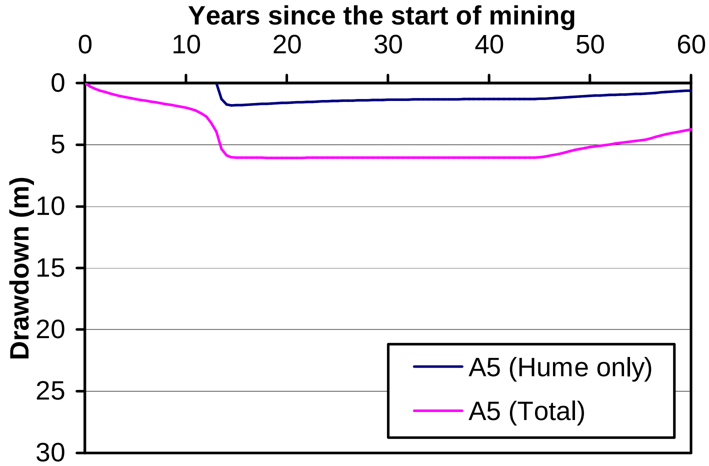
Nil Drawdown calculated at G10 and G11





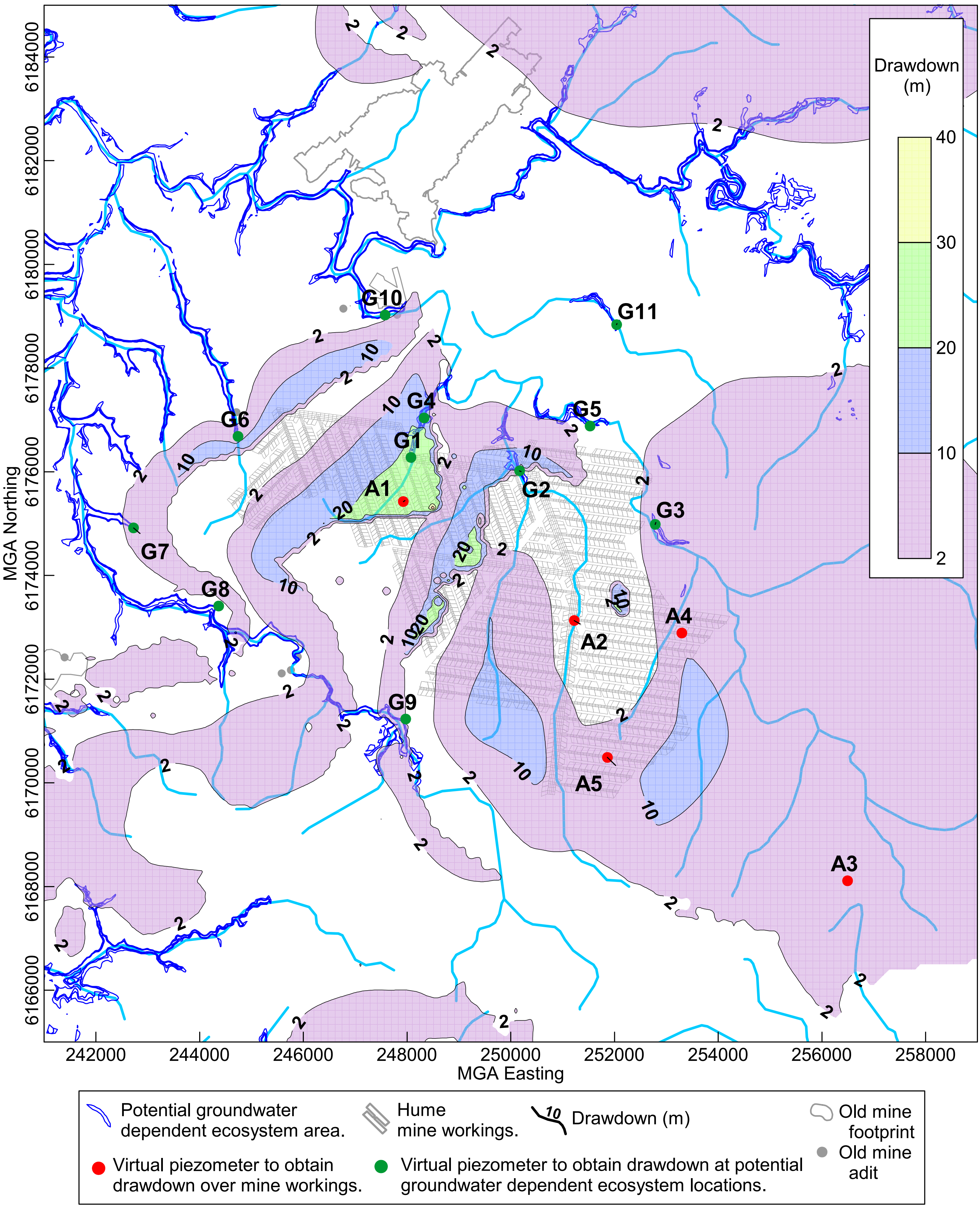




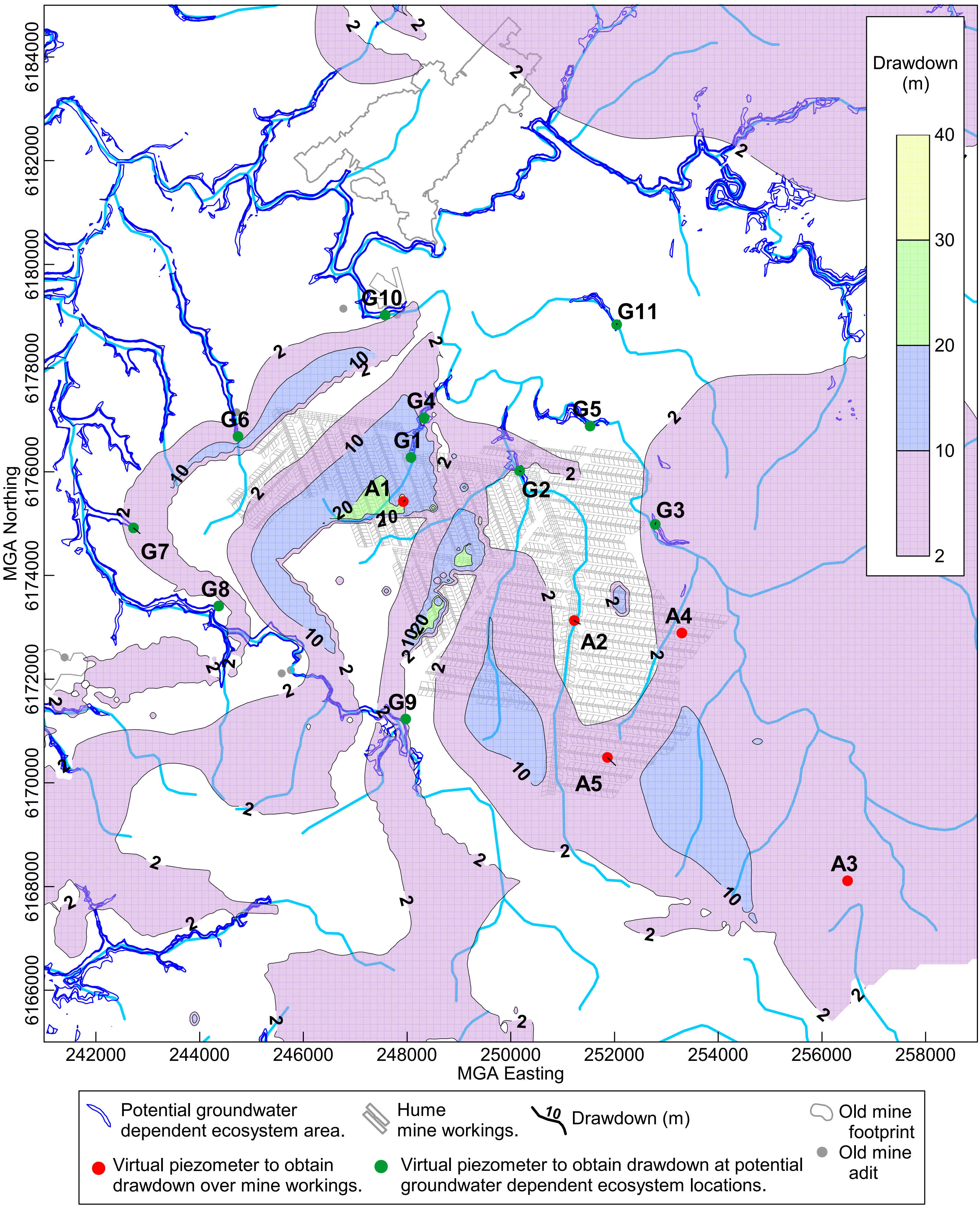


Appendix E - Total Drawdown of the Water Table at 17 and 30 Years Since the Start of Mining

TOTAL DRAWDOWN AT WATER TABLE AT 17 YEARS



TOTAL DRAWDOWN AT WATER TABLE AT 30 YEARS



Appendix F - Six-Monthly Accounts for Intercepted Baseflow to Surface Water Sources and Induced Release from Groundwater Storage in Groundwater Sources

Table 1. Modelled Intercepted Baseflow induced by Hume Operations

Years since the start of mining	Lower Wingecarribee R. (ML/day)	Longacre Ck. (ML/day)	Medway Rivulet (ML/day)	Oldbury Ck. (ML/day)	Belanglo Ck. (ML/day)	Wells Ck. (ML/day)	Wells Ck. Tributary (ML/day)	Lower Wollondilly R. (ML/day)	Bundanoon Ck. (ML/day)
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.5	0.018	0.000	0.035	0.000	0.000	0.011	0.013	0.000	0.000
1	0.177	0.000	0.057	0.000	0.000	0.021	0.020	0.000	0.000
1.5	0.177	0.000	0.088	0.000	0.001	0.075	0.033	0.000	0.000
2	0.000	0.000	0.143	0.000	0.002	0.072	0.033	0.000	0.000
2.5	0.090	0.000	0.177	0.000	0.004	0.070	0.032	0.000	0.000
3	0.314	0.000	0.248	0.000	0.006	0.068	0.031	0.000	0.000
3.5	0.475	0.000	0.243	0.000	0.008	0.065	0.031	0.000	0.000
4	0.654	0.000	0.242	0.000	0.009	0.063	0.030	0.000	0.000
4.5	0.486	0.000	0.236	0.000	0.011	0.061	0.030	0.004	0.000
5	0.575	0.000	0.224	0.000	0.012	0.059	0.029	0.027	0.000
5.5	0.653	0.000	0.215	0.000	0.013	0.057	0.029	0.005	0.000
6	0.518	0.000	0.206	0.000	0.014	0.055	0.029	0.000	0.000
6.5	0.493	0.000	0.354	0.000	0.014	0.054	0.028	0.000	0.000
7	0.231	0.000	0.418	0.000	0.015	0.052	0.028	0.000	0.000
7.5	0.311	0.000	0.703	0.000	0.015	0.050	0.027	0.000	0.000
8	0.331	0.000	0.756	0.000	0.016	0.048	0.027	0.000	0.000
8.5	0.321	0.000	0.799	0.000	0.016	0.047	0.026	0.000	0.000
9	0.323	0.054	0.820	0.000	0.016	0.045	0.026	0.000	0.000
9.5	0.232	0.062	0.753	0.000	0.017	0.044	0.026	0.000	0.000
10	0.762	0.054	0.811	0.001	0.017	0.043	0.025	0.000	0.000
10.5	0.601	0.142	0.804	0.002	0.017	0.042	0.025	0.000	0.000
11	0.580	0.106	0.841	0.002	0.017	0.041	0.025	0.000	0.000
11.5	0.510	0.052	0.784	0.002	0.017	0.041	0.025	0.000	0.000
12	0.442	0.224	0.790	0.002	0.017	0.040	0.025	0.000	0.000
12.5	0.453	0.292	0.754	0.002	0.017	0.040	0.025	0.000	0.000
13	0.538	0.311	0.721	0.002	0.017	0.039	0.025	0.000	0.000
13.5	0.491	0.307	0.645	0.001	0.017	0.039	0.025	0.000	0.000
14	0.357	0.290	0.601	0.000	0.016	0.039	0.024	0.000	0.000
14.5	0.230	0.249	0.460	0.000	0.016	0.039	0.024	0.000	0.000
15	0.586	0.176	0.537	0.000	0.016	0.039	0.024	0.000	0.000
15.5	0.583	0.111	0.510	0.000	0.015	0.039	0.024	0.000	0.000
16	0.632	0.046	0.477	0.000	0.015	0.040	0.024	0.041	0.000
16.5	0.721	0.015	0.376	0.000	0.015	0.040	0.024	0.046	0.000

Nil Loss in baseflow for:

Upper Wingecarribee R.
Black Bobs C.
Nattai R.

Table 1. Modelled Intercepted Baseflow induced by Hume Operations

Years since the start of mining	Lower Wingecarribee R. (ML/day)	Longacre Ck. (ML/day)	Medway Rivulet (ML/day)	Oldbury Ck. (ML/day)	Belanglo Ck. (ML/day)	Wells Ck. (ML/day)	Wells Ck. Tributary (ML/day)	Lower Wollondilly R. (ML/day)	Bundanoon Ck. (ML/day)
17	0.800	0.000	0.296	0.000	0.014	0.040	0.023	0.031	0.000
17.5	0.000	0.000	0.000	0.000	0.014	0.040	0.023	0.009	0.000
18	0.000	0.000	0.000	0.000	0.014	0.040	0.023	0.011	0.000
18.5	0.000	0.065	0.000	0.000	0.013	0.039	0.023	0.012	0.000
19	0.000	0.073	0.000	0.000	0.013	0.039	0.023	0.012	0.000
19.5	0.000	0.065	0.000	0.000	0.013	0.038	0.023	0.016	0.000
20	0.000	0.056	0.000	0.000	0.013	0.038	0.022	0.012	0.000
20.5	0.000	0.046	0.000	0.000	0.012	0.037	0.022	0.012	0.000
21	0.000	0.037	0.000	0.000	0.012	0.037	0.022	0.012	0.000
21.5	0.000	0.027	0.000	0.000	0.012	0.037	0.022	0.013	0.000
22	0.000	0.000	0.000	0.000	0.012	0.036	0.022	0.014	0.000
22.5	0.000	0.000	0.000	0.000	0.011	0.036	0.022	0.014	0.000
23	0.000	0.000	0.000	0.000	0.011	0.035	0.022	0.014	0.001
23.5	0.000	0.000	0.000	0.000	0.011	0.035	0.021	0.014	0.005
24	0.000	0.000	0.000	0.000	0.010	0.034	0.021	0.014	0.008
24.5	0.000	0.000	0.000	0.000	0.010	0.034	0.021	0.014	0.011
25	0.000	0.000	0.000	0.000	0.010	0.034	0.021	0.014	0.014
25.5	0.000	0.000	0.000	0.000	0.010	0.033	0.021	0.047	0.016
26	0.000	0.000	0.000	0.000	0.009	0.033	0.021	0.050	0.019
26.5	0.000	0.000	0.000	0.000	0.009	0.033	0.021	0.049	0.021
27	0.000	0.000	0.000	0.000	0.009	0.035	0.020	0.048	0.022
27.5	0.000	0.000	0.000	0.000	0.009	0.034	0.020	0.046	0.023
28	0.000	0.000	0.000	0.000	0.008	0.033	0.020	0.043	0.024
28.5	0.000	0.000	0.000	0.000	0.008	0.033	0.020	0.041	0.024
29	0.000	0.000	0.000	0.000	0.008	0.032	0.020	0.039	0.024
29.5	0.000	0.000	0.000	0.000	0.008	0.032	0.020	0.037	0.024
30	0.000	0.000	0.000	0.000	0.008	0.032	0.020	0.035	0.024
30.5	0.000	0.000	0.000	0.000	0.007	0.032	0.020	0.034	0.024
31	0.000	0.000	0.000	0.000	0.007	0.032	0.020	0.000	0.023
31.5	0.000	0.000	0.000	0.000	0.007	0.031	0.020	0.000	0.023
32	0.000	0.000	0.000	0.000	0.007	0.031	0.020	0.000	0.023
32.5	0.000	0.000	0.000	0.000	0.007	0.031	0.020	0.000	0.022
33	0.000	0.000	0.000	0.000	0.006	0.031	0.020	0.000	0.022
33.5	0.000	0.000	0.000	0.000	0.005	0.031	0.020	0.000	0.021

Table 1. Modelled Intercepted Baseflow induced by Hume Operations

Years since the start of mining	Lower Wingecarribee R. (ML/day)	Longacre Ck. (ML/day)	Medway Rivulet (ML/day)	Oldbury Ck. (ML/day)	Belanglo Ck. (ML/day)	Wells Ck. (ML/day)	Wells Ck. Tributary (ML/day)	Lower Wollondilly R. (ML/day)	Bundanoon Ck. (ML/day)
34	0.000	0.000	0.000	0.000	0.002	0.031	0.020	0.000	0.021
34.5	0.000	0.000	0.000	0.000	0.000	0.031	0.020	0.000	0.020
35	0.000	0.000	0.000	0.000	0.000	0.031	0.019	0.000	0.019
35.5	0.000	0.000	0.000	0.000	0.000	0.031	0.019	0.000	0.019
36	0.000	0.000	0.000	0.000	0.000	0.030	0.000	0.000	0.018
36.5	0.000	0.000	0.000	0.000	0.000	0.030	0.016	0.000	0.017
37	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.000	0.017
37.5	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.000	0.016
38	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.015
38.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.014
39	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.013
39.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.012
40	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.011
40.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.010
41	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.008
41.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.007
42	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.006
42.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004
43	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003
43.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
44	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
44.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
45	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
45.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
46	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
46.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
47	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
47.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
48	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
48.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
49	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
49.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
50	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 2. Modelled Release from Groundwater Storage induced by Hume Operations

Years since the start of mining	Nepean Management Zone 2 (ML/day)	Sydney Basin South (ML/day)	Nepean Management Zone 1 (ML/day)
0	0.000	0.001	0.000
0.5	0.000	0.000	0.274
1	0.001	0.000	0.079
1.5	0.002	0.000	1.005
2	0.003	0.000	1.087
2.5	0.003	0.000	2.185
3	0.003	0.000	1.796
3.5	0.002	0.000	2.545
4	0.001	0.000	2.233
4.5	0.000	0.000	2.682
5	0.000	0.000	2.369
5.5	0.000	0.000	2.317
6	0.000	0.000	2.200
6.5	0.000	0.000	2.792
7	0.000	0.000	2.759
7.5	0.000	0.000	3.503
8	0.000	0.000	3.154
8.5	0.000	0.000	3.986
9	0.000	0.000	3.669
9.5	0.000	0.000	4.740
10	0.000	0.000	3.630
10.5	0.000	0.000	4.210
11	0.000	0.000	4.053
11.5	0.000	0.000	4.476
12	0.000	0.000	4.167
12.5	0.000	0.000	4.336
13	0.000	0.000	4.046
13.5	0.000	0.000	4.605
14	0.000	0.000	4.566
14.5	0.000	0.000	5.206
15	0.000	0.000	4.616
15.5	0.000	0.000	4.824
16	0.000	0.000	4.625
16.5	0.000	0.000	4.106
17	0.000	0.000	3.922
17.5	0.000	0.000	4.426
18	0.000	0.000	4.168
18.5	0.000	0.000	3.276
19	0.000	0.000	3.061
19.5	0.000	0.000	2.891
20	0.000	0.000	2.741
20.5	0.000	0.010	1.797
21	0.000	0.014	1.728
21.5	0.000	0.021	1.143
22	0.000	0.026	1.153
22.5	0.000	0.035	0.500
23	0.000	0.040	0.100
23.5	0.000	0.040	0.000
24	0.000	0.041	0.000
24.5	0.000	0.041	0.000
25	0.000	0.042	0.000

Table 2. Modelled Release from Groundwater Storage induced by Hume Operations

Years since the start of mining	Nepean Management Zone 2 (ML/day)	Sydney Basin South (ML/day)	Nepean Management Zone 1 (ML/day)
25.5	0.000	0.042	0.000
26	0.000	0.040	0.000
26.5	0.000	0.038	0.000
27	0.000	0.035	0.000
27.5	0.000	0.032	0.000
28	0.000	0.028	0.000
28.5	0.000	0.025	0.000
29	0.000	0.022	0.000
29.5	0.000	0.019	0.000
30	0.000	0.017	0.000
30.5	0.000	0.015	0.000
31	0.000	0.014	0.000
31.5	0.000	0.014	0.000
32	0.000	0.013	0.000
32.5	0.000	0.013	0.000
33	0.000	0.012	0.000
33.5	0.000	0.011	0.000
34	0.000	0.010	0.000
34.5	0.000	0.009	0.000
35	0.000	0.008	0.000
35.5	0.000	0.006	0.000
36	0.000	0.005	0.000
36.5	0.000	0.004	0.000
37	0.000	0.005	0.000
37.5	0.000	0.005	0.000
38	0.000	0.004	0.000
38.5	0.000	0.002	0.000
39	0.000	0.000	0.000
39.5	0.000	-0.002	0.000
40	0.000	-0.005	0.000
40.5	0.000	0.000	0.000
41	0.000	0.000	0.000
41.5	0.000	0.000	0.000
42	0.000	0.000	0.000
42.5	0.000	0.000	0.000
43	0.000	0.000	0.000
43.5	0.000	0.000	0.000
44	0.000	0.000	0.000
44.5	0.000	0.000	0.000
45	0.000	0.000	0.000
45.5	0.000	0.000	0.000
46	0.000	0.000	0.000
46.5	0.000	0.000	0.000
47	0.000	0.000	0.000
47.5	0.000	0.000	0.000
48	0.000	0.000	0.000
48.5	0.000	0.000	0.000
49	0.000	0.000	0.000
49.5	0.000	0.000	0.000
50	0.000	0.000	0.000

Appendix G - Private Water Bore Register, Locations, Results, and Drawdown Hydrographs

Table 1. PRIVATE BORE DETAILS

Bore	Easting (mMGA)	Northing (mMGA)	Water Level (mbgl)*	Hydraulic Interval (mbgl) From	To	Water Column[#] (m)	Intersected Strata^	Screened Model Layers
GW011227	252755	6175769	0	12	40	40	HAW	1 **2** 3 4 5 6 7 8 9 10 11 12
GW017295	256273	6172008	3	58	76	73	WG	**1** 2 3 4 5 6 7 8 9 10 11 12
GW021817	245756	6174939	55	6	93	38	HAW	1 **2 3 4 5** 6 7 8 9 10 11 12
GW023322	248882	6173630	8	7	45	37	HAW	1 **2** 3 4 5 6 7 8 9 10 11 12
GW024688	249722	6174670	2	12	75	74	HAW	1 **2 3** 4 5 6 7 8 9 10 11 12
GW025808	250587	6169081	14	17	128	114	WG/HAW	**1 2 3** 4 5 6 7 8 9 10 11 12
GW026136	250554	6174076	20	20	53	33	HAW	1 **2** 3 4 5 6 7 8 9 10 11 12
GW026805	246680	6173940	23	3	83	60	HAW	1 **2 3 4** 5 6 7 8 9 10 11 12
GW028687	252433	6175391	3	8	52	49	HAW	1 **2** 3 4 5 6 7 8 9 10 11 12
GW028832	253958	6173704	8	40	132	124	HAW	1 **2 3 4** 5 6 7 8 9 10 11 12
GW031527	252625	6176814	2	6	40	38	HAW	1 **2** 3 4 5 6 7 8 9 10 11 12
GW032319	251374	6175856	12	19	38	26	HAW	1 **2** 3 4 5 6 7 8 9 10 11 12
GW035590	247831	6171936	26	2	34	8	WG/HAW	**1 2** 3 4 5 6 7 8 9 10 11 12
GW037851	248939	6176253	27	2	79	51	HAW	**1 2 3 4** 5 6 7 8 9 10 11 12
GW042642	255687	6172949	18	18	69	51	WG	**1** 2 3 4 5 6 7 8 9 10 11 12
GW047076	254720	6170814	8	6	90	82	WG/HAW	**1 2 3** 4 5 6 7 8 9 10 11 12
GW047117	251827	6177040	6	5	34	28	HAW	1 **2** 3 4 5 6 7 8 9 10 11 12
GW047157	248506	6175285	12	6	67	55	HAW	1 **2 3 4** 5 6 7 8 9 10 11 12
GW047443	249131	6169165	13	24	67	54	HAW	1 **2 3** 4 5 6 7 8 9 10 11 12
GW048345	251887	6174821	9	25	38	29	HAW	1 **2** 3 4 5 6 7 8 9 10 11 12
GW049172	249209	6175705	10	16	70	60	HAW	1 **2 3** 4 5 6 7 8 9 10 11 12
GW052538	244625	6175333	38	7	88	50	HAW/ICM	1 2 **3 4 5 6 7 8 9 10 11 12**
GW053331	251462	6177338	18	6	92	74	HAW	1 **2 3 4** 5 6 7 8 9 10 11 12
GW053793	247553	6173717	22	20	92	70	HAW	1 2 **3 4** 5 6 7 8 9 10 11 12
GW053801	247583	6171683	27	30	99	72	HAW/ICM	1 2 **3 4 5 6 7 8 9 10 11** 12
GW054137	251672	6177128	13	6	46	33	HAW	1 **2** 3 4 5 6 7 8 9 10 11 12
GW057683	252063	6176799	9	6	61	52	HAW	1 **2 3** 4 5 6 7 8 9 10 11 12
GW057906	250456	6174875	6	6	61	55	HAW	1 **2 3** 4 5 6 7 8 9 10 11 12
GW057908	250955	6176276	21	6	84	63	HAW	1 **2 3** 4 5 6 7 8 9 10 11 12
GW057943	252428	6169840	11	20	26	15	WG	**1** 2 3 4 5 6 7 8 9 10 11 12
GW060067	254057	6169020	37	6	76	39	WG	**1** 2 3 4 5 6 7 8 9 10 11 12
GW060125	252618	6175525	7	7	107	100	HAW	1 **2 3 4** 5 6 7 8 9 10 11 12
GW060199	253094	6174514	1	12	37	36	HAW	1 **2** 3 4 5 6 7 8 9 10 11 12
GW062326	250784	6169333	43	14	95	51	WG/HAW	**1 2 3** 4 5 6 7 8 9 10 11 12
GW064613	249108	6175671	14	7	43	29	HAW	1 **2** 3 4 5 6 7 8 9 10 11 12
GW066775	253213	6170077	50	50	86	36	HAW	1 **2** 3 4 5 6 7 8 9 10 11 12
GW066798	251660	6175678	10	10	32	22	HAW	1 **2** 3 4 5 6 7 8 9 10 11 12
GW066800	253274	6170634	14	14	81	67	WG/HAW	**1 2** 3 4 5 6 7 8 9 10 11 12
GW067303	247661	6171654	25	90	100	75	HAW/ICM	1 2 3 4 **5 6 7 8 9 10** 11 12
GW067305	250965	6174950	12	6	15	3	WG	**1** 2 3 4 5 6 7 8 9 10 11 12
GW067319	251579	6175830	10	10	31	21	HAW	1 **2** 3 4 5 6 7 8 9 10 11 12
GW068965	251659	6175774	14	8	37	23	HAW	1 **2** 3 4 5 6 7 8 9 10 11 12
GW069072	254350	6169571	60	99	120	60	HAW	1 **2 3** 4 5 6 7 8 9 10 11 12
GW071741	248620	6171839	25	12	85	60	HAW	1 **2 3** 4 5 6 7 8 9 10 11 12
GW072207	256328	6171699	33	91	109	76	HAW	1 **2** 3 4 5 6 7 8 9 10 11 12
GW072320	256462	6171059	33	91	109	76	HAW	1 **2** 3 4 5 6 7 8 9 10 11 12
GW072672	251924	6174305	24	12	122	98	HAW/ICM	1 **2 3 4 5 6 7 8 9 10 11** 12
GW100147	253307	6172269	20	20	80	60	HAW	1 **2** 3 4 5 6 7 8 9 10 11 12
GW100153	253247	6172606	20	20	85	65	HAW	1 **2** 3 4 5 6 7 8 9 10 11 12
GW102309	254109	6170271	45	45	67	22	HAW	1 **2** 3 4 5 6 7 8 9 10 11 12
GW102516	256418	6171364	11	14	91	80	WG/HAW	**1 2** 3 4 5 6 7 8 9 10 11 12
GW102588	244853	6174954	56	42	88	32	HAW/ICM	1 2 3 **4 5 6 7 8 9 10** 11 12
GW102689	252658	6172598	24	36	84	60	HAW	1 **2 3** 4 5 6 7 8 9 10 11 12
GW102694	253410	6168417	89	96	169	80	HAW	1 **2 3 4 5** 6 7 8 9 10 11 12
GW102705	246987	6171111	32	60	150	118	HAW/ICM	1 2 3 4 **5 6 7 8 9 10 11 12**
GW102713	251032	6175292	10	12	60	50	HAW	1 **2 3** 4 5 6 7 8 9 10 11 12

Table 1. PRIVATE BORE DETAILS

Bore	Easting (mMGA)	Northing (mMGA)	Water Level (mbgl)*	Hydraulic Interval (mbgl) From	Hydraulic Interval (mbgl) To	Water Column[#] (m)	Intersected Strata^	Screened Model Layers											
GW102757	251971	6167918	99	19	210	111	WG/HAW/ICM	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
GW102775	254164	6171706	52	59	116	64	HAW	1	**2**	**3**	4	5	6	7	8	9	10	11	12
GW102777	253902	6170034	44	59	103	59	HAW	1	**2**	**3**	4	5	6	7	8	9	10	11	12
GW102916	252708	6173638	42	48	108	66	HAW	1	2	**3**	**4**	5	6	7	8	9	10	11	12
GW103108	249748	6170021	35	60	114	79	HAW	1	2	**3**	**4**	5	6	7	8	9	10	11	12
GW103597	253347	6170885	50	6	90	40	WG/HAW	**1**	**2**	**3**	**4**	5	6	7	8	9	10	11	12
GW103692	255893	6170270	13	79	152	139	HAW	1	2	**3**	**4**	5	6	7	8	9	10	11	12
GW104213	254367	6171392	34	84	144	110	HAW	1	2	**3**	**4**	5	6	7	8	9	10	11	12
GW104404	254332	6175078	74	126	159	85	HAW	1	**2**	**3**	4	5	6	7	8	9	10	11	12
GW104421	251708	6175634	15	30	42	27	HAW	1	**2**	3	4	5	6	7	8	9	10	11	12
GW104468	252574	6173120	43	73	103	60	HAW	1	**2**	**3**	4	5	6	7	8	9	10	11	12
GW104486	251831	6174027	19	26	43	25	HAW	1	**2**	3	4	5	6	7	8	9	10	11	12
GW104523	253372	6170373	42	66	91	49	HAW	1	2	**3**	4	5	6	7	8	9	10	11	12
GW104526	249484	6169317	33	40	61	28	HAW	1	2	**3**	4	5	6	7	8	9	10	11	12
GW104684	250231	6169027	57	66	156	99	HAW/ICM	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	12
GW104727	252108	6169089	101	101	175	74	HAW	1	**2**	**3**	**4**	**5**	6	7	8	9	10	11	12
GW104728	254382	6172032	13	67	79	66	HAW	1	**2**	3	4	5	6	7	8	9	10	11	12
GW104745	251266	6174225	80	80	130	50	HAW	1	2	3	**4**	**5**	**6**	7	8	9	10	11	12
GW104917	255641	6168126	65	101	156	91	HAW	1	2	**3**	**4**	5	6	7	8	9	10	11	12
GW105068	253025	6170333	40	67	91	51	HAW	1	2	**3**	4	5	6	7	8	9	10	11	12
GW105079	253578	6171823	18	54	114	96	HAW	1	**2**	**3**	4	5	6	7	8	9	10	11	12
GW105082	250190	6168508	38	38	102	64	HAW	1	**2**	**3**	4	5	6	7	8	9	10	11	12
GW105102	255075	6169083	52	85	151	99	HAW	1	2	**3**	**4**	5	6	7	8	9	10	11	12
GW105396	250860	6169623	60	79	96	36	HAW	1	2	**3**	4	5	6	7	8	9	10	11	12
GW105744	253955	6170109	52	55	67	15	HAW	1	**2**	3	4	5	6	7	8	9	10	11	12
GW105950	254257	6167973	72	80	168	96	HAW/ICM	1	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	12
GW106245	255801	6169286	70	102	139	69	HAW	1	2	**3**	4	5	6	7	8	9	10	11	12
GW106489	249862	6173914	5	30	55	50	HAW	1	2	**3**	4	5	6	7	8	9	10	11	12
GW106491	249802	6173568	5	36	60	55	HAW	1	2	**3**	4	5	6	7	8	9	10	11	12
GW106517	254312	6170743	56	88	144	88	HAW	1	2	**3**	**4**	5	6	7	8	9	10	11	12
GW106710	248321	6172535	35	64	115	80	HAW	1	2	**3**	**4**	5	6	7	8	9	10	11	12
GW106711	247871	6172835	59	60	145	86	HAW/ICM	1	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
GW106718	247480	6173463	35	35	93	58	HAW	1	2	**3**	**4**	5	6	7	8	9	10	11	12
GW106855	254574	6170957	39	59	146	107	HAW	1	**2**	**3**	**4**	**5**	6	7	8	9	10	11	12
GW106906	255615	6171846	0	72	150	150	HAW	1	**2**	**3**	4	5	6	7	8	9	10	11	12
GW106958	254688	6174591	82	138	168	86	HAW	1	2	**3**	4	5	6	7	8	9	10	11	12
GW107006	254526	6169294	64	90	175	111	HAW/ICM	1	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	12
GW107120	255737	6168916	0	85	132	132	HAW	1	2	**3**	4	5	6	7	8	9	10	11	12
GW107240	251555	6176142	10	14	42	32	HAW	1	**2**	3	4	5	6	7	8	9	10	11	12
GW107535	249655	6172612	13	13	114	101	HAW	1	**2**	**3**	**4**	**5**	**6**	7	8	9	10	11	12
GW107677	249069	6168592	44	44	66	22	HAW	1	2	**3**	4	5	6	7	8	9	10	11	12
GW107807	251666	6171294	31	113	121	90	HAW	1	2	3	**4**	5	6	7	8	9	10	11	12
GW107964	244325	6175286	60	63	96	36	HAW/ICM	1	2	3	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
GW108004	251939	6171152	21	113	121	100	HAW	1	2	3	4	**5**	6	7	8	9	10	11	12
GW108194	251005	6172692	24	36	122	98	HAW/ICM	1	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	11	12
GW108195	250939	6172001	28	36	126	98	HAW/ICM	1	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	11	12
GW108825	248345	6176790	52	52	79	27	HAW/ICM	1	2	3	4	**5**	**6**	**7**	**8**	**9**	10	11	12
GW108833	253326	6170528	48	66	85	37	HAW	1	2	**3**	4	5	6	7	8	9	10	11	12
GW109039	254164	6171137	44	44	120	76	HAW	1	**2**	**3**	4	5	6	7	8	9	10	11	12
GW109084	250446	6170161	20	20	139	119	HAW	1	**2**	**3**	**4**	**5**	6	7	8	9	10	11	12
GW109323	252286	6169562	68	72	132	64	HAW	1	2	**3**	**4**	5	6	7	8	9	10	11	12
GW109918	248938	6176472	27	27	102	75	HAW	1	2	**3**	**4**	**5**	**6**	7	8	9	10	11	12
GW110236	251246	6174064	17	54	108	91	HAW	1	2	3	**4**	**5**	6	7	8	9	10	11	12
GW111395	252658	6169198	54	90	121	67	HAW	1	2	**3**	4	5	6	7	8	9	10	11	12
GW111551	253185	6173686	23	60	78	55	HAW	1	2	**3**	4	5	6	7	8	9	10	11	12
GW111795	254408	6169883	98	102	156	58	HAW	1	2	**3**	**4**	5	6	7	8	9	10	11	12

Table 1. PRIVATE BORE DETAILS

Bore	Easting (mMGA)	Northing (mMGA)	Water Level (mbgl)*	Hydraulic Interval (mbgl) From	Hydraulic Interval (mbgl) To	Water Column# (m)	Intersected Strata^	Screened Model Layers											
GW112440	248577	6172089	0	66	91	91	HAW	1	2	**3**	4	5	6	7	8	9	10	11	12
GW114544	254189	6175327	20	20	36	16	WG	**1**	2	3	4	5	6	7	8	9	10	11	12
GW115061	249128	6176639	23	114	129	106	ICM	1	2	3	4	5	6	7	8	9	10	11	**12**
GW067521	253702	6168715	18	21	33	15	WG	**1**	2	3	4	5	6	7	8	9	10	11	12
GW106103%	253879	6167685	27	27	66	39	Basalt	**1**	(separate model)										

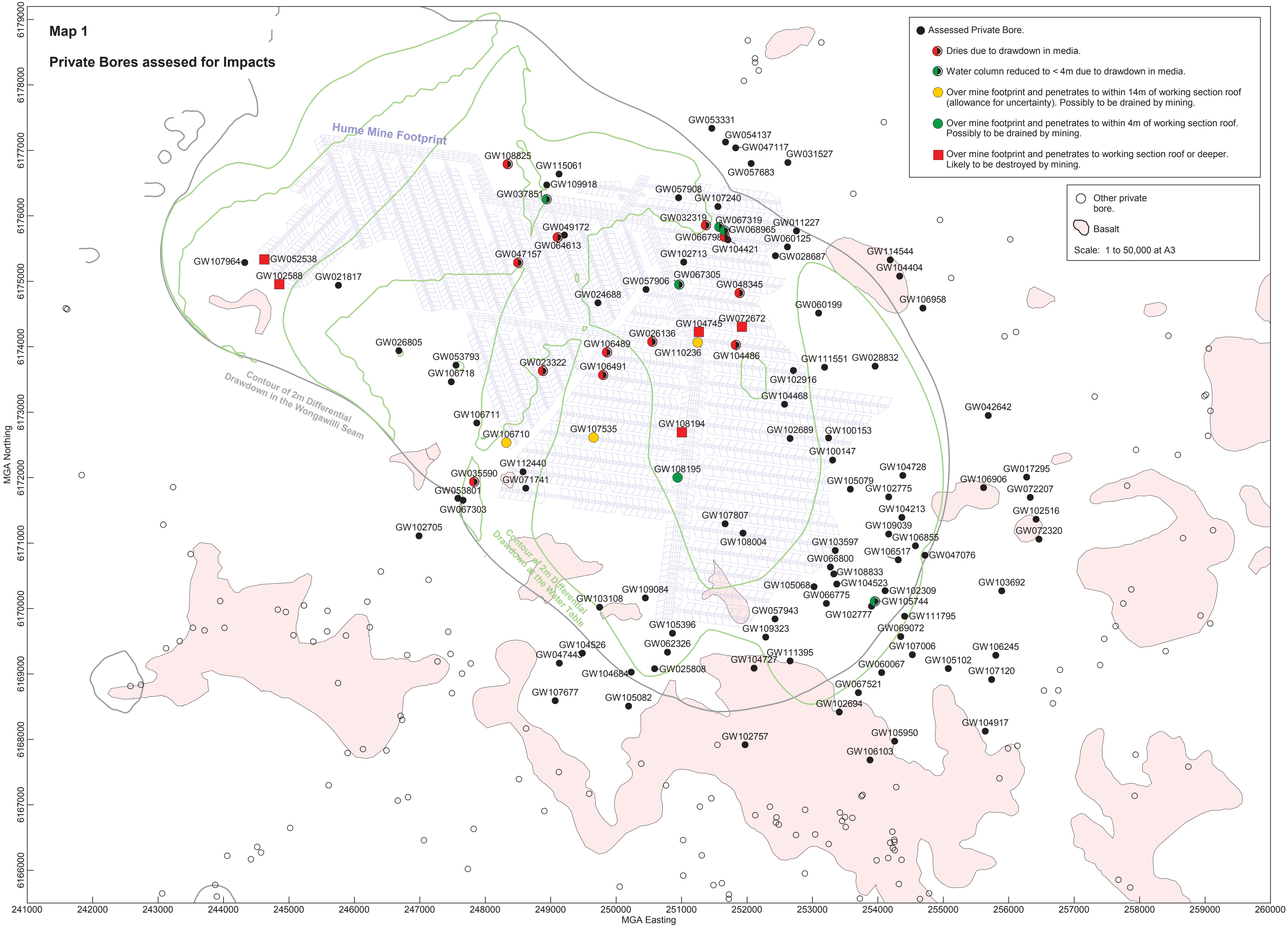
(cyan) No information for top of hydraulic interval, therefore set to recorded bore water level.
(grey) No information for top of hydraulic interval, therefore set to surrogate SWL (pre-mining water level from model).
(pink) Surrogate SWL (pre-mining water level from model).

^ HAW denotes Hawkesbury Sandstone, WG denotes Wianamatta Group, and ICM denotes Illawarra Coal Measures.

* Denotes metres below ground level.

% Drilled to 156m (into WG and HAW) but appears to have been backfilled.

The distance between the base of the bore and the pre-mining bore water level.



Map 1
Private Bores assesed for Impacts
Assessed Private Bore.
Dries due to drawdown in media.
Water column reduced to < 4m due to drawdown in media.
Over mine footprint and penetrates to within 14m of working section roof (allowance for uncertainty). Possibly to be drained by mining.
Over mine footprint and penetrates to within 4m of working section roof. Possibly to be drained by mining.
Over mine footprint and penetrates to working section roof or deeper. Likely to be destroyed by mining.
Other private bore.
Basalt
Scale: 1 to 50,000 at A3
Hume Mine Footprint
Contour of 2m Differential Drawdown in the Wongawilli Seam
Contour of 2m Differential Drawdown at the Water Table
GW053331
GW054137
GW047117
GW031527
GW057683
GW108825
GW115061
GW109918
GW037851
GW057908
GW107240
GW032319
GW067319
GW068965
GW011227
GW066798
GW060125
GW104421
GW028687
GW049172
GW064613
GW047157
GW102713
GW114544
GW104404
GW107964
GW052538
GW102588
GW021817
GW057906
GW067305
GW048345
GW024688
GW106958
GW060199
GW104745
GW072672
GW026136
GW026805
GW106489
GW110236
GW104486
GW053793
GW023322
GW111551
GW028832
GW106718
GW106491
GW102916
GW104468
GW042642
GW106711
GW108194
GW107535
GW102689
GW100153
GW106710
GW100147
GW112440
GW104728
GW017295
GW035590
GW071741
GW108195
GW105079
GW106906
GW053801
GW102775
GW072207
GW067303
GW104213
GW102516
GW107807
GW109039
GW072320
GW102705
GW108004
GW106855
GW103597
GW106517
GW047076
GW066800
GW108833
GW104523
GW105068
GW103692
GW109084
GW102309
GW066775
GW103108
GW105744
GW057943
GW102777
GW111795
GW105396
GW109323
GW069072
GW104526
GW062326
GW107006
GW047443
GW111395
GW104727
GW106245
GW105102
GW060067
GW104684
GW025808
GW107120
GW067521
GW107677
GW105082
GW102694
GW104917
GW105950
GW102757
GW106103
MGA Northing
MGA Easting
6179000
6178000
6177000
6176000
6175000
6174000
6173000
6172000
6171000
6170000
6169000
6168000
6167000
6166000
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Table 2. MODELLED IMPACTS ON PRIVATE BORES

Bore	Total Drawdown		Differential Drawdown				Proportion of max. total drawdown caused by Hume operations	Comment	
	Maximum (m)	Time to Maximum (Years)	Maximum (m)	Time to Maximum (Years)	Time to 2m drawdown (Years)	Time to 2m recovery (Years)		Drawdown (model)	Structural
GW011227	6.1	10.0	4.7	10.0	8.3	18.9	0.77		
GW017295	7.4	26.0	1.1	26.0	N/A *	N/A *	0.14		
GW021817	23.1	20.5	15.2	19.0	6.3	71.6	0.66		
GW023322	40.1	14.5	39.7	14.5	3.4	4.5	0.99	Goes dry	
GW024688	33.0	16.0	31.4	16.0	1.2	45.3	0.95		
GW025808	6.1	22.5	3.1	19.5	15.6	43.8	0.50		
GW026136	47.8	22.0	44.9	22.0	2.7	47.8	0.94	Goes dry	
GW026805	14.8	26.5	8.6	24.0	8.3	66.4	0.58		
GW028687	12.1	11.0	10.7	11.0	7.9	38.0	0.88		
GW028832	6.5	26.0	3.2	13.0	11.8	37.3	0.49		
GW031527	2.2	10.0	1.1	10.0	N/A *	N/A *	0.50		
GW032319	33.4	10.0	32.8	10.0	3.5	35.1	0.98	Goes dry	
GW035590	11.9	20.5	8.4	20.5	13.7	48.1	0.70	Goes dry	
GW037851	47.5	11.0	46.2	11.0	1.0	41.1	0.97	Water column reduces to < 4m	
GW042642	6.8	26.5	1.2	26.0	N/A *	N/A *	0.18		
GW047076	10.2	25.0	3.5	25.0	16.6	37.2	0.34		
GW047117	3.3	9.0	2.6	9.0	8.4	11.7	0.79		
GW047157	63.9	6.0	62.6	6.0	2.0	53.2	0.98	Goes dry	
GW047443	8.2	26.0	5.1	25.5	18.2	47.1	0.63		
GW048345	37.8	11.0	36.2	11.0	7.1	41.8	0.96	Goes dry	
GW049172	40.2	5.5	39.6	5.5	1.1	38.9	0.98		
GW052538	27.5	18.0	21.3	18.0	6.0	67.3	0.77		Over mine footprint and penetrates to working section roof or below. Likely to be intersected by mining
GW053331	2.4	3.0	2.0	3.0	2.9	3.0	0.83		
GW053793	24.2	16.5	20.1	16.0	8.0	58.2	0.83		
GW053801	8.1	22.5	5.0	21.5	20.1	44.7	0.62		
GW054137	3.1	9.5	2.4	9.5	8.6	11.3	0.77		
GW057683	3.5	9.0	2.9	9.0	8.1	11.8	0.83		
GW057906	40.9	12.0	39.8	12.0	1.1	43.1	0.97		
GW057908	14.9	10.0	14.5	10.0	6.7	28.0	0.97		
GW057943	9.2	17.0	4.2	15.5	14.2	48.3	0.46		
GW060067	11.4	26.0	4.6	25.5	17.4	46.4	0.40		
GW060125	9.5	10.0	8.0	10.0	7.7	36.8	0.85		
GW060199	9.2	13.0	6.6	12.5	9.4	40.2	0.71		
GW062326	13.9	22.0	10.5	22.0	14.7	54.8	0.76		
GW064613	52.1	5.0	51.5	5.0	1.1	41.0	0.99	Goes dry	
GW066775	15.2	17.5	9.9	17.5	14.1	55.5	0.65		

Table 2. MODELLED IMPACTS ON PRIVATE BORES

Bore	Total Drawdown		Differential Drawdown				Proportion of max. total drawdown caused by Hume operations	Comment	
	Maximum (m)	Time to Maximum (Years)	Maximum (m)	Time to Maximum (Years)	Time to 2m drawdown (Years)	Time to 2m recovery (Years)		Drawdown (model)	Structural
GW066798	34.7	10.0	34.0	10.0	6.0	36.9	0.98	Goes dry	
GW066800	14.5	17.0	9.1	17.0	13.6	53.0	0.63		
GW067303	8.7	22.0	5.7	21.5	16.3	46.4	0.65		
GW067305	0.3	7.5	0.0	7.5	N/A *	N/A *	0.01	Water column reduces to < 4m	
GW067319	20.6	10.0	19.9	10.0	5.1	34.9	0.97	Water column reduces to < 4m	
GW068965	19.9	10.0	19.2	10.0	6.1	34.9	0.96	Water column reduces to < 4m	
GW069072	9.4	25.5	4.2	25.5	17.0	43.2	0.44		
GW071741	22.3	18.5	18.9	18.5	12.7	55.7	0.85		
GW072207	7.4	26.0	1.2	25.5	N/A *	N/A *	0.16		
GW072320	7.6	26.0	1.1	25.5	N/A *	N/A *	0.14		
GW072672	48.6	12.0	46.3	12.0	7.8	45.2	0.95		Over mine footprint and penetrates to working section roof or below. Likely to be intersected by mining
GW100147	16.4	15.0	12.3	15.0	11.4	48.1	0.75		
GW100153	16.0	15.0	12.0	15.0	10.7	46.9	0.75		
GW102309	11.3	25.5	4.8	23.0	15.2	43.3	0.42		
GW102516	7.7	26.0	1.0	25.5	N/A *	N/A *	0.13		
GW102588	22.8	18.0	20.3	18.0	6.2	69.5	0.89		Over mine footprint and penetrates to working section roof or below. Likely to be intersected by mining
GW102689	17.8	15.0	11.9	15.0	12.2	43.7	0.67		
GW102694	12.3	28.5	0.0	2.5	N/A *	N/A *	0.00		
GW102705	4.4	32.0	1.8	27.0	N/A *	N/A *	0.41		
GW102713	45.8	11.5	45.0	11.5	2.2	38.8	0.98		
GW102757	4.0	31.0	2.4	28.5	23.0	37.5	0.61		
GW102775	10.6	16.5	5.9	16.0	13.1	42.8	0.56		
GW102777	11.8	25.5	5.5	22.5	15.0	46.4	0.46		
GW102916	39.6	12.0	36.6	12.0	9.1	50.3	0.92		
GW103108	13.1	23.5	9.8	23.0	15.6	56.2	0.75		
GW103597	14.7	17.0	9.4	17.0	13.4	52.0	0.64		
GW103692	8.4	26.0	1.6	25.5	N/A *	N/A *	0.19		
GW104213	10.2	17.0	5.2	16.5	13.8	42.2	0.51		
GW104404	5.0	27.5	1.6	13.5	N/A *	N/A *	0.31		
GW104421	20.6	10.0	19.9	10.0	6.1	36.7	0.96		
GW104468	22.2	13.0	18.5	13.0	9.9	49.0	0.84		
GW104486	44.1	12.5	41.5	12.5	8.1	46.3	0.94	Goes dry	

Table 2. MODELLED IMPACTS ON PRIVATE BORES

Bore	Total Drawdown		Differential Drawdown				Proportion of max.	Comment	
	Maximum (m)	Time to Maximum (Years)	Maximum (m)	Time to Maximum (Years)	Time to 2m drawdown (Years)	Time to 2m recovery (Years)	total drawdown caused by Hume operations	Drawdown (model)	Structural
GW104523	17.1	17.0	11.9	17.0	13.5	55.8	0.70		
GW104526	8.9	25.0	5.9	24.5	16.9	48.1	0.66		
GW104684	9.7	23.5	6.7	23.0	15.9	48.7	0.69		
GW104727	15.1	23.5	9.8	22.5	15.1	57.2	0.65		
GW104728	9.2	17.0	4.7	16.5	13.0	40.6	0.52		
GW104745	44.7	13.0	42.6	13.0	7.1	43.9	0.95		Over mine footprint and penetrates to working section roof or below. Likely to be intersected by mining
GW104917	8.4	31.0	1.4	27.0	N/A *	N/A *	0.17		
GW105068	21.9	17.0	16.8	17.0	13.3	57.8	0.77		
GW105079	15.1	16.0	10.6	16.0	12.2	48.4	0.70		
GW105082	6.1	25.5	3.8	25.0	18.2	42.0	0.62		
GW105102	8.6	26.0	2.5	25.5	22.4	35.0	0.29		
GW105396	19.1	21.0	15.4	21.0	14.1	56.8	0.81		
GW105744	11.5	25.5	5.1	22.5	15.1	45.1	0.45	Water column reduces to < 4m	
GW105950	10.0	32.5	2.9	28.5	23.1	42.9	0.29		
GW106245	8.5	26.5	1.5	26.0	N/A *	N/A *	0.18		
GW106489	56.6	21.0	54.2	21.0	2.1	53.6	0.96	Goes dry	
GW106491	72.7	21.0	70.0	21.0	3.0	55.9	0.96	Goes dry	
GW106517	10.8	25.5	4.4	22.5	16.1	41.4	0.41		
GW106710	35.4	14.0	32.3	14.0	11.1	55.3	0.91		Over mine footprint and penetrates to within 14m of working section roof (allowance for uncertainty). Possibly to be drained by mining.
GW106711	13.8	20.0	9.7	20.0	12.3	45.9	0.71		
GW106718	20.6	21.0	15.4	21.0	11.7	59.5	0.75		
GW106855	10.4	25.5	3.8	23.0	15.1	38.7	0.37		
GW106906	7.7	25.5	1.6	25.5	N/A *	N/A *	0.21		
GW106958	5.4	28.0	1.4	14.5	N/A *	N/A *	0.26		
GW107006	6.7	26.0	3.7	25.5	20.5	42.1	0.54		
GW107120	8.6	27.0	1.7	26.0	N/A *	N/A *	0.19		
GW107240	15.4	10.0	14.8	10.0	6.1	31.5	0.96		
GW107535	62.0	20.0	58.6	20.0	13.5	52.9	0.95		Over mine footprint and penetrates to within 14m of working section roof (allowance for uncertainty). Possibly to be drained by mining.
GW107677	4.9	28.5	2.6	27.0	22.0	38.9	0.52		
GW107807	64.0	17.0	59.7	17.0	12.1	60.3	0.93		
GW107964	18.6	20.5	12.5	20.5	6.5	64.0	0.67		
GW108004	84.2	16.0	80.0	16.0	12.2	61.5	0.95		

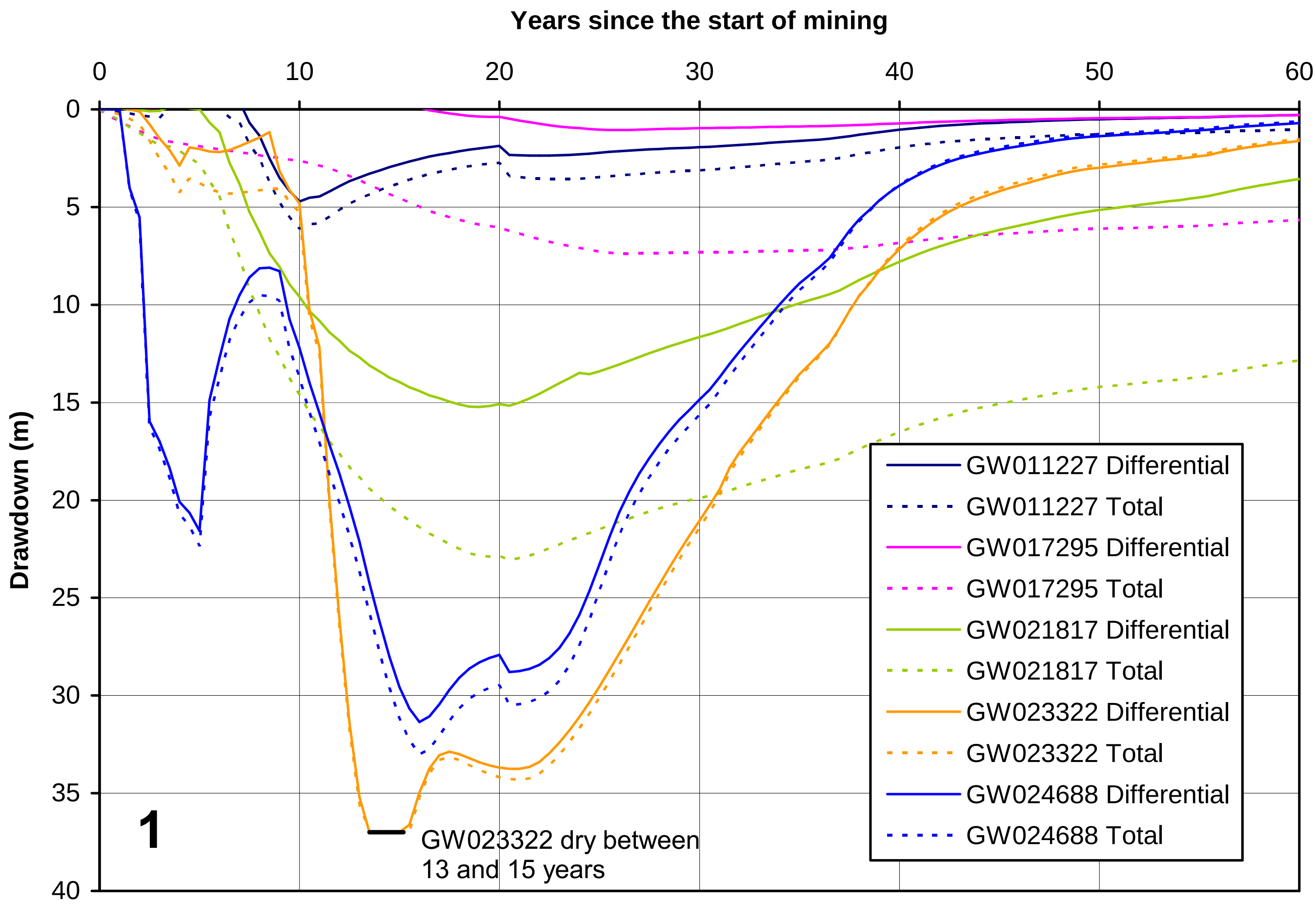
Table 2. MODELLED IMPACTS ON PRIVATE BORES

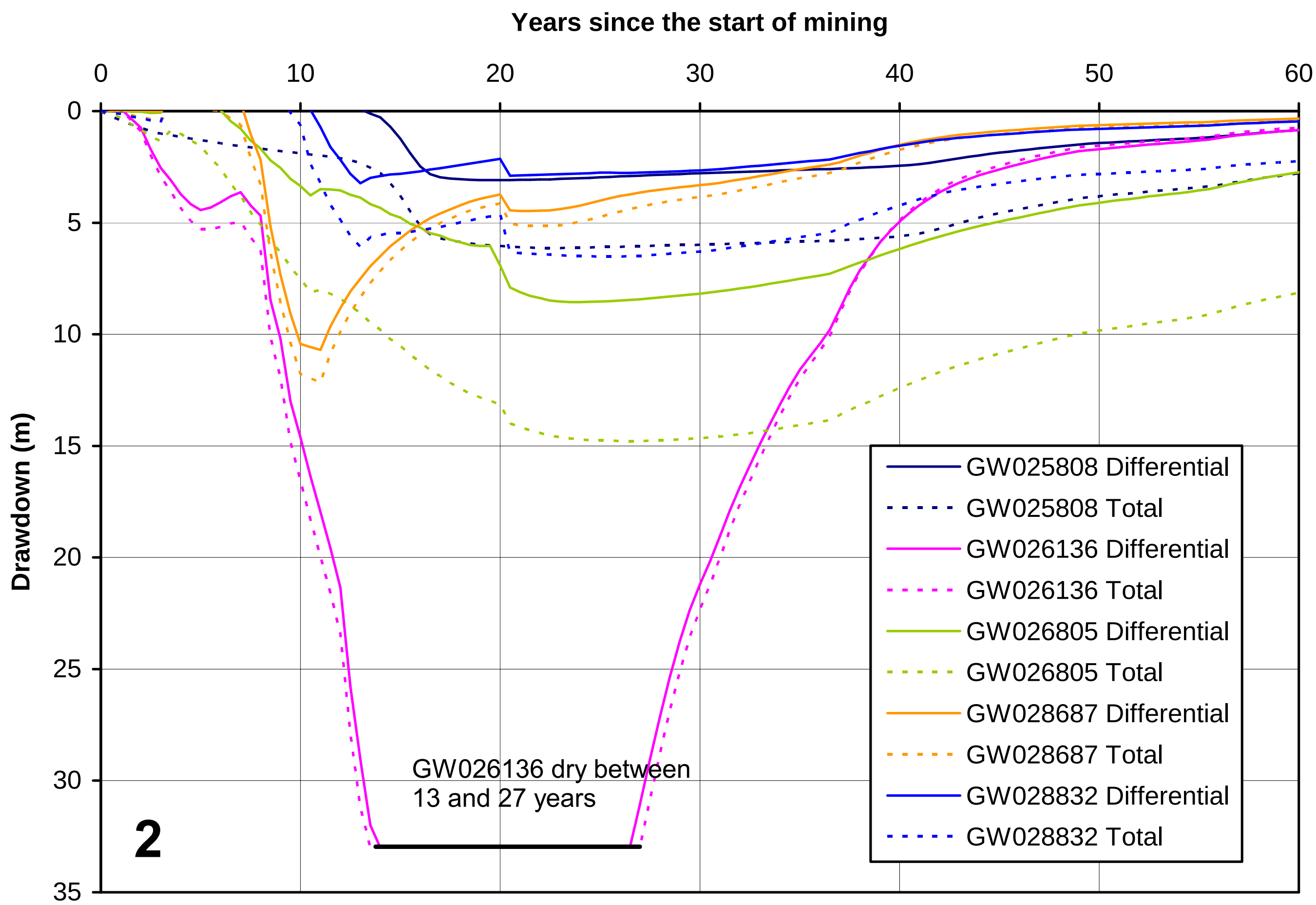
Bore	Total Drawdown		Differential Drawdown				Proportion of max. total drawdown caused by Hume operations	Comment	
	Maximum (m)	Time to Maximum (Years)	Maximum (m)	Time to Maximum (Years)	Time to 2m drawdown (Years)	Time to 2m recovery (Years)		Drawdown (model)	Structural
GW108194	48.8	22.0	44.6	22.0	14.5	48.0	0.91		Over mine footprint and penetrates to working section roof or below. Likely to be intersected by mining
GW108195	49.4	21.5	45.0	21.5	15.1	49.5	0.91		Over mine footprint and penetrates to within 4m of working section roof. Possibly to be drained by mining
GW108825	29.6	12.0	27.4	11.5	2.0	52.7	0.92	Goes dry	
GW108833	19.4	17.0	14.3	17.0	13.3	56.4	0.74		
GW109039	11.0	17.0	5.8	17.0	13.8	43.5	0.53		
GW109084	20.3	21.0	16.6	21.0	13.9	56.7	0.82		
GW109323	20.1	20.5	14.8	20.5	14.5	59.0	0.74		
GW109918	28.5	11.0	27.3	11.0	1.1	39.3	0.96		
GW110236	57.5	15.5	55.1	15.5	8.0	44.3	0.96		Over mine footprint and penetrates to within 14m of working section roof (allowance for uncertainty). Possibly to be drained by mining.
GW111395	14.7	24.0	8.8	22.5	15.1	56.5	0.60		
GW111551	15.6	12.0	12.7	12.0	9.4	45.1	0.82		
GW111795	9.3	25.5	3.8	25.5	17.5	41.3	0.41		
GW112440	33.0	18.0	29.6	18.0	11.8	56.9	0.90		
GW114544	5.0	28.0	1.3	14.5	N/A *	N/A *	0.26		
GW115061	22.1	11.0	21.1	11.0	1.1	37.1	0.96		
GW067521	9.3	18.5	5.0	18.0	13.4	31.5	0.54		
GW106103	0.14	20.7	0.07	20.0	N/A *	N/A *	0.52		

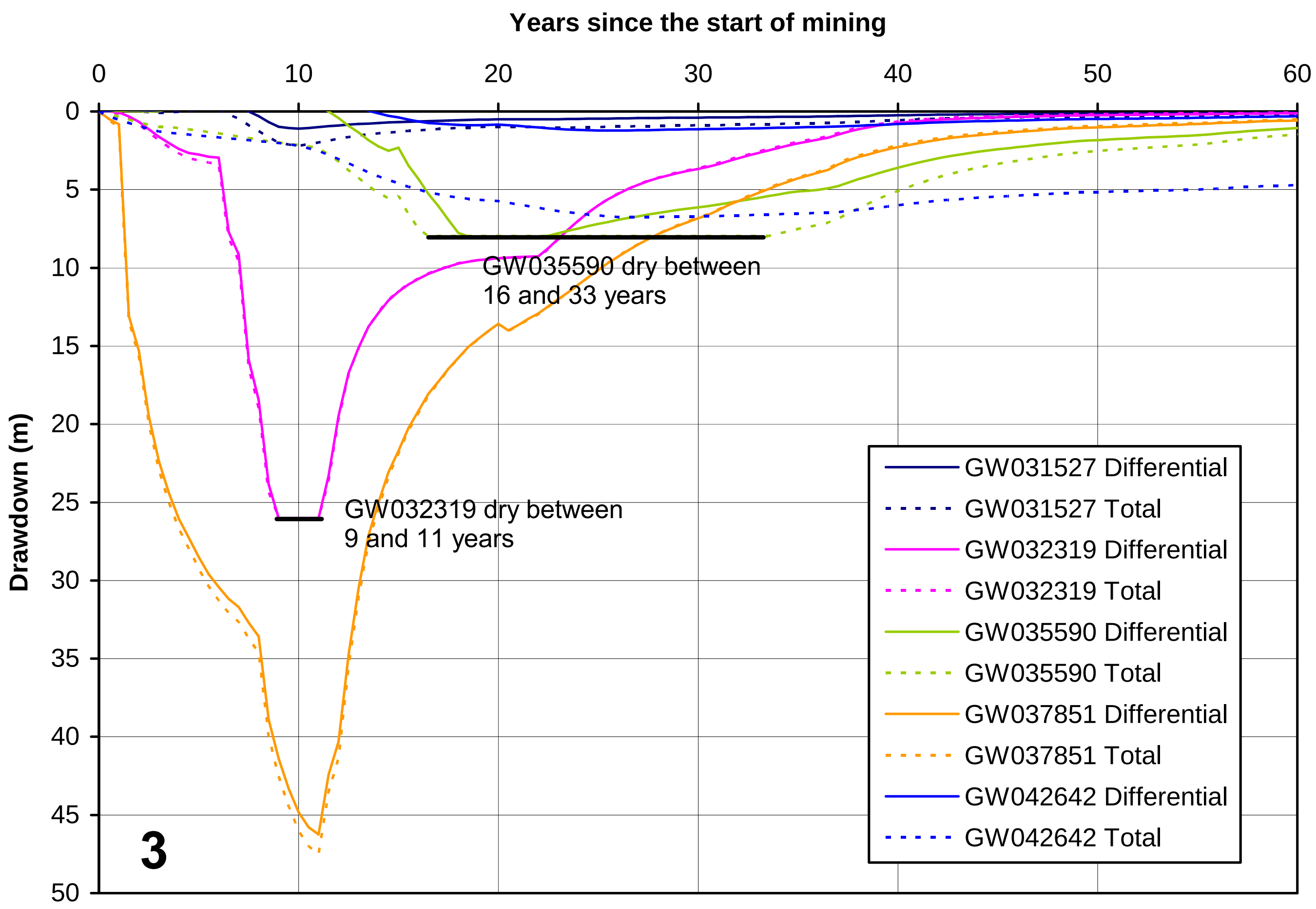
* Differential drawdown is less than 2m.

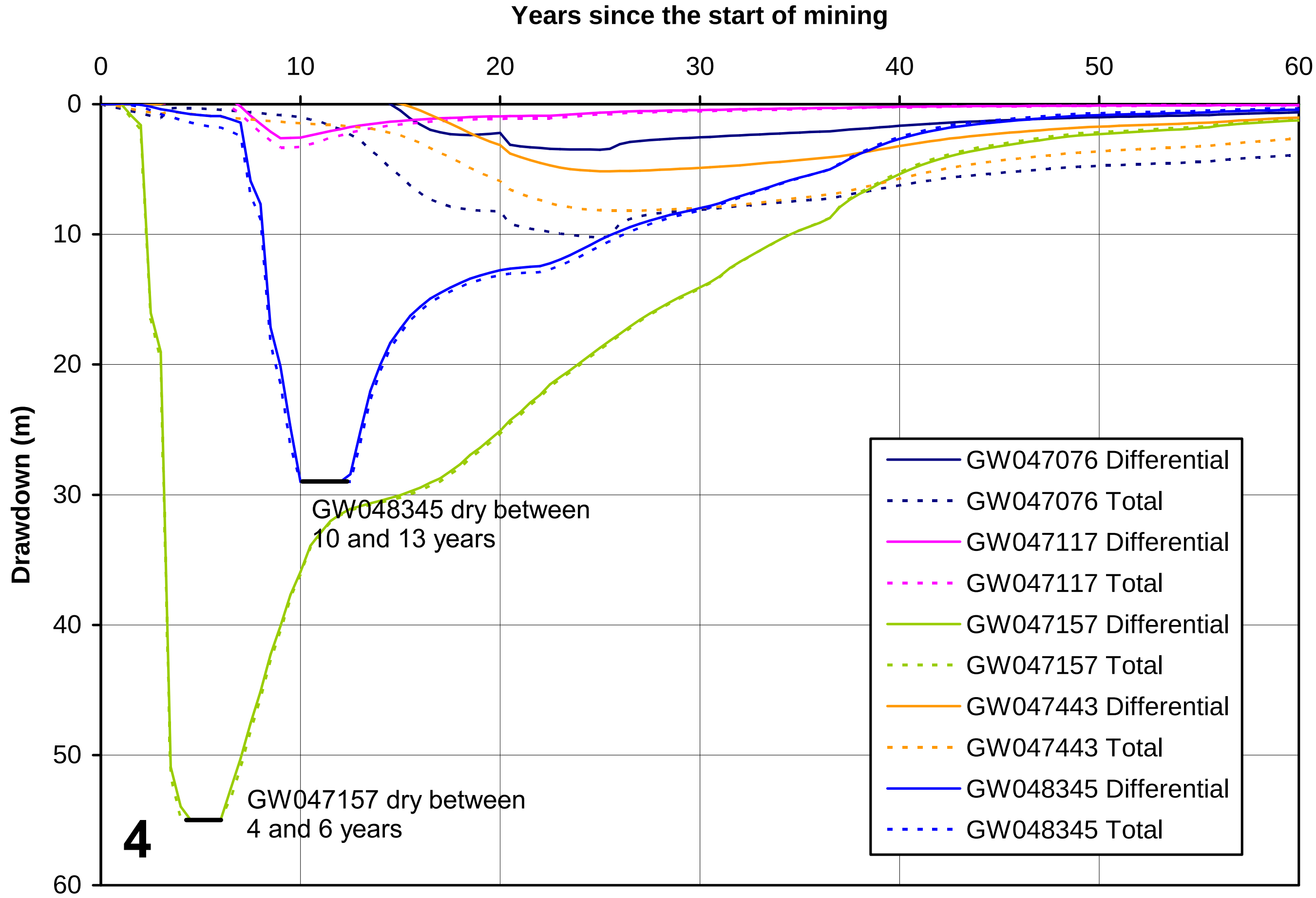
PRIVATE BORE CHART REGISTER

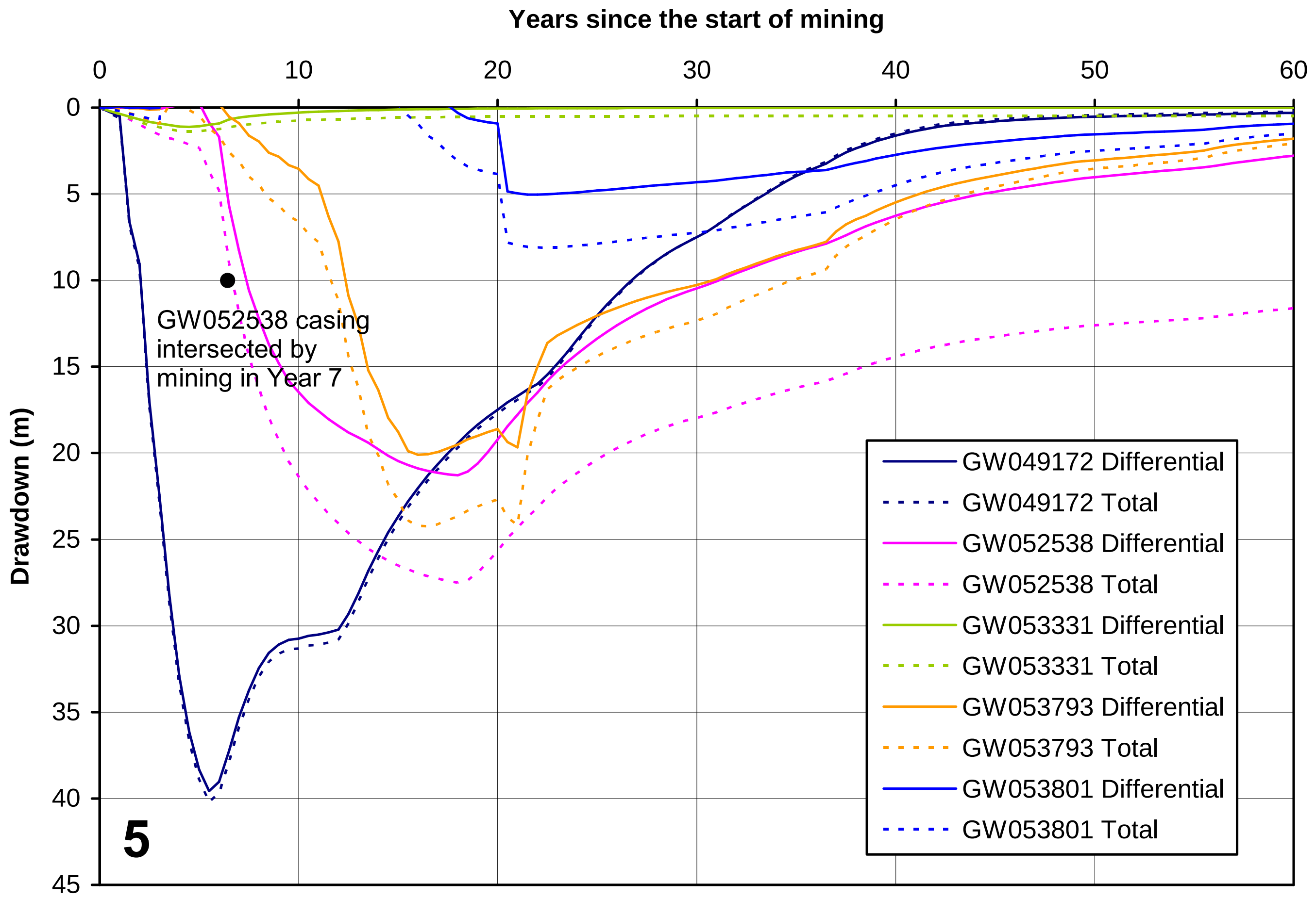
Bore	Chart	Bore	Chart	Bore	Chart
GW011227	1	GW072320	10	GW106906	19
GW017295		GW072672		GW106958	
GW021817		GW100147		GW107006	
GW023322		GW100153		GW107120	
GW024688		GW102309		GW107240	
GW025808	2	GW102516	11	GW107535	20
GW026136		GW102588		GW107677	
GW026805		GW102689		GW107807	
GW028687		GW102694		GW107964	
GW028832		GW102705		GW108004	
GW031527	3	GW102713	12	GW108194	21
GW032319		GW102757		GW108195	
GW035590		GW102775		GW108825	
GW037851		GW102777		GW108833	
GW042642		GW102916		GW109039	
GW047076	4	GW103108	13	GW109084	22
GW047117		GW103597		GW109323	
GW047157		GW103692		GW109918	
GW047443		GW104213		GW110236	
GW048345		GW104404		GW111395	
GW049172	5	GW104421	14	GW111551	23
GW052538		GW104468		GW111795	
GW053331		GW104486		GW112440	
GW053793		GW104523		GW114544	
GW053801		GW104526		GW115061	
GW054137	6	GW104684	15	GW102694	24
GW057683		GW104727		GW106103	
GW057906		GW104728			
GW057908		GW104745			
GW057943		GW104917			
GW060067	7	GW105068	16		
GW060125		GW105079			
GW060199		GW105082			
GW062326		GW105102			
GW064613		GW105396			
GW066775	8	GW105744	17		
GW066798		GW105950			
GW066800		GW106245			
GW067303		GW106489			
GW067305		GW106491			
GW067319	9	GW106517	18		
GW068965		GW106710			
GW069072		GW106711			
GW071741		GW106718			
GW072207		GW106855			


Years since the start of mining
0
10
20
30
40
50
60
0
5
10
15
20
25
30
35
40
Drawdown (m)
1
GW023322 dry between
13 and 15 years
GW011227 Differential
GW011227 Total
GW017295 Differential
GW017295 Total
GW021817 Differential
GW021817 Total
GW023322 Differential
GW023322 Total
GW024688 Differential
GW024688 Total

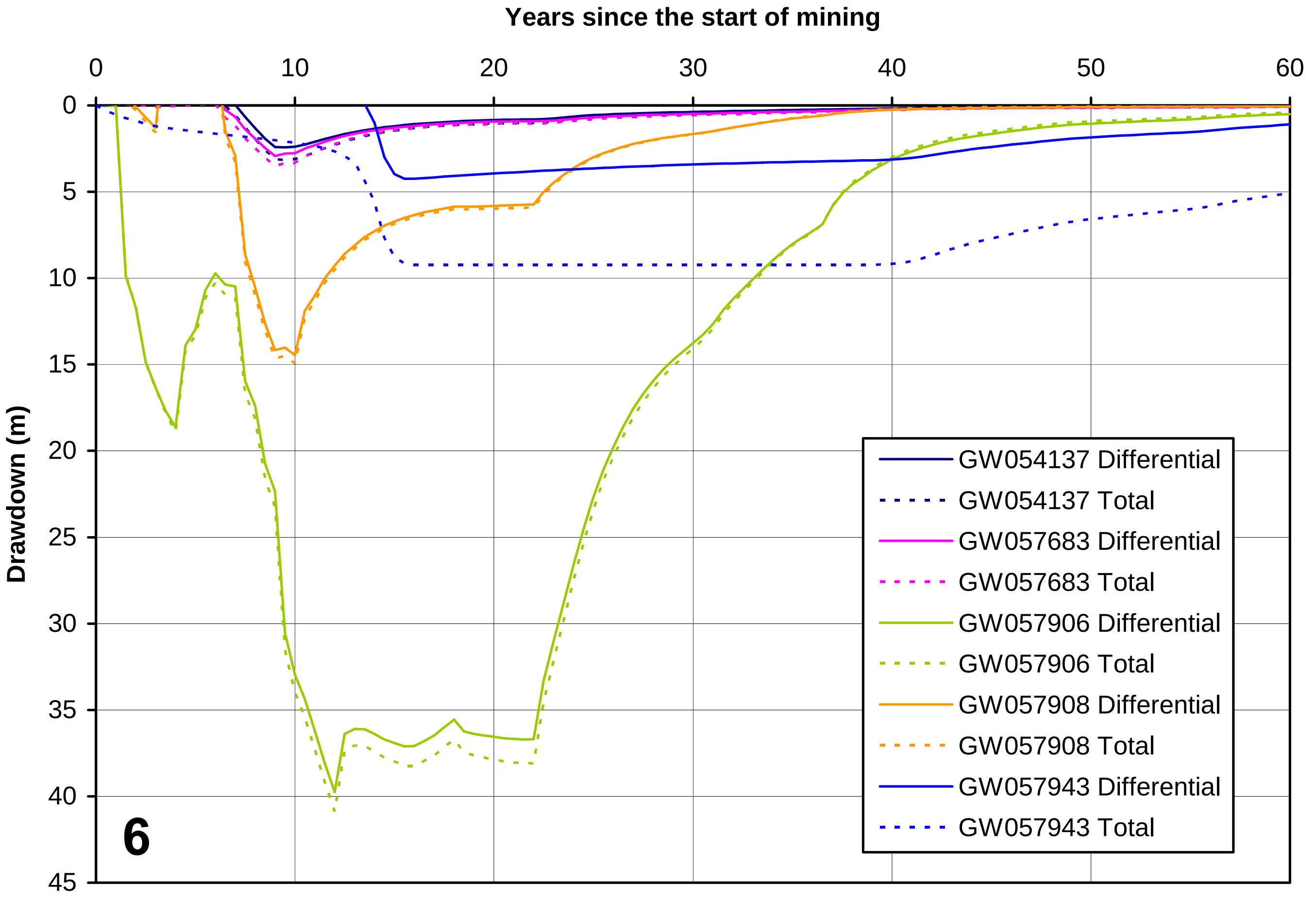

Years since the start of mining
0
10
20
30
40
50
60
0
5
10
15
20
25
30
35
Drawdown (m)
2
GW026136 dry between
13 and 27 years
GW025808 Differential
GW025808 Total
GW026136 Differential
GW026136 Total
GW026805 Differential
GW026805 Total
GW028687 Differential
GW028687 Total
GW028832 Differential
GW028832 Total


Years since the start of mining
0
10
20
30
40
50
60
0
5
10
15
20
25
30
35
40
45
50
Drawdown (m)
GW035590 dry between
16 and 33 years
GW032319 dry between
9 and 11 years
3
GW031527 Differential
GW031527 Total
GW032319 Differential
GW032319 Total
GW035590 Differential
GW035590 Total
GW037851 Differential
GW037851 Total
GW042642 Differential
GW042642 Total

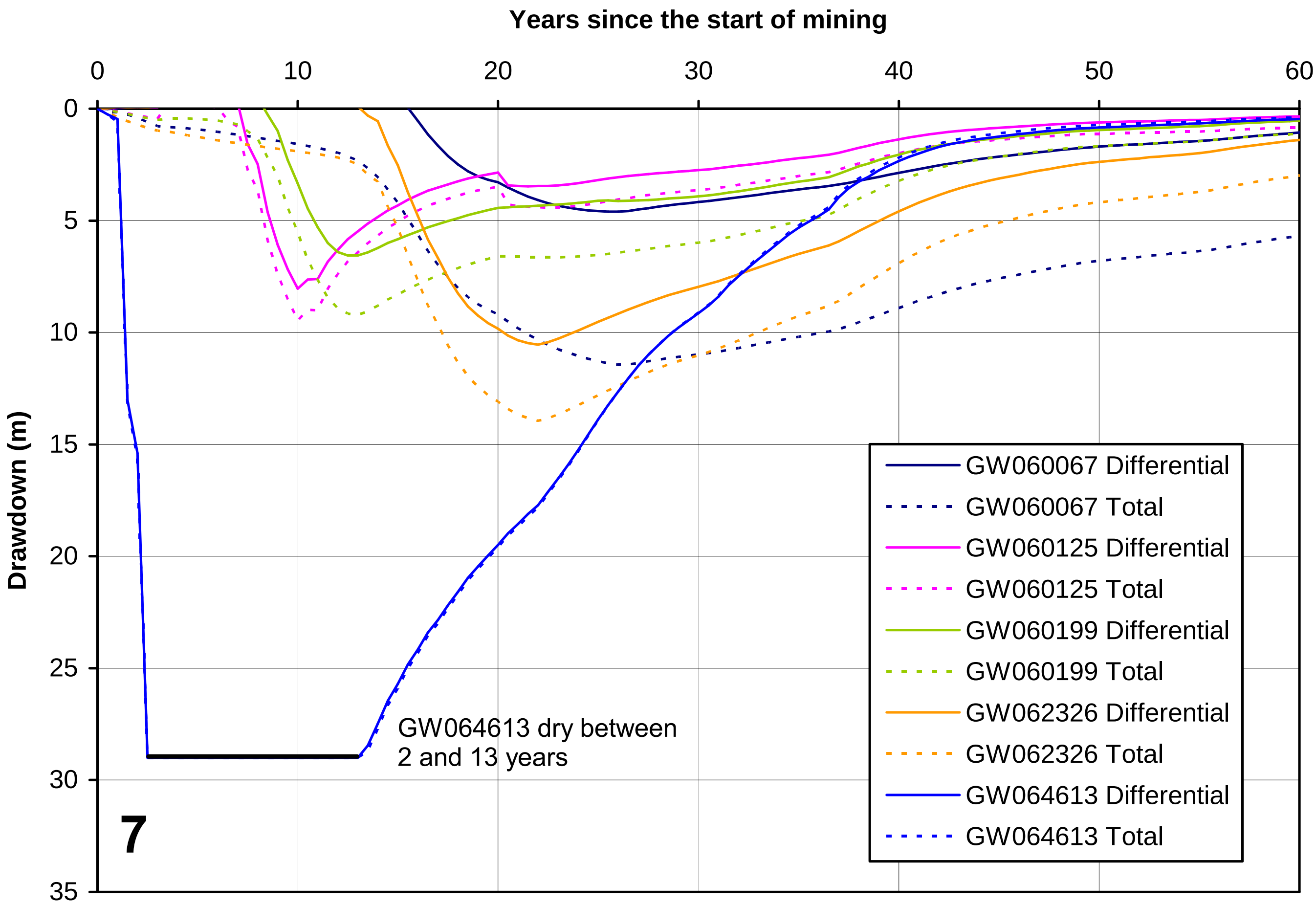

Years since the start of mining
0
10
20
30
40
50
60
0
10
20
30
40
50
60
Drawdown (m)
GW048345 dry between
10 and 13 years
GW047157 dry between
4 and 6 years
4
GW047076 Differential
GW047076 Total
GW047117 Differential
GW047117 Total
GW047157 Differential
GW047157 Total
GW047443 Differential
GW047443 Total
GW048345 Differential
GW048345 Total

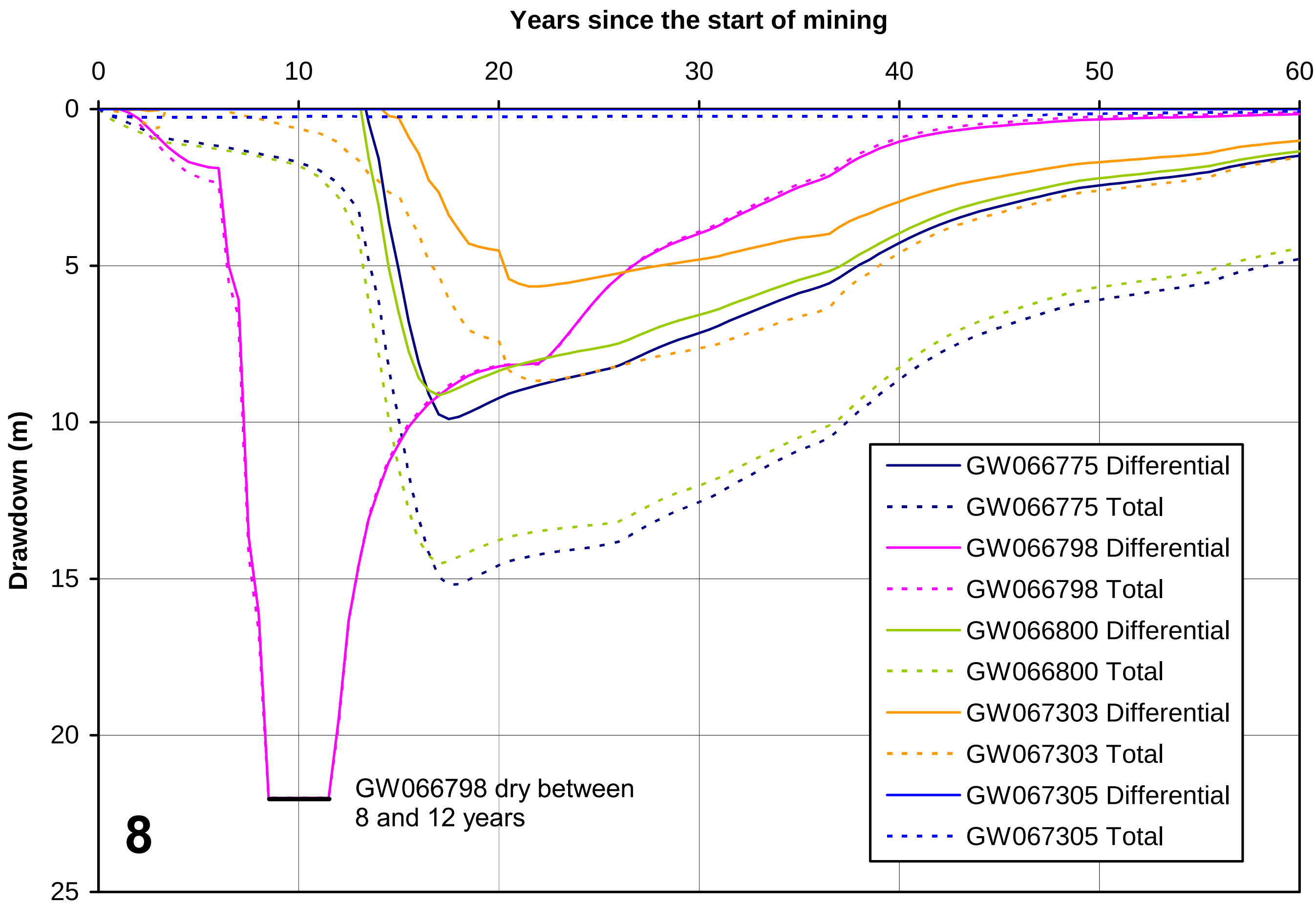


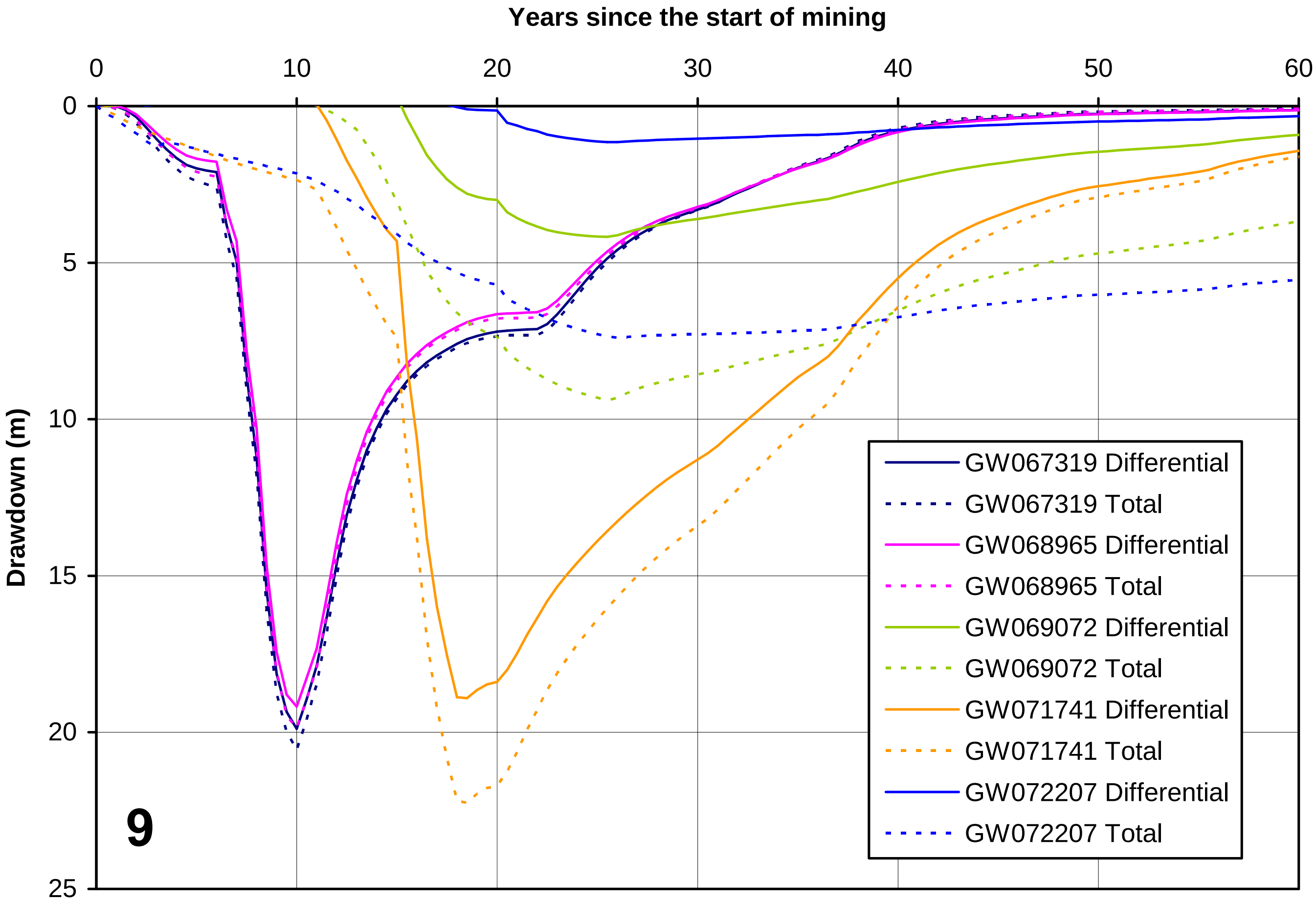
Years since the start of mining
0
10
20
30
40
50
60
Drawdown (m)
0
5
10
15
20
25
30
35
40
45
GW052538 casing intersected by mining in Year 7
GW049172 Differential
GW049172 Total
GW052538 Differential
GW052538 Total
GW053331 Differential
GW053331 Total
GW053793 Differential
GW053793 Total
GW053801 Differential
GW053801 Total
5

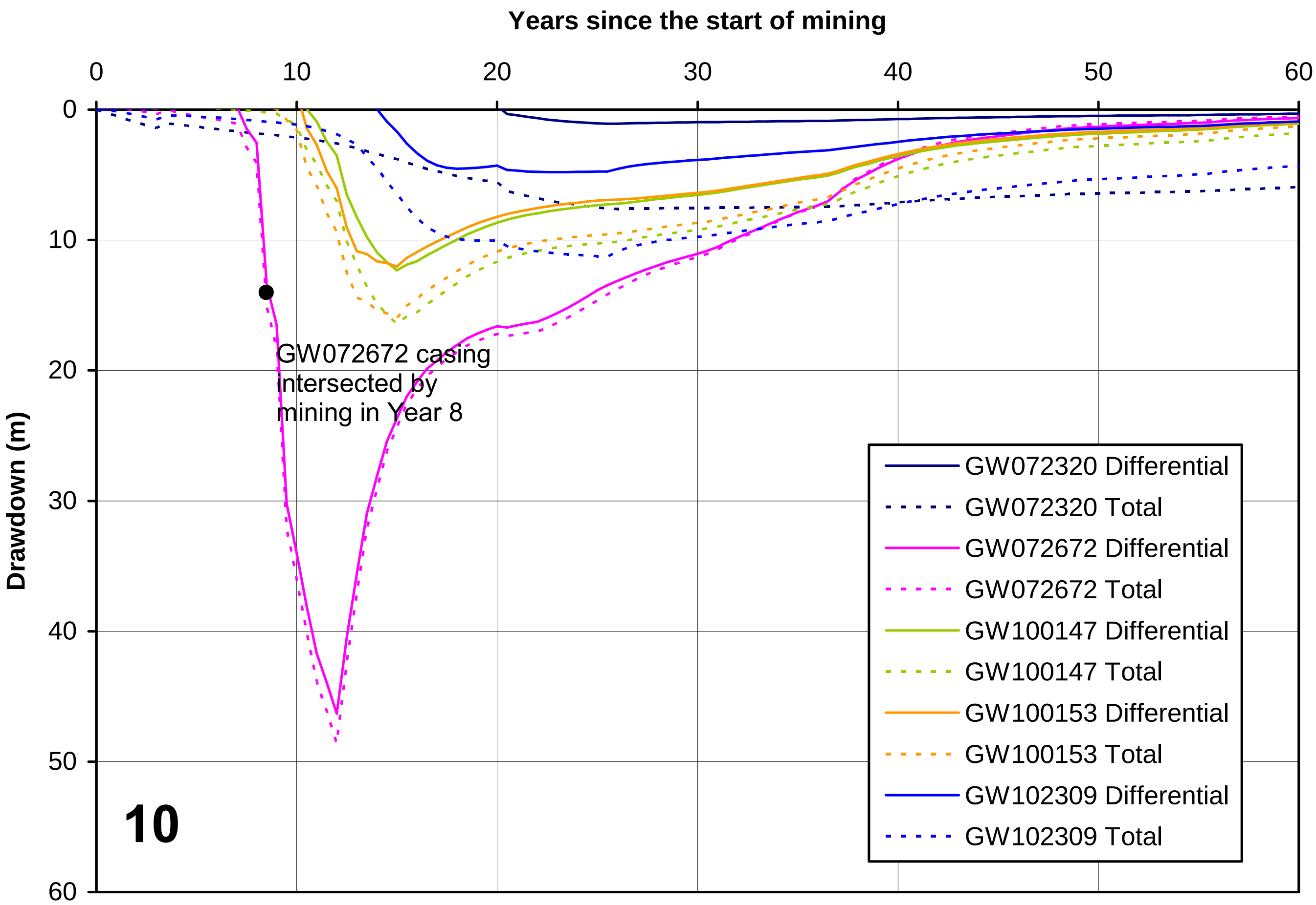


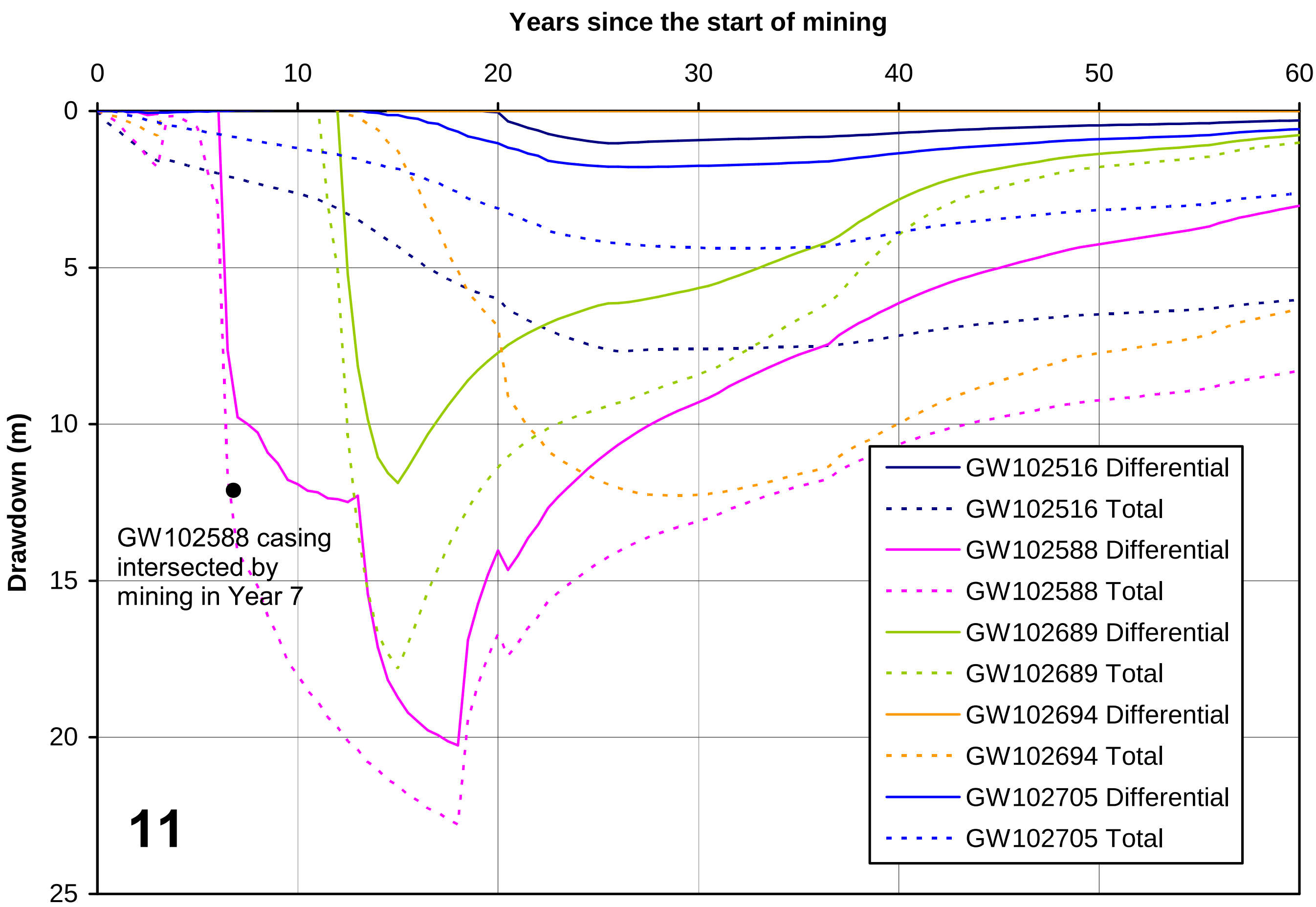
Years since the start of mining
0
10
20
30
40
50
60
Drawdown (m)
0
5
10
15
20
25
30
35
40
45
GW054137 Differential
GW054137 Total
GW057683 Differential
GW057683 Total
GW057906 Differential
GW057906 Total
GW057908 Differential
GW057908 Total
GW057943 Differential
GW057943 Total
6


Years since the start of mining
0
10
20
30
40
50
60
Drawdown (m)
0
5
10
15
20
25
30
35
GW064613 dry between
2 and 13 years
7
GW060067 Differential
GW060067 Total
GW060125 Differential
GW060125 Total
GW060199 Differential
GW060199 Total
GW062326 Differential
GW062326 Total
GW064613 Differential
GW064613 Total

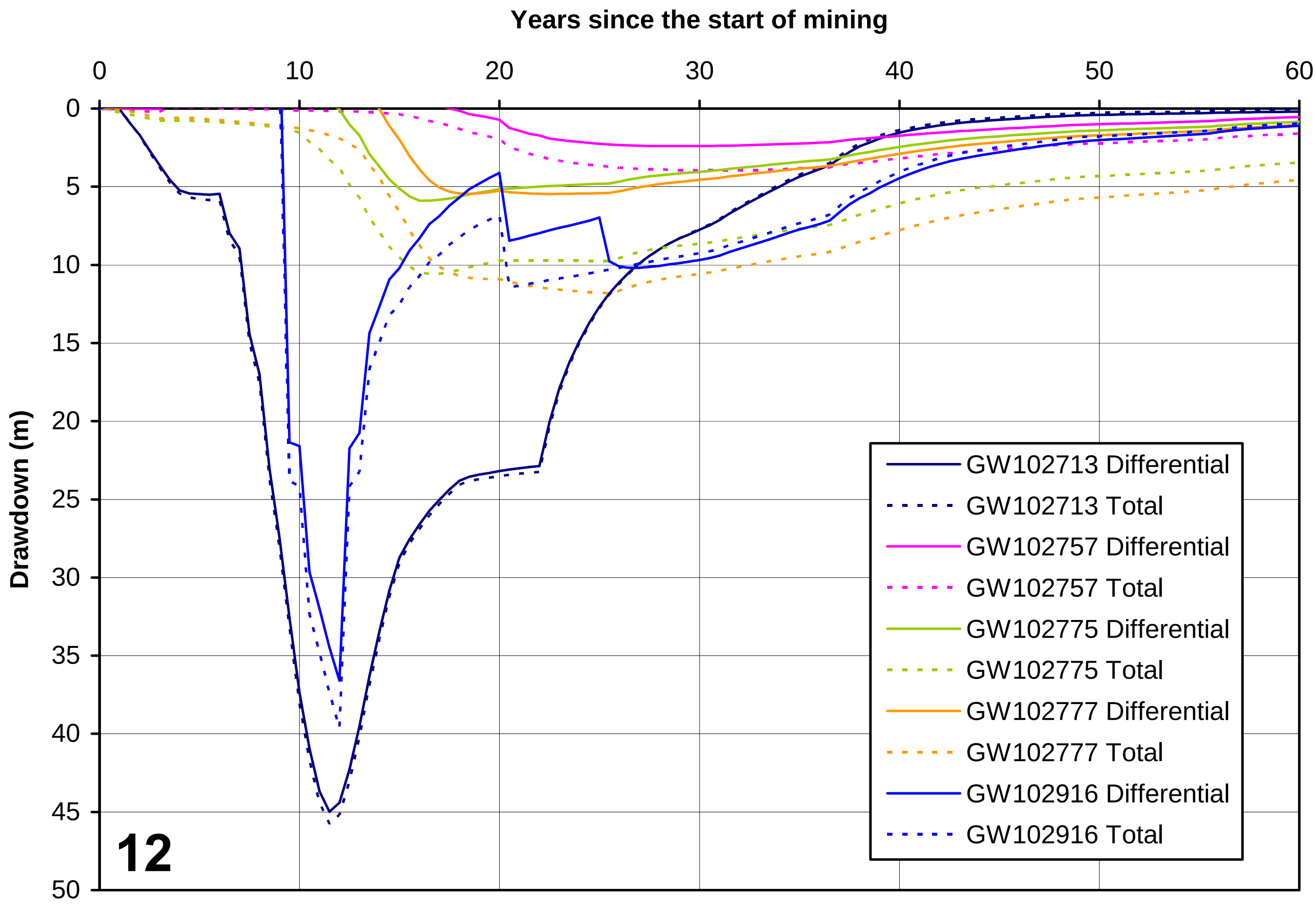

Years since the start of mining
0
10
20
30
40
50
60
Drawdown (m)
0
5
10
15
20
25
GW066798 dry between
8 and 12 years
8
GW066775 Differential
GW066775 Total
GW066798 Differential
GW066798 Total
GW066800 Differential
GW066800 Total
GW067303 Differential
GW067303 Total
GW067305 Differential
GW067305 Total


Years since the start of mining
0
10
20
30
40
50
60
0
5
10
15
20
25
Drawdown (m)
9
GW067319 Differential
GW067319 Total
GW068965 Differential
GW068965 Total
GW069072 Differential
GW069072 Total
GW071741 Differential
GW071741 Total
GW072207 Differential
GW072207 Total

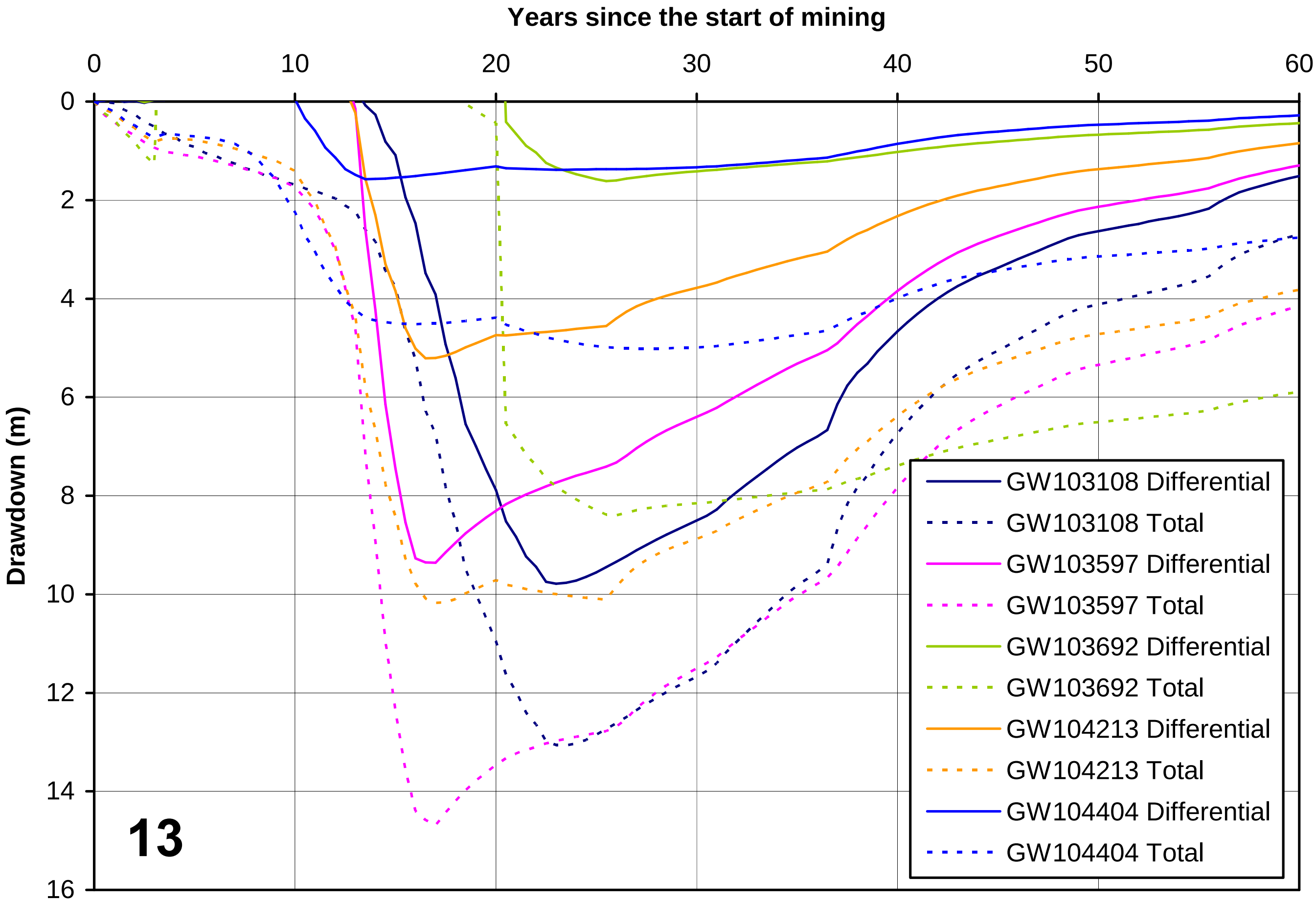

Years since the start of mining
0
10
20
30
40
50
60
0
10
20
30
40
50
60
Drawdown (m)
GW072672 casing
intersected by
mining in Year 8
10
GW072320 Differential
GW072320 Total
GW072672 Differential
GW072672 Total
GW100147 Differential
GW100147 Total
GW100153 Differential
GW100153 Total
GW102309 Differential
GW102309 Total



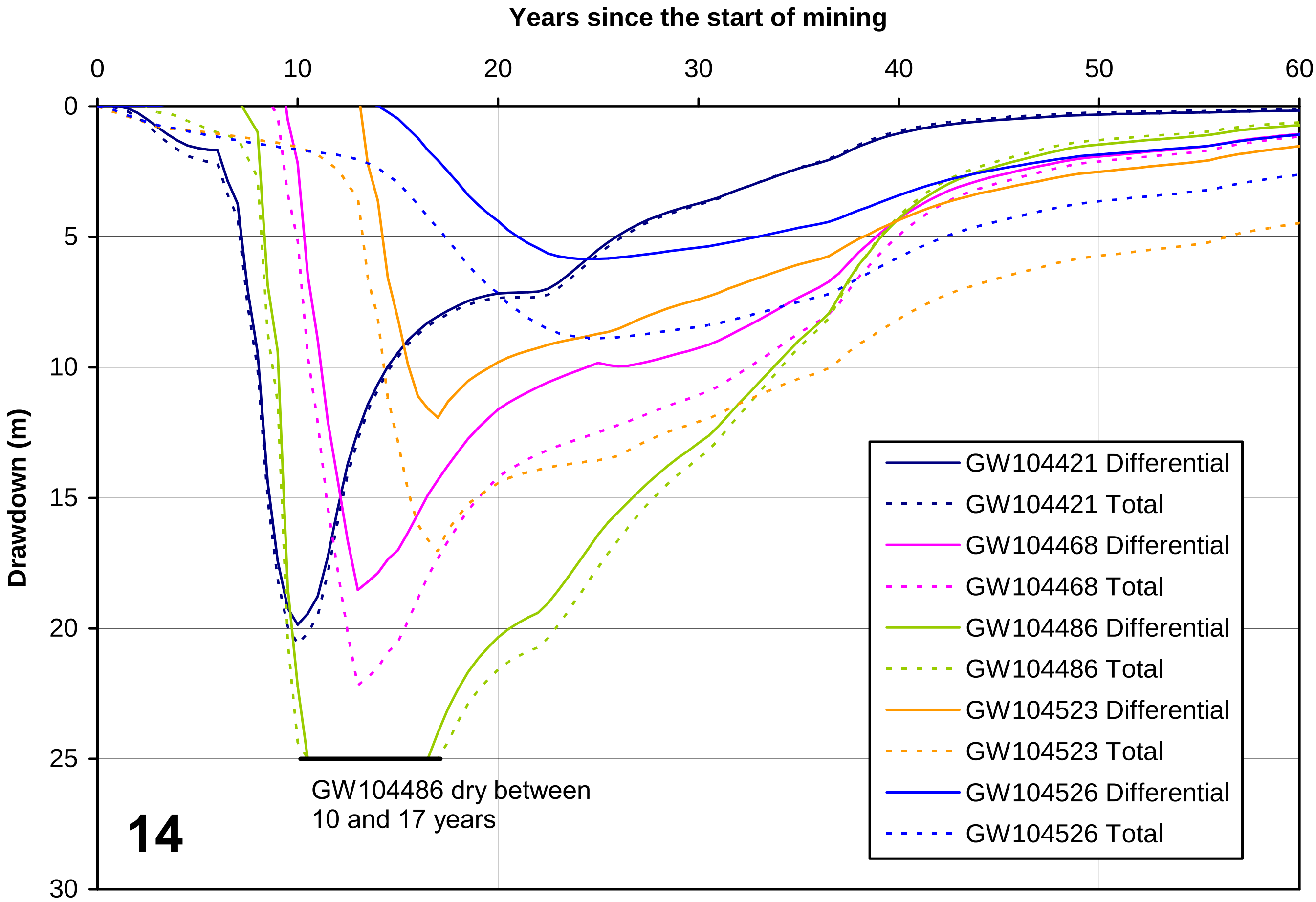
Years since the start of mining
0
10
20
30
40
50
60
0
5
10
15
20
25
Drawdown (m)
GW102588 casing intersected by mining in Year 7
11
GW102516 Differential
GW102516 Total
GW102588 Differential
GW102588 Total
GW102689 Differential
GW102689 Total
GW102694 Differential
GW102694 Total
GW102705 Differential
GW102705 Total



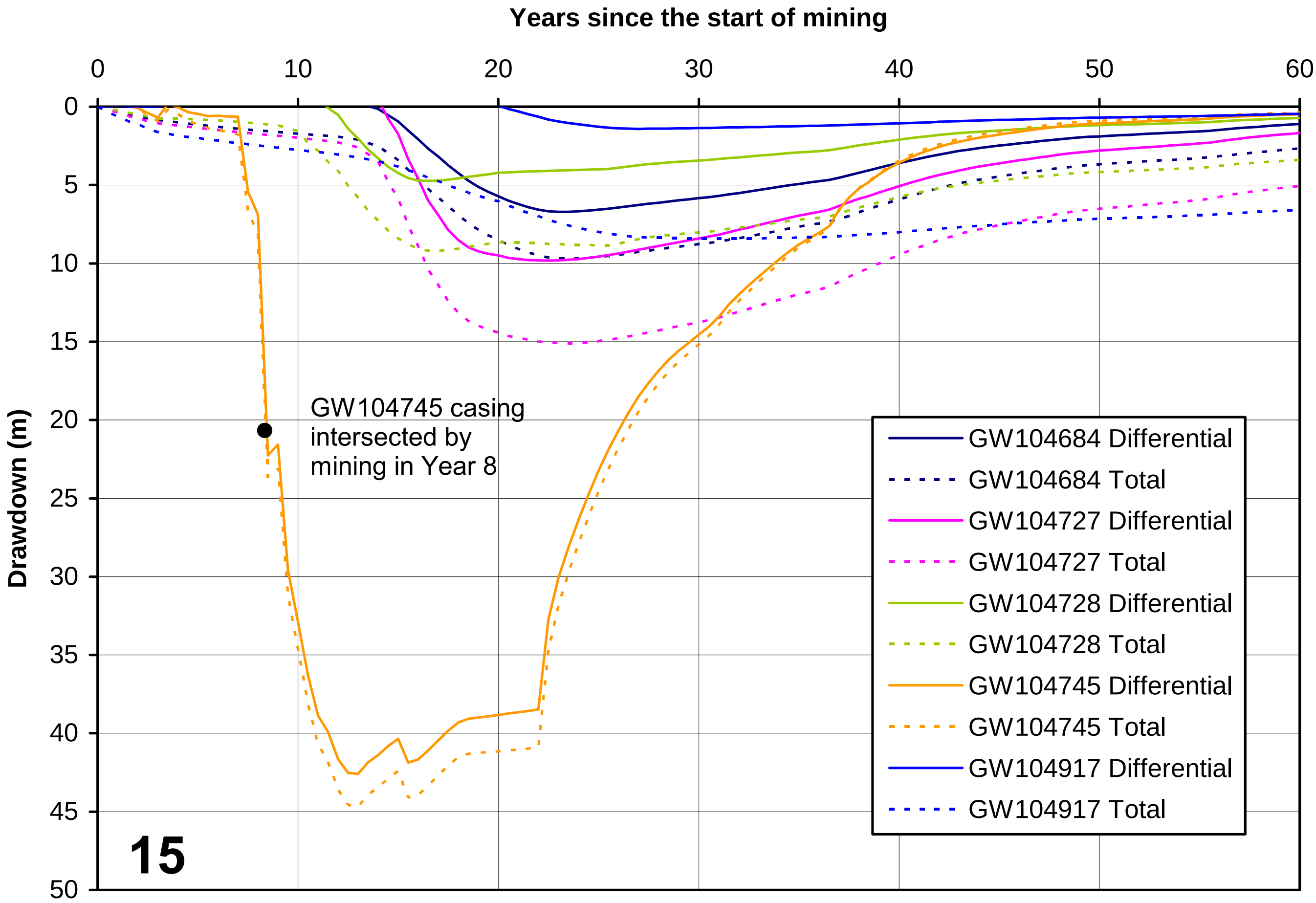
Years since the start of mining
0
10
20
30
40
50
60
0
5
10
15
20
25
30
35
40
45
50
Drawdown (m)
12
GW102713 Differential
GW102713 Total
GW102757 Differential
GW102757 Total
GW102775 Differential
GW102775 Total
GW102777 Differential
GW102777 Total
GW102916 Differential
GW102916 Total

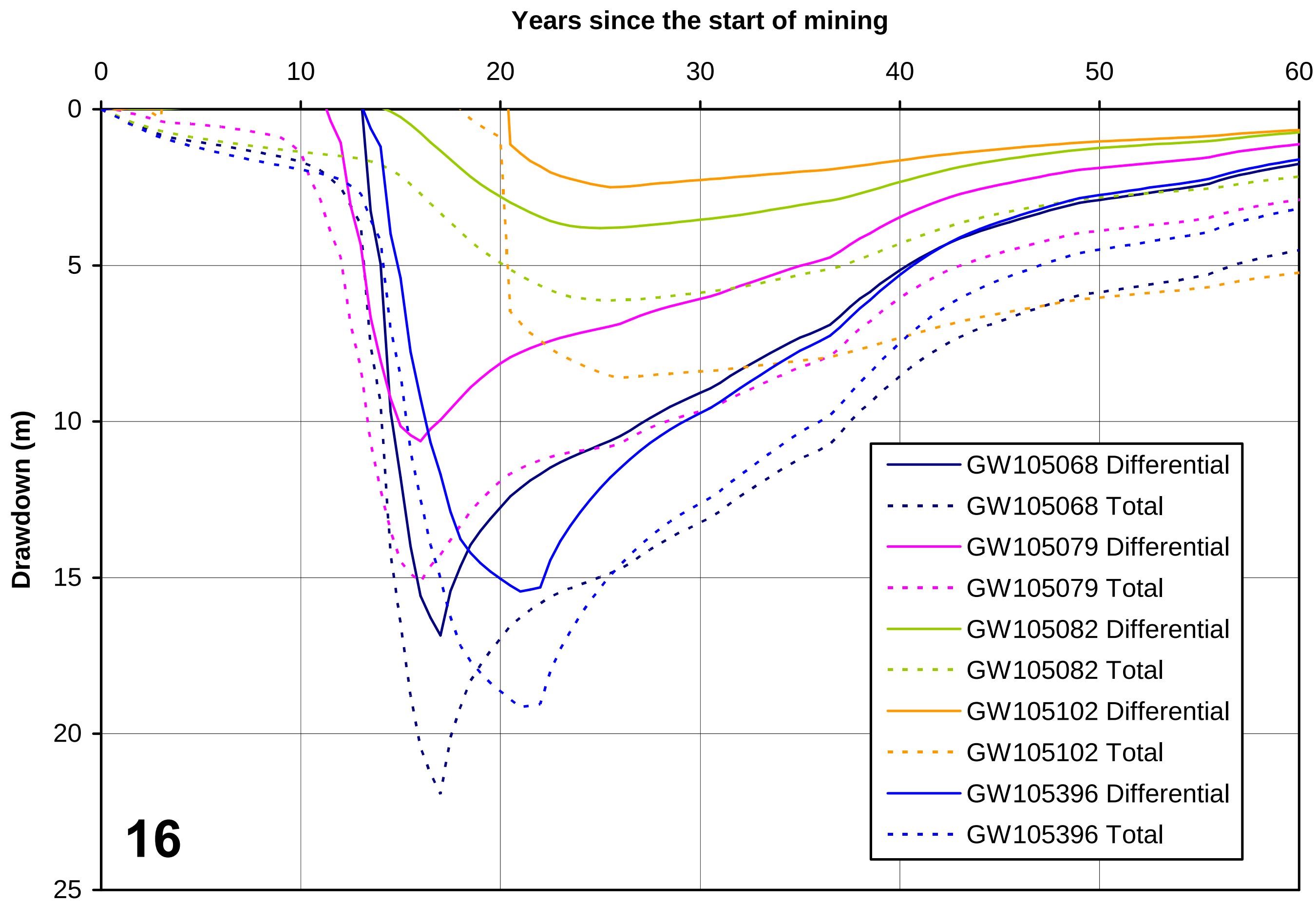


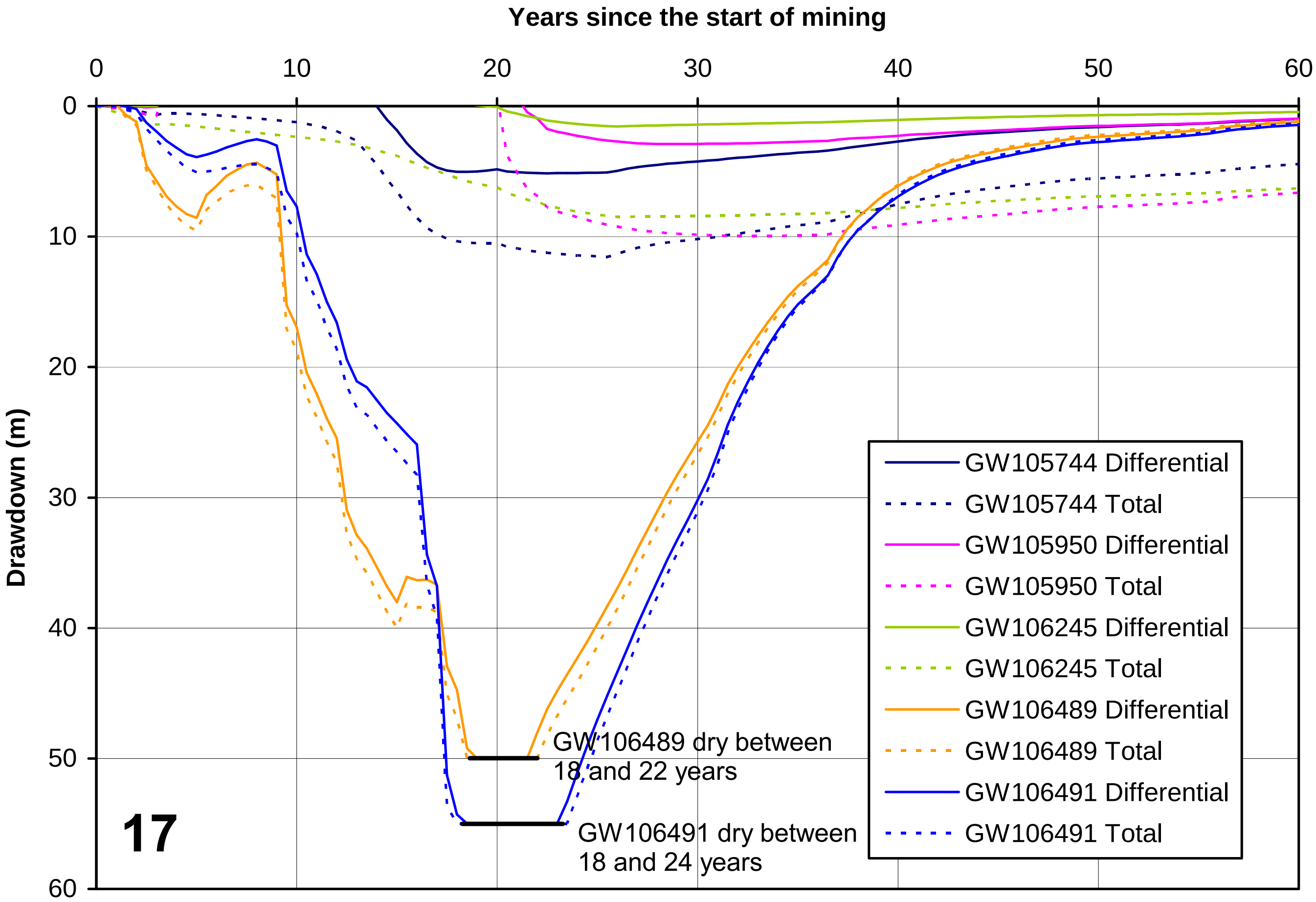
Years since the start of mining
0
10
20
30
40
50
60
0
2
4
6
8
10
12
14
16
Drawdown (m)
13
GW103108 Differential
GW103108 Total
GW103597 Differential
GW103597 Total
GW103692 Differential
GW103692 Total
GW104213 Differential
GW104213 Total
GW104404 Differential
GW104404 Total

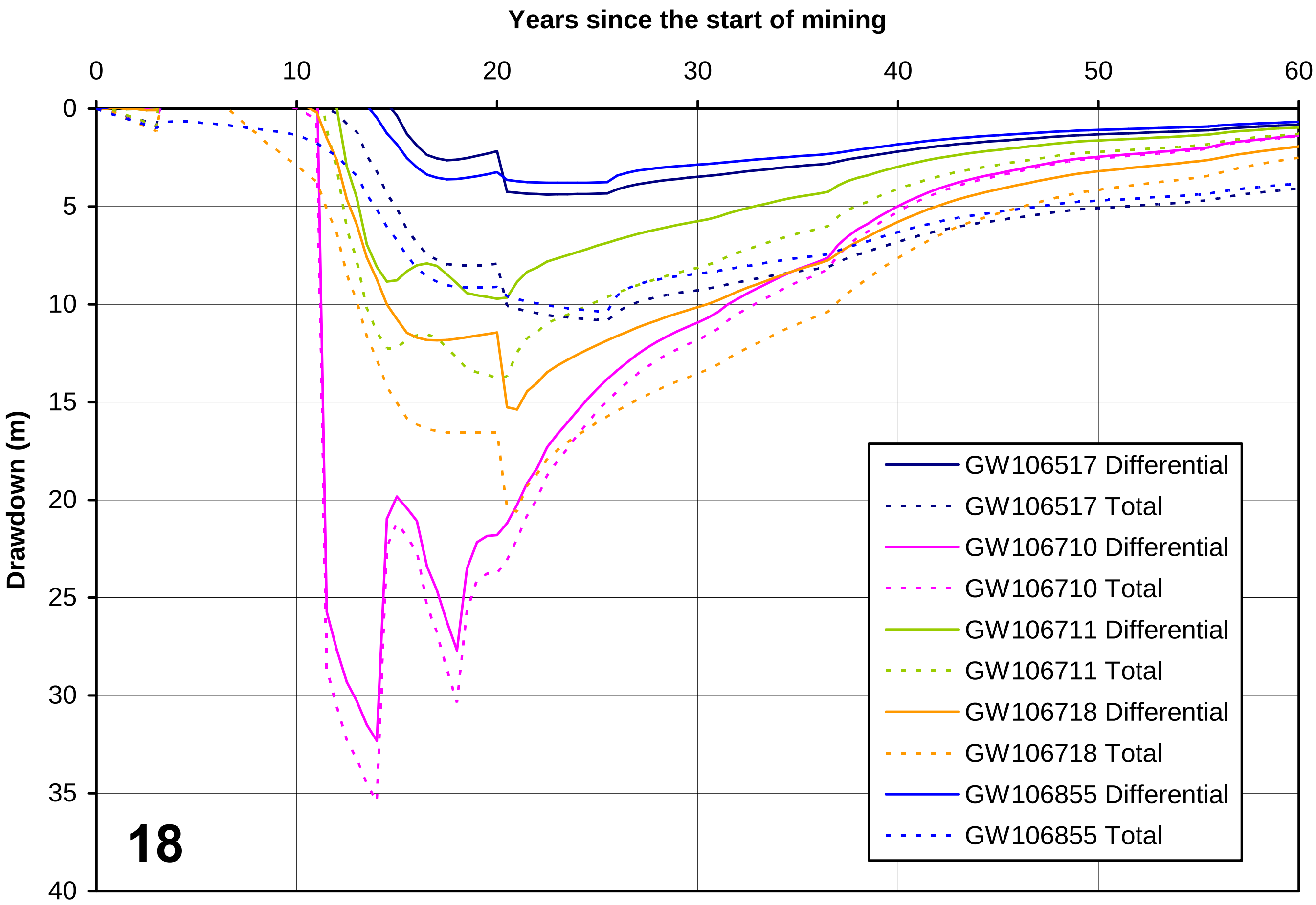


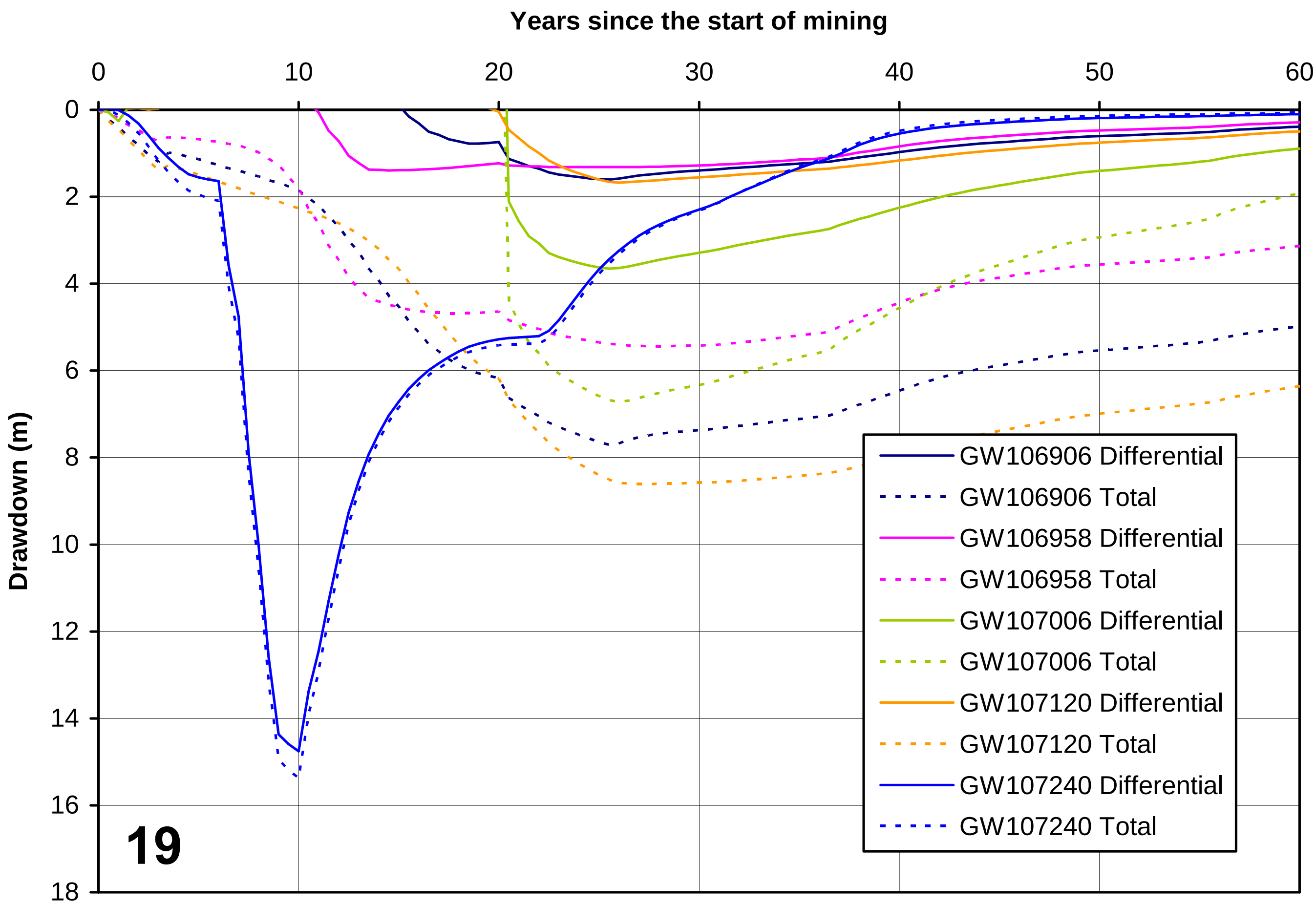
Years since the start of mining
0
10
20
30
40
50
60
0
5
10
15
20
25
30
Drawdown (m)
14
GW104486 dry between
10 and 17 years
GW104421 Differential
GW104421 Total
GW104468 Differential
GW104468 Total
GW104486 Differential
GW104486 Total
GW104523 Differential
GW104523 Total
GW104526 Differential
GW104526 Total


Years since the start of mining
0
10
20
30
40
50
60
0
5
10
15
20
25
30
35
40
45
50
Drawdown (m)
GW104745 casing
intersected by
mining in Year 8
GW104684 Differential
GW104684 Total
GW104727 Differential
GW104727 Total
GW104728 Differential
GW104728 Total
GW104745 Differential
GW104745 Total
GW104917 Differential
GW104917 Total
15

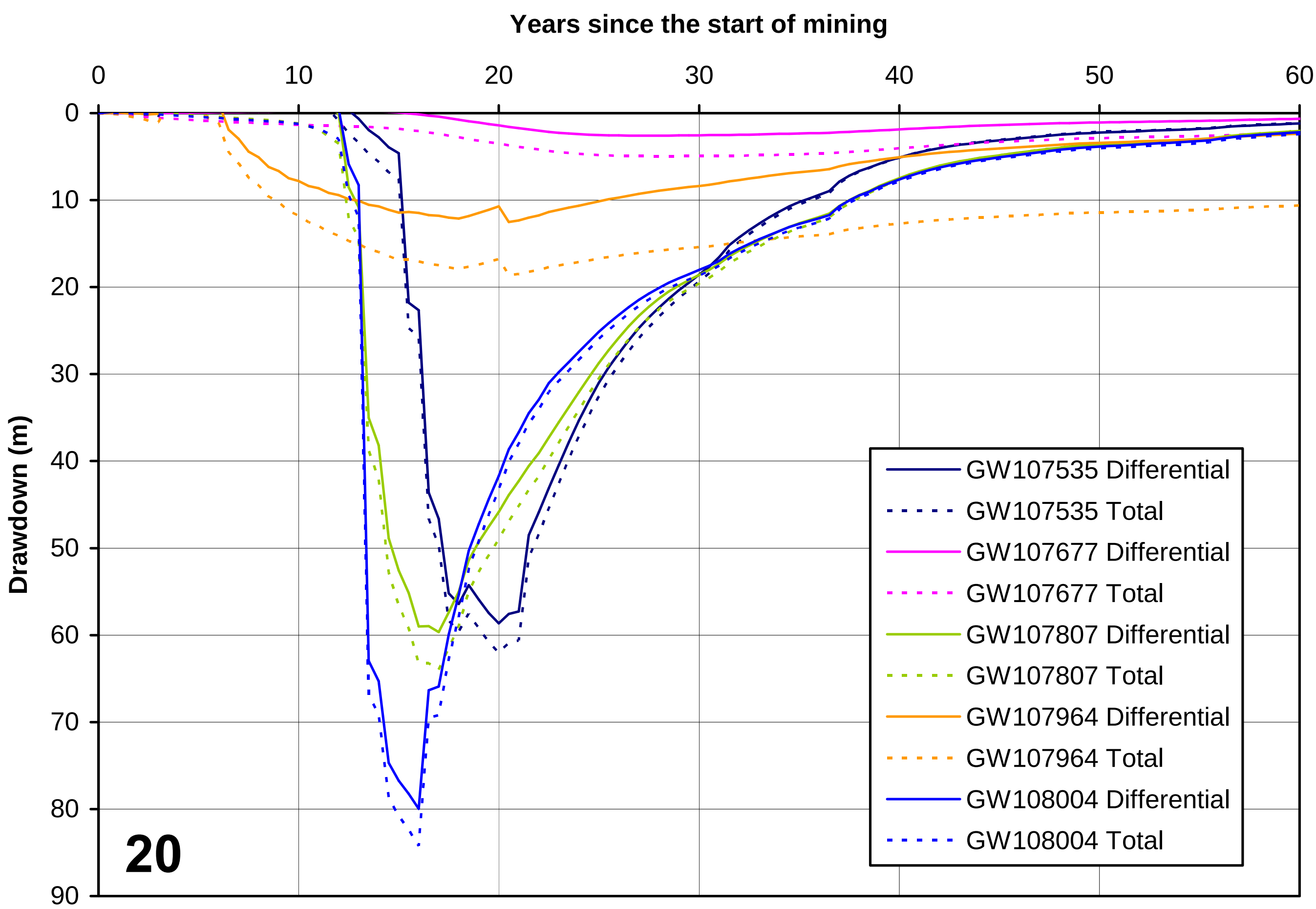

Years since the start of mining
0
10
20
30
40
50
60
0
5
10
15
20
25
Drawdown (m)
GW105068 Differential
GW105068 Total
GW105079 Differential
GW105079 Total
GW105082 Differential
GW105082 Total
GW105102 Differential
GW105102 Total
GW105396 Differential
GW105396 Total
16


Years since the start of mining
0
10
20
30
40
50
60
Drawdown (m)
0
10
20
30
40
50
60
GW105744 Differential
GW105744 Total
GW105950 Differential
GW105950 Total
GW106245 Differential
GW106245 Total
GW106489 Differential
GW106489 Total
GW106491 Differential
GW106491 Total
GW106489 dry between 18 and 22 years
GW106491 dry between 18 and 24 years
17

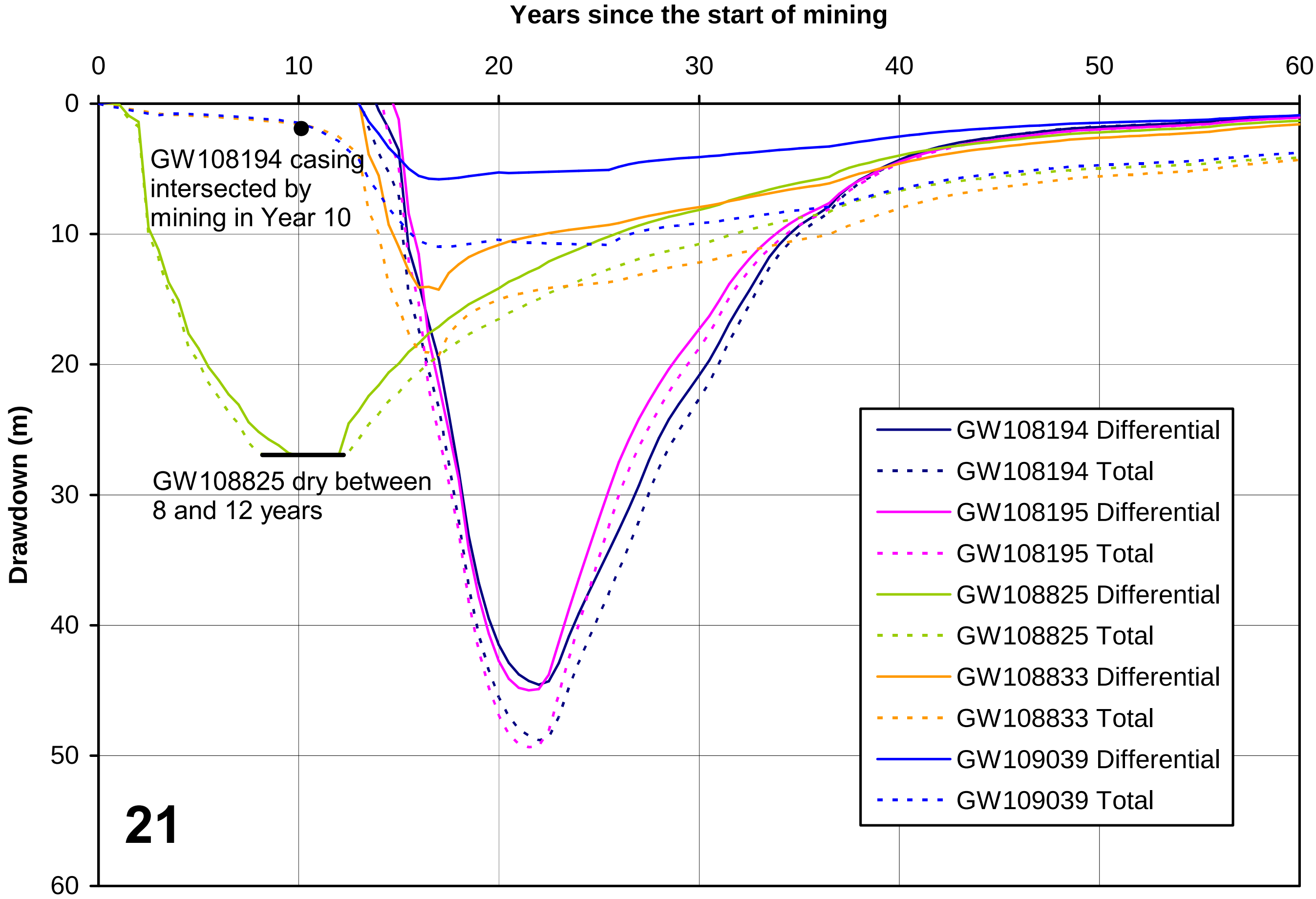

Years since the start of mining
0
10
20
30
40
50
60
Drawdown (m)
0
5
10
15
20
25
30
35
40
GW106517 Differential
GW106517 Total
GW106710 Differential
GW106710 Total
GW106711 Differential
GW106711 Total
GW106718 Differential
GW106718 Total
GW106855 Differential
GW106855 Total
18

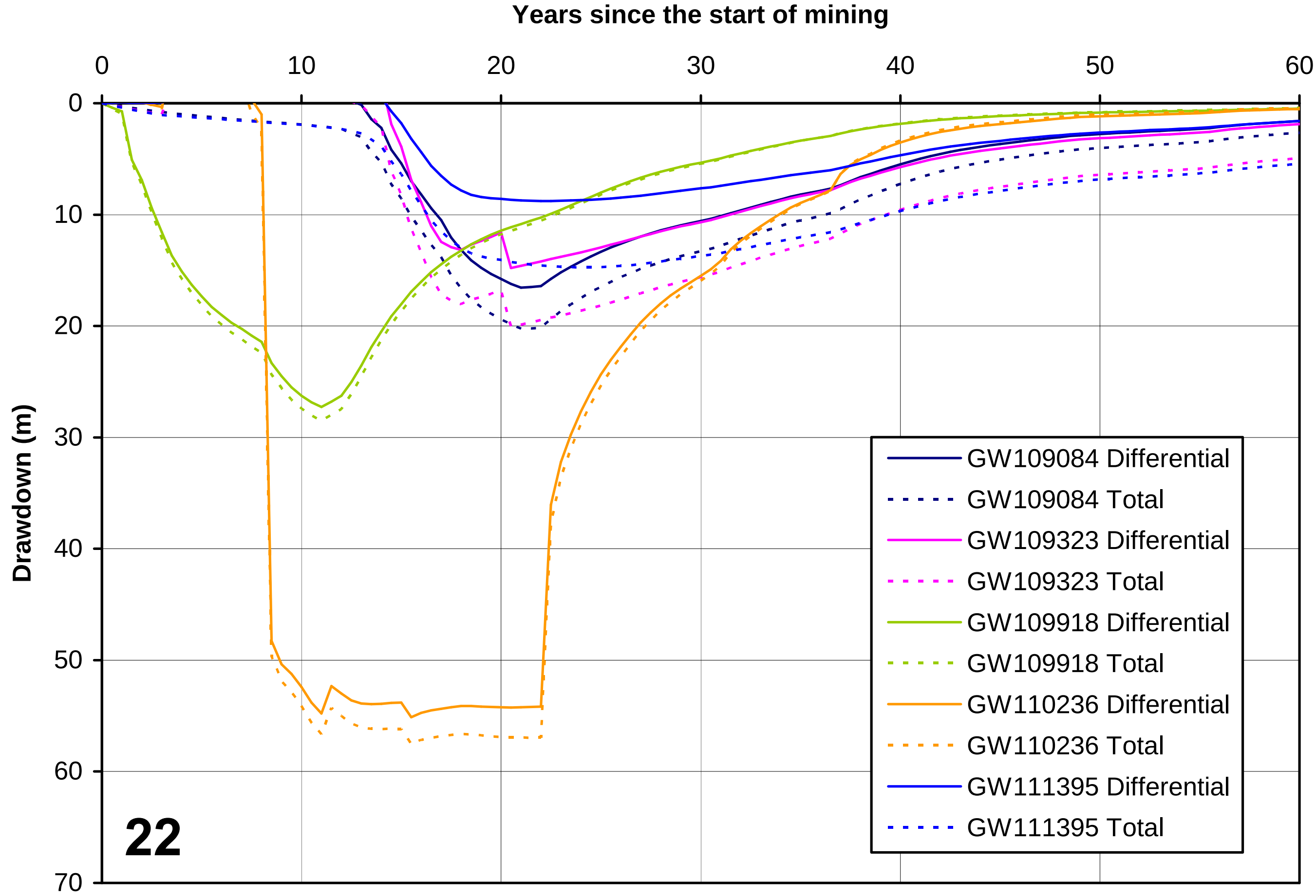


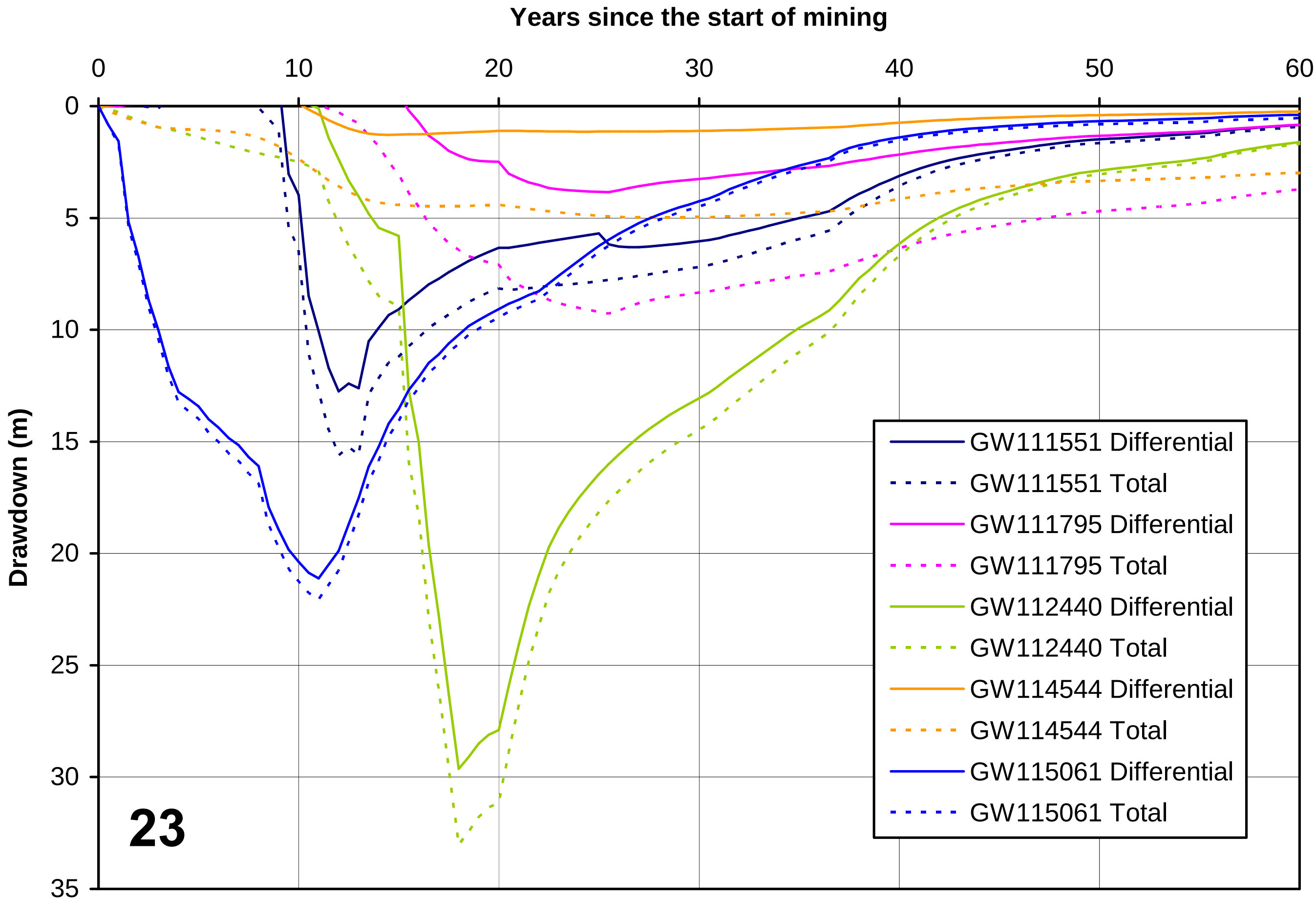
Years since the start of mining
0
10
20
30
40
50
60
0
2
4
6
8
10
12
14
16
18
Drawdown (m)
19
GW106906 Differential
GW106906 Total
GW106958 Differential
GW106958 Total
GW107006 Differential
GW107006 Total
GW107120 Differential
GW107120 Total
GW107240 Differential
GW107240 Total



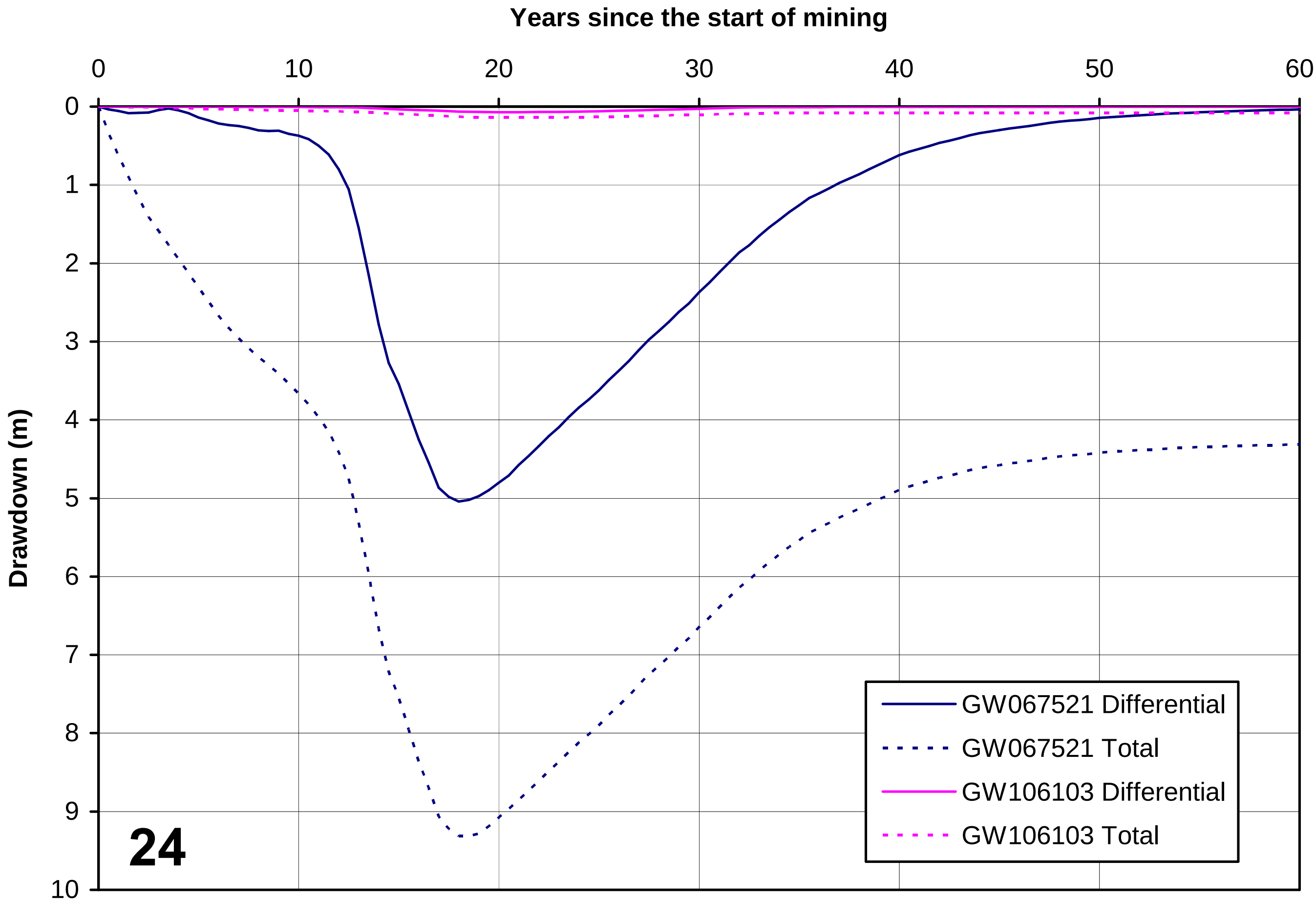
Years since the start of mining
0
10
20
30
40
50
60
0
10
20
30
40
50
60
70
80
90
Drawdown (m)
20
GW107535 Differential
GW107535 Total
GW107677 Differential
GW107677 Total
GW107807 Differential
GW107807 Total
GW107964 Differential
GW107964 Total
GW108004 Differential
GW108004 Total


Years since the start of mining
0
10
20
30
40
50
60
Drawdown (m)
GW108194 casing
intersected by
mining in Year 10
GW108825 dry between
8 and 12 years
21
GW108194 Differential
GW108194 Total
GW108195 Differential
GW108195 Total
GW108825 Differential
GW108825 Total
GW108833 Differential
GW108833 Total
GW109039 Differential
GW109039 Total


Years since the start of mining
0
10
20
30
40
50
60
70
Drawdown (m)
22
GW109084 Differential
GW109084 Total
GW109323 Differential
GW109323 Total
GW109918 Differential
GW109918 Total
GW110236 Differential
GW110236 Total
GW111395 Differential
GW111395 Total



Years since the start of mining
0
10
20
30
40
50
60
Drawdown (m)
0
5
10
15
20
25
30
35
GW111551 Differential
GW111551 Total
GW111795 Differential
GW111795 Total
GW112440 Differential
GW112440 Total
GW114544 Differential
GW114544 Total
GW115061 Differential
GW115061 Total
23



Years since the start of mining
0
10
20
30
40
50
60
Drawdown (m)
0
1
2
3
4
5
6
7
8
9
10
GW067521 Differential
GW067521 Total
GW106103 Differential
GW106103 Total
24

Appendix H - Basalt Model used to Assess Drawdown in Private Bore GW106103

1. Basalt Model

The basalt model was developed to calculate drawdown in bore GW106103 due to underground mining in the Hume lease. The model was developed using MODFLOW-SURFACT Version 3, distributed by Hydrogeologic, Inc. (Virginia, USA). It is an advanced version of the standard USGS MODFLOW algorithm and is able to simulate variably saturated flow. The software can accommodate unsaturated zones at depth. MODFLOW-SURFACT is operated within the Visual Modflow (Version 2009) pre- and post-processing environment, developed by Schlumberger Water Services.

The active model area (the model domain) is shown in Figure 1. It covers 15 km^2. Its boundary follows the limit of the southeastern basalt body that intersects the 2m differential drawdown contour in the Wongawilli Seam at 17 years since the start of mining (the highest drawdowns developed in any layer at any time in the main model). GW106103 is situated within this body (see Map 1 in Appendix G).

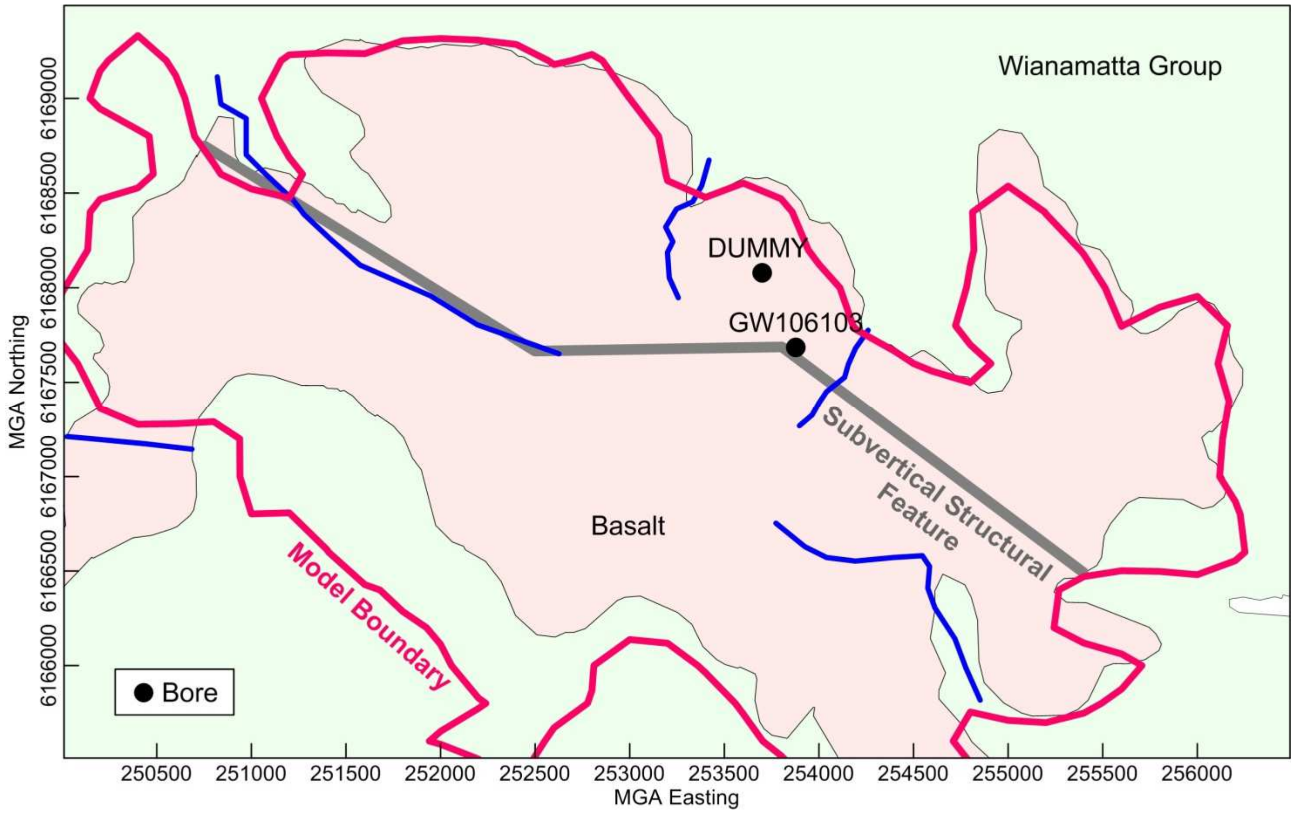


Figure 1. Map showing basalt model limits.

The model grid comprises 2 layers with 100 columns and 40 rows. Cell dimensions are 100 m x 100 m. Layer 1 represents the Robertson Basalt and Layer 2 represents a notional layer underlying the basalt that retards drainage to the underlying Wianamatta Group. The basalt thickness is based on structure contours developed from government records for bores in this body.

1.1. Calibration Targets

Calibration was undertaken in steady state simulation. Calibration targets comprised the following:

- Single hydraulic head measurements obtained from government records for 25 private bores located in the southeastern basalt body, obtained mostly between 1991 and 2006. These are listed in Table 1. All bores appear to be located in basalt.

Table 1. Hydraulic Head Calibration Targets.

Bore	Easting (mMGA)	Northing (mMGA)	Date Constructed	Depth (mbgl)*	Water Level (mbgl)	Bore Hydraulic Interval (mbgl)	
						From	To
GW011262	252352	6166970	1-Dec-55	9	4	4	9
GW014121	252487	6166696	1-Dec-56	24	8	20	24
GW014491	253454	6166753	1-Nov-56	23	9	9	23
GW066761	253508	6166662	16-Oct-92	18	4	12	18
GW066764	254253	6166435		24	14	14	24
GW066769	254252	6166466		24	7	7	24
GW066770	254362	6166160		33	10	18	33
GW069007	254188	6166419	4-Nov-91	36	10	10	36
GW069118	253610	6166800	25-Feb-91	30	18	18	30
GW072154	253249	6166401	17-Jan-94	27	10	13	27
GW072273	253044	6166546	31-Jan-92	18	4	12	18
GW072416	252451	6166806	24-Nov-94	18	7	11	18
GW100256	254259	6166306	10-Aug-93	30	8	8	30
GW100257	254231	6166339	12-Aug-93	36	11	12	36
GW101324	254223	6166588	26-Sep-95	15	7	7	15
GW101421	254321	6165789	13-Mar-96	37	9	13	37
GW102401	254158	6166186	20-Dec-96	78	14	25	78
GW102621	254577	6166721	11-Dec-98	25	13	17	25
GW102622	254626	6166784	13-Nov-98	42	13	23	42
GW102623	254576	6166752	15-Nov-98	27	11	20	27
GW102624	254548	6166844	18-Nov-99	21	11	15	21
GW102964	253499	6166812	1-Jan-56	23	15	15	23
GW104198	252443	6166728	5-Feb-02	36	11	12	36
GW107625	252749	6166539	15-Nov-05	31	7	11	31
GW108271	254281	6167270	26-Aug-06	66	15	57	66

* Denotes metres below ground level.

- Hydraulic conductivity estimated from measurements made at several locations in Australia and worldwide (shown in Figure 2). These mainly comprise 24-hour pumping tests.
- Estimates of rainfall recharge to the basalt (10% of annual rainfall), with 80% reporting to streams and springs, and 20% draining vertically to the underlying WG. The latter is considered conservatively high and favours increased drainage to the WG from the basalt, for a given drawdown in the WG. The rainfall recharge estimate represents the recharge that has acceded to the groundwater system following consumption in the unsaturated zone and consumption by mega flora. These estimates are based on baseflow analysis discussed in Coffey (2016).

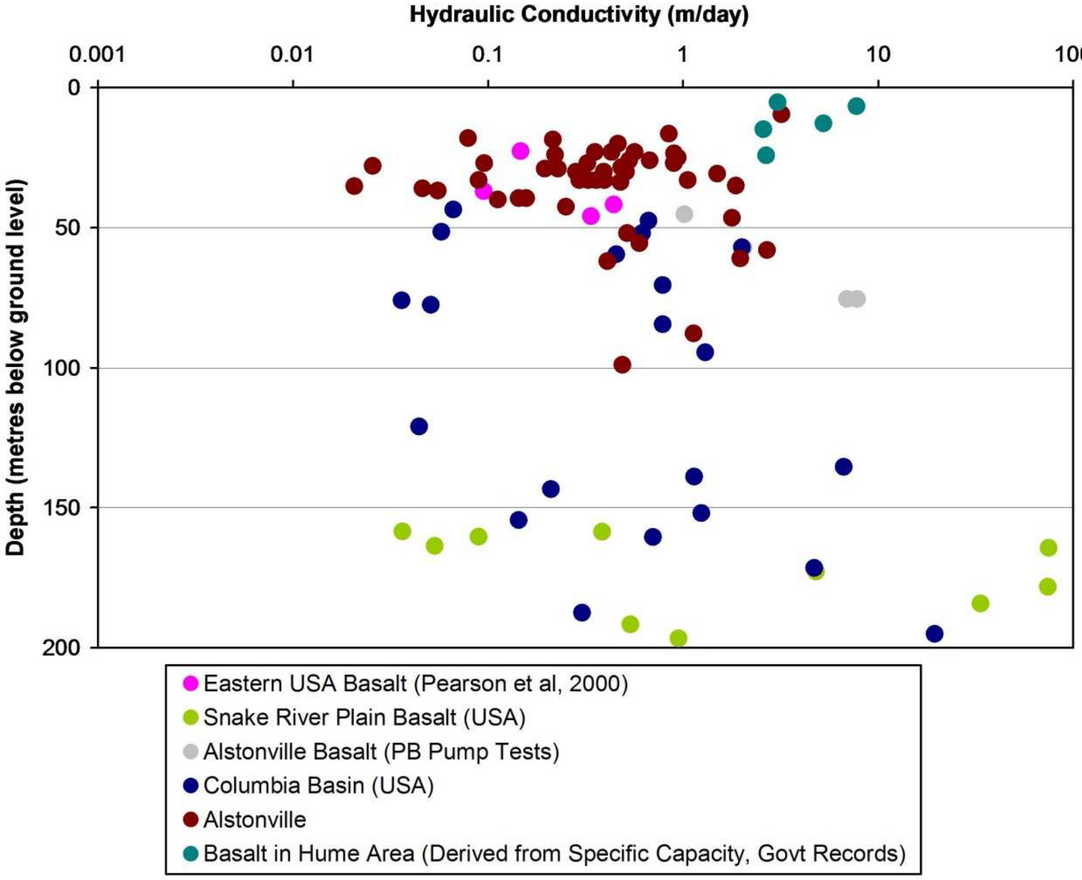


Figure 2. Measured hydraulic conductivity of basalt in the Hume area and around the world.

1.2. Boundary Conditions

Both layers were designated as variable type layers (a layer that will allow both unconfined and confined behaviour).

Layer 1 (basalt) hosts drains that represent streams and springs. Layer 2 is the notional retarding layer that represents altered WG. It hosts a general head boundary (GHB) with the external head comprising hydraulic head obtained at a dummy piezometer (see Figure 1) in Layer 1 of the main model, for the null and active mining predictive scenarios. These heads are shown in Figure 3. They contain the drawdown induced by Hume operations, and are discretised into yearly periods. There are two GHB zones, one on either side of the interpreted horizontal flow barrier. The external GHB head south of the barrier remains at null case values while the external GHB head north of the barrier varies according to the null or main scenarios. The location of the dummy piezometer provides heads intermediate between those underlying the northern boundary of the basalt and those underlying the basalt at the barrier. Drawdown in the main model south of the barrier is negligible.

The conductance term for the northern GHB zone is the main calibration parameter, and is a measure of the capability of the barrier underlying the basalt to retard vertical drainage.

Drainage channels and springs were simulated using the Drain package. Drain conductance was set to a high value of 1000 m^2/day, allowing the media hydraulic properties to control leakage to the channels. Elevations for the inverts of these features are based on digital elevation information available from the Australian Government, checked against LiDAR topographic survey data for the Hume Lease.

Given the length of time over which hydraulic measurements were made, rainfall was applied as a constant percentage of average rainfall for the area. The recharge used in the model is the component of rainfall that reports to drainage channels or springs, or that drains vertically to the underlying WG.

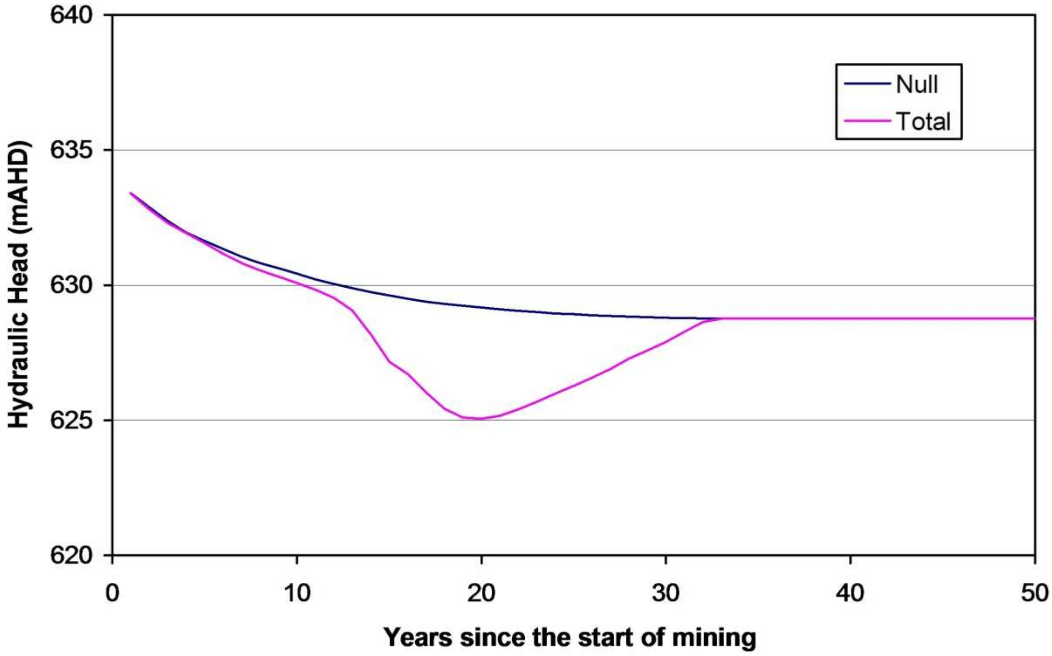


Figure 3. The external hydraulic head assigned for the GHB boundary condition.

1.3. Calibration Results

Figure 4 shows modelled and observed hydraulic heads for steady state calibration. The normalised root-mean-squared (NRMS) error is 20% and considered reasonable, given the length of time over which observations have been made, the uncertainty in water levels reported in government records, and the small total head difference of the target dataset. Residuals are reasonably normally distributed.

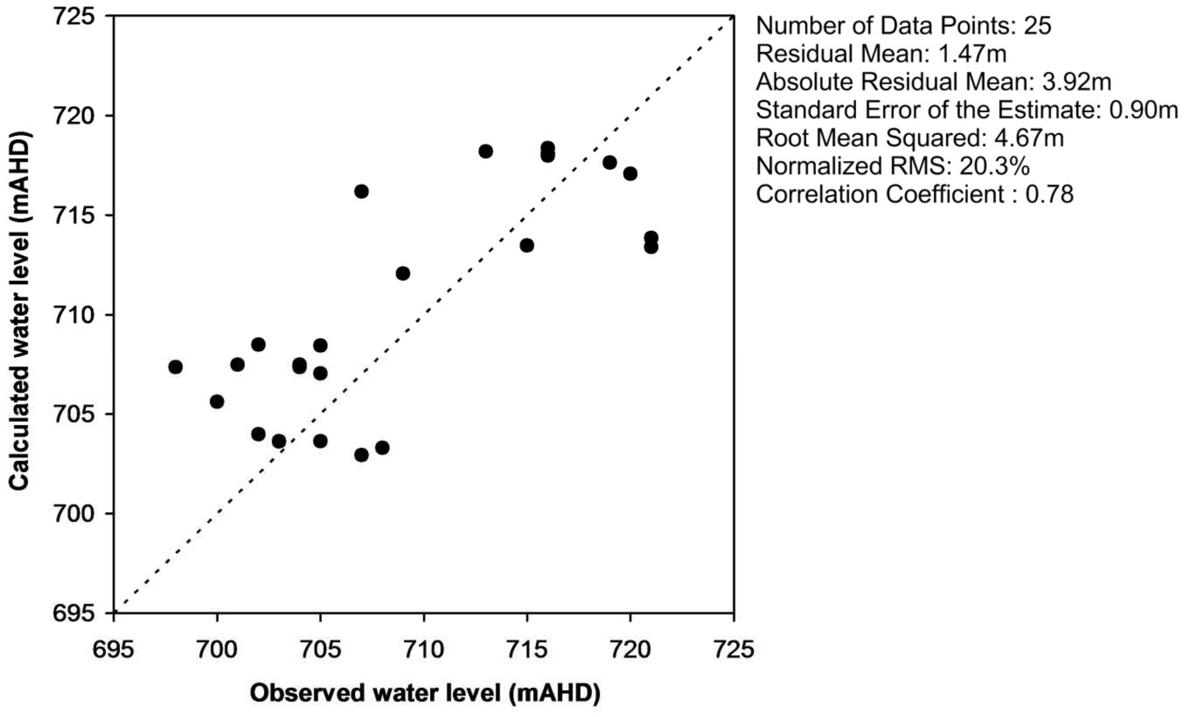


Figure 4. Observed and calculated steady state water levels.

The modelled steady state flow budget is listed in Table 2. The flow budget discrepancy is less than 0.005% and is considered reasonable. Drainage to the underlying WG comprises 20% of the recharge to the basalt, with the remainder discharging at streams and springs. The calibrated K for the basalt is 0.8m/day, considered reasonable based on observations in Figure 2.

Table 2. Modelled steady state flow budget.

IN (ML/day)		OUT (ML/day)	
Rainfall Recharge	2.73	Discharge to streams and springs	2.20
		Drainage to underlying WG	0.53
TOTAL	2.73	TOTAL	2.73
Discrepancy: +0.00 ML/day (+0.0 %)			

The calibrated GHB conductance is 0.03m^2/day which equates to a vertical hydraulic conductivity of the lateral retarding layer under the basalt of about 0.0003 m/day.

1.4. Predictive Simulation and Results

The calibrated model was run in transient mode for predictive simulations over a period of 100 years, using a specific yield of 4% for the basalt.

Figure 5 shows the modelled total and differential drawdown at bore GW106103. The total and differential drawdowns achieve maximums of 0.14m and 0.07m respectively.

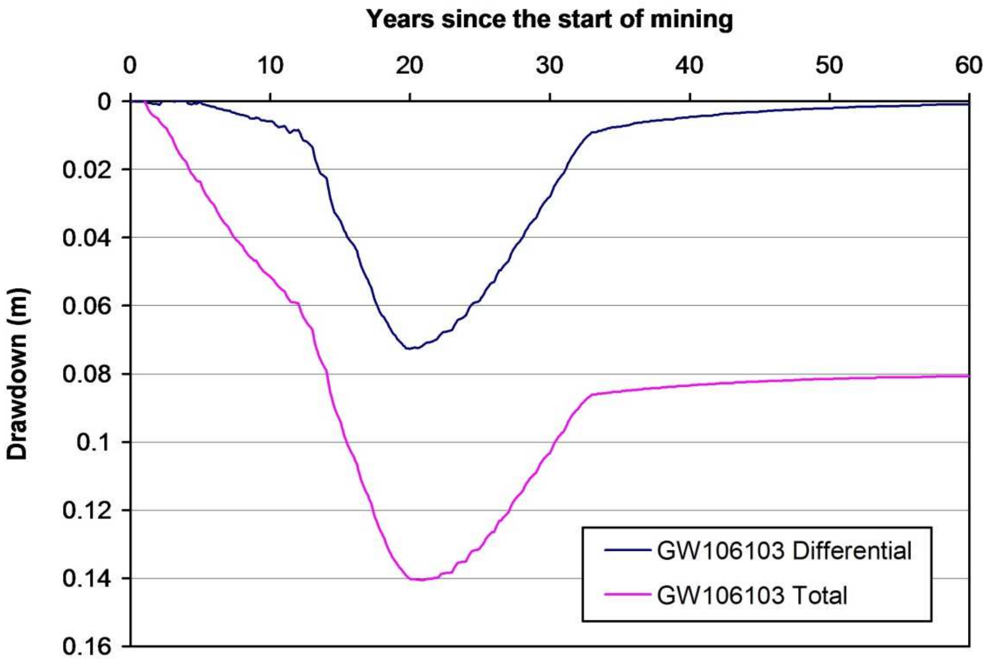


Figure 5. Modelled hydrographs for private basalt bore GW106103.