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SPECIALISTS MANAGING THE EARTH

GROUNDWATER STUDY
AREA 3B DENDROBIUM COAL MINE

NUMERICAL MODELLING

BHP Billiton

GEOTLCOV24507AA-AB2
2 October 2012

Coffey Geotechnics Pty Ltd ABN 93 056 929 483
8/12 Mars Road Lane Cove West NSW 2066 Australia

2 October 2012

BHP Billiton
PO Box 514
Unanderra NSW 2526

Attention: Richard Walsh

Dear Richard

RE: Groundwater Study

Area 3B Dendrobium Coal Mine

Numerical Modelling

Coffey Geotechnics Pty Ltd (Coffey) is pleased to provide BHP Billiton (BHP) with our report on numerical flow modelling for the Area 3B Groundwater Study for Dendrobium Coal Mine. It presents the numerical simulation methodology and results.

We draw your attention to the enclosed sheet entitled “Important Information about your Coffey Report” which should be read in conjunction with this report. Should you have any questions regarding this report please contact the undersigned.

For and on behalf of Coffey Geotechnics Pty Ltd

Paul Tammetta

Associate Hydrogeologist

Attachment A: Attachments

Distribution: Original and 1 copy held by Coffey Geotechnics Pty Ltd

1 electronic copy to BHP

1 electronic copy to Heritage Computing

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EXECUTIVE SUMMARY

This report presents the results of an assessment of alternative panel lengths for Area 3B at Dendrobium Colliery. The assessment was undertaken by Coffey Geotechnics Pty Ltd (Coffey) for BHP Billiton (BHP). The purpose of the assessment was to estimate the impacts of mining in Dendrobium Mine Area 3B on the groundwater system and Lakes Avon and Cordeaux, for cases involving either no extension, 100m extension, or 200m extension to Longwalls 13 to 18 (which approach Lake Avon) of the current mine plan.

An analysis of a substantial database provided by BHP, and obtained from published sources, was undertaken to support numerical model development and calibration. The results of the data analysis are reported separately (Coffey, 2012).

A regional numerical groundwater flow model was developed for the study, using MODFLOW-SURFACT Version 3. It is an advanced version of the standard USGS MODFLOW algorithm and is able to simulate variably saturated flow. The model was simultaneously calibrated to hydraulic heads, baseflow to rivers (surface discharges), inflow to Dendrobium Mine (deep discharges in the mine area), and inflows to other mines (deep discharges in the regional area). This has considerably reduced the uncertainty in model outputs.

Predictive modelling was undertaken to quantify the following components of loss from Lakes Avon and Cordeaux due to mining in Dendrobium Mine Area 3B:

- Baseflow (groundwater) recharge to a lake that is diverted away from the lake by mining. This comprises groundwater that would normally flow towards the lake and recharge it, but has been diverted towards the mine.
- Seepage induced from a lake by mining. This comprises lake water that is induced to seep out of the lake and into the ground as a result of mine development.

A probabilistic approach has been used to assess lake losses. The following results were obtained:

- The modelled probability distributions for induced seepages from Lakes Avon and Cordeaux, due to mining in Area 3B with 200m panel extensions, fall in the tolerable range and comply with the probability criterion applied by the NSW Dams Safety Committee for Lake Cordeaux.
- The modelled Decile 5 induced seepages from Lakes Avon and Cordeaux, due to mining in Area 3B with 200m panel extensions, are 0.05 and 0.01 ML/day respectively.
- The modelled Decile 5 diverted baseflows for Lakes Avon and Cordeaux, due to mining in Area 3B with 200m panel extensions, are 0.61 and 0.48 ML/day respectively.
- The modelled Decile 5 diverted baseflow for rivers in the Northwest Catchment, due to mining in Area 3B with 200m panel extensions, is 0.98 ML/day.
- There is marginal difference between the 200m panel extension and no panel extension cases.

The model results apply only to the case where significant deformation from caving is limited to the interpreted limit of the collapsed zone. Model results do not take into account significant deformation that may be caused by the disturbance of extraordinary defects or other extraordinary structural features, which can lead to the creation of extreme permeability pathways extending beyond the collapsed zone.

1 INTRODUCTION

This report presents the results of an assessment of alternative panel lengths for Area 3B at Dendrobium Colliery. The assessment was undertaken by Coffey Geotechnics Pty Ltd (Coffey) for BHP Billiton (BHP). The purpose of the assessment was to estimate the following:

- Impacts of mining in Area 3B of Dendrobium Colliery on Lakes Avon and Cordeaux.
- Future groundwater inflows into the Area 3B workings.
- Impacts of extending some of the longwalls in Area 3B closer to Lake Avon.

The assessment has employed numerical modelling methods. It has been undertaken generally in accordance with Coffey proposals GEOTLCOV24507AA-AA (dated 14 February 2012) and GEOTLCOV24507AB-AA (dated 30 August 2012).

This report presents numerical model development, calibration, and predictive simulations and results. The report will be used by BHP in support of mining within the NSW Dams Safety Committee (DSC) Notification Area. As such the DSC needs to be confident that the model uses the data from Dendrobium and successfully reproduces historical mine inflows and groundwater levels.

An analysis of a substantial database provided by BHP, and obtained from published sources, was undertaken to support numerical model development and calibration. The results of the data analysis are reported separately (Coffey, 2012).

The regional location of the mine is shown in Drawing 1.

2 HYDROGEOLOGICAL CONCEPTUAL MODEL

The data analysis undertaken in Coffey (2012) provides a solid platform for development of a hydrogeological conceptual model. The unusually large amount of hydraulic conductivity and river baseflow information, together with substantial information on local and regional mine inflows (for Dendrobium Mine and other mines), allows the uncertainty created by the correlation of rainfall recharge and hydraulic conductivity in a model to be minimised significantly.

A summary of the data analysis is provided below. The hydrogeological conceptual model developed from the data analysis is also presented.

2.1 Groundwater Recharge

Recharge to the groundwater system is reliant on rainfall recharge. Rainfall infiltration is typically about 6% of rainfall. Based on the data analysis, it is assessed that in virgin catchments, about half of this recharge (about 3% of rainfall) would report to drainage channels for transport out of the system. The remainder (about 3%) would be consumed by evapotranspiration, ocean discharge, escarpment discharge (mostly evapotranspiration anyway), and downgradient lateral groundwater flow out of the model area.

At present, the model area is located in a catchment where the groundwater recharge reporting to lakes and drainage channels is assessed to be a maximum of about 1% of rainfall (probably about 0.7% to 0.8% most of the time). Most of the remaining recharge of about 2% or more of rainfall is probably being diverted towards the mine voids.

2.1.1 Stream Baseflow

A water balance has been developed for the catchment encompassing lakes and rivers in the model area northwest of the escarpment (Coffey, 2012). This catchment is referred to as the Northwest Catchment. The water balance takes into account stream flow gauging data (from four gauging stations), lake evaporation, changes in lake storage, and licensed river water use. The water balance suggests that the average groundwater inflow to lakes and rivers in the Northwest Catchment was about 14 ML/day between 1991 and 2006.

2.2 Aquifer Properties

Hydraulic conductivity decreases with depth for both the rock matrix and defects. Figure 1 shows a running log-average of corrected core permeability test results, and a running log-average of packer test results, from the Dendrobium Mine and other areas in the Southern Coalfield. The break in slope of the packer test curves at around 100m depth indicates that the mode of hydraulic conductivity control begins changing at that depth. Bulk hydraulic conductivities and matrix hydraulic conductivities converge at about 200m depth. Above this depth, matrix conductivities are lower than bulk conductivities. This suggests that in the top 200m of an unmined rock profile in the mine area, the bulk hydraulic conductivity of a large rock volume is controlled mostly by open defects and fracture flow. Below 200m, the hydraulic conductivity is controlled mainly by the rock matrix. This is not to say that defect apertures will all be closed below 200m depth. In fact, it will be highly likely that some defects will be open below 200m depth, but not in the same numbers nor aperture widths as at shallower depths, unless significant structures exist such as large igneous intrusions. Where the matrix conductivity prevails, the vertical anisotropy might be small.

Storativity also decreases with depth. Vertical anistropy is also believed to decrease with depth, given the greater proportion of matrix flow at depth.

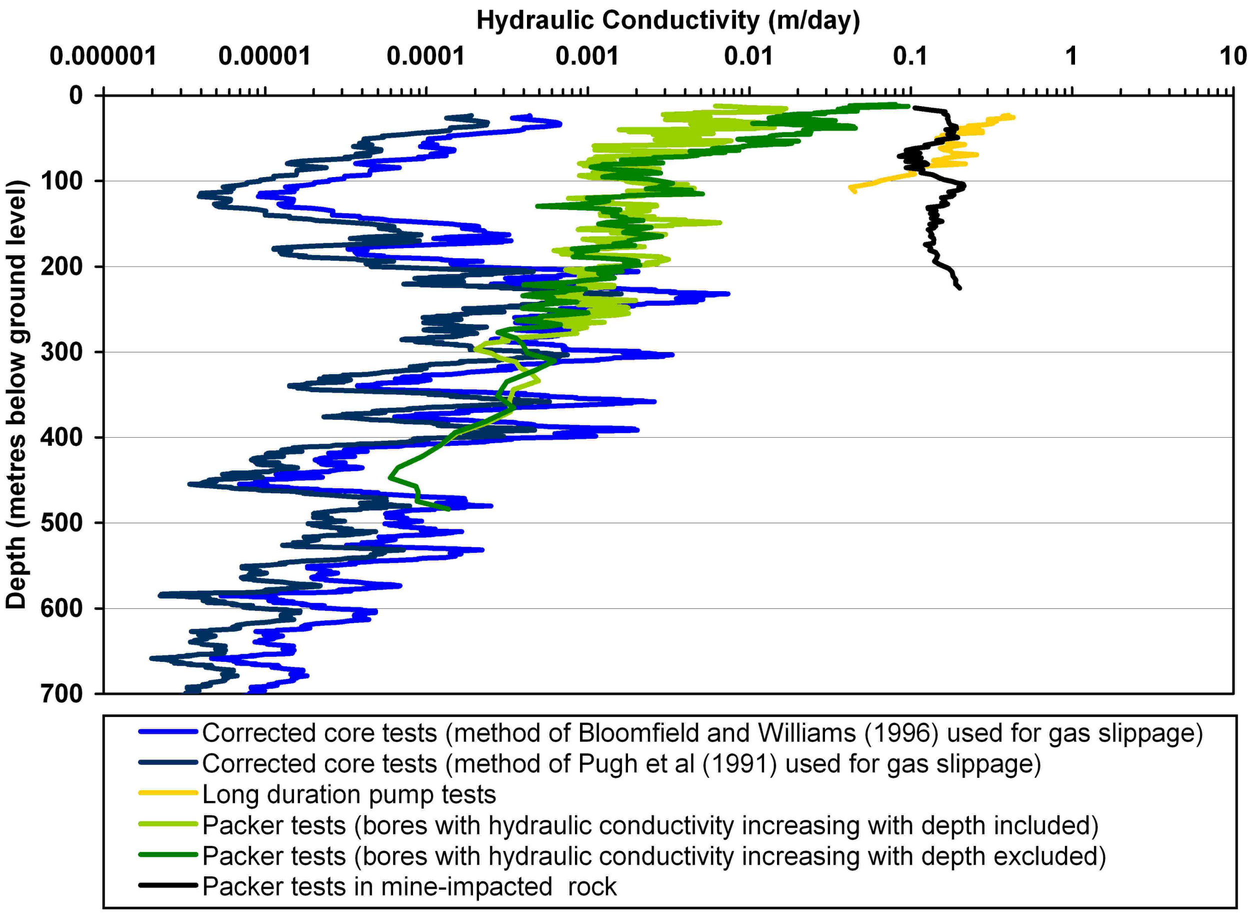


Figure 1. Log average core hydraulic conductivity (corrected for overburden pressure and for two alternative correction schemes for gas slippage) compared to log average hydraulic conductivity from packer tests and pump tests. A 30-point running average was employed for core data and a 10-point running average for packer and pump test data.

2.3 Groundwater Levels

Groundwater levels at Dendrobium Mine are monitored by an extensive network of vibrating wire piezometer (VWP) and standpipe piezometer (SP) installations. Monitoring data used for this groundwater assessment are from 94 boreholes at 76 monitoring sites (hosting 464 VWPs and 9 SPs). Groundwater level monitoring data are presented in detail in Coffey (2012). Locations of groundwater level monitoring sites are shown in Drawing 2.

Prevailing hydraulic heads have large vertical gradients due to historical mining in the area. Figure 2 shows interpreted hydraulic head contours along a cross section going through DDHs 85, 24, 87, 38, 39, Longwalls 5, 4, and 3, DDHs 47 and 73, Lake Cordeaux, and DDH35, for 15 September 2009. The figure shows a characteristic layer cake pattern for the hydraulic head contours, which is observed at other mines in the Western Coalfield in similar terrains.

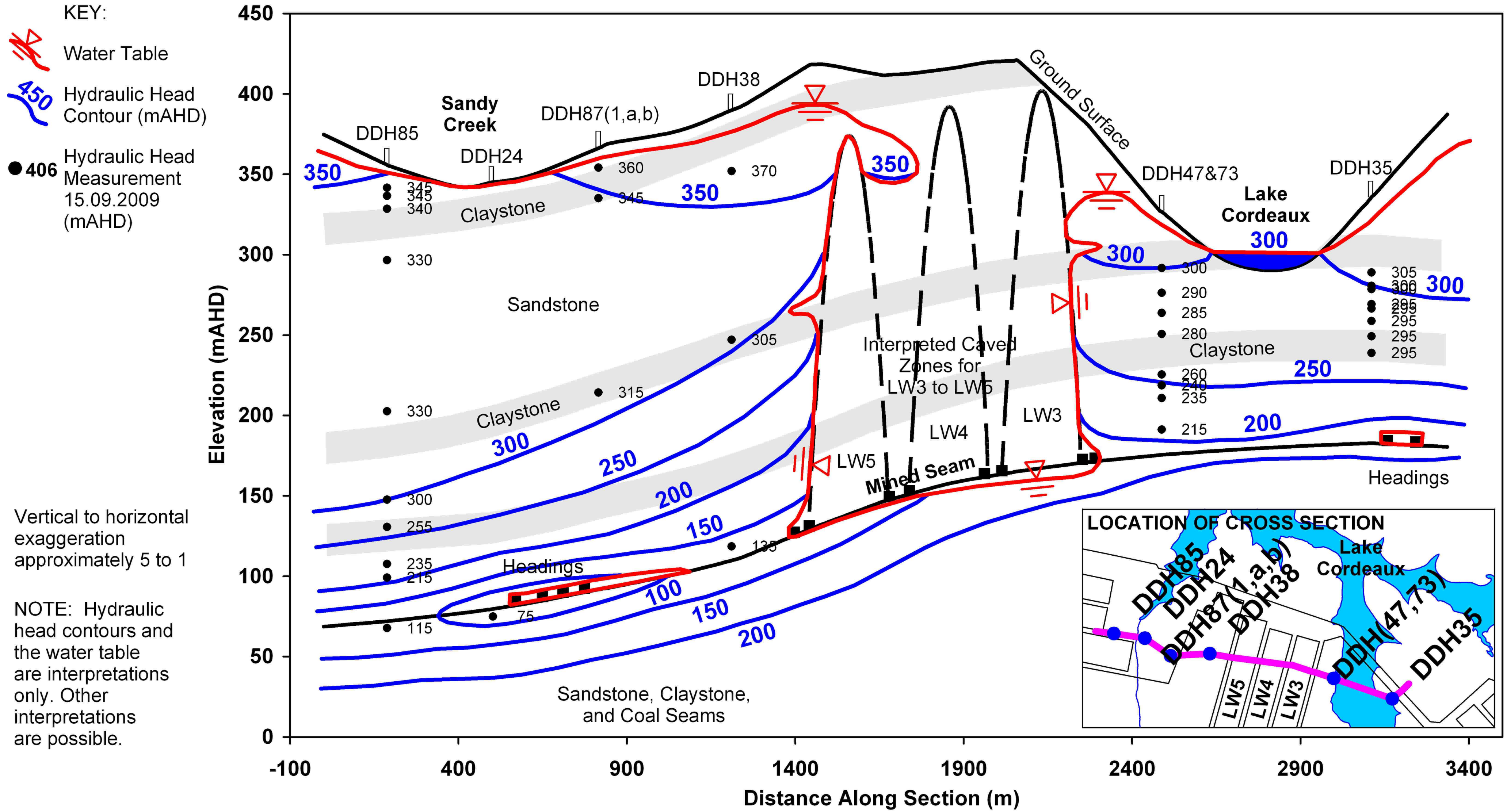


Figure 2. Interpreted hydraulic head contours along a cross section through Longwalls 3 to 5, for 15 September 2009.

There is extensive depressurisation in the Wongawilli Seam. The unusually large extent of depressurisation in the mined seam (compared to other strata) is seen at other mines and may be due to the effect of coal shrinkage caused by long-term degasification (from groundwater depressurisation), and the increase in hydraulic conductivity associated with this process (Gray, 2011). In contrast, hydraulic head contours in the Mesozoic sandstones are further apart. The hydraulic head contours are relatively flat and illustrate the vertical hydraulic head gradient in two dimensions.

2.4 Groundwater Discharge

Groundwater discharge occurs via the following processes:

- Discharge to local streams and lakes.
- Discharge to mine voids.
- Discharge to the ocean, escarpment, and evapotranspiration.
- Downgradient lateral discharge past the northern boundary of the model area.

2.5 Groundwater Inflows to Mine Workings

2.5.1 Dendrobium Mine

Given the proximity of Dendrobium workings to Lakes Avon and Cordeaux, BHP monitors volumes of water pumped out of the Dendrobium workings, changes in coal moisture (from insitu to stockpile), and ventilation moisture losses. This information is used by BHP to calculate the groundwater inflow to the workings, and thereby check for potential inflow events that may indicate inflow from the lakes. Figure 3 shows the calculated groundwater inflow to the mine workings. Overall, inflows have increased from around 1ML/day in 2006 to about 5 ML/day in 2012. Identification of the controlling influences is made difficult by the presence of Bulli Seam workings above Longwalls 1 and 2 (which were drained prior to mining), the presence of historical full extraction mining in the Wongawilli Seam adjacent to Longwalls 1 and 2, and inflow events potentially associated with intense rainfall and / or drainage processes for the crinanite.

Ziegler and Middleton (2011) undertook an assessment of the relationship between rainfall and calculated groundwater inflow 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 Ziegler and Middleton (2011) by first plotting the cumulative value of these variables over time, then fitting a linear trend line to these cumulative curves, and finally calculating the difference between the cumulative curve and the fitted trend line. This resulted in positive residuals for wet periods and negative residuals for dry periods. They applied this process to inflows for each of Dendrobium Areas 1 and 2, and found a significant correlation between inflow and rainfall residuals.

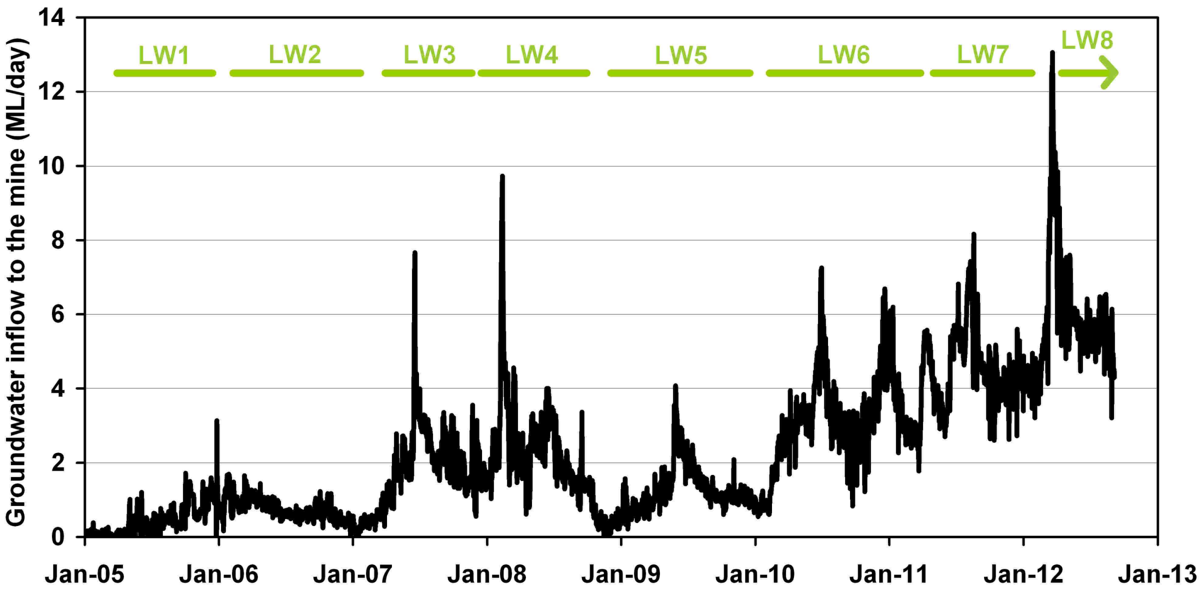


Figure 3. Groundwater inflows to the Dendrobium underground workings, calculated by BHP from pumping and hygrometer measurements.

In the current study, the method of Ziegler and Middleton (2011) has been applied to the combined calculated groundwater inflow to Dendrobium Areas 1, 2, and 3. However, instead of a linear trend line, a 2nd degree polynomial trend line is applied to the cumulative curves to find the residuals. Figure 4 shows the residuals for rainfall and inflow, versus time. There is a clear relationship between these variables. The highest degree of correlation was found for a 7-week lag between inflow and rainfall.

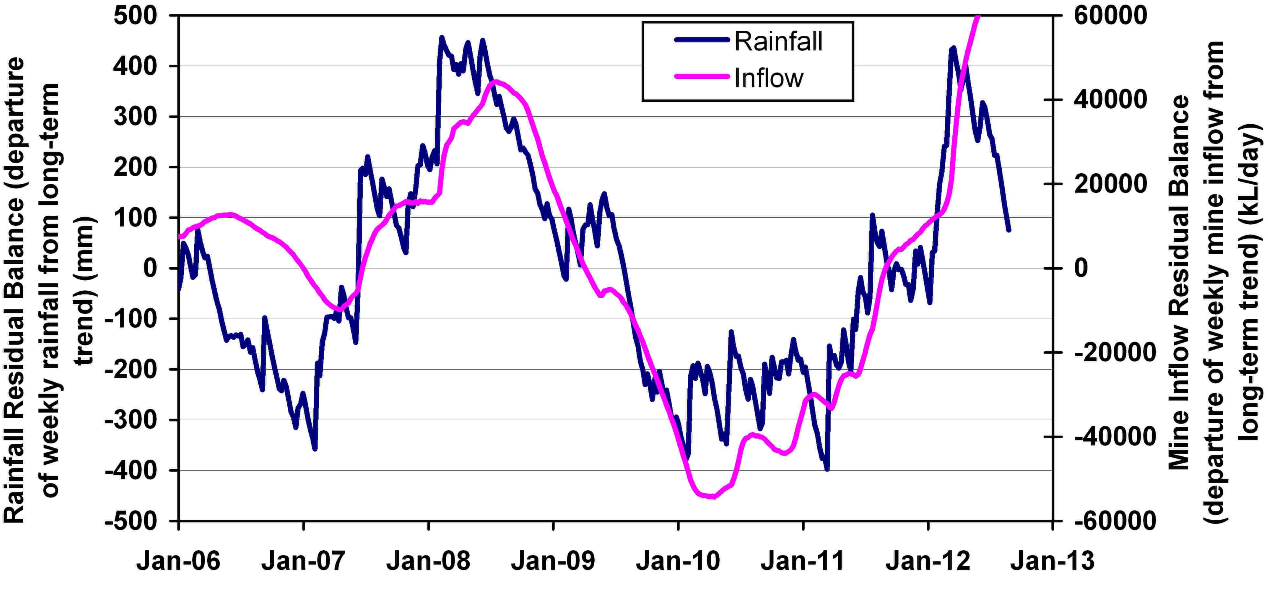


Figure 4. Departures of rainfall and mine inflow from their long-term trends, for Dendrobium Coal Mine Areas 1, 2, and 3.

2.5.2 Other Mines in the Southern Coalfield

The model that was developed for this study is regional, and incorporates several other mines within its boundary, as shown in Drawing 3. As an aid to calibration it is useful to review recorded groundwater inflows to other mines in the Southern Coalfield, especially those within the model area.

In the early 1980s Lake Avon was undermined by panels Blue 2 and Blue 3/4 of the Wongawilli-1 Colliery at depths of between 90m and 180m. In December 1982 inflows increased from a relatively stable 0.7ML/day to 2.4ML/day over a period of one day (NSW Dams Safety Committee, 1986). Inflows gradually declined to about 0.8ML/day by August 1986.

Williamson (1978) (in Anderson et al, 1989) reported several measurements of groundwater inflow to full extraction coal mines that took into account ventilation losses. These are listed in Table 1. Table 2 lists more recent inflow measurements for several collieries, from various published sources.

Based on the information in Tables 1 and 2, and taking account of increases in inflows with time (for active collieries), the combined inflow to three coal mines in the northern part of the model area (the "northern mines") is estimated to have been about 9 to 11 ML/day in 2011, and the combined inflow to other collieries in the model area (except Dendrobium) is estimated to have been about 25 to 35 ML/day in 2011.

Table 1. Measured groundwater inflows to full extraction coal mines (Williamson, 1978).

Colliery	Mined Seams	Groundwater Inflow (ML/day)	
		Overall Average	Wet Conditions
Nebo	Bulli	4.97	9.93
Wongawilli	Wongawilli and Bulli	2.62	5.45
Huntley	Wongawilli and Tongarra	3.93	
Bulli	Bulli	0.24	
Kemira	Bulli	0.80	
Corrimal	Bulli	1.30	
South Bulli	Bulli and Balgownie	2.16	

Table 2. Recent measurements of groundwater inflows to other full extraction coal mines.

Colliery	Groundwater Inflow (ML/day)	Time period	Reference
Tahmoor	4.73	Apr 2009 to Apr 2011	Tahmoor Coal (2011)
Appin	1.2	Historical	BHP (undated) (Bulli Seam Operations Environmental Assessment)
Appin	1.01		Water Solutions (2003)
Tower	0.10		Water Solutions (2003)
Westcliff	0.10	2001	Water Solutions (2003)
Westcliff	1.64	2004 to 2009 inclusive	Gilbert and Associates (2009)
Appin and Douglas combined	1.35	Jan 2004 to Sep 2004.	Illawarra Coal (2007)
NRE No.1	0.54		Geoterra (2010a)
NRE Wongawilli	4.16	2005 to 2009 inclusive	WRM (2010)
NRE Wongawilli	4.99		Geoterra (2010b)
Elouera*	3.29 6.57	June 1998 June 2001	ACA (2006)
Elouera*	10.37		Geoterra (2010b)

* Mining occurred between 1993 and 2007.

2.6 Ground Deformation

2.6.1 Groundwater Desaturation above a Longwall Panel

Research conducted by Mr Paul Tammetta (and submitted for publication) has revealed a set of 15 well-resolved measurements of the height of groundwater desaturation above a longwall panel (H), above panel centrelines, from Australia and around the world (see Coffey, 2012, for a more detailed discussion). For each measurement, a large number of hydraulic head measurement devices have recorded the post-mining (and frequently the pre-mining) hydraulic head across the interface between the saturated and unsaturated zones, providing a direct estimate for H.

Figure 5a shows results from the H database. A clear relationship between mined thickness (t) and the ratio of H / w (where w = void width) is apparent. The consistency of the relationship is made more remarkable given the diverse range of lithologies and void geometries represented in the dataset.

Although the relationship is clearly visible, there are several difficulties associated with displaying the relationship as t versus H / w. Firstly, there is increasing divergence of the dataset at small t. Secondly, the relationship most closely resembles an exponential integral which cannot be calculated analytically. The database was subjected to an inversion process where the relationship between H and various combinations of the three critical parameters, w, t, and overburden thickness d, was investigated. Figure 5b shows the same data as Figure 5a using an alternative parameterisation. The variable u is used (where $u = w\, t^{1.4}\, d^{0.2}$, and w, t and d are in metres), and the logarithmic line of best fit through the dataset is estimated as (H in metres):

$$H = 1438 \ln(4.315\times10^{-5}\, u + 0.9818) + 26$$

The fitted line passes through the origin, and more accurately represents H at large and small u. The divergence in the dataset at small u is reduced from Figure 5a, an important factor in maximising the reliability of a relationship. The root mean squared error of fit between the function and the 15 data points is 7.3%.

Also shown on Figure 5b is a dataset of measurements from multiple-device boreholes, where the measurements confirmed either saturated or unsaturated conditions, thereby limiting the possible range of H. Unsaturated results were selected only where the absence of saturation could be confirmed from the uppermost measurement to the mined seam. Other data not discussed here indicate that H over the chain pillars is smaller, and may reduce to zero in some circumstances.

Comparison of deformation and hydraulic head databases not discussed here (see Coffey, 2012) indicates that the desaturated zone and the zone of large downward movement are coincident. The deformation data indicate a paraboloid shape for the zone of large downward movement, or collapsed zone, above a longwall panel.

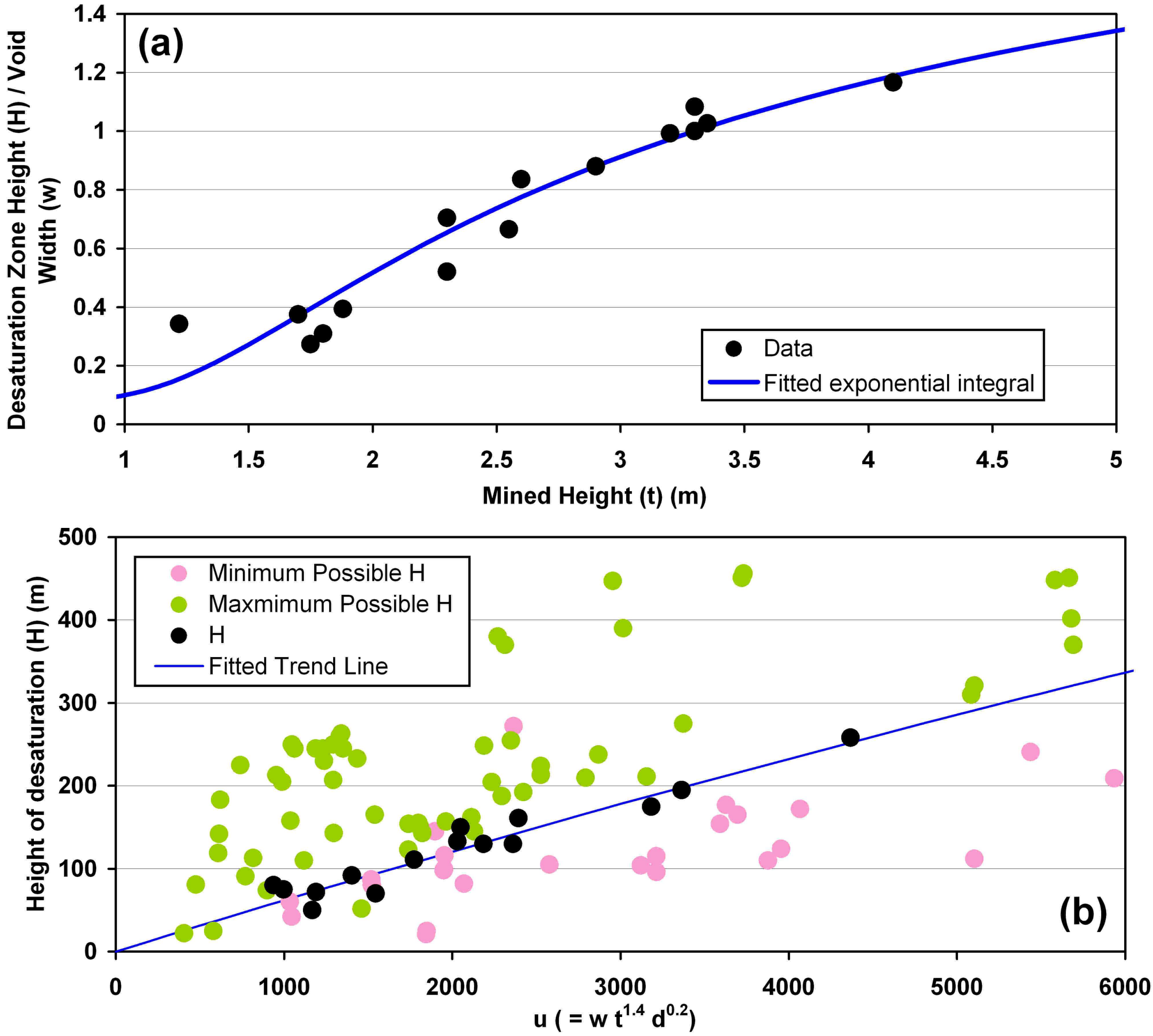


Figure 5. Database of measurements of the height of the desaturated zone (H) above longwall panel centrelines. H (divided by void width) is first plotted against the mined height (a), and then (as H only) against the parameter u, where u is a function of the three main geometric parameters for a longwall panel (b).

Monitoring locations DDH08 and DDH09 were installed over chain pillars and a caved longwall centreline, respectively, at the Elouera longwall mine immediately south of Dendrobium Area 3B. The hydraulic heads mesh accurately with H values predicted by the relation derived above. Figure 6 shows the interpreted post-mining hydraulic heads associated with these longwalls. Hydraulic head gradients are strongly downward, with contours draping around the collapsed zones. This representation serves as a conceptual model for development of post-mining hydraulic heads down the profile at Dendrobium.

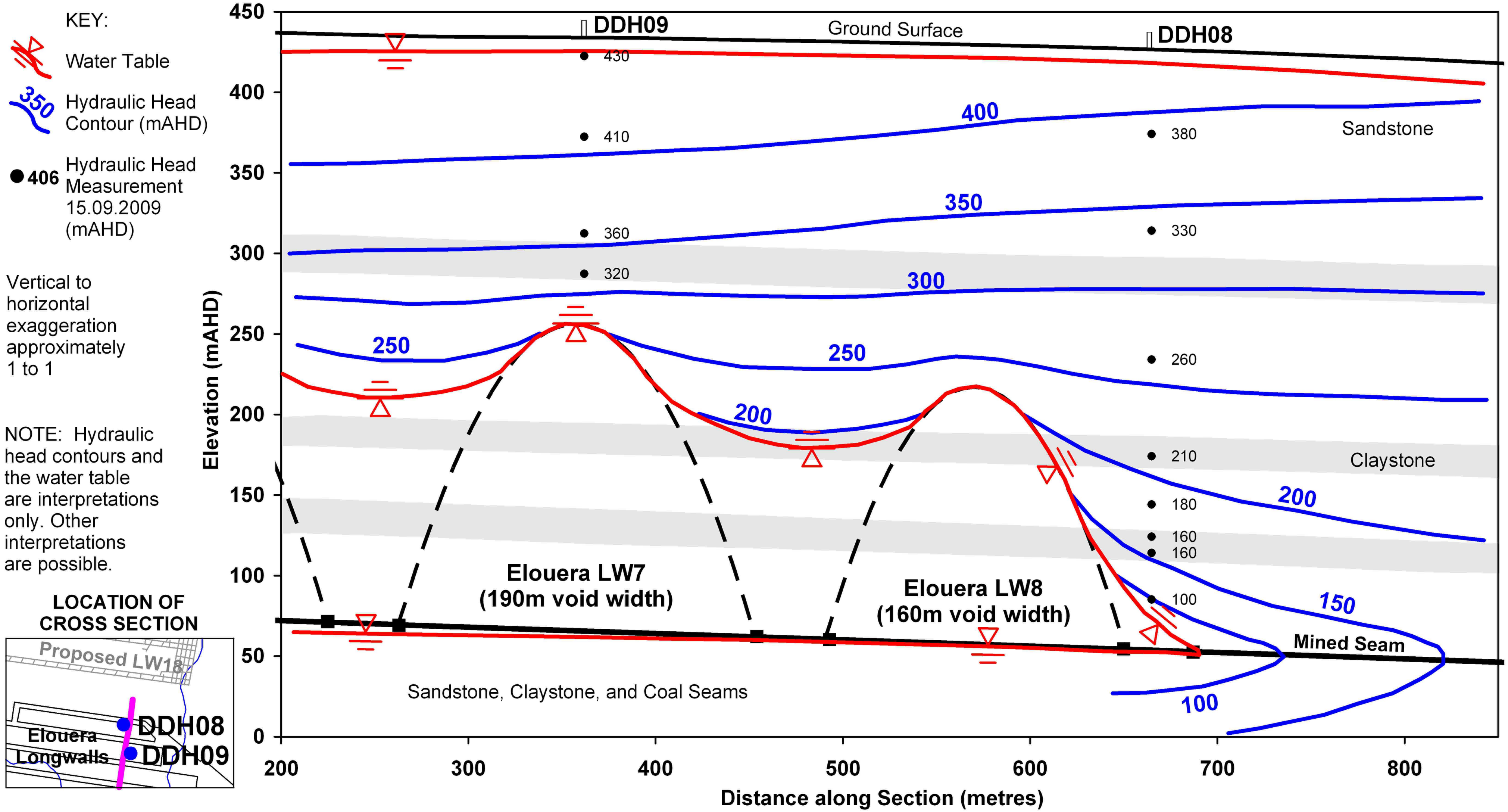


Figure 6. Interpreted post-mining (15 September 2009) hydraulic head contours along a cross section through Elouera Longwalls 7 and 8.

2.6.2 Ground Deformation Conceptual Model

The longwall caving process will create the following two distinct zones above each longwall panel:

- The collapsed zone, and
- The disturbed zone.

These zones are illustrated in Figure 7. The Collapsed Zone is parabolic in cross-section, and reaches from the mined horizon to a maximum height approximately equal to H (the height of desaturation above a longwall) over centrepanel. This zone is severely disturbed and is completely drained of groundwater during caving. It is subsequently unable to maintain a positive pressure head. It will behave as a drain while the void is kept dewatered, and during early recovery. Within this zone, the matrix of rock blocks may continue draining for extended periods however the defects will immediately transport this water downward to discharge from the mine. Hydraulic conductivity undergoes increases throughout the zone. Post-mining stresses are low.

The Disturbed Zone overlies the Collapsed Zone. It maintains positive groundwater pressure heads. Some information available for long-term groundwater behaviour in the disturbed zone suggests that pressure heads remain relatively stable, except for immediate lowering associated with drainage of lower strata and minor increases in the storatvity of the medium. Hydraulic conductivity undergoes increases and decreases in this zone. Post-mining stresses have reduced by smaller amounts, and may have increased in some zones. Mine-induced desaturation in the disturbed zone occurs above the chain pillars. Here, H is smaller than over centrepanel, and may even be zero if the pillar is flanked by one panel only. Apart from w and t, H above the chain pillars is likely to be more strongly dependent on d, and is likely to also be dependent on the chain pillar width.

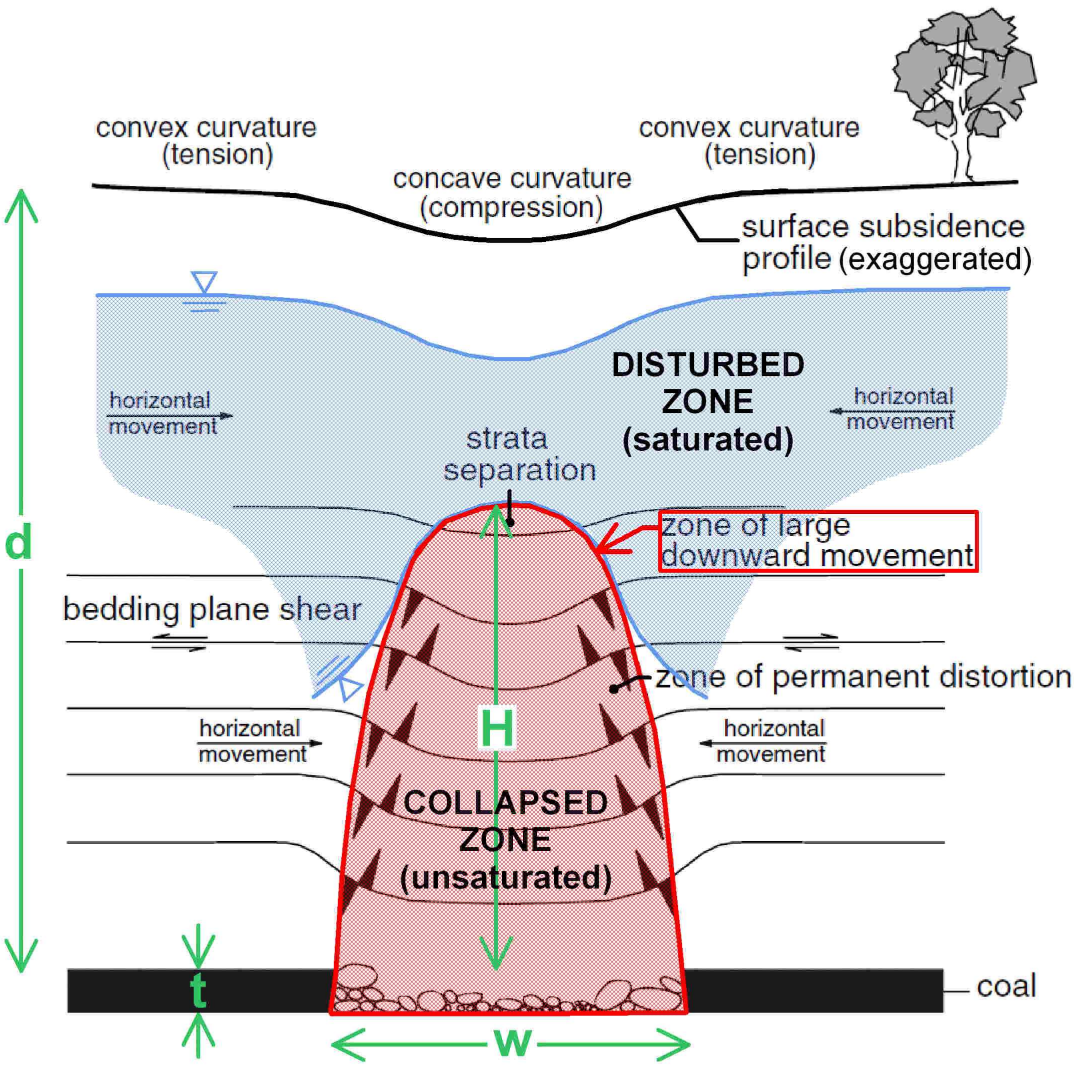


Figure 7. Conceptual model for ground deformation above a caved longwall panel, modified from Holla and Barclay (2000). The zone of large downward movement forms the collapsed zone, which desaturates.

2.6.3 Interpreted Height of the Collapsed Zone at Dendrobium

For a mined thickness of 3.4m, the height of the collapsed zone will be about 250m for a 250m void width (240m panels) and about 310m for a 310m void width (300m panels). Using average strata thicknesses, the height of the collapsed zone extends upward to about 20m below the base of the Bald Hill Claystone, for 240m-wide panels, and to about 15m above the base of the Hawkesbury Sandstone for 300m-wide panels. Using the actual widths for Longwalls 1 to 7, and proposed widths for other panels, Figure 8 shows where the assessed height of the collapsed zone over centre panel reaches the surface, based on the assessments made in this report. The southern parts of Longwalls 1, 2, and 3 have collapsed zones that reach the surface and provide a means of exacerbating mine inflows during high rainfall events. The assessment indicates that collapsed zones reach the surface also at some other locations.

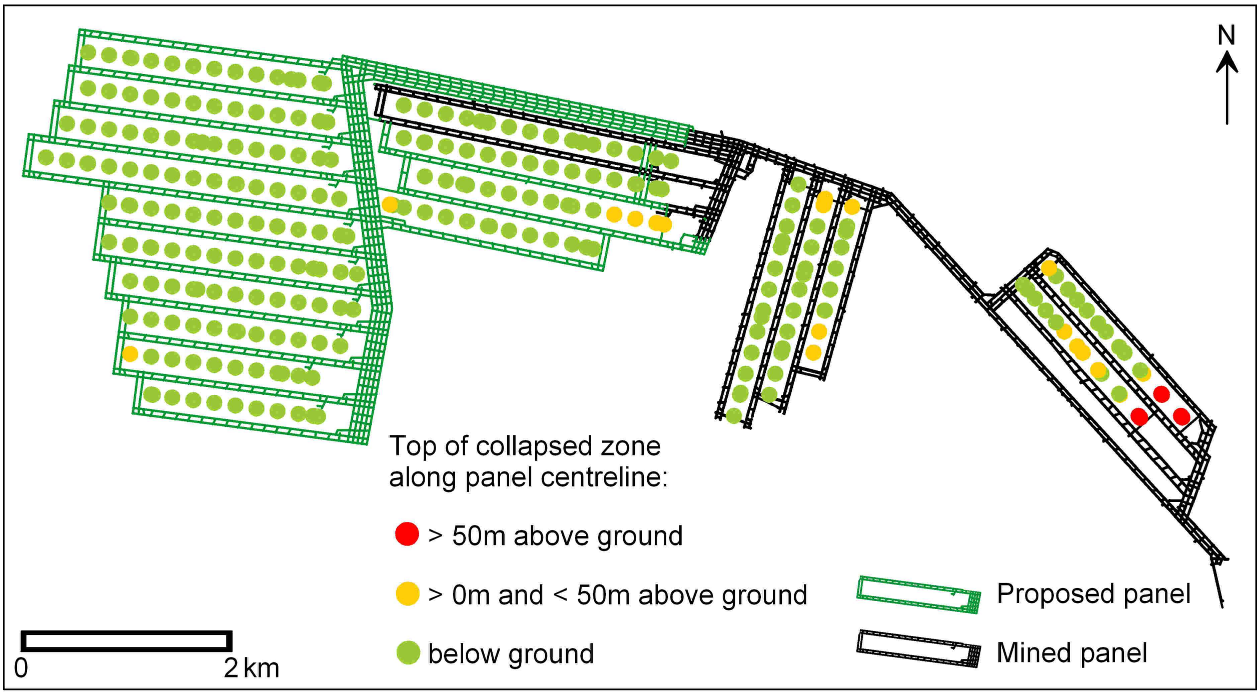


Figure 8. Estimated height of collapsed zone for mined and proposed panels.

Groundwater inflows to the workings calculated by BHP on an area-by-area-basis are shown in Figure 9. The collapsed zones for the panels of Area 3A mined so far (Longwalls 6, 7, and the western half of 8) are interpreted to have not reached the surface. For Area 3A the calculated inflow increases linearly as the goaf area increases, indicating a source that is not dominated by meteorological variations. In contrast, the inflow to Area 2 (Longwalls 3, 4, and 5) oscillates significantly, and provides most of the departure of the cumulative inflow curve (for all mine areas) from the long-term trend.

Inflows to Area 1 in Figure 9 were similar to inflows to Area 2 at first, but have become more subdued and less influenced by meteorological variations. This may be related to the presence of Bulli Seam workings directly above Longwalls 1 and 2 (which were drained prior to mining but may now be intercepting a component of vertical recharge from above), or to the presence of full extraction mining in the Wongawilli Seam (the Kemira longwalls) adjacent to Longwalls 1 and 2. The Kemira workings are currently being used as a water storage for excess mine water. The drainage complexity created by these workings in close proximity to Longwalls 1 and 2 may have altered the groundwater inflow pattern to Dendrobium Mine Area 1. Other factors that could have subdued the inflow response may include advantageous soil, or other surface or structural features, in the area where the collapsed zones of Longwalls 1 and 2 are interpreted to reach the surface.

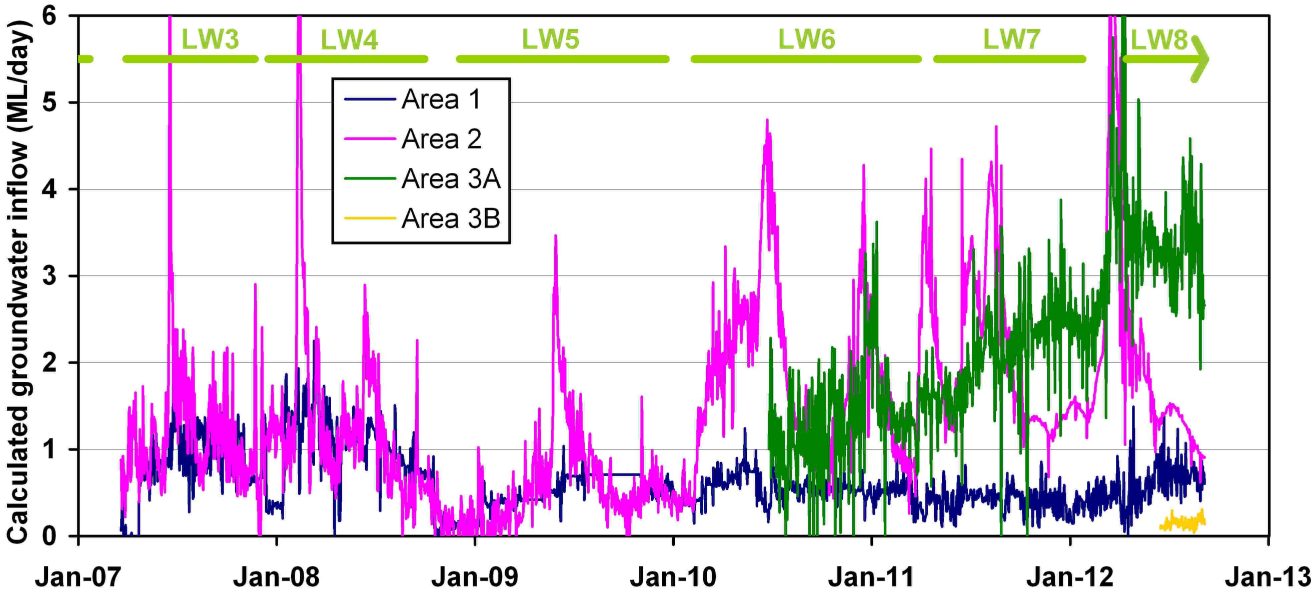
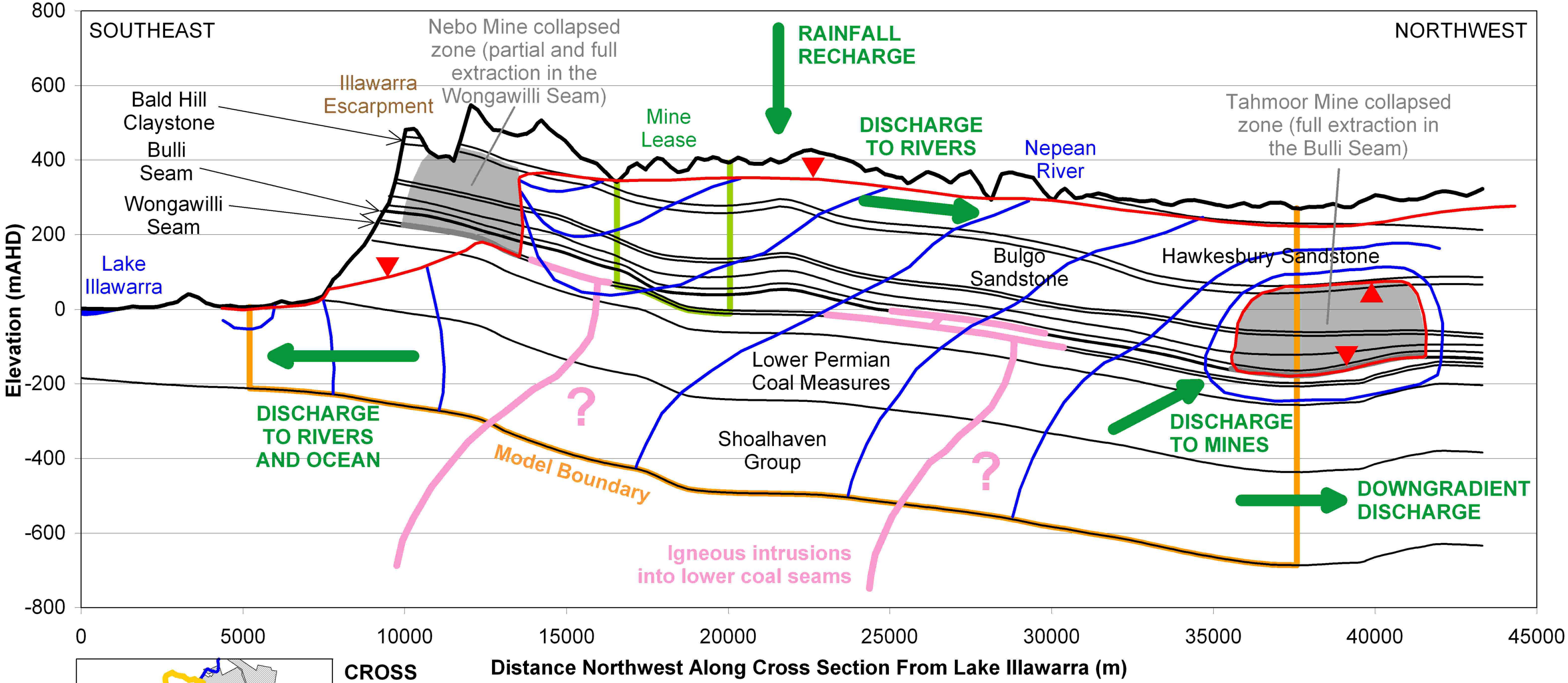
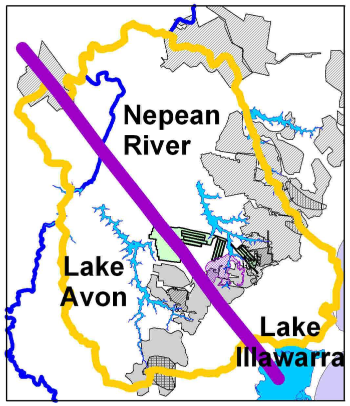


Figure 9. Groundwater inflow to the workings, calculated by BHP, for each mine area.

2.6.4 Regional Hydrogeological Cross-Section

Figure 10 shows a north-south cross section through the regional area with actual structure contours for the base of important lithologies. The figure illustrates the main elements of the conceptual model as they are interpreted to apply to the regional area around the Dendrobium mine. Also shown are the numerical model boundaries. Schematic hydraulic head contours are drawn to illustrate the expected overall hydraulic head field.





CROSS SECTION LOCATION

KEY:

Schematic water table

Schematic hydraulic head contour

Flow component of the groundwater system

Figure 10. Illustration of the various components of the hydrogeological conceptual model.

3 NUMERICAL MODEL DEVELOPMENT

A regional groundwater flow numerical model has been developed to simulate mining of panels in Dendrobium Mine Areas 1, 2, 3A, and 3B. 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, as are developed during longwall mining. 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 (see Figures 11 and 13) covers 770km^2 within a window of 34km east-west by 39km north-south. The southeastern portion of the model area traverses the Illawarra Escarpment. The physical model boundary follows natural features and has been selected so that the hydraulic heads in the model are set up by rainfall recharge and groundwater sinks at the extremities of the model area (in conjunction with interior boundary conditions such as mines and rivers). 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 to this is the ocean, where the invariant head assumption is valid, and the hydraulic head elevation, and position, of the constant head boundary can be accurately determined.

The model grid comprises 15 layers with 225 columns and 239 rows. Cell dimensions are 50m by 50m over Longwalls 3 to 8 in Areas 1 and 2, and Longwalls 13 to 18 in Area 3B (the ones which approach Lake Avon), expanding to 100m by 100m over the remaining Dendrobium longwalls (mined and proposed), then expanding to 200m by 200m at the extremities of the model area. The finer grid is placed where detail is required during model calibration and predictive simulations.

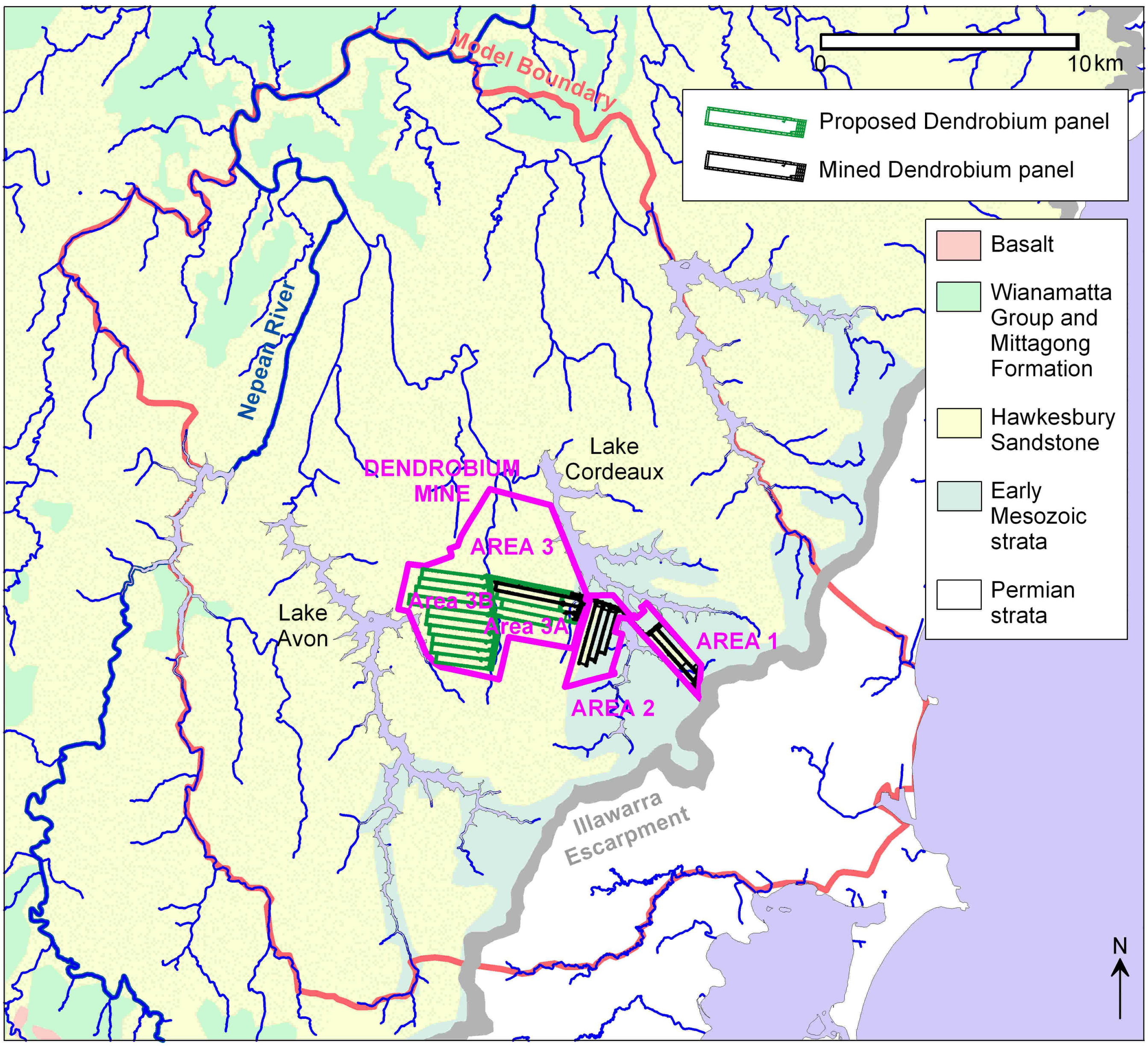


Figure 11. Model area.

15 model layers are used to represent lithological contrasts and mining-induced stratigraphic changes. These layers and their average thicknesses are listed in Table 3. The crinanite intrusion is present in the model in Layers 2 to 5. The Hawkesbury Sandstone is represented by two layers to handle the large natural vertical hydraulic gradients present within it, and to allow assignment of the height of the collapsed zone for panels of 300m width.

The Wianamatta Group and Mittagong Formation occur in the northwest of the model area (near Tahmoor and Appin Mines) as three isolated zones of limited extent and thickness. The average thickness in the Appin Mine area is about 10m (Coffey, 2012). The Group and Formation are indirectly represented by a lower rainfall recharge to the Hawkesbury Sandstone, where required. They are far from the Dendrobium mine area and this approach is considered reasonable. Very few of the drainage channels in the model area intersect the Wianamatta Group or the Mittagong Formation.

The Bulgo Sandstone is represented by two layers to allow assignment of the height of the collapsed zone for panels of 240m width. The base of the model terminates at the lower boundary of the Shoalhaven Group.

Table 3. Model layer thicknesses for the Dendrobium Mine area.

Stratum	Model Layer	Layer Thickness (m)	Comment
Hawkesbury Sandstone (Upper)	1	Variable[1]	Includes three isolated tracts of Wianamatta Group and Mittagong Formation in the Tahmoor and Appin areas.
Hawkesbury Sandstone (Lower)	2	20	Includes the Garie and Newport Formations.
Bald Hill Claystone	3	20	
Bulgo Sandstone (Upper)	4	45	
Bulgo Sandstone (Lower)	5	83	Average (varies between nil and 182m).
Stanwell Park Claystone	6	10	
Scarborough Sandstone	7	39	Average (varies between nil and 97m).
Wombarra Claystone	8	27	Average (varies between 9m and 57m).
Coalcliff Sandstone	9	15	
Bulli Seam	10	3	
Lawrence & Loddon Sandstones	11	27	Average (varies between 1m and 71m).
Wongwilli Seam	12	9	Defined as being between the top of Ply 1 (WW01) to the base of Ply 11 (WW11).
Kembla Sandstone	13	50	
Lower Permian Coal Measures	14	180	
Shoalhaven Group	15	250	
Crinanite (upper)	2	Variable[2]	Crinanite is not present in model layer 1.
Crinanite (upper middle)	3	Variable[2]	
Crinanite (lower middle)	4	Variable[2]	
Crinanite (lower)	5	Variable[2]	

NOTES:
1. Varies between 0m and about 110m between Lakes Avon and Cordeaux along Model Row 133 (see Figures 16 and 18 below).
2. Average total thickness over most of the crinanite extent (in plan) is about 100m.

Structure contours for the most critical geological horizons were compiled mainly from data provided by BHP for the Appin and Dendrobium areas. These data sets were combined into a seamless single data set, with control at the edges of the model area provided by structure contour maps developed by the NSW Department of Minerals and Energy from coal exploration boreholes drilled in the Southern Coalfield. Structure contour surfaces for the model were interpolated for six fundamental surfaces, consisting of the bases of the Wianamatta Group, Hawkesbury Sandstone, Bulgo Sandstone, Scarborough Sandstone, Bulli Seam, and Wongawilli Seam Ply 11. For the purpose of modelling, other surfaces (for example, the base of the Stanwell Park Claystone) were developed from these six fundamental surfaces using constant, or proportioned, thicknesses.

The outcrop geology calculated by intersecting the interpolated surfaces is compared to a published geology map in Figure 12 (Wollongong-Port Hacking Geological Series Sheet 9029-9129, NSW Geological Survey, Department of Mineral Resources, Edition 1, 1985). The calculated outcrops agree closely with the published geology map.

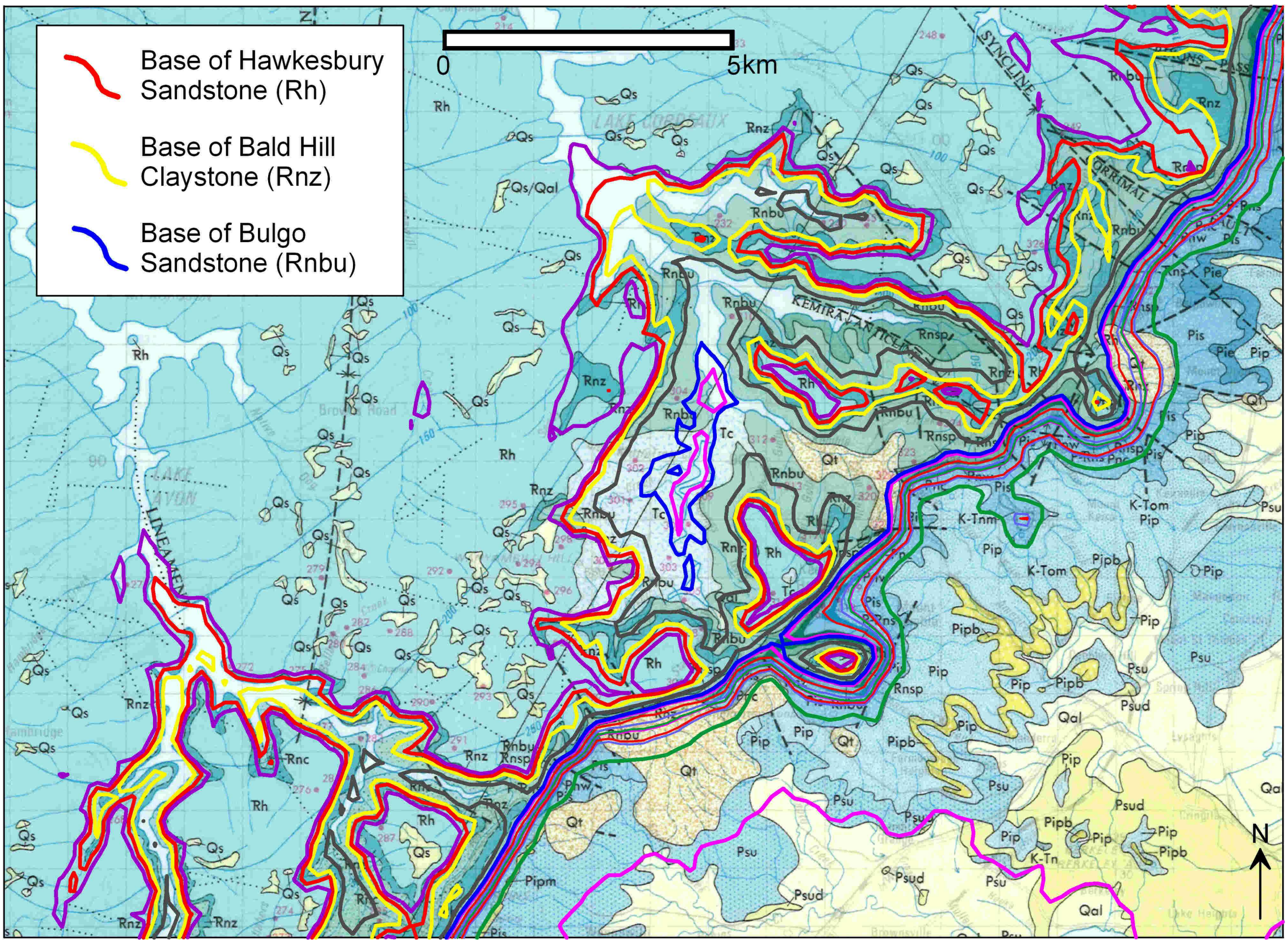


Figure 12. Comparison of model layer outcrops and published geology. Geological base is from the Wollongong-Port Hacking Geological Series Sheet 9029-9129 (NSW Geological Survey, Edition 1, 1985)

A high-resolution regional digital elevation model for the ground in the numerical model area was developed from the Shuttle Radar Topography Mission (SRTM) worldwide 90m digital elevation Version 4 database, provided on the internet by the Consortium for Spatial Information of the Consultative Group on International Agricultural Research (CGIAR-CSI). These data are provided to a resolution of 1m.

3.2 Aquifer Parameter Zonation

Each model layer is modelled with a single hydraulic conductivity (K) zone with the following exceptions:

- Layers 2, 3, 4, and 5 are host to the crinanite. The crinanite has a separate K zone for each layer.
- Layers 10 and 12 (the mined coal seams) employ multiple zones to simulate the additional extension of increases in K in the mined seams arising from degassification and other processes.

Each K zone has a single lateral K and a single vertical K. For the probabilistic analysis of mine inflow during predictive simulations, the K zones of the upper five layers are replaced by randomly generated K fields that vary from cell to cell within a zone. Storativity zones are linked to K zones, except that single-valued storativity zones are retained in the probabilistic analysis.

Lateral K anisotropy is not used however modelling results below, and drawdown observations at other mines, suggest that some degree of anisotropy is present. Maximum lateral hydraulic conductivity is probably oriented north-northeast south-southwest along the direction of maximum horizontal stress.

3.3 Boundary Conditions

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

- No-flow at topographic divides.
- Discharge zones at lakes and streams.
- Other underground mines (where significant hydraulic gradients towards the collapsed zones are present).

Drainage channels were simulated using the SURFACT Drain package. Drain conductance is set to a high value of 100m^2/day and allows the aquifer hydraulic properties to control leakage to the drain. Elevations for the inverts of these channels are approximate only, having been estimated mainly from 1:25,000 topographic maps of the area.

The Illawarra Escarpment is treated as a line of drain cells to simulate consumption of groundwater at the escarpment by seepage and evapotranspiration.

Lakes Avon, Cordeaux, Nepean and Cataract were simulated using the River package. This allows water to be exchanged with the aquifer in either direction, depending on the aquifer hydraulic head compared to the river stage. Lake cells occur in the upper 4 layers due to layer dips and extent of the lakes. Riverbed conductance is not calibrated but is adopted from HC (2010) as 25m^2/day for 50m by 50m cells. For a 50m x 50m cell, and soil thickness of 2m on the lake bottom, this equates to a vertical hydraulic conductivity of 0.02m/day. This value is relatively high and therefore conservative, in that a lower conductance may reduce seepage from the lakes. Water level elevations for lakes were based on supplied data and have been kept constant for all simulations. These elevations are as follows:

- Lake Nepean: 308mAHD
- Lake Avon: 312mAHD
- Lake Cordeaux: 298mAHD

- Lake Cataract: 284mAHD

The lowest ground elevation of the model area occurs at the coast to the southeast. Here, Lake Illawarra and the ocean were simulated using a constant head boundary at an elevation of 0.1mAHD.

In practice, evapotranspiration is a virtually constant offset to the rainfall recharge in natural conditions, but use of the Evapotranspiration package may underestimate the effects of plant transpiration when drawdown occurs below the extinction depth. This is because the interception and transpiration of rainfall recharge in the unsaturated zone may not be adequately simulated. In this work, there is no requirement to assess impacts on trees and other vegetation, therefore evapotranspiration is not modelled explicitly but is addressed in the assessment of recharge.

Rainfall recharge as modelled in this study represents recharge that enters the aquifer. The model area is divided into four recharge zones based on average annual rainfall. These zones are shown in Figure 13. They trend northeast-southwest, being bounded by interpreted contours of average rainfall. The annual average rainfall values used as limits in defining these zones are:

- Zone A: Rainfall < 1050 mm/year (northwest sector)
- Zone B: 1050 mm/year ≤ Rainfall < 1250 mm/year (central and coastal sectors)
- Zone C: 1250 mm/year ≤ Rainfall (escarpment sector)

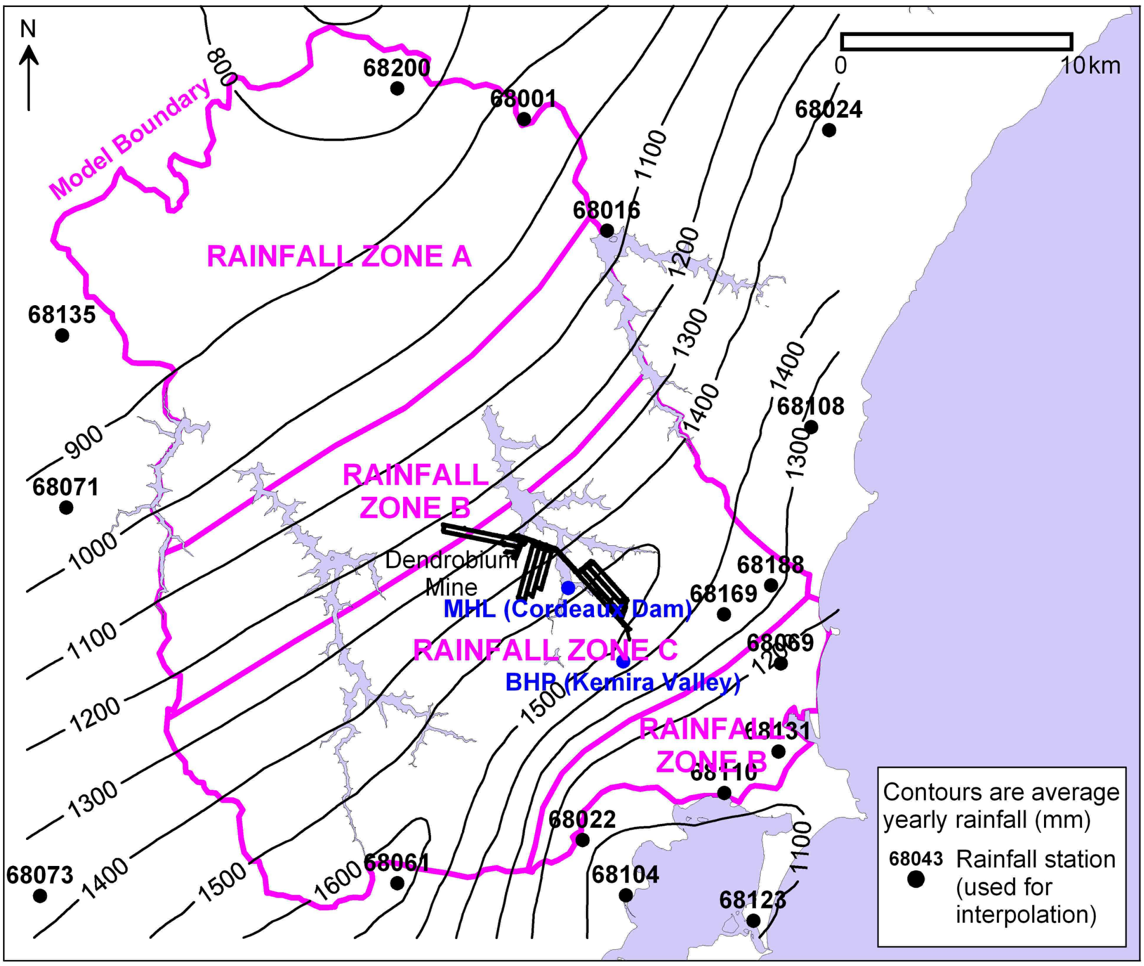


Figure 13. Rainfall zonation adopted for numerical simulation.

Leakage from unconsolidated sediments into the mine voids is 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 (see Figure 12) and borehole logs.

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

3.3.1 Longwall Caving

Longwall mining and development headings are simulated using the Drain package. When a part of the seam is mined, the drain package is activated with the drain elevation set to 10cm above seam level. Neighbouring mine drain elevations are also set to 10cm above seam level. Development headings are excavated ahead of longwall mining.

For a mined thickness of 3.4m, the height of the collapsed zone will be about 250m for a 250m void width (240m panels) and about 310m for a 310m void width (300m panels). Using average strata thicknesses, the height of the collapsed zone extends upward to about 20m below the base of the Bald Hill Claystone, for 240m panels, and to about 15m above the base of the Hawkesbury Sandstone for 300m panels.

Longwall caving is simulated by draining the collapsed zone above a panel using the drain package. When caving occurs, drains are activated in model layers 5 to 12 for 240m panels, and layers 3 to 12 for 300m panels. The shape of the modelled drained volume (the collapsed zone) in cross-section is more square than the parabolic shape of the collapsed zone observed in the field, therefore the uppermost drained model layer, and the drain elevation in that layer, is slightly lower than H (the peak of the parabolic-shaped collapsed zone).

Most of the change in aquifer properties occurs within the collapsed zone, but since the zone is maintained in a dewatered state, these changes do not impact the functioning of the model. Changes in aquifer properties above the collapsed zone are less severe, and the overall vertical K field between ground surface and H is not expected to change greatly (the overall vertical hydraulic conductivity may decrease, but this is conservatively not incorporated). Similarly, the overall lateral K field between ground surface and H, over the collapsed zone, is not expected to change in such a way as to affect model outcomes, except where storativity is concerned.

Separate investigation into the ability of SURFACT (or any algorithm) to accurately calculate the drawdowns and fluxes caused by sudden but small instantaneous storage increases (from longwall caving) above the collapsed zone, as part of the current project, indicated that this calculation is best done analytically. The drawdown due to these sudden storativity increases will ultimately impact the lakes and rivers, either directly (as seepage from the water courses or lakes to satisfy the drawdown), or by intercepting baseflow (if the drawdown occurs at elevations above the water courses or lake water levels). Sudden changes in storativity (and the water therefore required to fill these) are calculated analytically, and are distributed amongst the rivers and Lakes Avon and Cordeaux according to the seepage proportions for lakes and rivers calculated by the model. It was found that the total rate of volume creation is less than 1% of the total inflow to the workings for all simulated time.

3.3.2 Limitations

Neither the functioning of the numerical model, nor the conceptual model for caving, account for:

- the collapsed zone reaching higher than the assessed amounts, nor to
- disturbance of extraordinary defect features such as a significant fault zone.

The model will not calculate impacts caused by either of these processes.

Extraordinary defects are those that are significant outliers in the population of defects for a rock (in terms of vertical continuity, lateral continuity, and aperture width), and may represent unstable, large scale defect planes. Disturbance of extraordinary defects can lead to the creation of extreme permeability pathways extending beyond the collapsed zone. Any water storages nearby (either underground or at the surface) that are well outside the collapsed zone can be connected directly to the collapsed zone via these disturbed extraordinary defects. Of the H measurements shown in Figure 5b, only one measurement is interpreted to have suffered the effects of disturbance of an extraordinary defect. It is the pink dot located at a u value of around 2300 and an H value of around 270m, where mining took place under the ocean. For this event, a vertical fault was suspected although the cause was never definitively identified in an inquiry. It is assessed that these events are rare but not easily predictable, and consequences can be most severe.

3.4 Comparison to the Area 3A Numerical Model (HC, 2010)

A numerical groundwater flow model was developed in 2009 (also in the MODFLOW-SURFACT environment) by Heritage Computing (HC, 2009b) for use in assessing the mechanism and water source for high mine inflow events that occurred in June 2007, February 2008, and June 2008 in Area 2 of the Dendrobium mine. The extent of the model set for this original purpose. The model was later modified and used to assess the effect of mining closer to Lake Cordeaux at Longwalls 6 to8 in Area 3A at the Dendrobium Mine (HC, 2010). This model will be referred to as the Area 3A model. For comparing to the Area 3A model, the model developed by Coffey for the current (Area 3B) study will be referred to as the Area 3B model.

The main differences between the Area 3A and Area 3B models are model extent, model calibration, conceptualisation of longwall caving, and methodology for the probabilistic modelling analysis. These differences are discussed below.

3.4.1 Extent

Area 3A Model: Covers a rectangular area of 54km^2 (9km by 6km), due to its original purpose. At the physical model boundary, constant heads are specified in most layers, usually on the northern, eastern and southern boundaries.

Area 3B Model: The active model area covers 770 km^2 within a window of 34 km east-west by 39 km north-south (1326 km^2). The physical model boundary follows natural features and was selected so that the hydraulic heads in the model are set up by rainfall recharge and groundwater sinks at the extremities of the model area (in conjunction with interior boundary conditions such as mines and rivers). Figure 14 shows the Area 3A and Area 3B model boundaries.

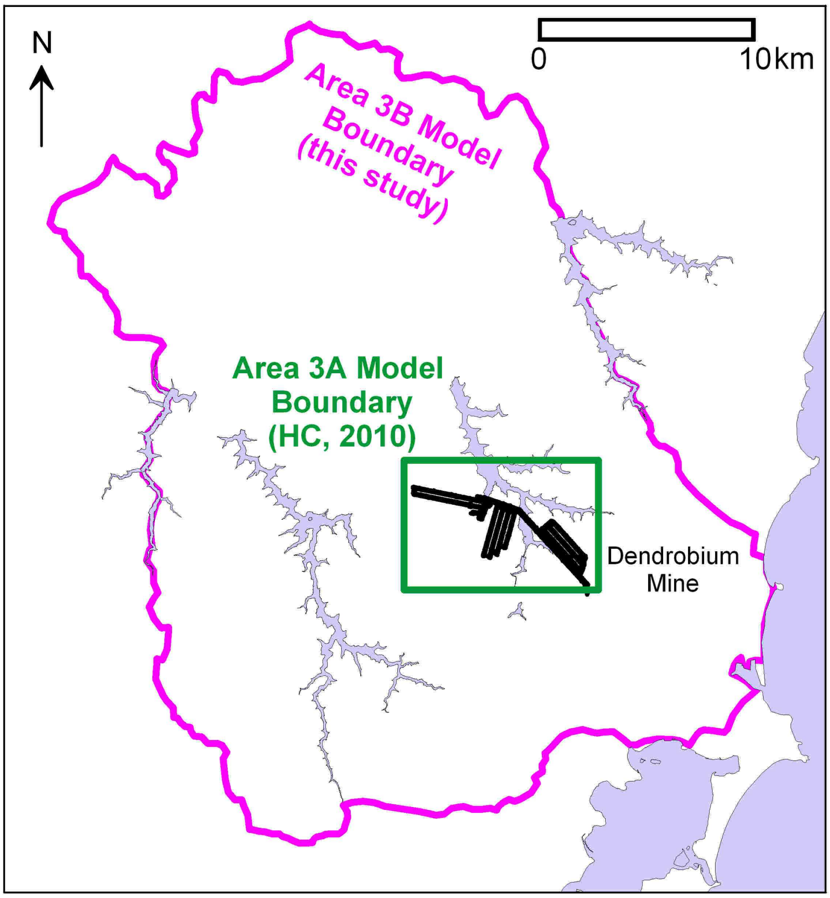


Figure 14. Extent of the Dendrobium Mine Area 3A numerical groundwater flow model (HC, 2010), compared to the model developed herein.

3.4.2 Calibration

Area 3A Model: The development of the initial head distribution (for calibration) is based on the constant heads that are specified in most layers at the physical model boundary.

Area 3B Model: The initial head distribution was developed by simulating mining at all the known mines inside the model boundary, from the beginning, up until the start of Dendrobium mining, using transient simulation with the same natural physical boundary conditions as the calibration model, without the use of constant heads (except at the ocean far to the southeast). See below for further information.

3.4.3 Longwall Caving

Area 3A Model: The collapsed zone extends up to the Stanwell Park Claystone. Instead of the zone being desaturated, the model changes the vertical hydraulic conductivity in this zone to simulate caving, with heads in this zone allowed to vary.

Area 3B Model: The collapsed zone extends upwards to the Bulgo Sandstone for 240m-wide panels (Longwalls 6 and 7), and to the Hawkesbury Sandstone for 300m-wide panels (Longwall 8 onwards). The collapsed zone becomes desaturated throughout the zone. See below for further information.

3.4.4 Probabilistic Analysis

Area3A Model: The analysis is undertaken by changing the values of aquifer properties in various layers. The hydraulic conductivity property is uniform everywhere within a layer, except where one formation changes to another in the same layer. Parameters are perturbed by between 0.5 and 2 orders of magnitude. The perturbation is transmitted to every cell within a formation within a layer. The three parameters selected for perturbation were:

- Bulgo Sandstone hydraulic conductivity.
- Stanwell Park Claystone hydraulic conductivity.
- Collapsed zone vertical hydraulic conductivity.

Area 3B Model: A manual stochastic analysis is undertaken by generating random realisations of the hydraulic conductivity field for each of the upper five model layers (the Hawkesbury Sandstone, Bald Hill Claystone, and Bulgo Sandstone), based on a statistical analysis of packer test results over specific depth intervals. A realisation is a randomly-generated perturbation of the measured hydraulic conductivity field using the mean and standard deviation of this field over a specific depth interval. Each realisation is for one layer and takes the form of a matrix of hydraulic conductivity values (leaving the crinanite unchanged), where the values vary from cell to cell within the matrix.

4 MODEL CALIBRATION

Given the signifcant number of mining stresses in the model area, and the age of these stresses, model calibration was conducted as a two-stage process as follows:

1. Simulation of the effects of mining at other mines (without Dendrobium) over a long time period in transient mode to a point at the beginning of Dendrobium operations. The final hydraulic head distribution is then used as the starting water level for the next stage.

2. Transient calibration of the numerical model by matching targets to model outputs, during mining of Longwalls 1 to 5. Longwall 6 is used for verification.

4.1 Calibration Targets

Stage 1 targets comprised 141 pre-(Dendrobium)mining hydraulic head measurements from 22 monitoring sites, providing an average of about 7 measurements down the profile at each site. This characterised the critical vertical hydraulic head gradients.

Stage 2 targets comprised:

- Hydrographs from 94 piezometers at 21 monitoring sites at the Dendrobium Mine, over the period of mining of Longwalls 3 to 6. This represents an average of nearly 5 piezometers at each site, located throughout the vertical profile. These sites are listed in Appendix A.
- Measured inflows to Dendrobium Mine.
- Estimated baseflow to lakes and rivers in the model area northwest of the Illawarra Escarpment.
- Measured inflows to surrounding full extraction mines.

4.2 Sources of Uncertainty in Observed Hydraulic Heads

There are four main sources of uncertainty, or error, in comparing observed hydraulic heads and modelled ones. These are:

- Accuracy of the VWPs. In Coffey (2012) it was shown that the Decile 5 variation in measurements of two VWPs at the same location is 7.8m. This uncertainty relates to the resolution of the instruments and is in addition to the uncertainty that is always present between measurements and the true hydraulic head.
- Vertical position of a VWP. Vertical hydraulic gradients in proximity to mining will be significantly greater than 0.5. Away from the workings, gradients of 0.5 or less are observed. In a numerical model, a layer will have only one head value per cell (an average value, applicable to the centre of the cell). Assuming a 50m thick layer, with a VWP unit located at either the top or the bottom of the layer, then if the model is perfectly replicating the system, the VWP and model heads will differ by half of 25m, or 12.5m. This error depends on, amongst other things, the layer thickness and the vertical gradient.
- Timing of development headings. Although panel mining progress was relatively well known, detailed information on the progress of development headings was unavailable at the time of modelling. This error might be significant for the evolution of development headings in Area 3 during mining in Area 2.

- Water levels in old workings. Water levels in old workings surrounding the Dendrobium Mine, reduced to mAHD, were unavailable at the time of modelling. Water levels in all mines are assumed to be at 10cm above the seam floor (replicating a situation of maintained dewatering). For mines where the goaf has appreciable ponded water, then hydraulic heads near the goaf may differ significantly from model calculations. The magnitude of this error recedes moving away from the goaf.

4.3 Stage 1 Calibration

Figure 15 shows modelled and observed hydraulic heads for the end of stage 1 transient calibration. Aquifer properties were varied during the calibration runs with the aim of improving the fit between observed and modelled heads. Considering the sources of uncertainty present in comparing observed and modelled hydraulic heads, the results are better than anticipated.

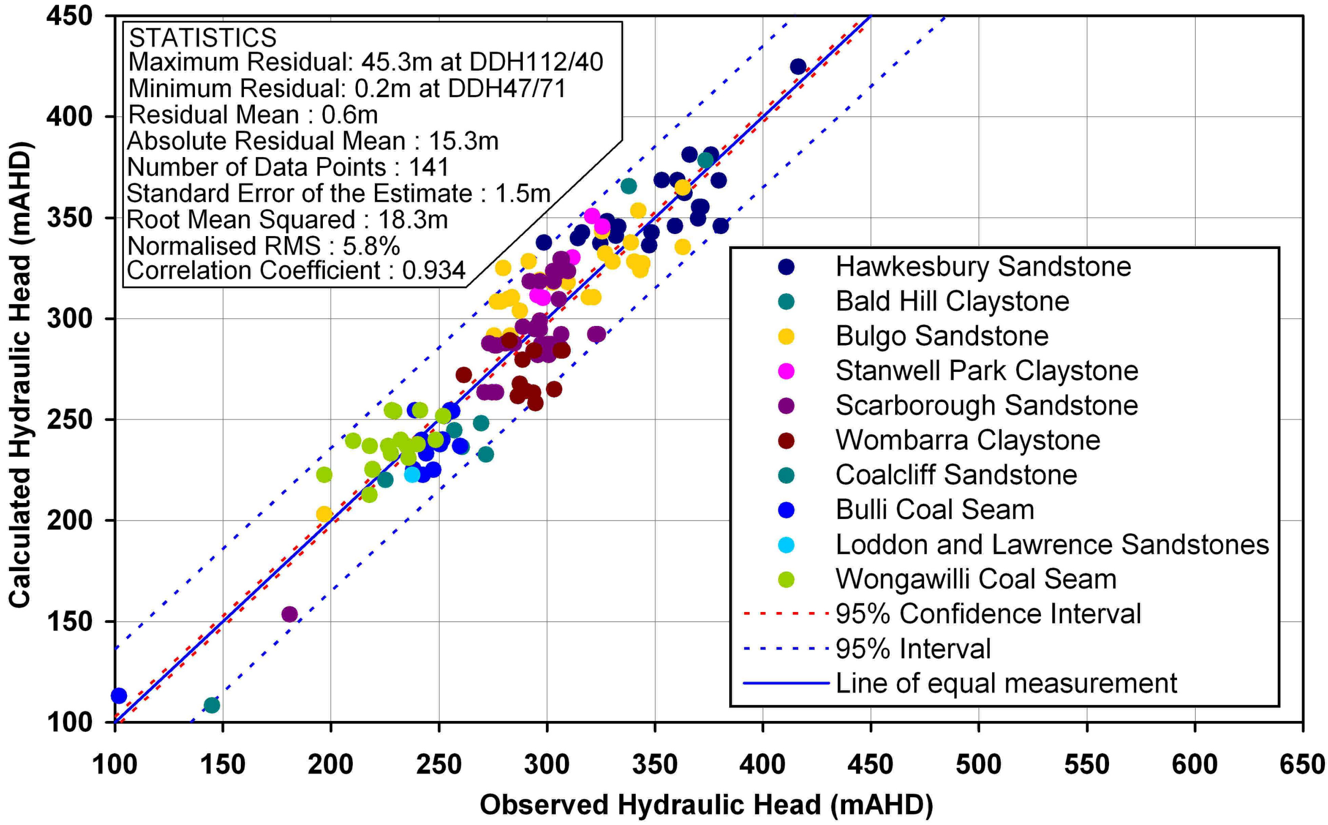


Figure 15. Observed and modelled hydraulic heads prior to Dendrobium operations (Stage 1 Calibration).

Figure 16 shows the pre-mining hydraulic head distribution along model column 126 (running north-south through Wongawilli and Appin collieries), and illustrates the vertical hydraulic gradients that are developed for the start of the calibration period. The figure illustrates the modelled (quantified) hydraulic head contours that represent the schematic contours sketched in Figure 10.

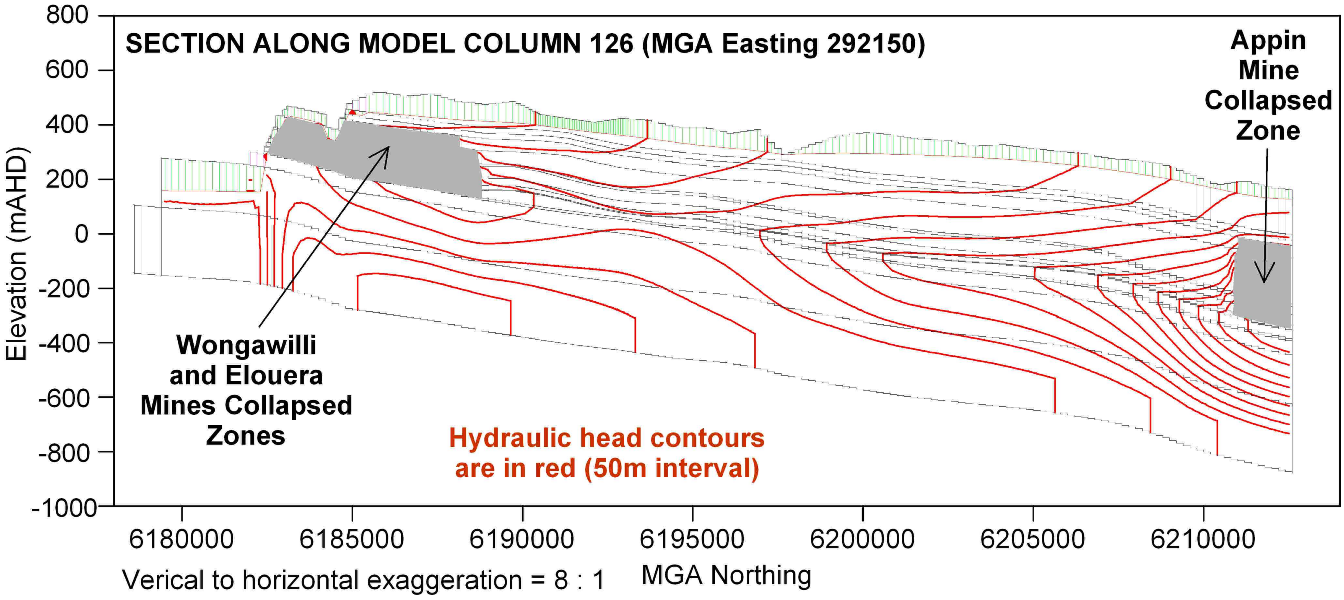


Figure 16. Modelled hydraulic head contours along a north -south cross-section of the model (Column 126) running through Wongawilli and Appin collieries, prior to mining at Dendrobium.

4.4 Stage 2 Calibration

Stage 2 calibration was undertaken for the period 1 March 2005 to 4 November 2009. Adaptive time stepping was used with the model solver, so actual stress period lengths were slightly different to the specified ones. Actual stress periods had an average length of about 60 days. Rainfall recharge varied dynamically. Parameter change was performed manually. A verification period covering the mining of Longwall 6 (simulation from 5 November 2009 to 30 April 2011) was undertaken following calibration, and model outputs were consistent with observations.

4.4.1 Hydraulic Heads

Appendix B presents modelled and observed hydrographs of hydraulic head. The modelled heads reproduce the observed heads accurately, despite the uncertainty present in comparing modelled and observed heads. Drawdowns in strata above the Stanwell Park Claystone (for example DDH38 and DDH117), and fast-acting drawdowns at long distances (for example DDH39), are successfully reproduced. The overall drawdown response is accurately replicated, with minor overestimates and underestimates in some hydrographs. Modelled heads for the verification period also replicated observed heads accurately.

Figure 17 shows the modelled watertable for 27 February 2011 (the end of mining at Longwall 6), and shows little change from the pre-Dendrobium mining watertable. The Illawarra escarpment is conspicuous as a major groundwater divide with steep lateral hydraulic gradients.

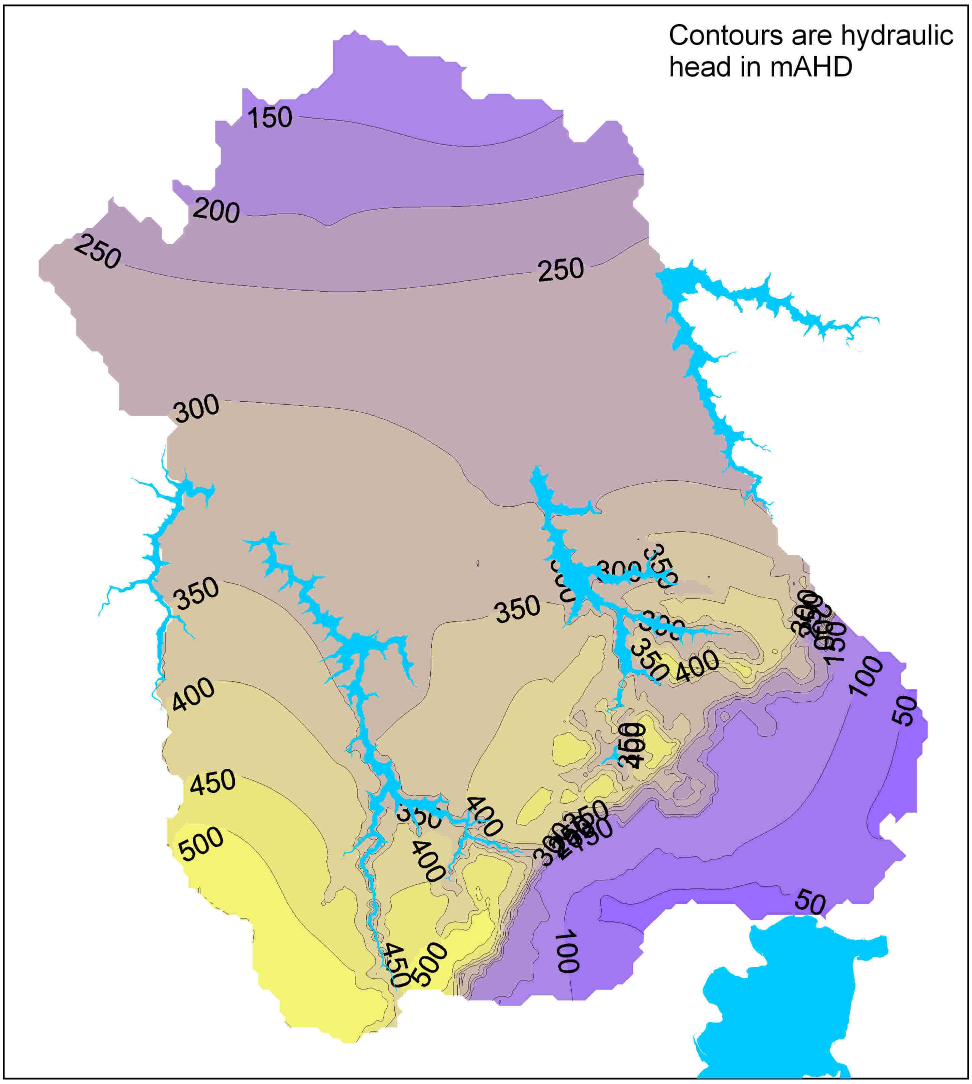


Figure 17. Modelled watertable for 27 February 2011 (after mining of Longwall 6).

Figure 18 shows the modelled hydraulic head distribution after mining of Longwall 5, along an east-west cross-section through Longwalls 5 to 3 (model row 133), at approximately the same location as the interpreted cross section of Figure 2. The modelled hydraulic heads are confirmed by the manually interpolated contours, and the model is realistically simulating the hydraulic heads developing around the caved longwalls.

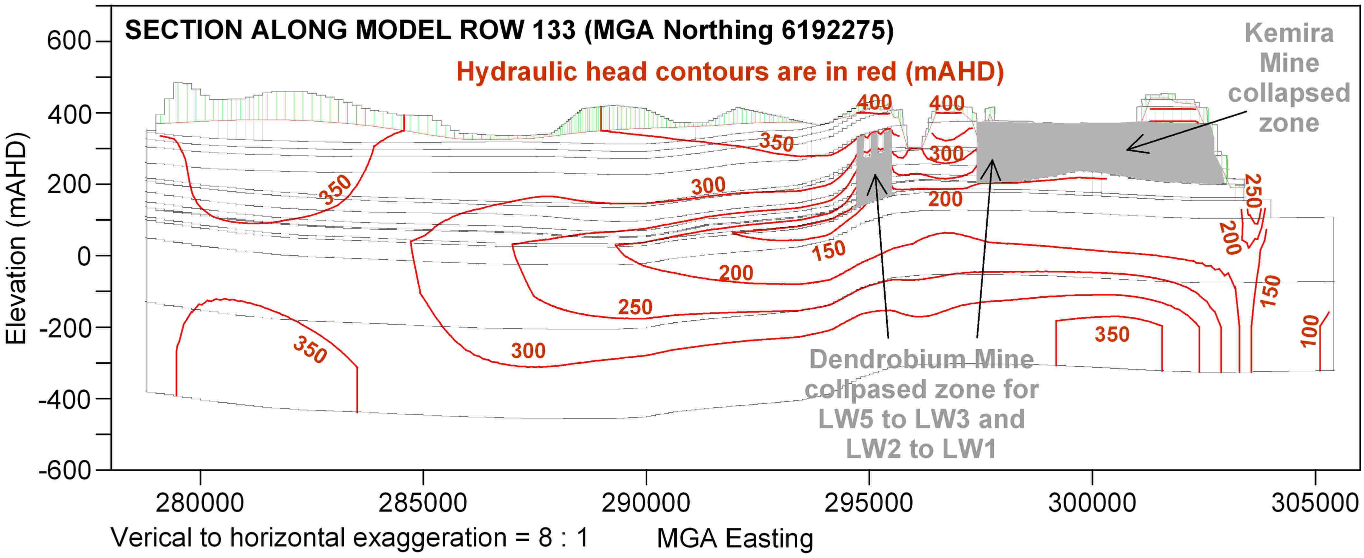


Figure 18. Modelled hydraulic head contours along an east-west cross-section of the model (Row 133) running through Dendrobium Area2 workings and the Kemira Mine, after mining of Longwall 5.

4.4.2 Groundwater Inflows

Modelled groundwater inflows to the Dendrobium Mine are shown in Figure 19, compared to groundwater inflows as calculated by BHP from measurements of pumped volumes and moisture in coal and ventilation. All groundwater inflows modelled for the Dendrobium Mine in this study (calibration and prediction) include inflows to mined Longwalls 1 to 6.

The match between modelled and calculated groundwater inflows is influenced by the effects of rainfall recharge, during severe rainfall events, through collapsed zones that have reached the surface. This is supported by the analysis of rainfall and inflow residuals in Ziegler and Middleton (2011) and in the current study (see above), and results from tritium analysis (Ecoengineers, 2012). Based on water chemistry data, PB (2012) suggests that the proportion of modern water increases during inflow events (where an event is an occurrence where sudden increases in inflow to the workings are sustained, usually during high rainfall events, with decrease in inflows occurring soon after).

Despite the effects of rainfall, the match is considered reasonable, with modelled inflows capturing the broad variation of calculated inflows. The greatest difference between calculated and modelled inflows is for the period covering the mining of Longwall 5.

Figure 19 also shows additional inflow calculations using pumping and hygrometer measurements made after model calibration and verification were complete (Longwalls 7 and part of 8). The modelled future inflows (discussed in later sections) are compared to these additional data and the match is considered good.

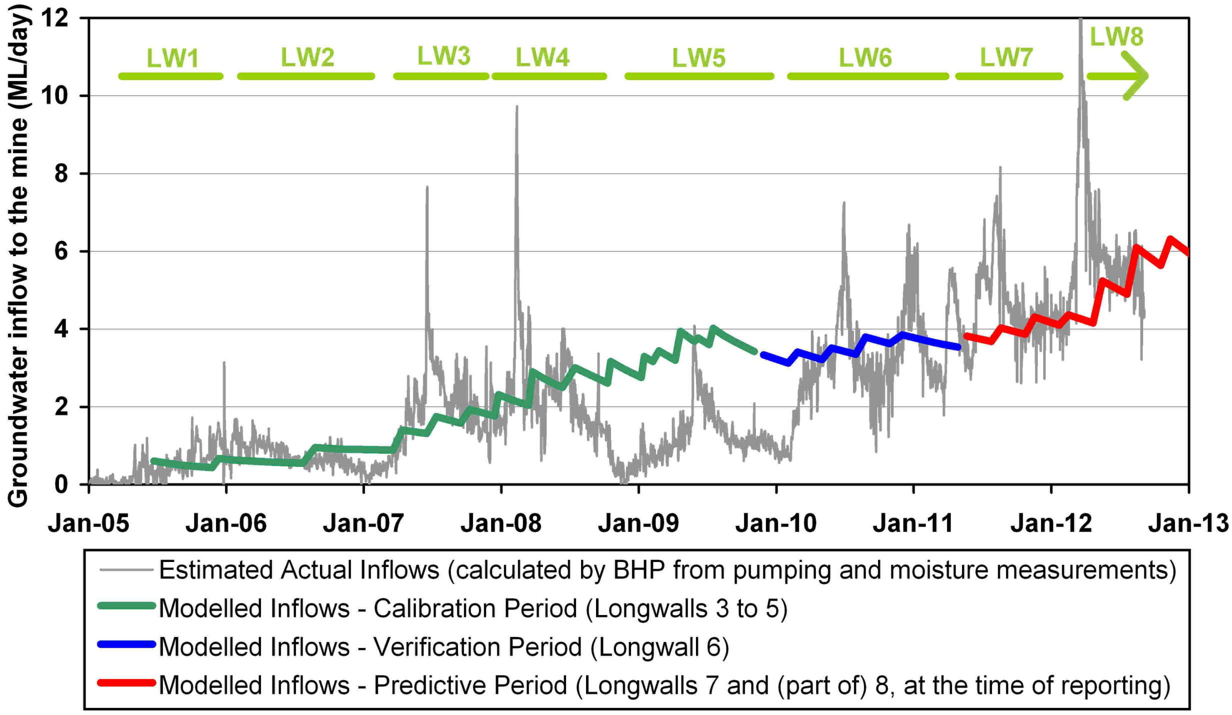


Figure 19. Calibrated groundwater inflows to the Dendrobioum mine.

Figure 20 shows modelled groundwater inflows to Dendrobium Mine Area 2 (Longwalls 3, 4, and 5) on a stratigraphic basis. Development headings are initially in Area 2, but then move into the eastern part of Area 3A towards the end of the calibration period, where they provide the bulk of the total inflow to the underground workings. The next highest contributors of inflow are the Scarborough and Bulgo sandstones, which are stratigraphically the highest strata in the collapsed zone overlying the longwalls.

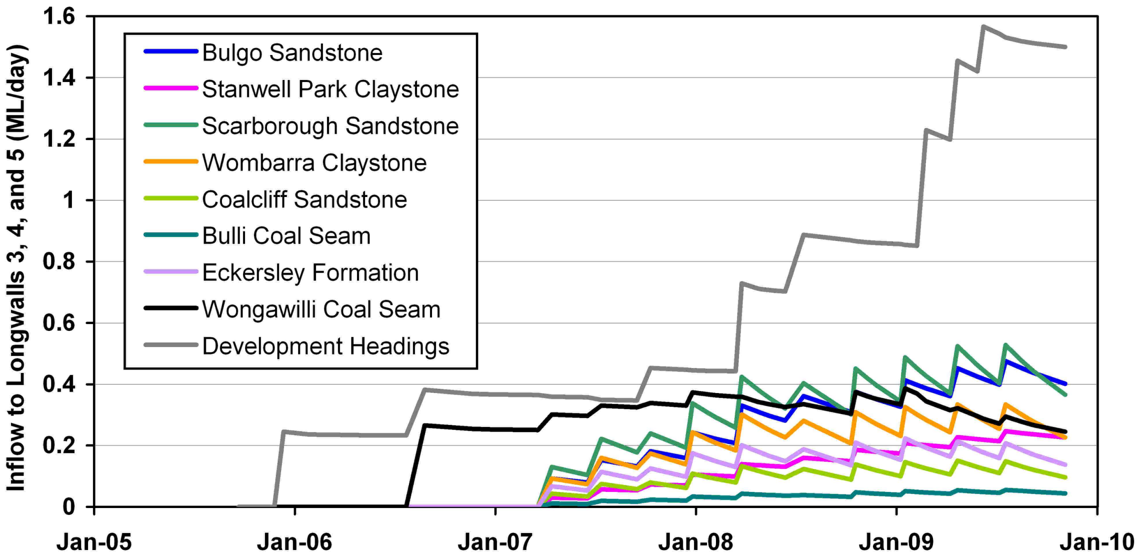


Figure 20. Calibrated groundwater inflows to Dendrobium Mine Area 2 (Longwalls 3, 4, and 5) on a stratigraphic basis.

4.4.3 Aquifer Properties

Calibrated aquifer properties are listed in Table 4.

Table 4. Calibrated aquifer properties.

Stratum	Model Layer	Kh[1] (m/day)	Kv[2] (m/day)	Kv/Kh	Specific yield	Specific storage (m^{-1})
Hawkesbury Sandstone (Upper)	1	0.12	0.00012	0.001	0.015	1.00E-06
Hawkesbury Sandstone (Lower)	2	0.025	0.00075	0.03	0.012	1.00E-06
Bald Hill Claystone	3	0.012	0.00036	0.03	0.01	1.00E-06
Bulgo Sandstone (Upper)	4	0.005	0.00025	0.05	0.008	9.00E-07
Bulgo Sandstone (Lower)	5	0.0017	0.000136	0.08	0.007	8.00E-07
Stanwell Park Claystone	6	0.001	0.00006	0.06	0.006	7.00E-07
Scarborough Sandstone	7	0.0008	0.000096	0.12	0.005	6.00E-07
Wombarra Claystone	8	0.00062	0.0000372	0.06	0.005	5.00E-07
Coalcliff Sandstone	9	0.0005	0.00006	0.12	0.005	4.00E-07
Bulli Seam	10	0.00045	0.000054	0.12	0.005	2.00E-07
Lawrence & Loddon Sandstones	11	0.00035	0.000042	0.12	0.005	3.00E-07
Wongawilli Seam	12	0.3[3]	0.000009	0.03	0.005	2.00E-07
Kembla Sandstone	13	0.00025	0.00004	0.16	0.005	3.00E-07
Lower PCM	14	0.00008	0.0000128	0.16	0.005	3.00E-07
Shoalhaven Group	15	0.00001	0.0000018	0.18	0.005	3.00E-07
Crinanite (upper)	2	0.1	0.001	0.01	0.015	1.00E-06
Crinanite (upper middle)	3	0.05	0.0015	0.03	0.012	1.00E-06
Crinanite (lower middle)	4	0.03	0.0015	0.05	0.01	1.00E-06
Crinanite (lower)	5	0.01	0.0015	0.15	0.008	8.00E-07

Notes:
1. Kh denotes horizontal hydraulic conductivity.
2. Kv denotes vertical hydraulic conductivity.
3. Where WW11 is undisturbed, Kh is estimated to be about 0.0003 m/day.

Figure 21 shows the substantial similarity between measured and calibrated hydraulic conductivities. At shallow depths the calibrated hydraulic conductivities are about 4 times higher than packer testing results, consistent with typical upscaling seen between Hawkesbury Sandstone packer tests and long-term pump tests in the Sydney area (Tammetta and Hewitt, 2004). The calibrated hydraulic conductivity of the Wongawilli Seam outside the collapsed zone indicates an impact from mining (due to permeability increase from shrinkage processes).

The calibrated rainfall recharge rate is an average of 2.7% of incident rainfall over the model area. For mining areas, calibrated drain conductances were $1m^2$/day for old (surrounding) mines, and $0.1m^2$/day for Dendrobium longwalls and development headings.

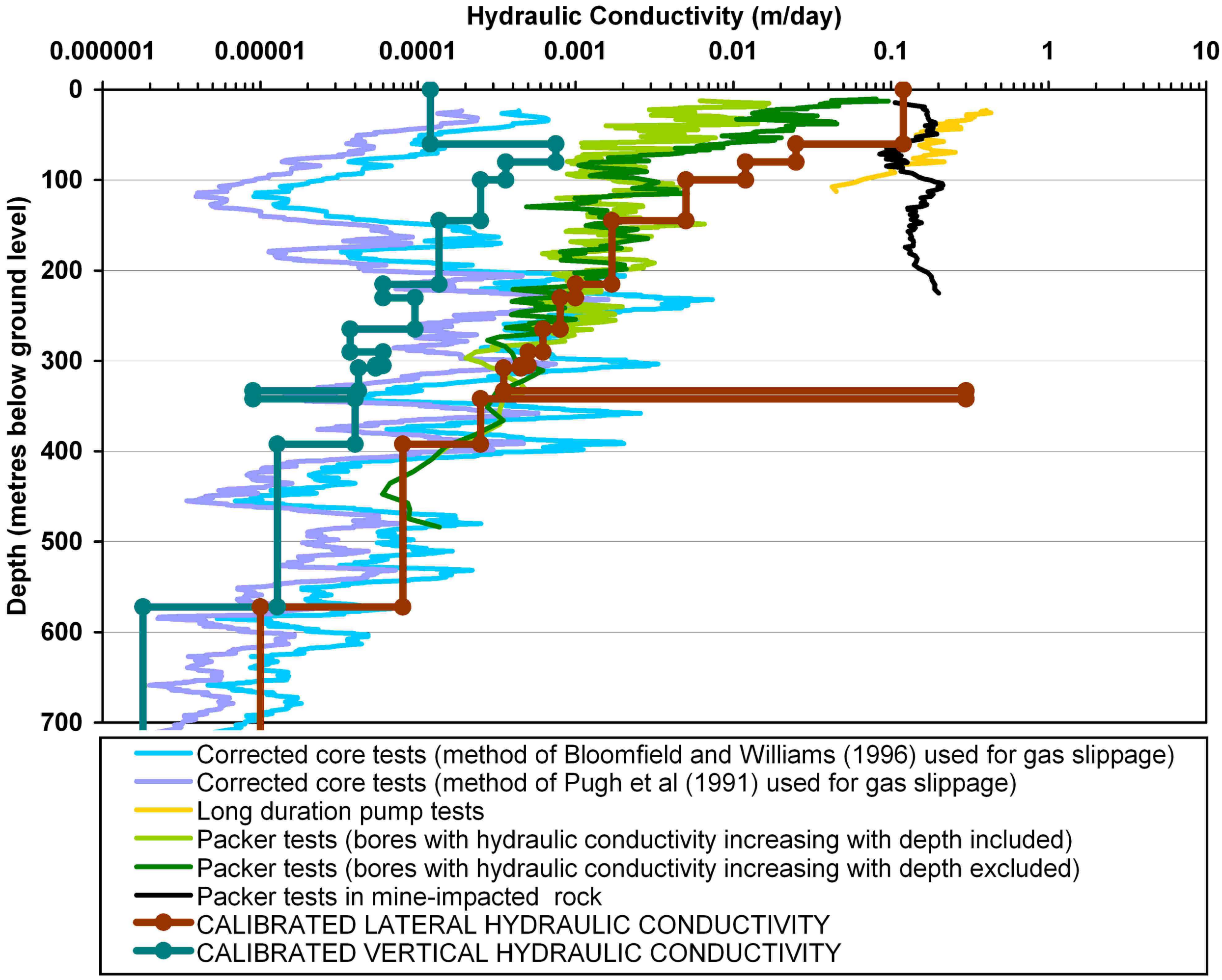


Figure 21. Calibrated hydraulic conductivity distributions.

4.4.4 Flow Budget

The modelled flow budget for the model area for 27 February 2011 (end of mining at Longwall 6) is listed in Table 5a. The modelled net discharge to the lakes and rivers of the Northwest catchment is 13.25 ML/day, accurately reproducing the estimate of 14 ML/day made in Coffey (2012). The modelled total inflow to the Dendrobium Mine is 3.65 ML/day.

The modelled baseflow to, and seepage from, the lakes for the case of no mining at Dendrobium are listed in Table 5b. The modelled total losses (the sum of diverted baseflow and induced seepage) from lakes and rivers, from mining at Dendrobium, total 0.34 ML/day or about 9% of the inflow to the mine.

Modelled inflows to the three northern mines total 5.7ML/day. Given the shape of the model area, the position of the model boundary, and the nature of the groundwater system, it is estimated that the modelled inflow comprises about 50% of what would be a total modelled inflow, giving about 11ML/day. This compares most favourably with the estimate of a total northern mine inflow of about 10ML/day made above (and in Coffey, 2012).

Table 5a. Modelled flow budget for the model area for 27 February 2011 (end of mining at Longwall 6).

IN (ML/day)		OUT (ML/day)	
Rainfall Recharge	75.84	Increase in Aquifer Storage	10.26
		Downgradient Seepage	7.14
		Escarpment Seepage	2.87
Northwest Catchment		Northwest Catchment	
Seepage from Lake Cordeaux	1.22	Baseflow to Lake Cordeaux	1.96
Seepage from Lake Avon	0.00	Baseflow to Lake Avon	3.27
		Baseflow to Rivers (and other lakes)	9.24
		Southeast Catchment	
		Ocean Seepage	2.38
		Baseflow to Rivers	3.53
		Inflow to Northern Mines	5.65
		Inflow to Eastern and Southern Mines	27.11
		Inflow Dendrobium Mine	
		Area 1	0.20
		Area 2	0.80
		Area 3	2.65
TOTAL IN	77.06	TOTAL OUT	77.06
DISCREPANCY = 0.003%			

Table 5b. Modelled flow budget for lakes Avon and Cordeaux (and rivers of the Northwest Catchment) for 27 February 2011 (end of mining at Longwall 6) for the case of no mining at Dendrobium.

IN (ML/day)		Mining Loss*	OUT (ML/day)		Mining Loss*
Seepage from Lake Cordeaux	1.21	0.01	Baseflow to Lake Cordeaux	2.14	0.18
Seepage from Lake Avon	0.00	0.00	Baseflow to Lake Avon	3.31	0.04
			Baseflow to Rivers (and other lakes)	9.35	0.11

* Refers to the loss due to mining at Dendrobium.
It is calculated by subtracting the no-mining seepage from the mining seepage, or subtracting the mining baseflow from the no-mining baseflow.

The modelled inflows to other mines total 27.1ML/day. Given the shape of the model area, position of the model boundary, and the nature of the groundwater system, it is estimated that the modelled inflow comprises about 90% of what would be a total modelled inflow, giving about 30ML/day. This compares most favourably with the estimate of about 30ML/day made above (and reported in Coffey, 2012).

48% of the total rainfall recharge is consumed by mine inflow. This is equivalent to about 1.3% of incident rainfall, and agrees with estimations of the fate of rainfall recharge in Coffey (2012).

5 PREDICTIVE SIMULATION

Calibration results indicate that the numerical model parameters and outputs are simultaneously consistent with measured aquifer properties, surface discharges (baseflow to rivers), and deep discharges (inflow to mines). This provides the model with a significant level of reliability, and greatly reduces uncertainty in model results. The calibrated model has been used as the basis for a predictive model that simulates mining in Area 3B.

The purpose of predictive modelling was to:

- Estimate future groundwater inflows to Dendrobium Mine Area 3 workings.
- Statistically quantify the following components of the loss from lakes Avon and Cordeaux due to mining in Area 3B of Dendrobium Mine:
  - Baseflow (groundwater) recharge to a lake that is diverted away from the lake by mining. This comprises groundwater that would normally flow towards the lake and recharge it, but has been diverted towards the mine.
  - Seepage induced from a lake by mining. This comprises lake water that is induced to seep out of the lake and into the ground as a result of mining at Dendrobium.

5.1 Proposed Mining

The proposed mining in Area 3B comprises Longwalls 9 to 18, as shown in Figure 22. This longwall layout has been used in numerical simulations. Longwall 8 is currently being mined.

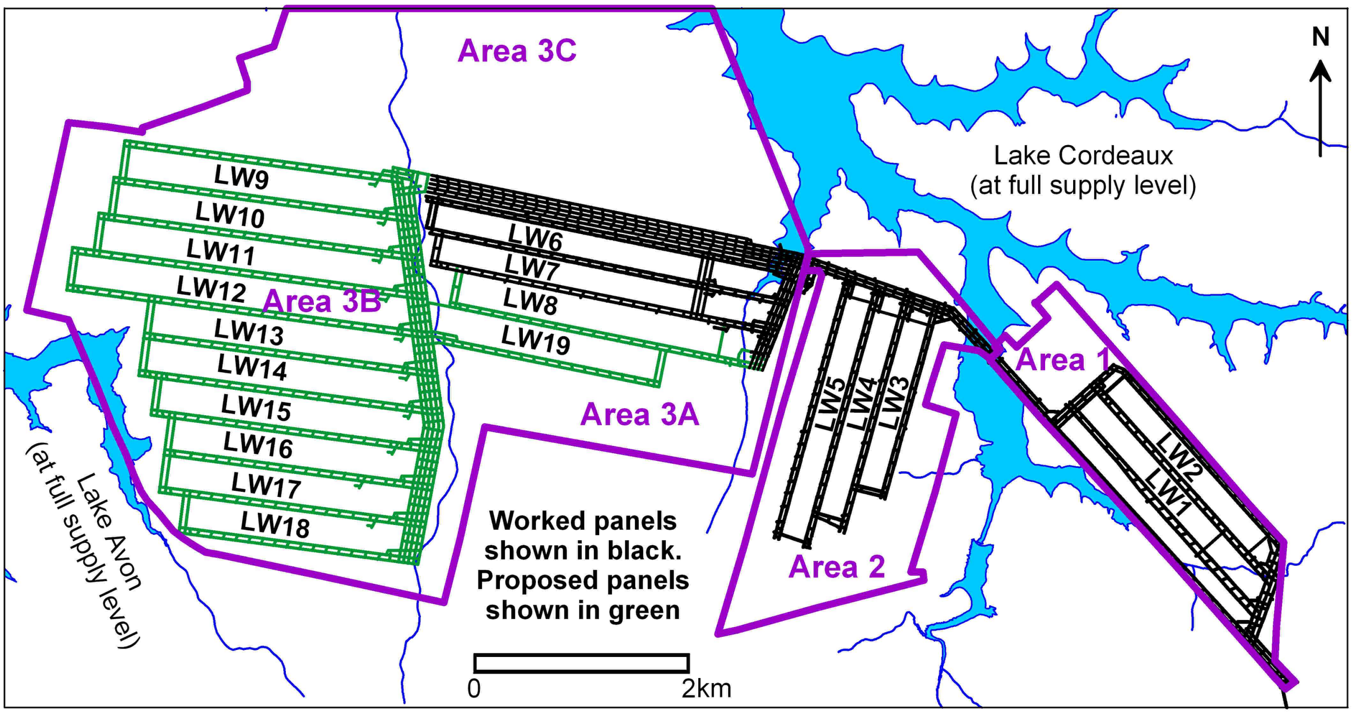


Figure 22. Worked and proposed longwalls at Dendrobium Coal Mine that have taken part in the numerical simulation

Mining will occur in the Wongawilli Seam using conventional longwall methods. Longwall 7 (240m width) and Longwall 8 (300m width) of Area 3A will be mined before mining commences in Area 3B (with Longwall 9). Longwall 19 is the last longwall to be mined but is in Area 3A. All Area 3B longwalls will be 300m in width. The direction of retreat is from west to east for all longwalls except 19 (east to west). Mining takes place between the present time and 30 March 2033.

Longwalls 13 to 18 come closest to Lake Avon. They are all located 250m away from the closest point of the Lake Avon full supply level boundary, except for Longwall 13 (260m away), Longwall 14 (290m away), and Longwall 15 (350m away).

For all simulations, the induced seepage and diverted baseflow from the lakes have been obtained by differencing the results of a mining simulation with its no-(Dendrobium)mining counterpart.

Longwall production dates and dimensions used in the simulations are listed in Table 6. Predictive simulation was undertaken for the period March 2011 to April 2040, providing about 17 years of post-mining simulation. As for calibration modelling, adaptive time stepping was used with the model solver. The average length of actual stress periods was about 120 days during longwall mining (up to 2023). Actual stress period lengths after 2023 were about 420 days.

Table 6. Longwall dates and dimensions used in calibration and predictive simulations.

Long-wall	Start date	End date	Mining days	Change-out days	Panel width (m)	Panel length (m)	Mining rate (m/day)	Area
1	30-Mar-05	15-Dec-05	260		242	1738	6.7	1
2	9-Feb-06	22-Jan-07	347	56	242	1987	5.7	1
3	30-Mar-07	22-Nov-07	237	67	236	1607	6.8	2
4	17-Dec-07	30-Sep-08	288	25	236	1959	6.8	2
5	4-Dec-08	18-Dec-09	379	65	237	2299	6.1	2
6	9-Feb-10	29-Mar-11	413	53	239	2576	6.2	3A
7	2-May-11	25-Jan-12	268	34	240	2390	8.9	3A
8	15-Apr-12	2-Feb-13	293	81	300	2515	8.6	3A
9	7-Mar-13	25-Jan-14	324	33	300	2275	7.0	3B
10	27-Feb-14	10-Jan-15	317	33	300	2458	7.8	3B
11	12-Feb-15	5-Jan-16	327	33	300	2566	7.8	3B
12	7-Feb-16	17-Feb-17	376	33	300	2881	7.7	3B
13	23-Mar-17	28-Jan-18	311	34	300	2280	7.3	3B
14	2-Mar-18	19-Jan-19	323	33	300	2389	7.4	3B
15	21-Feb-19	30-Dec-19	312	33	300	2298	7.4	3B
16	2-Feb-20	1-Dec-20	303	34	300	2075	6.8	3B
17	3-Jan-21	7-Nov-21	308	33	300	1803	5.9	3B
18	10-Dec-21	1-Sep-22	265	33	300	1732	6.5	3B
19	4-Oct-22	30-Mar-23	177	33	300	1952	11.0	3A

Note: Panel lengths for Longwalls 10 to 19 were estimated from drawings supplied by BHP.

The following predictive modelling was undertaken to calculate the induced seepage and diverted baseflow from Lakes Avon and Cordeaux by mining in Area 3B at Dendrobium Mine:

- Conventional modelling: Simulation of induced seepage and diverted baseflow for mining to within 250m (no panel extension), 150m (100m panel extension), and 50m (200m panel extension) of the Lake Avon full supply level boundary.
- Probabilistic (stochastic) modelling: Simulation of induced seepage and diverted baseflow using a number of equivalent realisations of the three-dimensional hydraulic conductivity field of the groundwater system for the cases of mining to within 250m (no panel extension) and 50m (200m panel extension) of the Lake Avon full supply level boundary.

5.2 Tolerability Criteria

In 2005 the NSW Dams Safety Committee (DSC) adopted a risk-based policy in assessing risk to dams from mining activities (Hilyard et al, 2011). These risks include mine subsidence (from underground mining) and loss of storage due to mining activities. The tolerability criteria for loss of stored water from a major Sydney water supply dam, due to mining, are shown in Figure 23 (after Figure 4 of Hilyard et al, 2011). These criteria are incorporated into a probability function, which comprises a probability criterion. It is understood that the DSC has set this criterion for Lake Cordeaux, for mining at Dendrobium Mine. The probability scale is understood to refer to time. It is assumed that the total time, to which the probability refers, is that time during which lake loss due to mining at Dendrobium is non-zero.

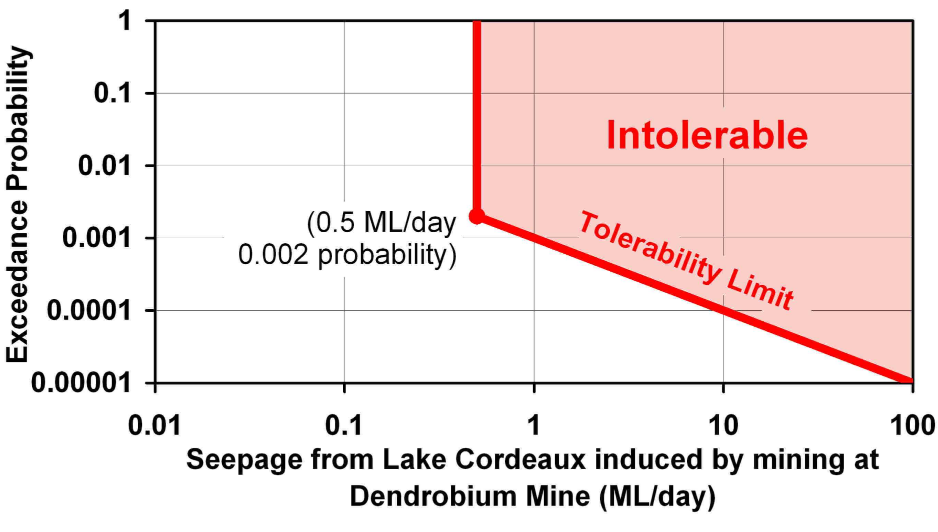


Figure 23. Probability criterion applied by the NSW Dams Safety Committee to losses from Lake Cordeaux induced by mining at Dendrobium Mine.

This probability criterion is understood to apply only to one of the possible avenues of lake loss (due to mining), being seepage induced from the lake, of water that is already held by the lake. It is further understood that the probability criterion does not apply to baseflow (groundwater) recharge to the lake that is diverted away from the lake by mining. It is understood that tolerability criteria have not as yet been set for Lake Avon, for mining at Dendrobium Mine.

5.3 Conventional Numerical Analysis for Mining to within 250m, 150m, and 50m of the Lake Avon FSL Boundary

5.3.1 Results

Figure 24 shows the modelled inflow to the Dendrobium workings for the three cases of proximity to Lake Avon. Groundwater inflows increase to around 11ML/day by 2016 then remain stable. In 2023 mining stops and inflows begin falling however the simulation continues to keep the mine workings fully drained (the fall in inflow at this point is due to cessation of advance of the working face, not to the beginning of water level recovery).

A conspicuous finding is the small difference in inflows between cases. This is due to the vertical anisotropy of the ground and the depth of the workings. The difference between the 50m case (200m panel extension) and the 250m case (no panel extension) at the time of maximum inflow to the mine (2023) is about 0.2ML/day (about 2% of the total inflow). This would appear to be supported by the similarity in observations reported in NSW Dams Safety Committee (1986) (mining under Lake Avon) and Ziegler and Middleton (2011) (mining near Lake Cordeaux).

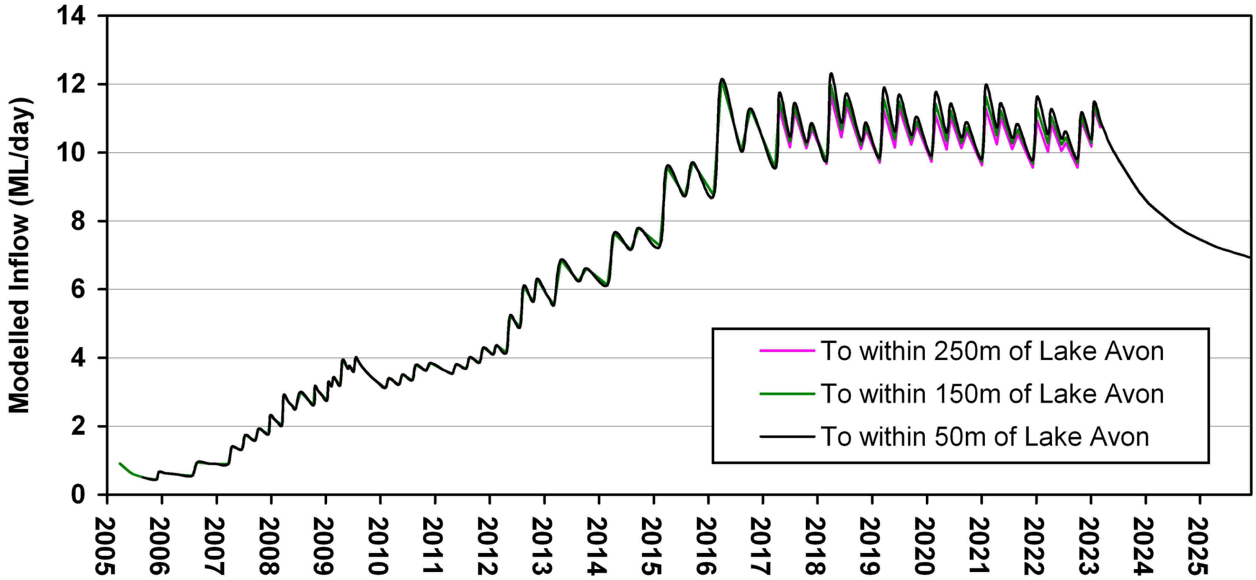


Figure 24. Modelled future groundwater inflows to Dendrobioum Mine for the cases of mining to within 250m, 150m, and 50m of the Lake Avon FSL.

Figure 25 shows the modelled future groundwater inflow to the Dendrobium Mine for the case of mining to within 50m (200m panel extension) of the Lake Avon FSL, and the consequent diverted baseflow, and induced seepage, from lakes Avon and Cordeaux, and local rivers.

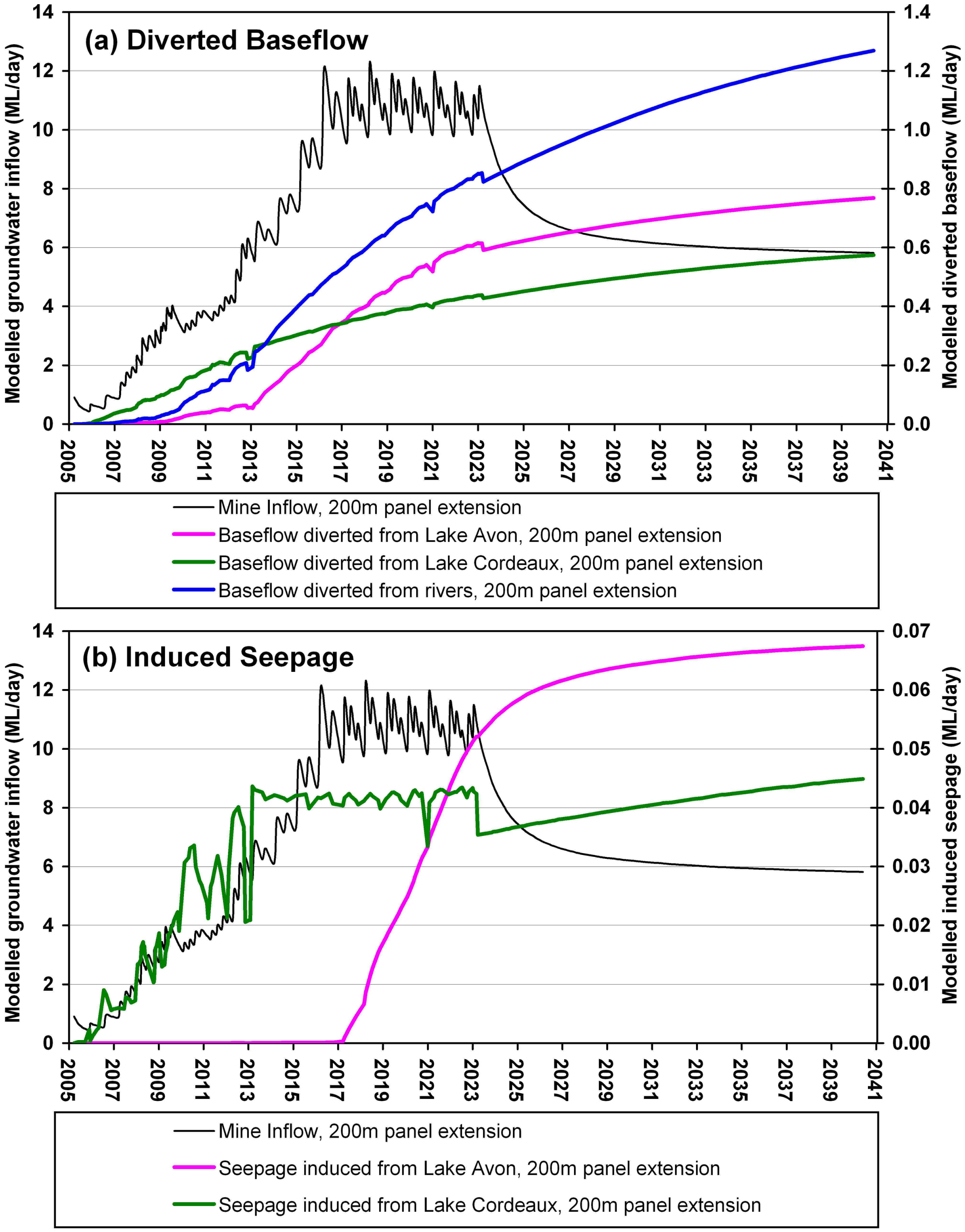


Figure 25. Modelled future groundwater inflows to the Dendrobium Mine for mining to within 50m of the Lake Avon FSL, and the consequent (a) diverted baseflow from the lakes and rivers, and (b) the induced seepage from the lakes, due to mining.

Diverted baseflow and induced seepage for the other cases (extensions of 0m and 100m) for 2023 (end of mining) are listed in Table 7, just before the end of mining of Longwall 19. There is no perceptible change in losses between the cases, for rivers and Lake Cordeaux. However, for Lake Avon, an additional 0.03 ML/day of diverted baseflow and an additional 0.02 ML/day of induced seepage are caused in going from the no extension case to the 200m extension case.

Table 7. Modelled diverted baseflow and induced seepage for mid 2023 (end of mining in Area 3B).

Flow Vector	Case		
	No extension (ML/day)	100m panel extension (ML/day)	200m panel extension (ML/day)
Groundwater inflow to the mine	10.74	10.83	10.93
Baseflow diverted away from Lake Avon	0.58	0.60	0.61
Seepage induced from Lake Avon	0.03	0.04	0.05
Baseflow diverted away from Lake Cordeaux	0.44	0.44	0.44
Seepage induced from Lake Cordeaux	0.04	0.04	0.04
Baseflow diverted away from rivers	0.85	0.85	0.85

Figure 25 shows that the diverted baseflow and induced seepage continue rising long after mining has ceased. An attempt was made to find the maxima reached by these losses (under the condition of continued mine pumping, without mining) but this was not possible as the model run times for these investigative predictive runs became untenably long. Therefore, the maxima were estimated analytically using two methods:

- Fitting the parts of the curves after 2023 to exponential growth functions and finding the asymptotes.
- Fitting the parts of the curves after 2023 to sin functions, assuming the start of a half-cycle is at 2006. This method also provides a coarse estimate of the time that the loss is non-zero. The total time of non-zero seepage is estimated as double the time to reach the maximum.

Fits to less than 1% RMS error were obtained for all five curves for both functions. The calculated maxima, and time of non-zero seepage, are listed in Table 8.

Table 8. Estimated peak losses (diverted baseflow and induced seepage), and time to reach peak losses, for mining to within 50m of Lake Avon (200m panel extension).

Flow Vector	Maximum (exp. function) (ML/day)	Maximum (sin function) (ML/day)	Time to reach maximum (sin function) (Years)*
Baseflow diverted away from Lake Avon	0.845	0.772	38
Seepage induced from Lake Avon	0.067	0.067	32
Baseflow diverted away from Lake Cordeaux	0.656	0.582	41
Seepage induced from Lake Cordeaux	0.055	0.047	46
Baseflow diverted away from rivers	1.536	1.292	41

* Starting in 2006. The total time of non zero seepage is assumed to be double this amount.

The sin function produces smaller maxima than the exponential function. The difference between the values provides a coarse indicator of the error in analytically attempting to find the maxima that would be calculated by the numerical model, and is in addition to the error between modelled and observed quantities.

Should pumping in the mine stop sooner than a maximum in the loss curves is reached, it is possible that the maxima could be smaller. The most beneficial situation is where pumping is switched off after Longwall 19 (the last panel) and groundwater levels are allowed to recover.

The curve for post-mining groundwater inflow to the mine (modelled inflows after 2023) was fitted to an exponential decay function, assuming dewatering continues, and the asymptote was found to be 5.81ML/day, which is nearly achieved after 17 years from cessation of mining.

5.3.2 Flow Budget

Table 9a lists the flow budget for the model area for March 2023 (at the end of mining of Longwall 19) for the case of mining to within 50m of Lake Avon (200m panel extension).

Table 9a. Modelled flow budget for the model area for 31 March 2023 (end of mining at Longwall 19) for the case of 200m panel extension (mining to within 50m of Lake Avon).

IN (ML/day)		OUT (ML/day)	
Rainfall Recharge	64.14	Downgradient Seepage	7.13
Release from Aquifer Storage	3.80	Ocean Seepage	2.90
		Inflow to other mines, Baseflow to distant rivers, and Escarpment seepage	33.68
Northwest Catchment		Northwest Catchment	
Seepage from Lake Cordeaux	1.30	Baseflow to Lake Cordeaux	2.09
Seepage from Lake Avon	0.06	Baseflow to Lake Avon	3.59
		Baseflow to Rivers (and other lakes)	9.14
		Inflow to Dendrobium Mine	
		Area 1	0.19
		Area 2	0.36
		Area 3	3.87
		Area 3B	6.35
TOTAL IN	69.30	TOTAL OUT	69.30
DISCREPANCY = -0.001%			

At the end of mining in Area 3B, the modelled total inflow to the Dendrobium Mine is 10.77 ML/day. The modelled net groundwater discharge to the lakes and rivers of the northwest catchment is 13.45 ML/day. The modelled baseflow to, and seepage from, the lakes for the case of no mining at Dendrobium are listed in Table 9b. The modelled total losses (the sum of diverted baseflow and induced seepage) from the lakes and rivers for the 200m panel extension case amount to about 2 ML/day, or about 18% of the total mine inflow at that time (which is modelled as being generally stable from 2016). This is consistent with estimates made in DSC (1986) (mining under Lake Avon) and Ziegler and Middleton (2011) (mining near Lake Cordeaux) using independent methods. Model results for the total losses from lakes and rivers at the end of mining of Longwall 6 give a proportion of 9% of total mine inflow (see above), indicating that the proportion is heavily time-dependent.

Table 9b. Modelled flow budget for lakes Avon and Cordeaux (and rivers of the Northwest Catchment) for 31 March 2023 (end of mining at Longwall 19) for the case of no mining at Dendrobium.

IN (ML/day)		Mining Loss*	OUT (ML/day)		Mining Loss*
Seepage from Lake Cordeaux	1.26	0.04	Baseflow to Lake Cordeaux	2.53	0.44
Seepage from Lake Avon	0.01	0.05	Baseflow to Lake Avon	4.20	0.61
			Baseflow to Rivers (and other lakes)	9.99	0.85

* Refers to the loss due to mining at Dendrobium.
It is calculated by subtracting the no-mining seepage from the mining seepage, or subtracting the mining baseflow from the no-mining baseflow.

5.4 Probabilistic Numerical Analysis for Mining to within 250m and 50m of the Lake Avon FSL Boundary

5.4.1 Development of Random Hydraulic Conductivity Fields

The single most important parameter that governs groundwater flow is the hydraulic conductivity. Conventional modelling has used aquifer property zones which are large compared to the resolution of the quantity they represent. For hydraulic conductivity this is the volume of aquifer tested by each packer test. Each conventional hydraulic conductivity zone in the model has a single lateral K and a single vertical K. Where packer test measurements are made at many locations, a database of test results with means and standard deviations over specific depth intervals can be developed (see below, and Coffey, 2012). However, when transferring these statistics to a model parameter zone that covers an area much larger than the packer testing volume, it is not possible to apply a single statistic of the database (say the 10th percentile lateral hydraulic conductivity) to the entire zone, if it is assumed that the database is a good representation of the population. This is because, if this is done, the 10th percentile value now becomes the median value for that zone, which is unrepresentative.

To conduct a probabilistic analysis, the observed three-dimensional hydraulic conductivity field may be perturbed using a random generator, together with some probability function for the property, so that the median and standard deviation of the perturbed (output) field (known as a realisation) remain the same as the population of values of the observed field.

Fortunately the hydraulic conductivity database for the Dendrobium Mine area is substantial (being complemented by numerous published packer test results for the Southern Coalfield) and a good representation of the hydraulic conductivity field in the regional area. The database lends itself well to a statistical analysis. The hydraulic conductivity database plotted in Figure 13 of Coffey (2012) (excluding long term pump tests and tests in strata overlying the mined seam) was analysed for its variation over the depth intervals of the upper five model layers. It is these layers that will have the greatest influence on seepage between the lakes and the collapsed zone. It is also these layers where hydraulic conductivity will be greatest, being mostly controlled by defects.

Table 10 lists the results of the analysis. The dataset indicates a decreasing standard deviation with depth, indicating the decreasing influence of the defect population on hydraulic conductivity as depth increases. The trend for standard deviation is not related to the sample size because an assessment of standard deviation for varying batch sizes of the same dataset shows that the standard deviation is stable after 20 tests or more are included in a batch.

Table 10. Variability in packer test results for the upper model layers.

Stratum	Model layer	Calibrated Kh[1] (m/day)	Standard deviation of log(Kh)	No of tests
Hawkesbury Sandstone (Upper)	1	0.12	0.92	91
Hawkesbury Sandstone (Lower)	2	0.025	0.84	27
Bald Hill Claystone	3	0.012	0.73	24
Bulgo Sandstone (Upper)	4	0.005	0.70	57
Bulgo Sandstone (Lower)	5	0.0017	0.68	53

1. Kh denotes lateral hydraulic conductivity

An automated stochastic process ("Monte Carlo" simulation) was not possible given the large model run time and the input/output complexity involved in batch simulation with the numerical model. The approach for probabilistic analysis of induced seepages has been to conduct a limited stochastic analysis by generating 11 random realisations of the lateral hydraulic conductivity (Kh) field for each of the upper five model layers (the Hawkesbury Sandstone, Bald Hill Claystone, and Bulgo Sandstone), giving 55 realisations. Each realisation is for one layer and takes the form of a randomly generated matrix of hydraulic conductivity values (leaving the crinanite unchanged), where the values vary from cell to cell. Each matrix is generated using the mean and standard deviation of the packer test result population that falls within the depth interval of a layer, assuming a radius of influence of 50m for the average packer test. The realisations are not spatially conditioned by the location of the packer tests.

The vertical anisotropy (Kv/Kh) is assumed to remain unchanged from the calibrated model, so that the vertical hydraulic conductivity (Kv) is calculated from each Kh matrix using the calibrated Kv/Kh ratios.

The realisations are used to generate 11 random models, with each conductivity array in the upper 5 layers being different from corresponding arrays in all the other models. Each model is then run three times: for the 50m offset case, for the 250m offset case, and for the case of no mining at Dendrobium (the null case). The conventional predictive model (see Section 5.3 above) is added to the model pool, giving 12 random models for each case. A total of 36 model runs was required to obtain the results.

5.4.2 Lake Loss versus Time

It was not possible to run each model a sufficient length of time to find the peak of the lake loss (induced seepage or diverted baseflow) response, due to the long model run times. The time scale of the stress (mining at Dendrobium) is found from predictive simulations to be much smaller than the time scale of the lake seepage response. To limit the seepage response to a finite time, it is assumed that there will be no more mining after completion of mining in Area 3B, and that the Dendrobium goaf will remain dewatered until 2041. This mining scenario is a compromise between the following extremes:

- Stopping of mining AND dewatering in 2023 (after completion of mining in Area 3B).
- Continued mining in Area 3C, and maintenance of dewatered workings in all mine areas during Area 3C mining and beyond.

The chosen mining scenario allows the seepage curves to reach a peak and begin falling. The time to reach the peak seepage is found by fitting the seepage curves after 2023 to a sin equation. The time to reach the fitted peak is referenced to 2006, and is listed in Table 8 above. The total time of non-zero seepage is estimated as double this amount. Sinusoidal fitting indicates that non-zero diversion of baseflow, or induction of seepage, caused by mining at Dendrobium, occurs for between 60 and 90 years from 2006, for the chosen mining scenario.

Nine river / lake loss values, equi-spaced in time, covering the estimated period of non-zero loss were obtained for each case of a random model. These values consist of the estimated peak loss and four values either side of the peak. These values evenly cover the estimated time period where river / lake loss is estimated to be non-zero. This generates a total of 108 loss values for each case. This methodology is shown in Figure 26.

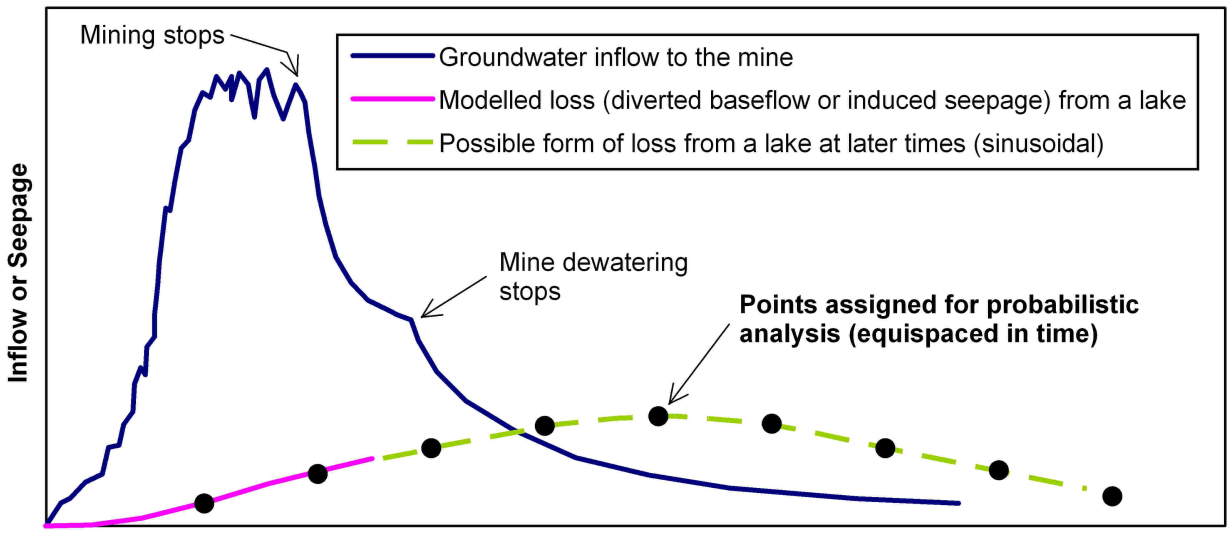


Figure 26. Methodology for obtaining lake loss values (induced seepage or diverted baseflow) for probabilistic assessment. The values are equispaced in time, and cover the estimated period of non-zero loss from a lake caused by mining at Dendrobium.

5.4.3 Results

To assess the results, an assessment was first conducted of the modelled groundwater inflows to the Dendrobium Mine at the end of mining (2023) for the 24 variants of the adopted mining scenario. Figure 27 shows the probability distributions for the results. The distributions occupy a thin band between 10ML/day and 11.5ML/day, with no unusual outliers. The narrowness of the range is attributed to the exceptionally large size of the imposed stress (longwall panels that are kilometres in length) compared to the spatial variability in the hydraulic conductivity field as is able to be defined using the spatial continuity of the packer test database. Greater variability in modelled inflow would be seen for smaller imposed stresses.

Mine inflow results indicate no realisations can be discarded.

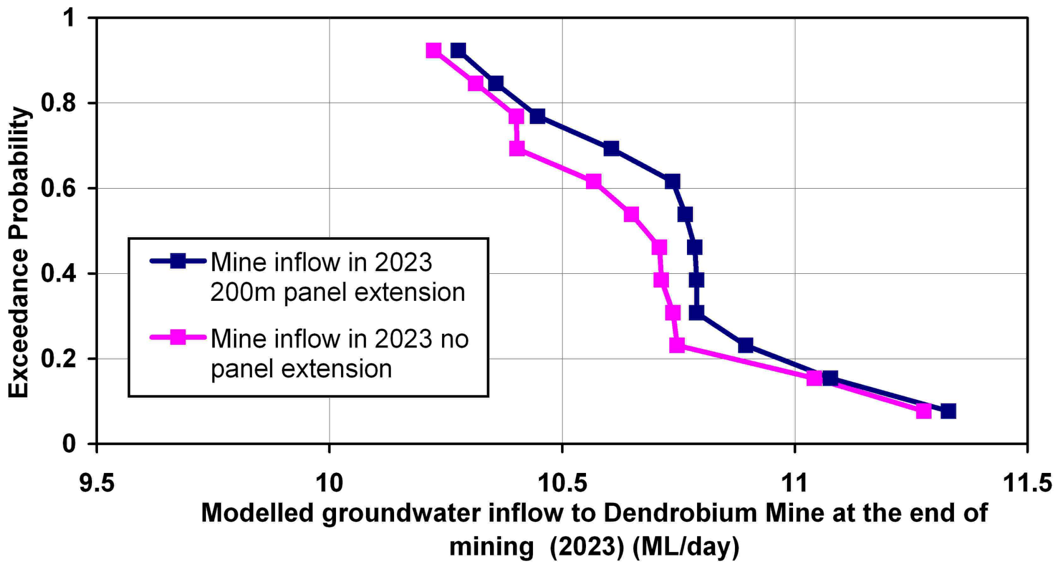


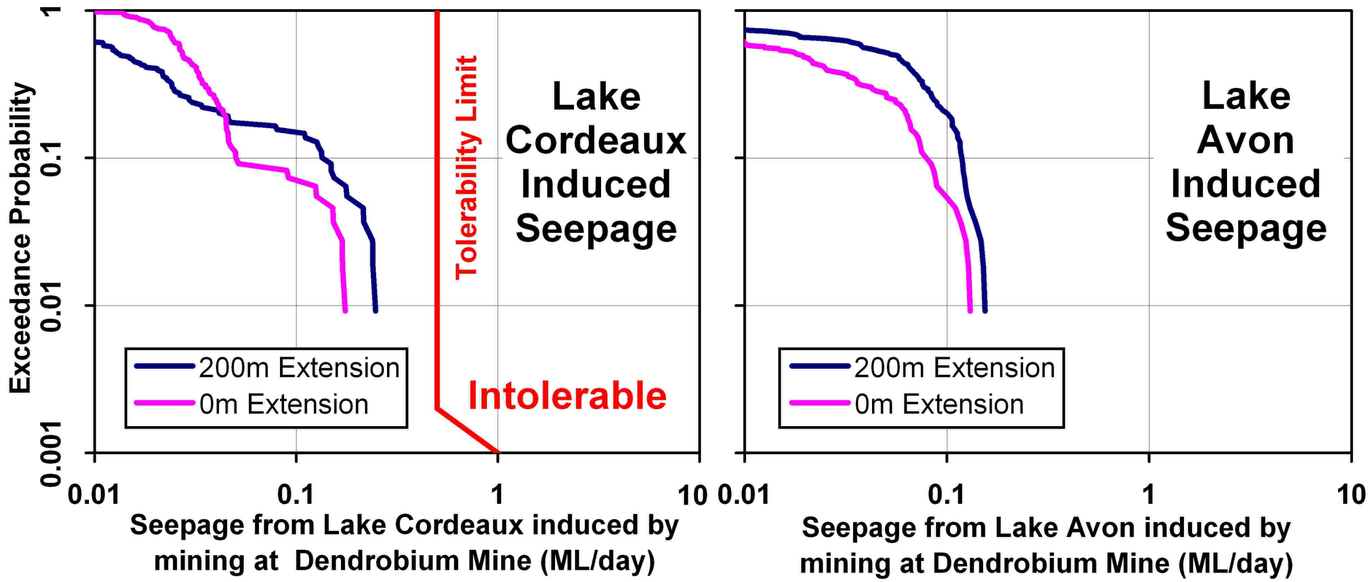
Figure 27. Modelled groundwater inflow to the Dendrobium mine at the end of mining for the cases of 100m panel extension and no extension.

The results of the probabilistic assessment are shown in Figure 28. The probability curve for the modelled induced seepage from Lake Cordeaux falls inside the tolerable range. The maximum induced seepages from Lakes Cordeaux and Avon for the case of 200m panel extensions (0.25 and 0.15 ML/day respectively) are within the tolerable range.

Statistics for lake losses are listed in Table 11. The statistics include all realisations. The Decile 5 losses for the 200m extension and no extension cases total 2.11 and 2.10 ML/day respectively, a negligible difference. This is about 20% of the average later-time groundwater inflow during Area 3B mining.

Table 11. Modelled lake and river loss statistics.

Flow Vector	Case	Maximum (Decile 0.1) (ML/day)	Decile 1 (ML/day)	Decile 5 (ML/day)	Minimum (Decile 9.9) (ML/day)
Baseflow diverted away from Lake Avon	0m Extension	0.80	0.74	0.60	0.32
	200m Extension	0.97	0.81	0.61	0.33
Baseflow diverted away from Lake Cordeaux	0m Extension	0.66	0.58	0.47	0.27
	200m Extension	0.67	0.62	0.48	0.26
Baseflow diverted away from rivers	0m Extension	1.46	1.31	0.95	0.38
	200m Extension	1.76	1.35	0.98	0.39
Seepage induced from Lake Avon	0m Extension	0.13	0.08	0.02	0.00
	200m Extension	0.15	0.12	0.05	0.00
Seepage induced from Lake Cordeaux	0m Extension	0.18	0.05	0.03	0.01
	200m Extension	0.25	0.13	0.01	0.00



NOTES:
1. Tolerability criteria imposed by the DSC for mining-induced losses from Lake Cordeaux are understood to apply only to water in the lake that is induced to seep out of the lake and into the ground as a result of mining, not to baseflow (groundwater) recharge to the lake that is diverted away from the lake by mining.
2. It is understood that no tolerability criteria for mining-induced losses are available for Lake Avon.
3. The entire curve for lake or river loss (due to mining at Dendrobium Mine) versus simulation time has not been obtained with the model, due to untenably long run times (the peak of the curve occurs after the end of the maximum simulation time). Instead, the maximum of this curve, and its duration, have been estimated indirectly, by fitting a sin function to that part of the curve that is available from simulation. This imparts an additional element of uncertainty to the analysis.

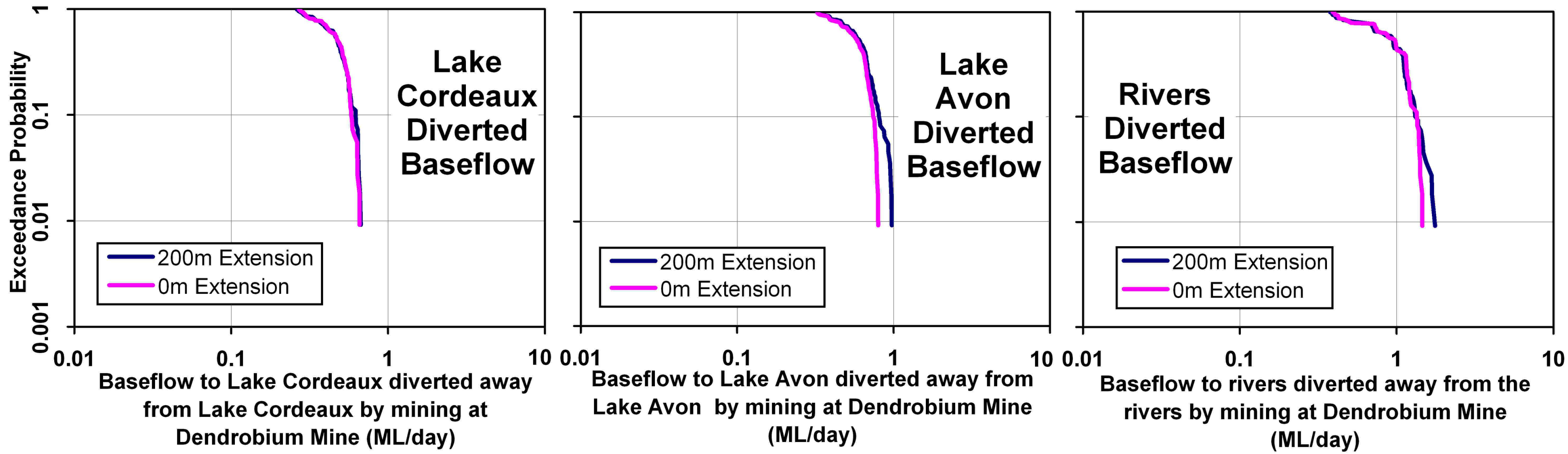


Figure 28. Modelled diverted baseflow and induced seepage for lakes and rivers, versus probability, due to mining at Dendrobium Mine Area 3B.

6 CONCLUSIONS

A regional numerical groundwater flow model has been simultaneously calibrated to the observed hydraulic conductivity distribution, hydraulic heads, baseflow to rivers (surface discharges), inflow to Dendrobium Mine (deep discharges in the mine area), and inflows to other mines (deep discharges in the regional area). This has considerably reduced the uncertainty in model outputs.

Induced seepages have been estimated, using a numerical model, for Lake Cordeaux, Lake Avon, and rivers, due to mining at the Dendrobium Mine. Two cases have been assessed in a probabilistic numerical analysis: 200m panel extensions and no panel extensions, for Longwalls 13 to 18 (which approach Lake Avon). For these cases, the panels come to within about 50m and 250m, respectively, of the Lake Avon full supply level boundary. A probabilistic approach has been used to assess lake losses. The following results are obtained:

- The modelled probability distributions for induced seepages from Lakes Avon and Cordeaux, due to mining in Area 3B with 200m panel extensions, fall in the tolerable range and comply with the probability criterion applied by the NSW Dams Safety Committee for Lake Cordeaux.
- The modelled Decile 5 induced seepages from Lakes Avon and Cordeaux, due to mining in Area 3B with 200m panel extensions, are 0.05 and 0.01 ML/day respectively.
- The modelled Decile 5 diverted baseflows for Lakes Avon and Cordeaux, due to mining in Area 3B with 200m panel extensions, are 0.61 and 0.48 ML/day respectively.
- The modelled Decile 5 diverted baseflow for rivers in the Northwest Catchment, due to mining in Area 3B with 200m panel extensions, is 0.98 ML/day.
- There is marginal difference between the 200m panel extension and no panel extension cases.

The model results apply only to the case where significant deformation from caving is limited to the interpreted limit of the collapsed zone. Model results do not take into account significant deformation that may be caused by the disturbance of extraordinary defects or other extraordinary structural features, which can lead to the creation of extreme permeability pathways extending beyond the collapsed zone.

7 RECOMMENDATIONS

7.1 Further Modelling

Further modelling should be conducted to confirm the shape and duration of the lake and river loss curves calculated by the model. These are vital data upon which the probabilistic analysis hinges, but the shape as calculated by the model is not yet known. An asymmetrical shape to this curve, rather than the symmetrical sin function, could significantly change the probability distribution of loss values.

A predictive run for the base scenario should be run for an extended time period to quantify the pattern of the diverted baseflow and induced seepage responses. A mining schedule reaching further into the future would be required to undertake this.

7.2 Lake Bed Material

In this study the riverbed conductance used to quantify the vertical hydraulic conductivity of the lake bed material has been taken from HC (2010) and is slightly conservative. This parameter is difficult to calibrate for the lakes. Laboratory testing results of this material (with appropriate scaling of results) could provide a more realistic estimate.

The lakes are drowned river valleys hence samples could be obtained from similar areas that have not been submerged. Alternatively, samples could be taken of the lake beds. Sampling locations would need to cover a large area. Samples should then be subjected to laboratory testing for vertical hydraulic conductivity. With appropriate scaling, these values could then be used in further modelling as a guide for the riverbed conductance parameter used for the lakes.

7.3 Hydraulic Conductivity Fields

If further modelling is undertaken, an opportunity would be available to use spatially conditioned realisations for the hydraulic conductivity distributions being used in the model. This constrains the realisations to represent the observed spatial distribution of hydraulic conductivity measurements. If appropriate data are available, this approach may more realistically generate hydraulic conductivity fields for the area between Lake Cordeaux and Dendrobium Areas 1 and 2, and for the area between Lake Avon and proposed Longwalls 13 to 18. These are areas of elevated importance in controlling the seepage from the lakes to the mine.

If appropriate data are available, it is recommended that realisations that are spatially conditioned to the locations of hydraulic testing results be used in numerical simulation. This may improve the reliability of results, particularly for the area between Lake Avon and Area 3B, where most of the seepage from Lake Avon to the panels will occur.

7.4 Additional Data

It is understood that hydraulic head measurements have been made at several monitoring sites immediately south of Dendrobium Area 2, in the NRE Wongawilli Colliery located in the old Nebo Mine (Geoterra, 2010). These data are understood to be publicly available and should be reviewed. The monitoring sites are in an area where no water level data are available in the current database for the Dendrobium Mine. Use of these data may extend the coverage of the contour plots of hydraulic head developed for the hydrogeological conceptual model, and may better inform hydraulic head patterns in the horizontal plane.

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For and on behalf of Coffey Geotechnics Pty Ltd

Paul Tammetta

Associate Hydrogeologist

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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.

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Important information about your **Coffey** Report

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.

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

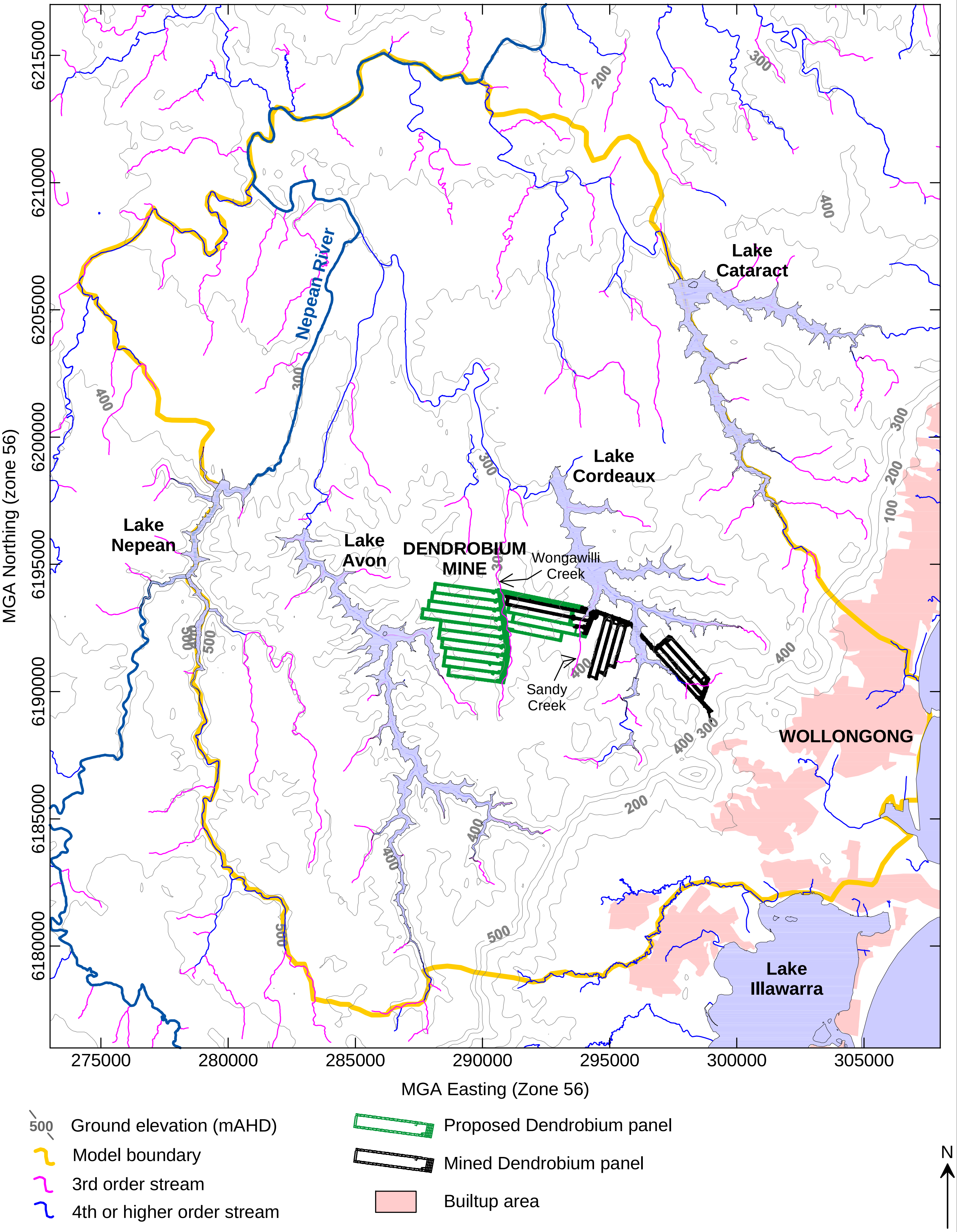
Coffey is familiar with a variety of techniques and approaches that can be used to help reduce risks for all parties to a project, from design to construction. It is common that not all approaches will be necessarily dealt with in your site assessment report due to concepts proposed at that time. As 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



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approved	RJB	project:	Groundwater Study Dendrobium Mine Area 3B Numerical Modelling
date	5 June 2012	title:	**Location of Dendrobium Mine and regional topography**
scale	1:200,000	project no:	GEOTLCOV24507AA-AB2
original size	A4	figure no:	**Drawing 1**

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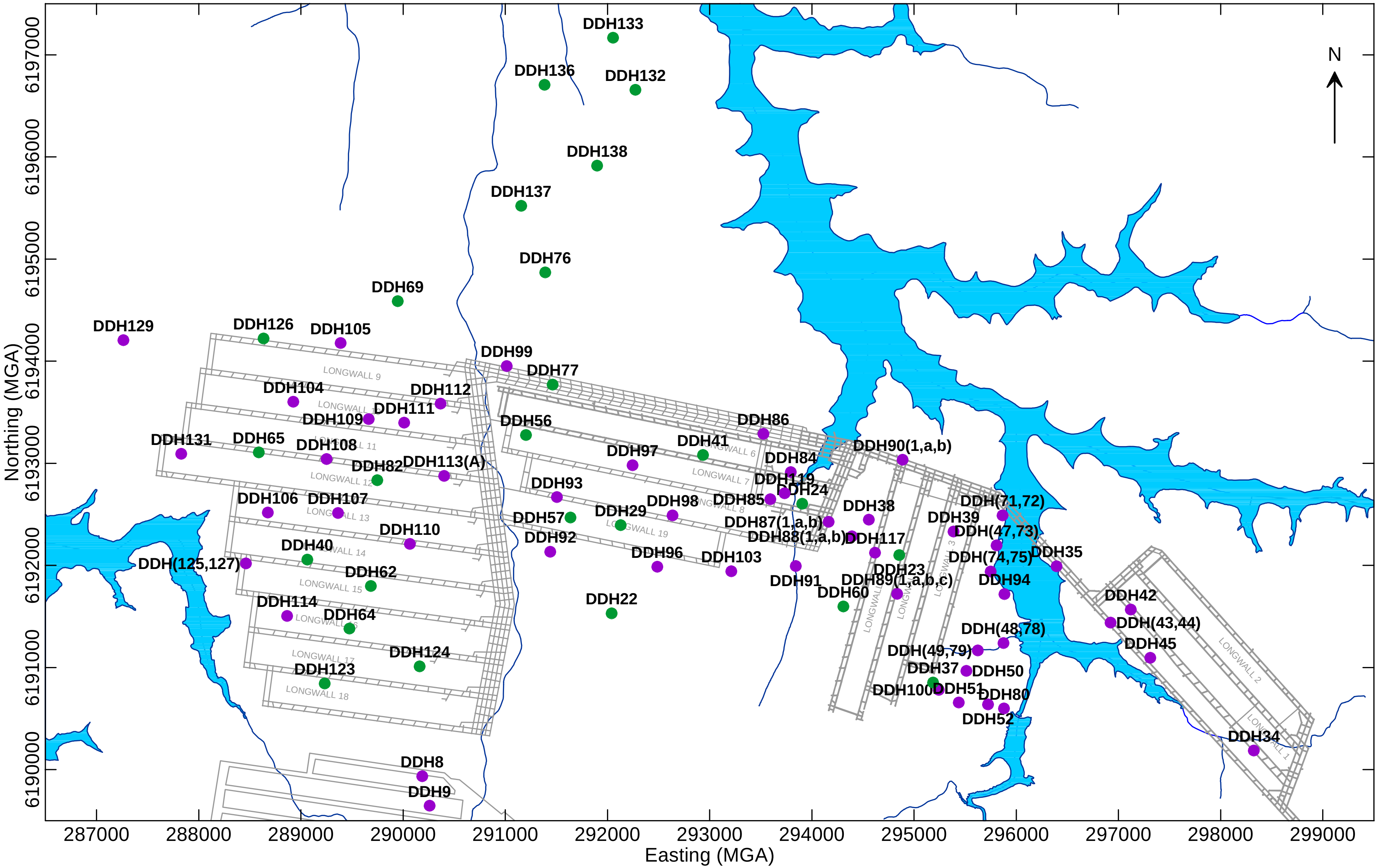

KEY:

- ● 3 or more monitoring points at the site.
- ● 2 or less monitoring points at the site.

drawn	PT	coffey geotechnics SPECIALISTS MANAGING THE EARTH	client:	BHP Billiton
approved	RJB		project:	Groundwater Study Dendrobium Mine Area 3B Numerical Modelling
date	7 Jun 2011		title:	**Groundwater level monitoring sites at Dendrobium Coal Mine**
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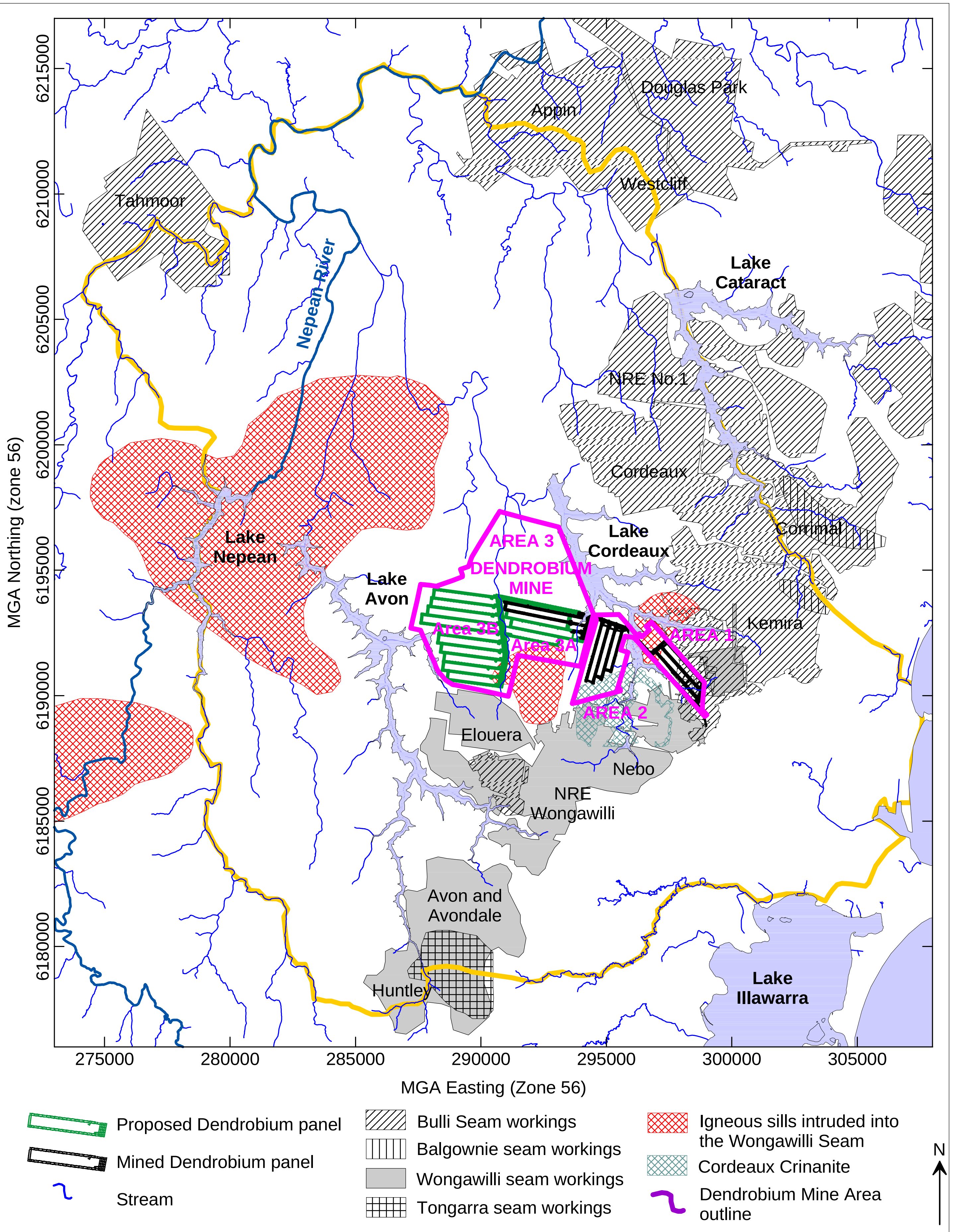

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original size	A4	figure no:	**Drawing 3**

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Appendix A

Stage 2 Calibration Hydraulic Head Target Sites

Table A1. Stage 2 Calibration Hydraulic Head Target Sites

Monitoring Site	VWP No.	Depth (mbgl)*	Stratum
DDH22	1	358	WW11
DDH23	1	266	WW11
DDH34	1	19	SPCS
DDH34	2	55	SCSS
DDH34	3	70	WOCS
DDH38	1	25	BHCS
DDH38	2	130	BUSS
DDH38	3	170	SCSS
DDH38	4	259	WW11
DDH39	2	122	SPCS
DDH39	3	152	SCSS
DDH39	4	234	WW11
DDH41	1	351	WW11
DDH50	7	10	SPCS
DDH50	6	20	SCSS
DDH50	5	45	SCSS
DDH50	3	60	WOCS
DDH50	2	86	BUCO
DDH50	1	117	WW11
DDH56	1	371	WW11
DDH57	1	317	WW11
DDH60	1	236	WW11
DDH69	1	422	WW11
DDH76	1	329	BUCO
DDH76	2	357	WW11
DDH84	1	10	HASS
DDH84	2	15	HASS
DDH84	3	88	UpperBUSS
DDH84	4	100	BUSS
DDH84	6	173	SCSS
DDH84	7	200	SCSS
DDH84	8	216	WOCS
DDH84	9	240	WOCS
DDH84	10	250	BUCO
DDH84	11	277	WW11
DDH94	1	39	SCSS
DDH98	1	74	HASS
DDH98	2	119	UpperBUSS
DDH98	3	213	BUSS
DDH98	4	245	SCSS
DDH98	5	263	SCSS
DDH98	6	282	WOCS
DDH98	7	312	BUCO
DDH98	8	341	WW11
DDH99	2	46	UpperHASS
DDH99	3	110	UpperBUSS
DDH99	4	189	BUSS
DDH99	5	228	SCSS
DDH99	6	254	SCSS
DDH99	7	306	BUCO
DDH99	8	333	WW11

Monitoring Site	VWP No.	Depth (mbgl)*	Stratum
DDH103	2	21	HASS
DDH103	3	65	UpperBUSS
DDH103	4	169	BUSS
DDH103	5	204	SCSS
DDH103	6	210	SCSS
DDH103	7	256	BUCO
DDH103	8	290	WW11
DDH108	1	10	UpperHASS
DDH108	2	144	HASS
DDH108	3	202	UpperBUSS
DDH108	4	295	BUSS
DDH108	5	320	SCSS
DDH108	6	343	SCSS
DDH108	7	383	BUCO
DDH108	8	414	WW11
DDH110	1	9	UpperHASS
DDH110	2	133	HASS
DDH110	3	176	UpperBUSS
DDH110	4	254	BUSS
DDH110	5	270	SPCS
DDH110	6	316	SCSS
DDH110	7	360	BUCO
DDH110	8	388	WW11
DDH112	1	9	UpperHASS
DDH112	2	46	UpperHASS
DDH112	3	87	HASS
DDH112	4	123	UpperBUSS
DDH112	5	169	BUSS
DDH112	6	219	BUSS
DDH112	7	249	SCSS
DDH112	8	261	SCSS
DDH112	9	273	SCSS
DDH112	10	294	WOCS
DDH112	11	318	BUCO
DDH112	12	346	WW11
DDH117	1	10	HASS
DDH117	2	39	UpperBUSS
DDH117	3	83	BUSS
DDH117	4	118	BUSS
DDH117	5	132	BUSS
DDH117	6	164	SCSS
DDH117	7	181	SCSS
DDH117	8	232	BUCO

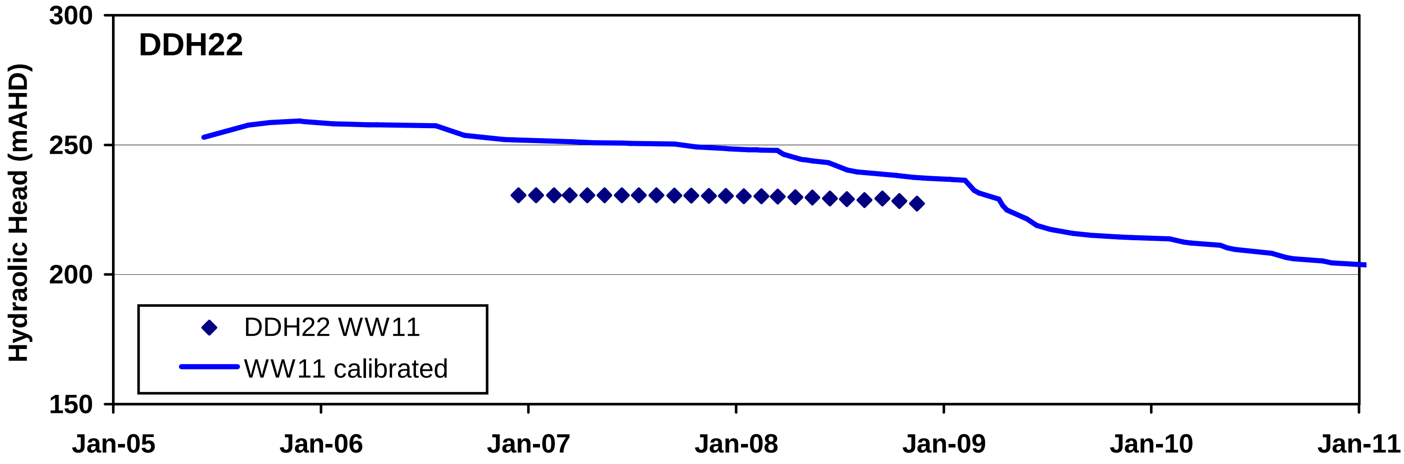
* Denotes metres below ground level.

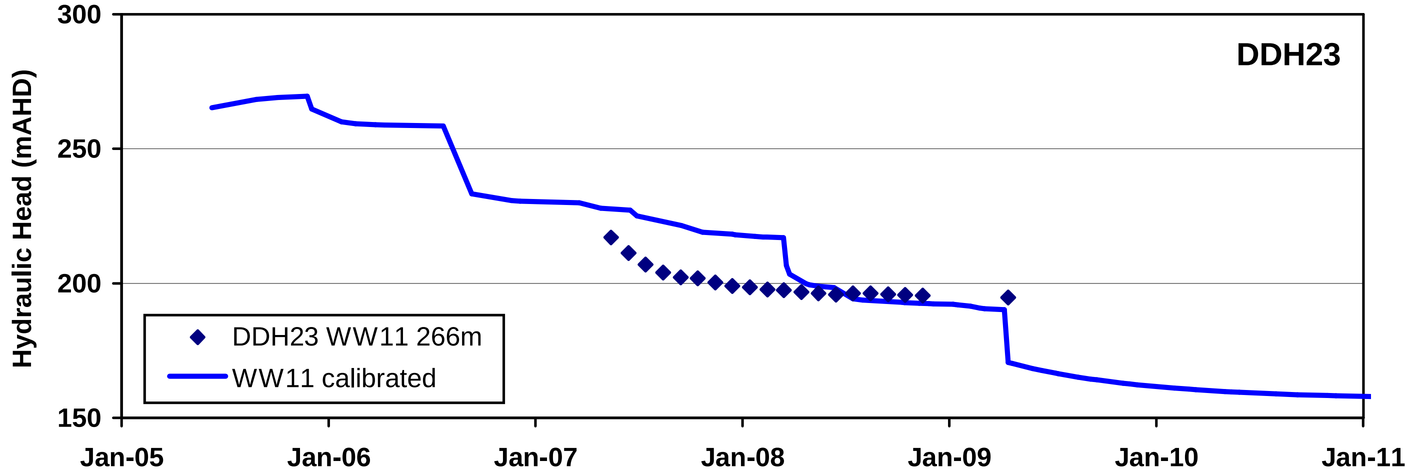
Lithology Key

Abbreviation	Stratum
BACO	Balgownie Coal Seam
BHCS	Bald Hill Claystone
BUCO	Bulli Coal Seam
BUSS	Bulgo Sandstone
CCSS	Coalcliff Sandstone
CDX	Cordeaux Crinanite
HASS	Hawkesbury Sandstone
SCSS	Scarborough Sandstone
SPCS	Stanwell Park Claystone
WOCS	Wombarra Claystone
WW11	Wongawilli Coal Seam (Ply 11)

Appendix B

Calibrated Model Hydrographs


DDH22
Hydraolic Head (mAHD)
300
250
200
150
DDH22 WW11
WW11 calibrated
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11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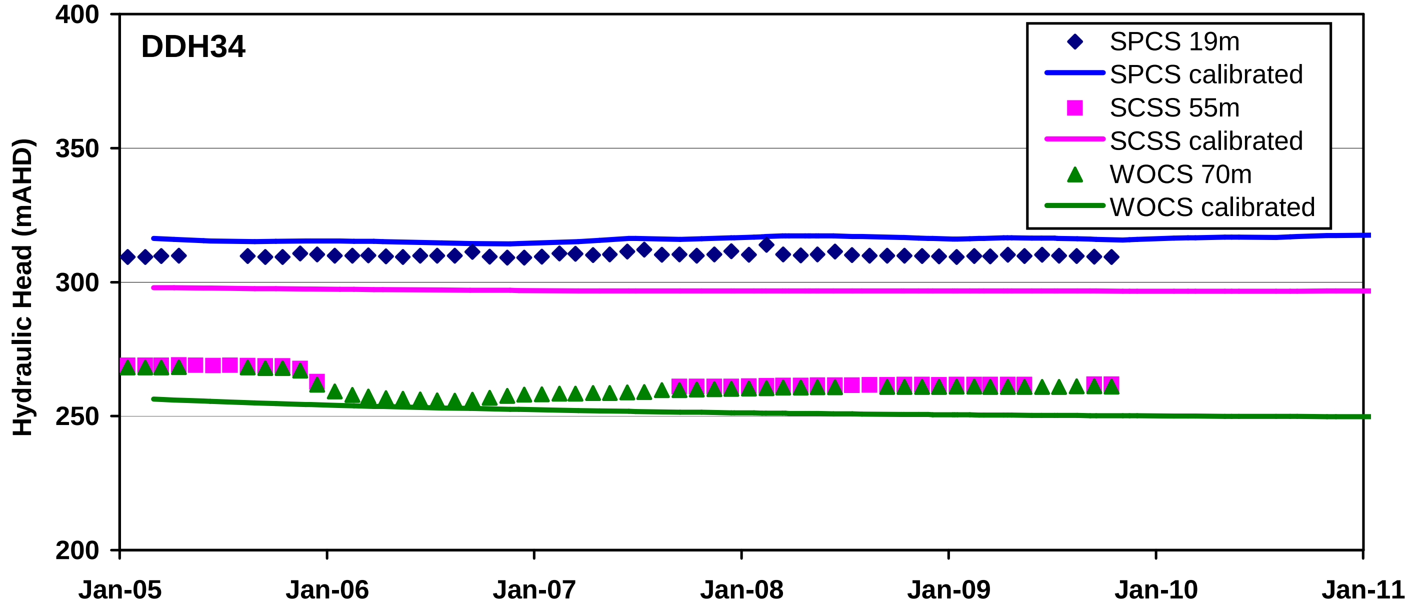
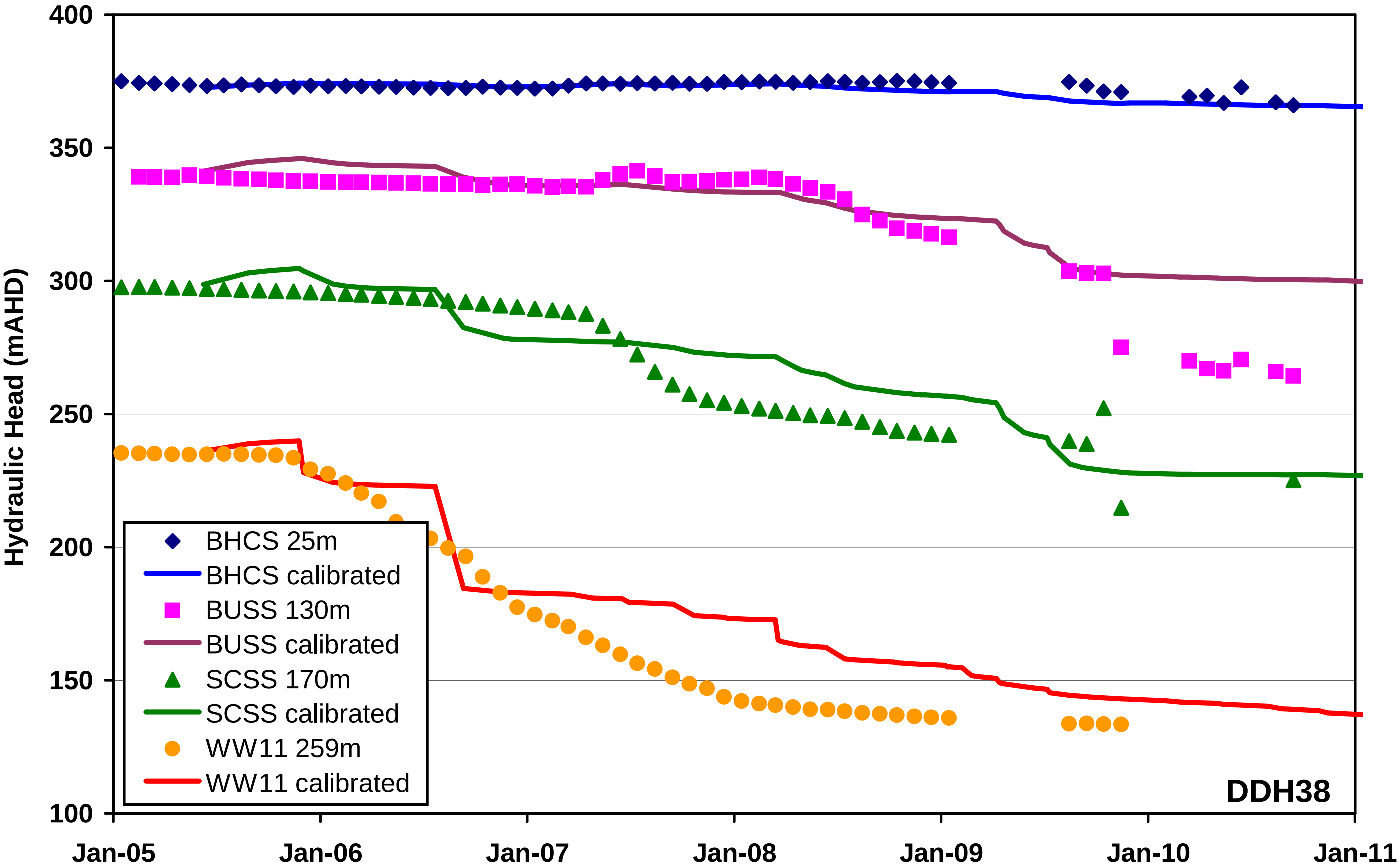
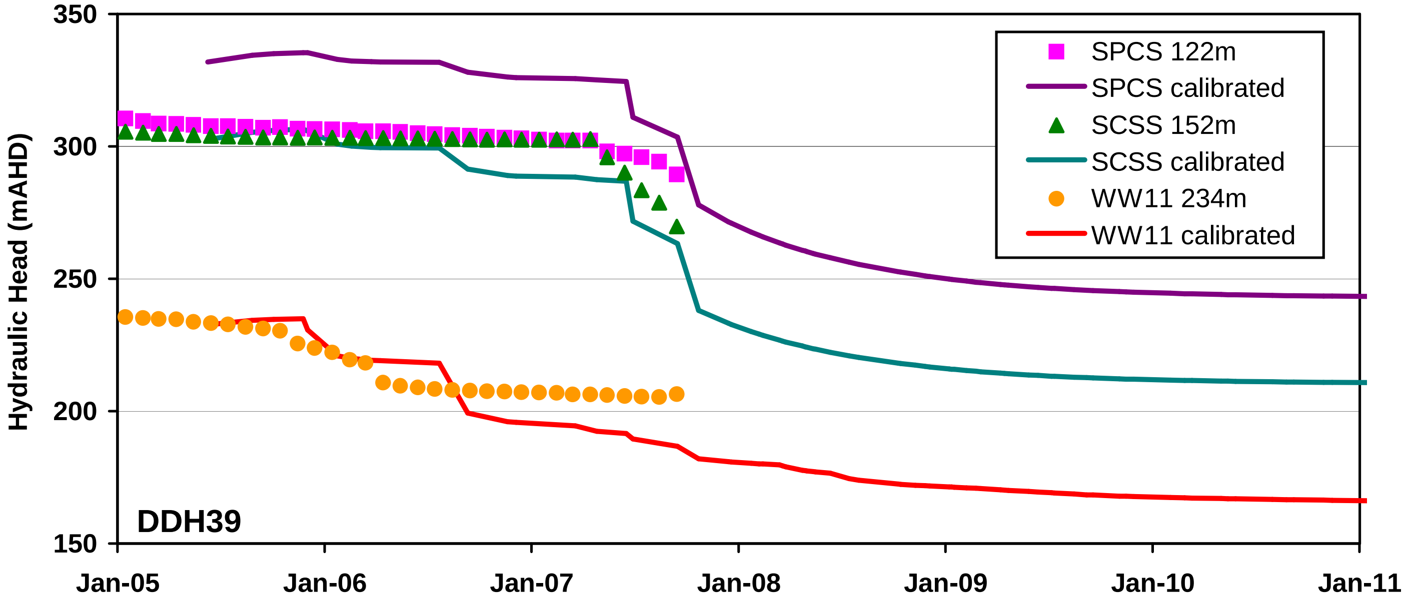
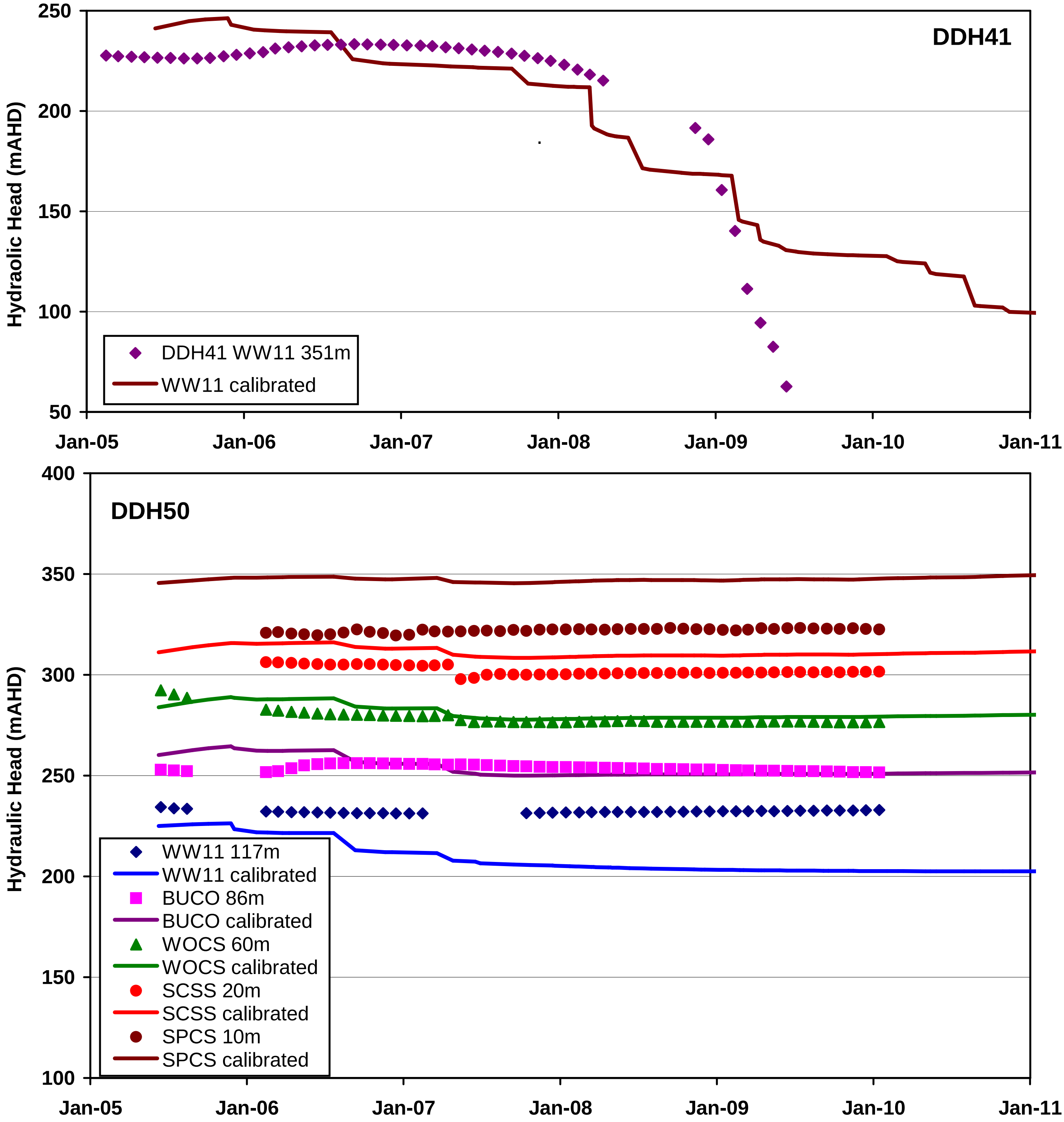
Hydraulic Head (mAHD)
300
250
200
150
DDH23 WW11 266m
WW11 calibrated
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11


DDH34
Hydraulic Head (mAHD)
400
350
300
250
200
SPCS 19m
SPCS calibrated
SCSS 55m
SCSS calibrated
WOCS 70m
WOCS calibrated
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11


400
350
300
250
200
150
100
Hydraulic Head (mAHD)
BHCS 25m
BHCS calibrated
BUSS 130m
BUSS calibrated
SCSS 170m
SCSS calibrated
WW11 259m
WW11 calibrated
DDH38
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11


350
300
250
200
150
Hydraulic Head (mAHD)
SPCS 122m
SPCS calibrated
SCSS 152m
SCSS calibrated
WW11 234m
WW11 calibrated
DDH39
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11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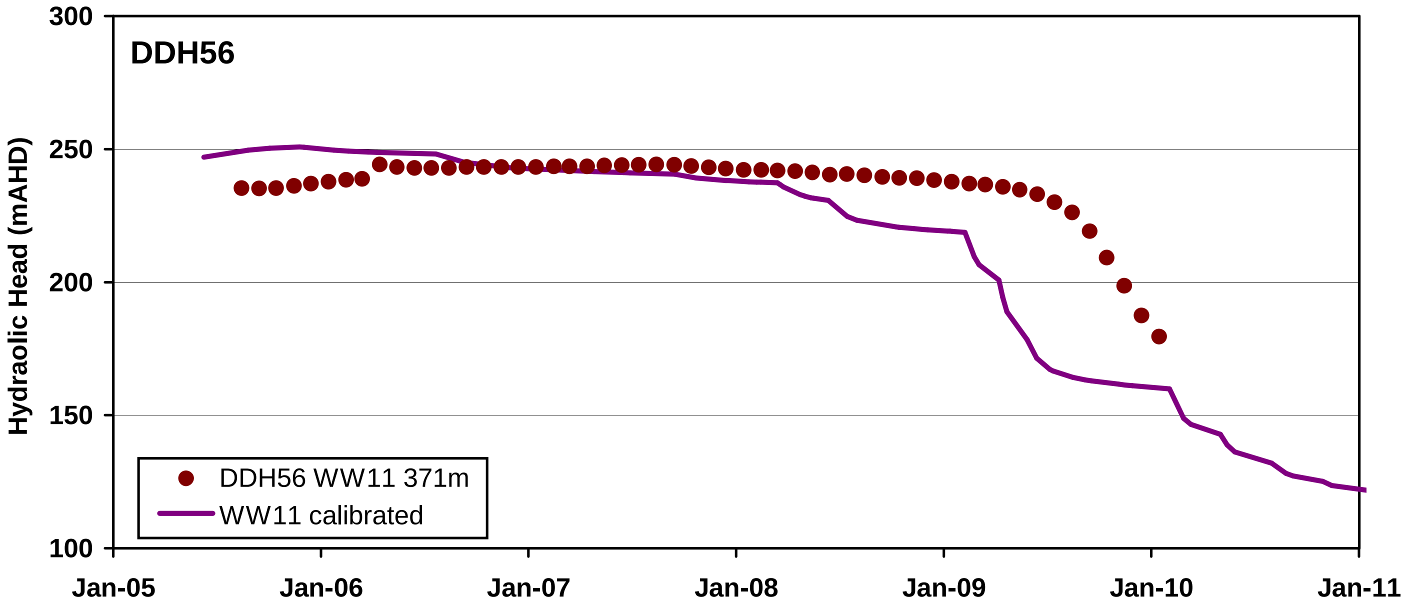
Hydraulic Head (mAHD)
250
200
150
100
50
DDH41 WW11 351m
WW11 calibrated
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11
DDH50
Hydraulic Head (mAHD)
400
350
300
250
200
150
100
WW11 117m
WW11 calibrated
BUCO 86m
BUCO calibrated
WOCS 60m
WOCS calibrated
SCSS 20m
SCSS calibrated
SPCS 10m
SPCS calibrated
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11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250
200
150
100
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WW11 calibrated
Jan-05
Jan-06
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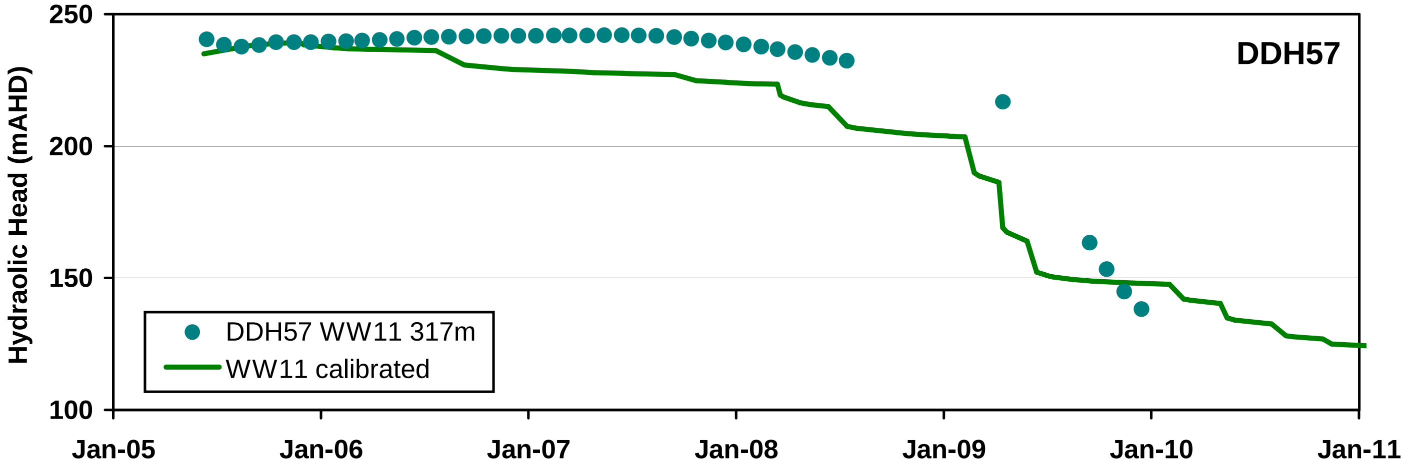
Jan-09
Jan-10
Jan-11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Hydraulic Head (mAHD)
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150
100
DDH57 WW11 317m
WW11 calibrated
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Jan-06
Jan-07
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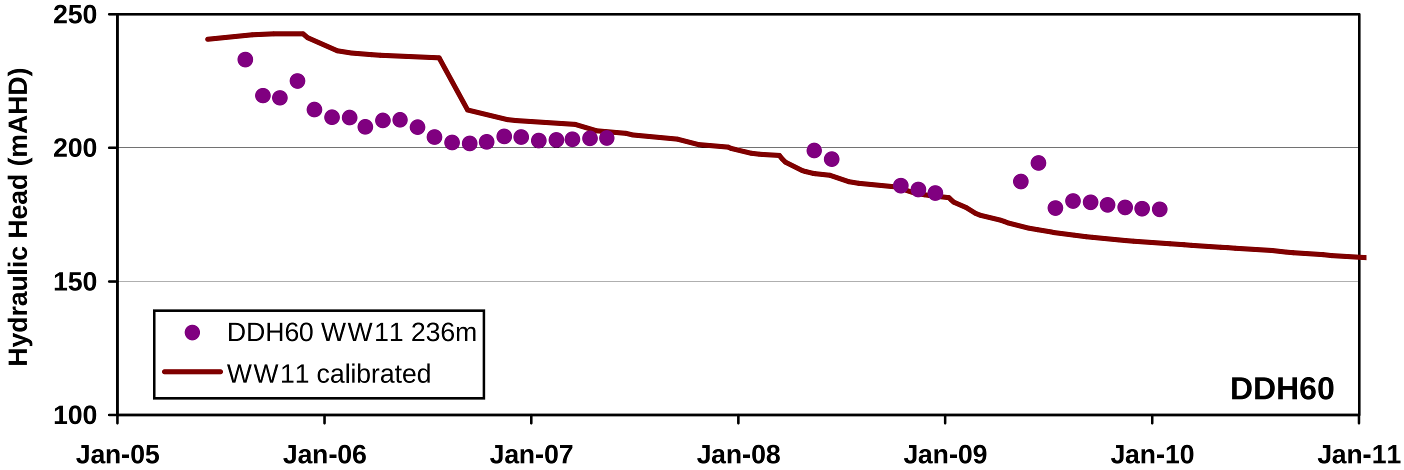
Jan-09
Jan-10
Jan-11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Hydraulic Head (mAHD)
250
200
150
100
DDH60 WW11 236m
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Jan-06
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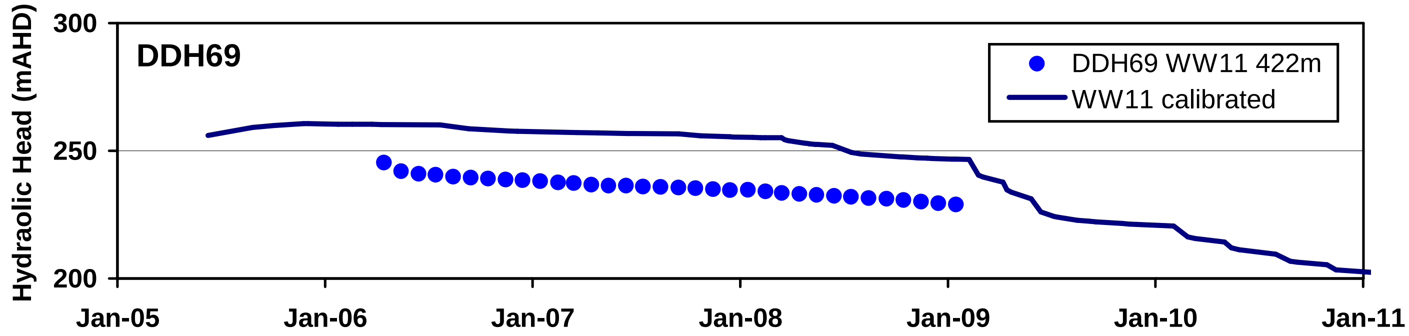
Jan-09
Jan-10
Jan-11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250
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DDH69 WW11 422m
WW11 calibrated
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Jan-06
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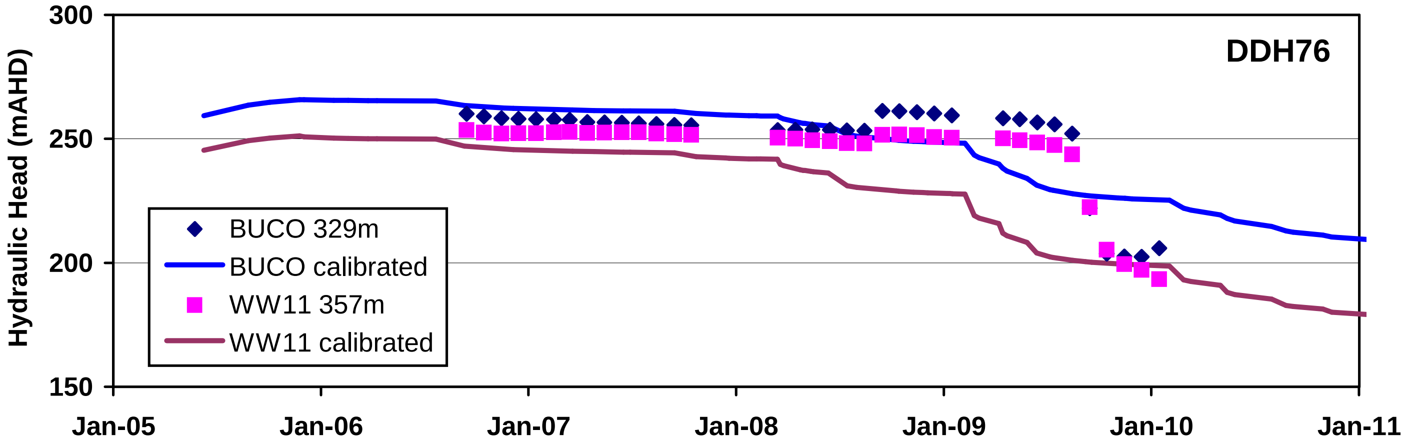
Jan-09
Jan-10
Jan-11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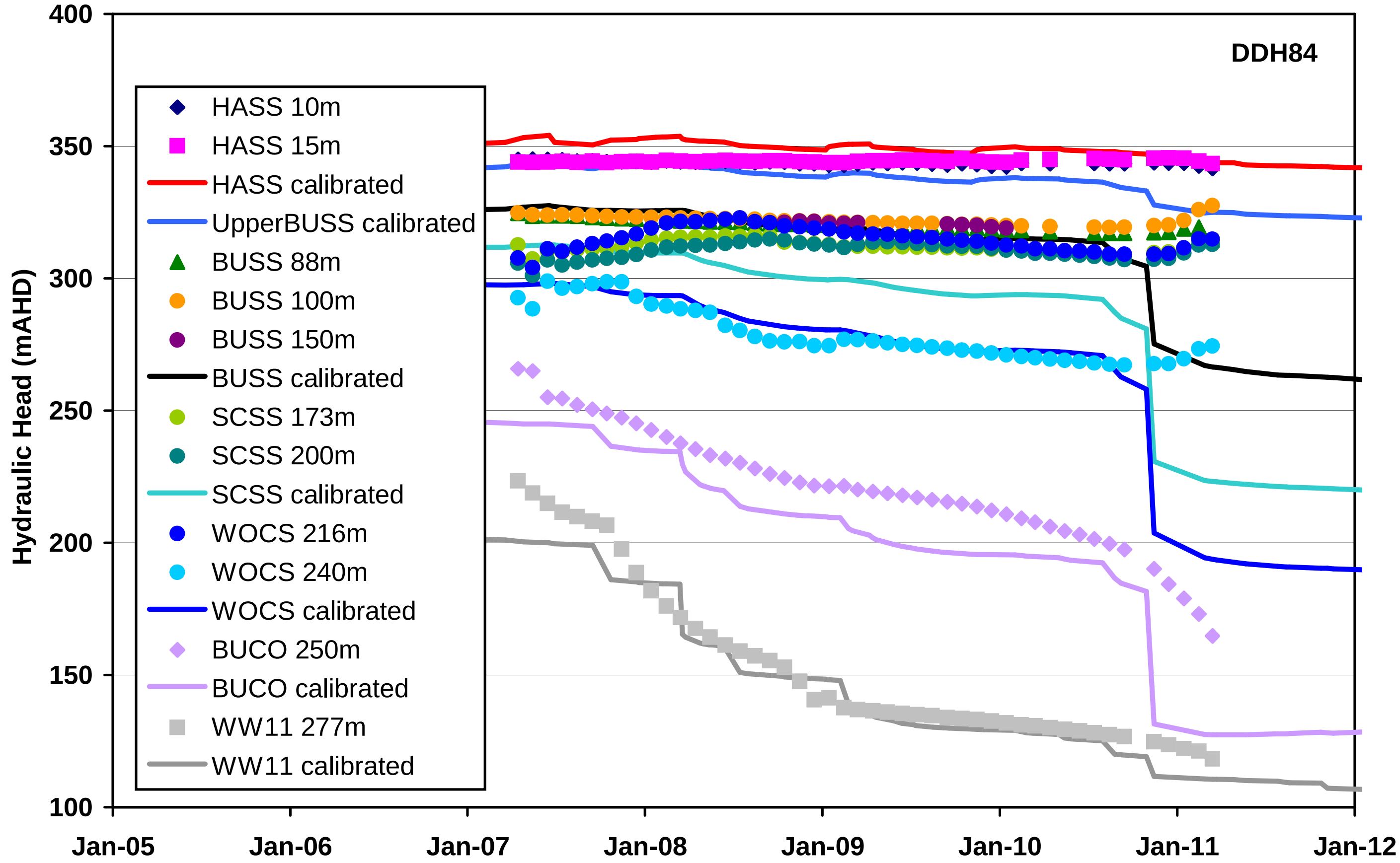
Hydraulic Head (mAHD)
300
250
200
150
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11
BUCO 329m
BUCO calibrated
WW11 357m
WW11 calibrated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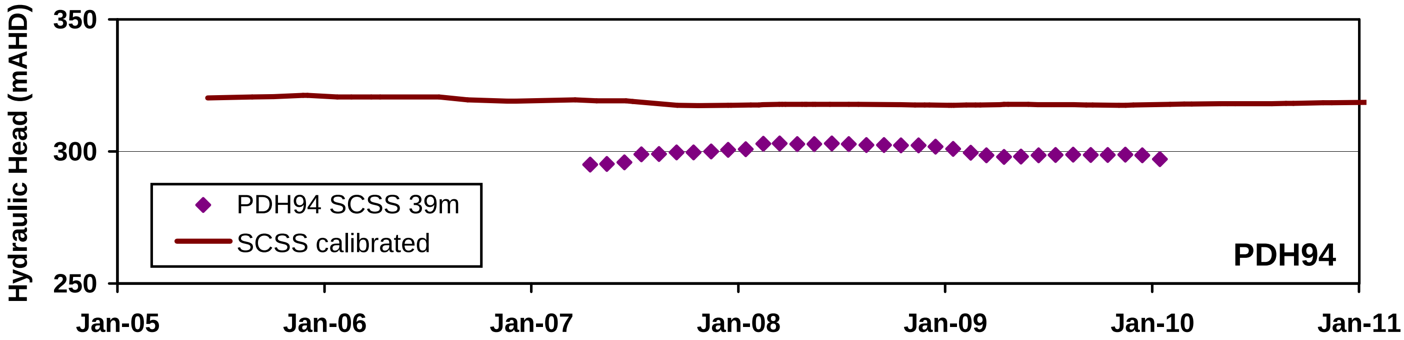
Hydraulic Head (mAHD)
400
350
300
250
200
150
100
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11
Jan-12
HASS 10m
HASS 15m
HASS calibrated
UpperBUSS calibrated
BUSS 88m
BUSS 100m
BUSS 150m
BUSS calibrated
SCSS 173m
SCSS 200m
SCSS calibrated
WOCS 216m
WOCS 240m
WOCS calibrated
BUCO 250m
BUCO calibrated
WW11 277m
WW11 calibrated


PDH94
Hydraulic Head (mAHD)
350
300
250
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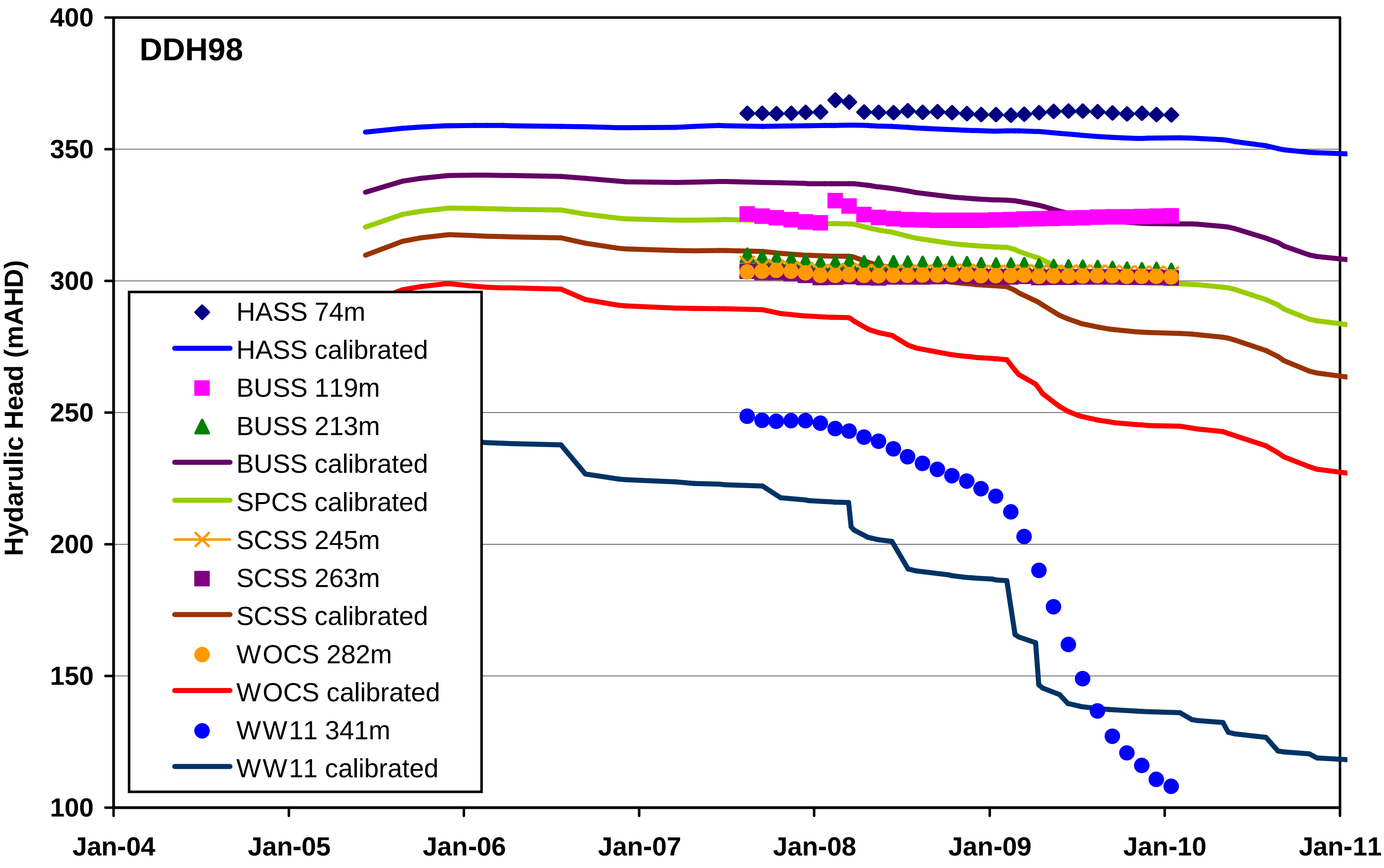
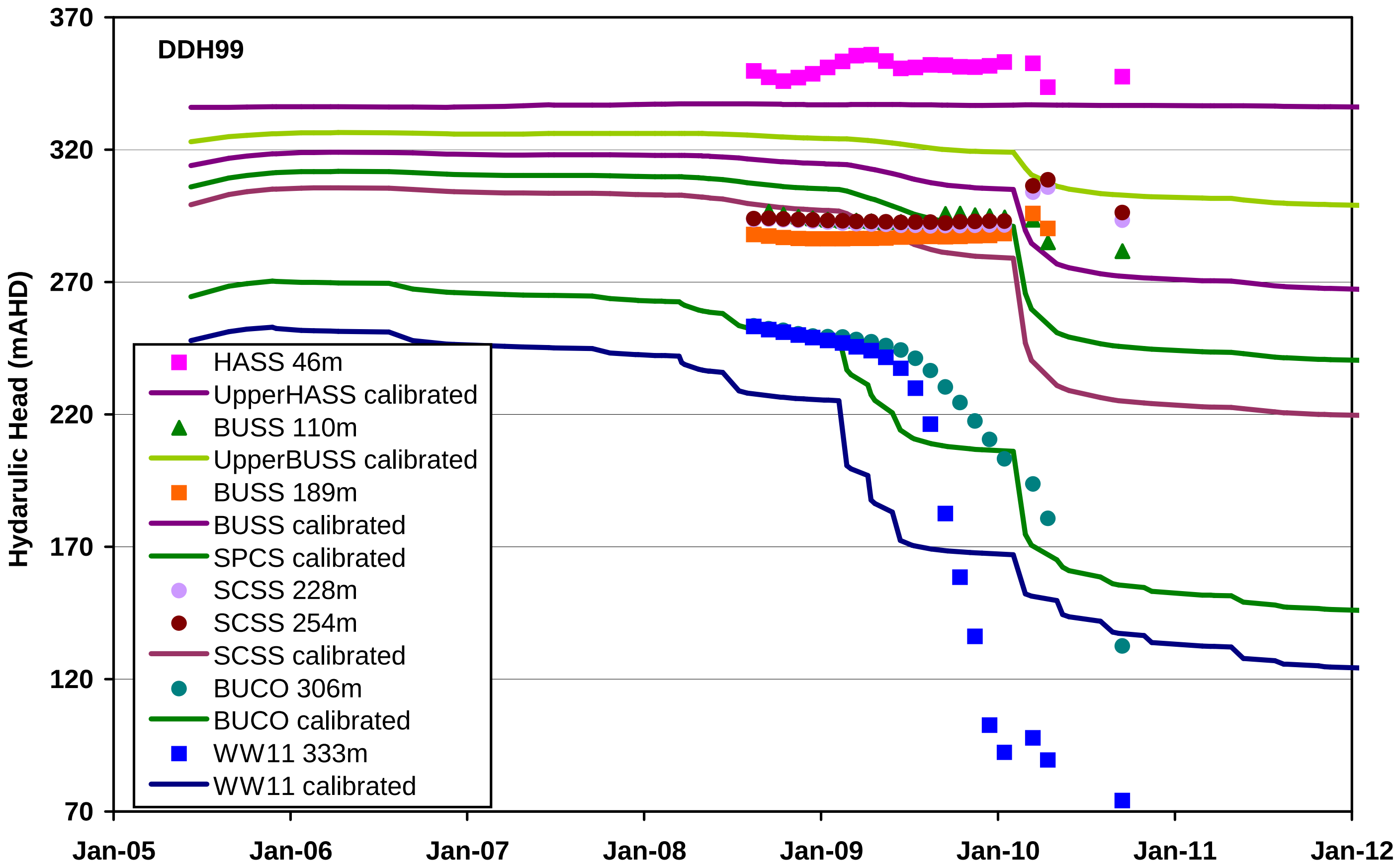
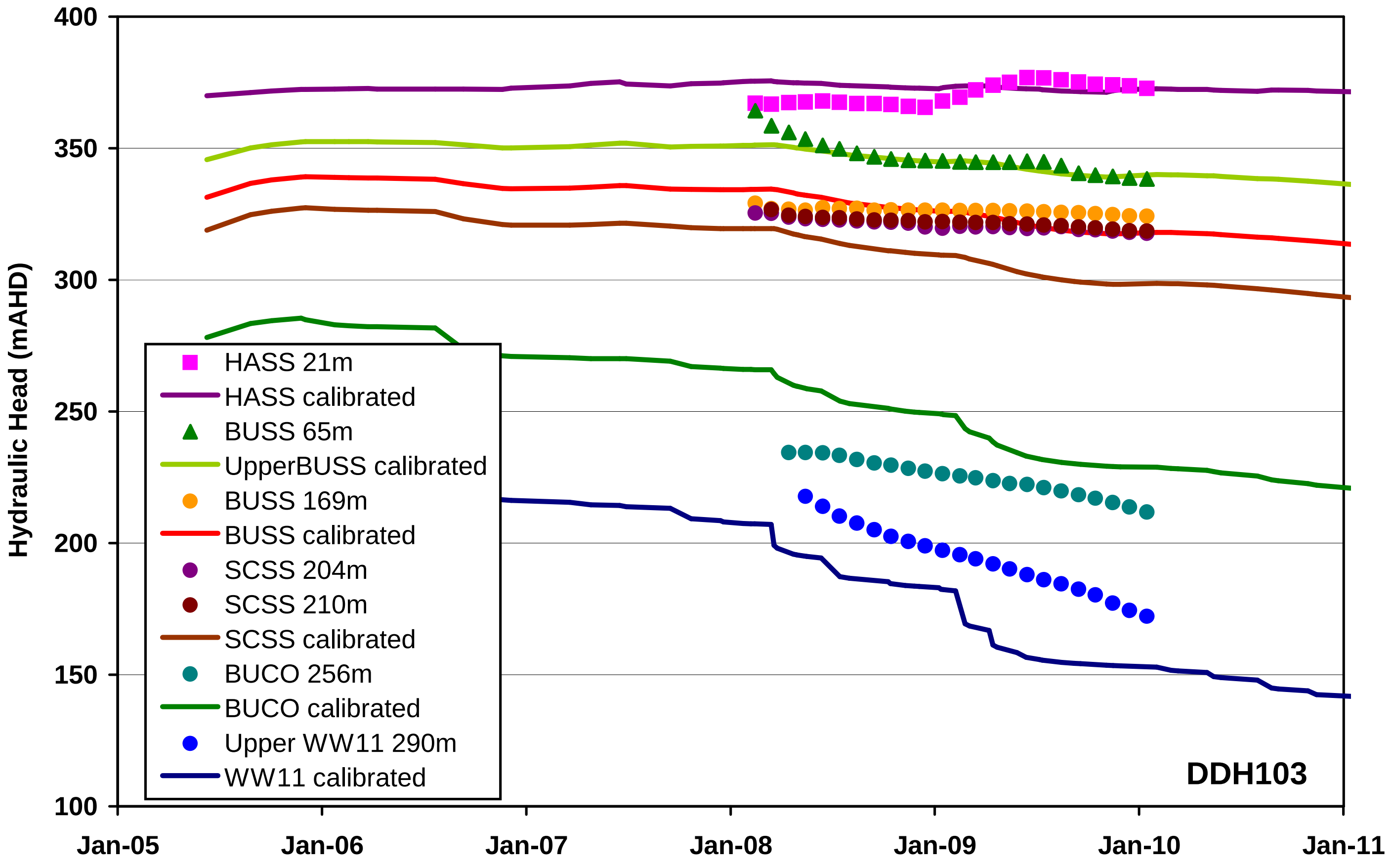
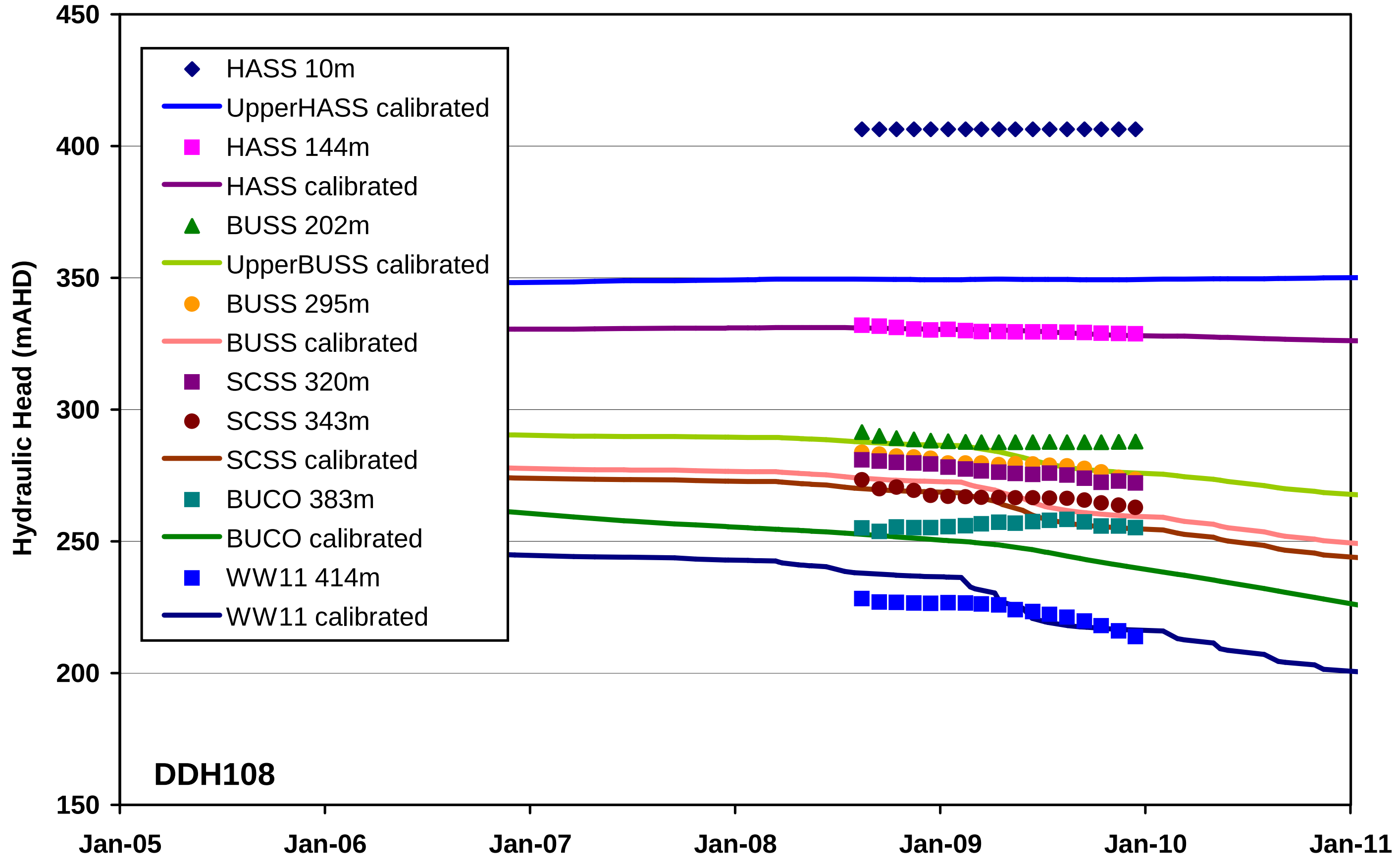
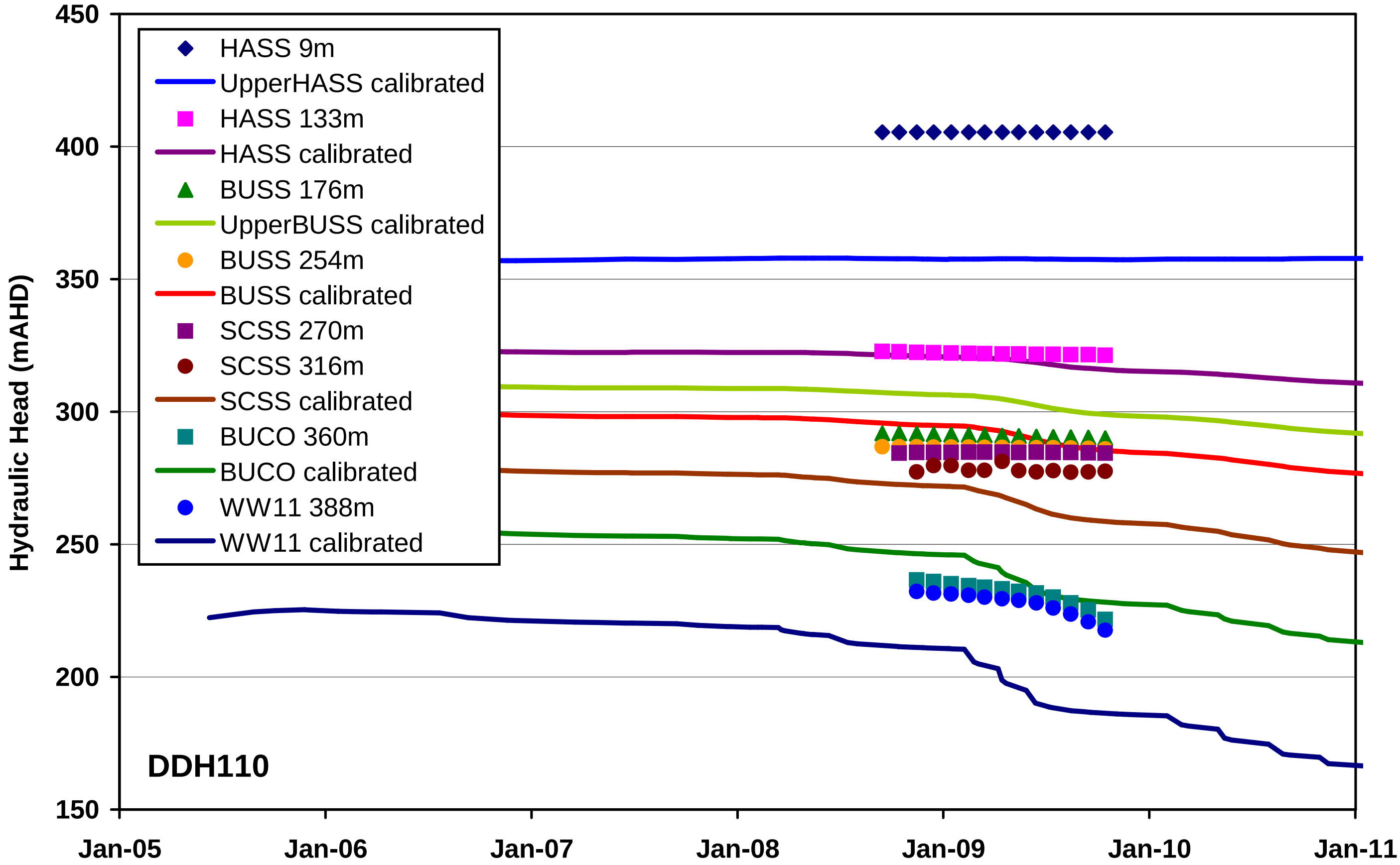
Jan-06
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11
PDH94 SCSS 39m
SCSS calibrated

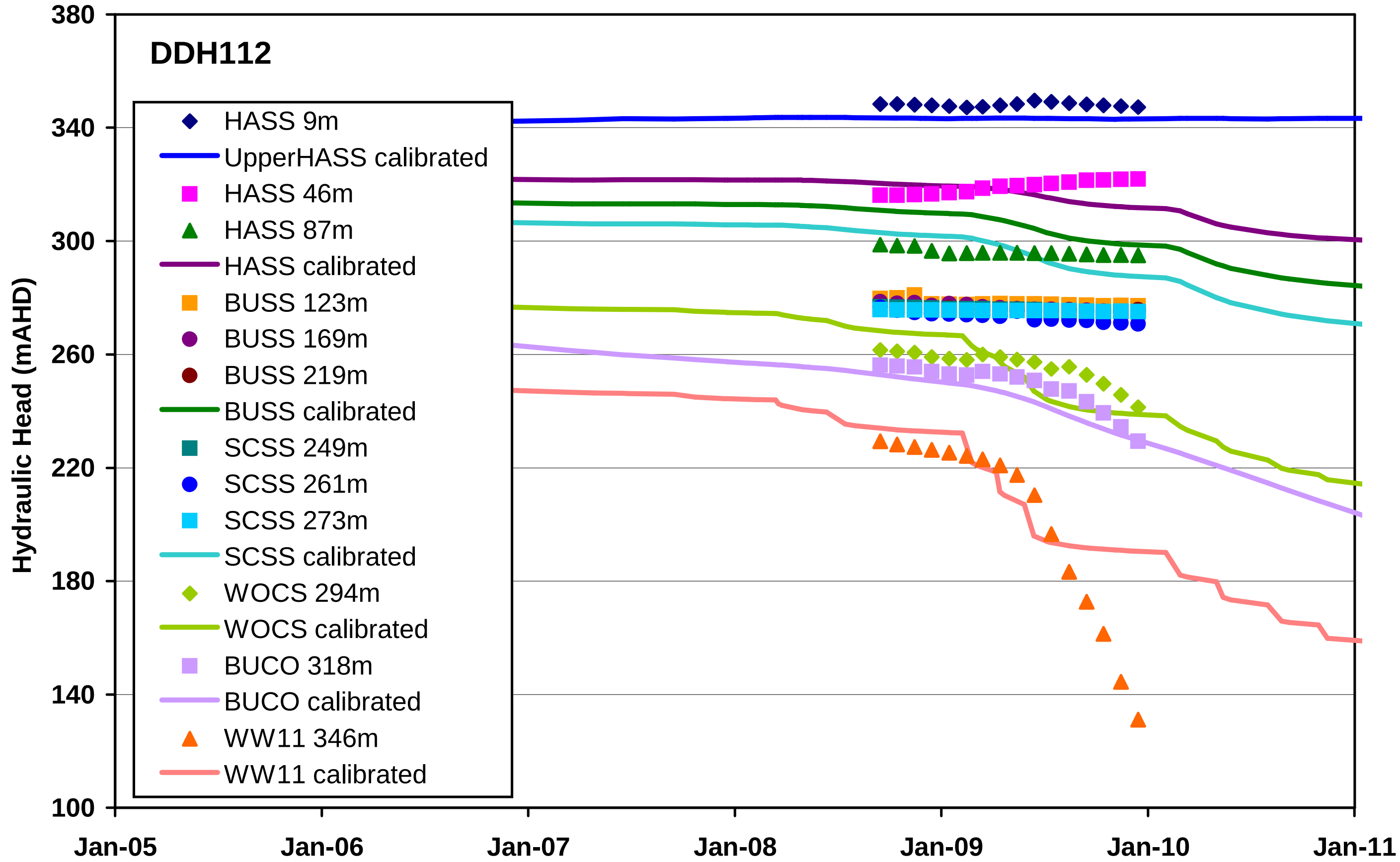

DDH98
Hydraulic Head (mAHD)
400
350
300
250
200
150
100
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11
HASS 74m
HASS calibrated
BUSS 119m
BUSS 213m
BUSS calibrated
SPCS calibrated
SCSS 245m
SCSS 263m
SCSS calibrated
WOCS 282m
WOCS calibrated
WW11 341m
WW11 calibrated

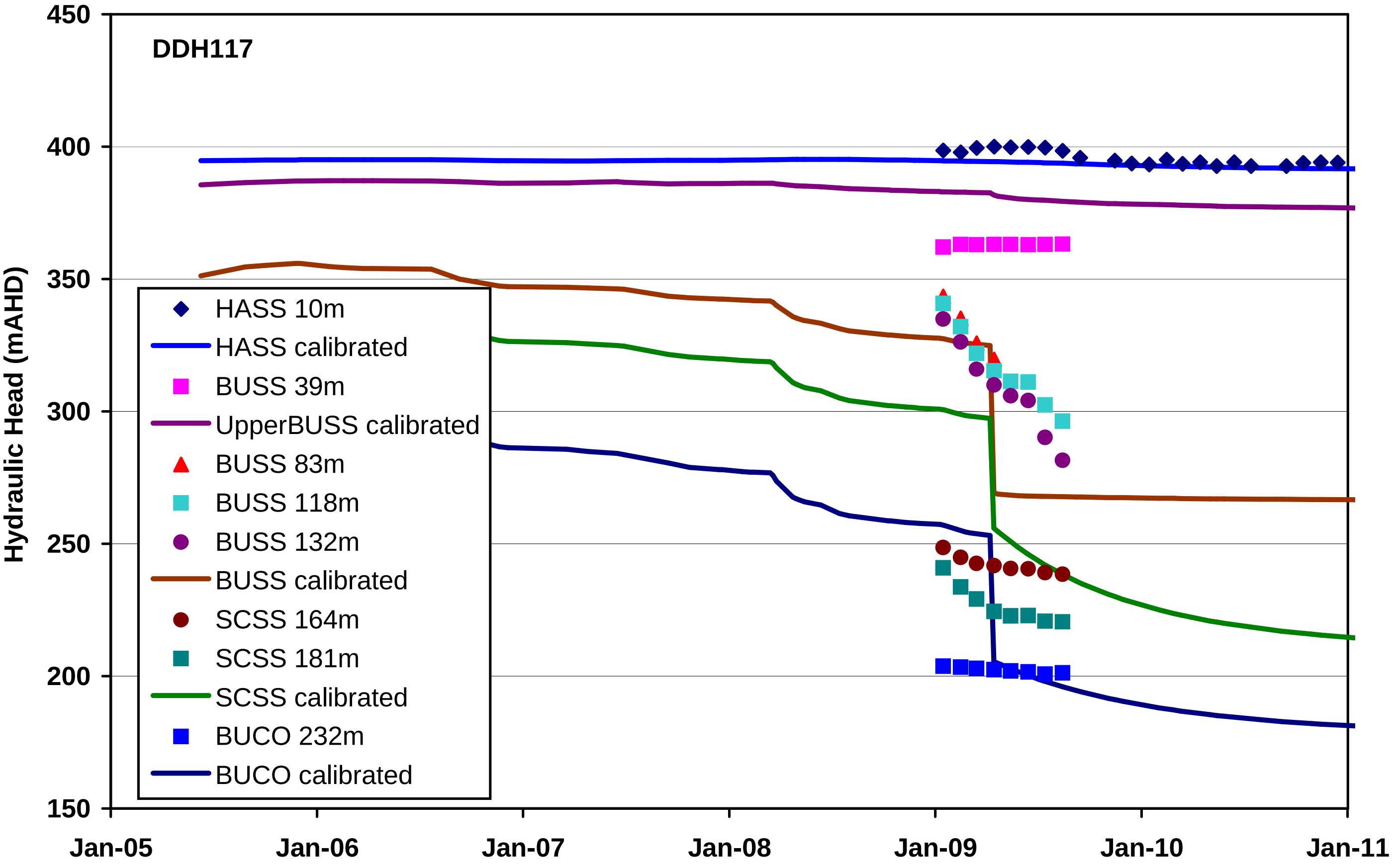

DDH99
Hydraulic Head (mAHD)
370
320
270
220
170
120
70
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11
Jan-12
HASS 46m
UpperHASS calibrated
BUSS 110m
UpperBUSS calibrated
BUSS 189m
BUSS calibrated
SPCS calibrated
SCSS 228m
SCSS 254m
SCSS calibrated
BUCO 306m
BUCO calibrated
WW11 333m
WW11 calibrated


Hydraulic Head (mAHD)
400
350
300
250
200
150
100
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11
HASS 21m
HASS calibrated
BUSS 65m
UpperBUSS calibrated
BUSS 169m
BUSS calibrated
SCSS 204m
SCSS 210m
SCSS calibrated
BUCO 256m
BUCO calibrated
Upper WW11 290m
WW11 calibrated
DDH103


Hydraulic Head (mAHD)
450
400
350
300
250
200
150
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11
HASS 10m
UpperHASS calibrated
HASS 144m
HASS calibrated
BUSS 202m
UpperBUSS calibrated
BUSS 295m
BUSS calibrated
SCSS 320m
SCSS 343m
SCSS calibrated
BUCO 383m
BUCO calibrated
WW11 414m
WW11 calibrated
DDH108


Hydraulic Head (mAHD)
450
400
350
300
250
200
150
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11
DDH110
HASS 9m
UpperHASS calibrated
HASS 133m
HASS calibrated
BUSS 176m
UpperBUSS calibrated
BUSS 254m
BUSS calibrated
SCSS 270m
SCSS 316m
SCSS calibrated
BUCO 360m
BUCO calibrated
WW11 388m
WW11 calibrated


Hydraulic Head (mAHD)
380
340
300
260
220
180
140
100
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11
DDH112
HASS 9m
UpperHASS calibrated
HASS 46m
HASS 87m
HASS calibrated
BUSS 123m
BUSS 169m
BUSS 219m
BUSS calibrated
SCSS 249m
SCSS 261m
SCSS 273m
SCSS calibrated
WOCS 294m
WOCS calibrated
BUCO 318m
BUCO calibrated
WW11 346m
WW11 calibrated


DDH117
Hydraulic Head (mAHD)
450
400
350
300
250
200
150
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11
HASS 10m
HASS calibrated
BUSS 39m
UpperBUSS calibrated
BUSS 83m
BUSS 118m
BUSS 132m
BUSS calibrated
SCSS 164m
SCSS 181m
SCSS calibrated
BUCO 232m
BUCO calibrated

Lithology Key

Abbreviation	Stratum
BACO	Balgownie Coal Seam
BHCS	Bald Hill Claystone
BUCO	Bulli Coal Seam
BUSS	Bulgo Sandstone
CCSS	Coalcliff Sandstone
CDX	Cordeaux Crinanite
HASS	Hawkesbury Sandstone
SCSS	Scarborough Sandstone
SPCS	Stanwell Park Claystone
WOCS	Wombarra Claystone
WW11	Wongawilli Coal Seam (Ply 11)