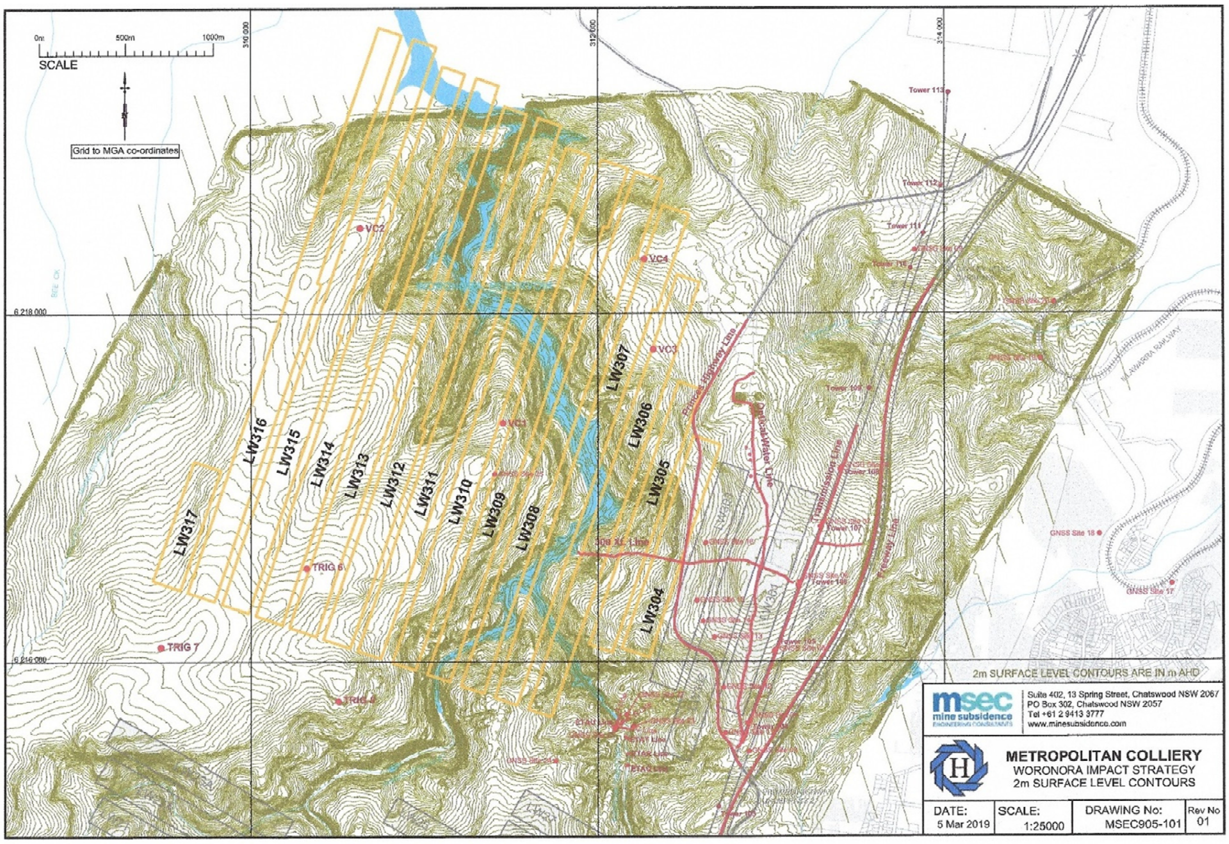
WORONORA RESERVOIR IMPACT STRATEGY

– STAGE 2 REPORT



Metropolitan Coal
Longwall mining near and beneath Woronora Reservoir

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Cover Image

The mine plan diagram on the front cover of this report has been extracted from MSEC Drawing MSEC905-101, dated 5 March 2019. (The scale shown in the title block of the plan should not be used).

New Company

It should be noted that HydroSimulations has recently been sold and is now known as SLR Consulting Australia Pty Ltd. Dr N. Merrick the former Director of HydroSimulations is now Technical Director of SLR.

Disclaimer

Bruce Hebblewhite is employed as a Professor within the School of Minerals & Energy Resources Engineering, at The University of New South Wales (UNSW). In accordance with policy regulations of UNSW regarding external private consulting, it is recorded that his contribution to this report has been prepared in his private capacity as an independent consultant, and not as an employee of UNSW. The report does not necessarily reflect the views of UNSW and has not relied upon any resources of UNSW.

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1.0 INTRODUCTION AND SCOPE

This impact strategy investigation and report was initiated by the Department of Planning and Environment (DPE) for the proposed longwall mining by Metropolitan Coal Pty Ltd (MCPL) near and beneath the Woronora Reservoir.

Extension of longwall mining at Metropolitan Coal (MC) was previously approved for Longwall 20 onwards under Section 75 J of the New South Wales (NSW) Environmental Planning and Assessment Act, 1979 (EP&A Act) on 22 June 2009. This approval was granted by the Minister for Planning (following assessment by the Planning Assessment Commission panel) at the time that indicated that it included mining the entire 300 series of longwall panels[1], many of which pass beneath the Woronora Reservoir.

Conditions set out by the DPE *Record of Decision* (DPE 2017) indicated in *Condition 2* of the Longwalls 301 and 302 approval that there should be: *"Engagement of independent experts to prepare a Woronora Reservoir Impact Strategy, which provides a staged plan of action for further investigations and a report into the impacts of mining near the Reservoir".* The DPE indicated that the issues to be covered in the Impact Strategy report should relate to:

- the likelihood of diversion of surface waters into the underlying strata;
- probable leakage rates;
- connectivity between the reservoir and mine workings;
- characterisation of fractures (pre- and post-mining) including shear planes;
- recommendations for additional subsidence monitoring;
- possible bathymetric survey of the Reservoir; and
- preparation of a report outlining the findings of the investigations to provide the basis of an assessment of future mining near and beneath the Reservoir.

On the 24 May 2017 the DPE advised Metropolitan Coal that three independent persons with many years of extensive experience in the coal industry and academia had been appointed to develop the Impact Strategy Report in relation to the above scope of work. The Impact Strategy Panel members appointed were:

- Professor Bruce Hebblewhite, private mining/geotechnical consultant, and Chair of Mining Engineering, School of Minerals & Energy Resources Engineering (formerly School of Mining Engineering) at the University of NSW, to deal with the geotechnical aspects;
- Professor Emeritus Tom McMahon, Department of Infrastructure Engineering, University of Melbourne to deal with surface water aspects; and

[1] Up to LW316, that is the most distant longwall to the NW and LW317 to the west.

- Dr Frans Kalf, of Kalf and Associates Pty Ltd, a hydrogeologist and a specialist numerical modelling developer and consultant in both government and private industry to deal with the groundwater issues.

Resource Strategies, a company with wide experience in environmental review of investigations in the mining industry, is co-ordinating the work between the Impact Strategy Panel and the mining company. Different sections of the Impact Strategy reports produced have been prepared by the individual Impact Strategy Panel members, in accordance with their particular areas of expertise.

Figure 1.1 shows the proposed mining panel layout beneath the Woronora Reservoir, as originally submitted to DPE by MCPL in the Longwalls 301-303 Extraction Plan (November 2016).

This Stage 2 report represents the second stage of the Impact Strategy required in response to this scope of work, based on further data and analysis arising from the ongoing monitoring programs, including those recommended in the original Stage 1 report, dated 19 September 2017. (A summary of the findings from the Stage 1 Report is included in the next section).

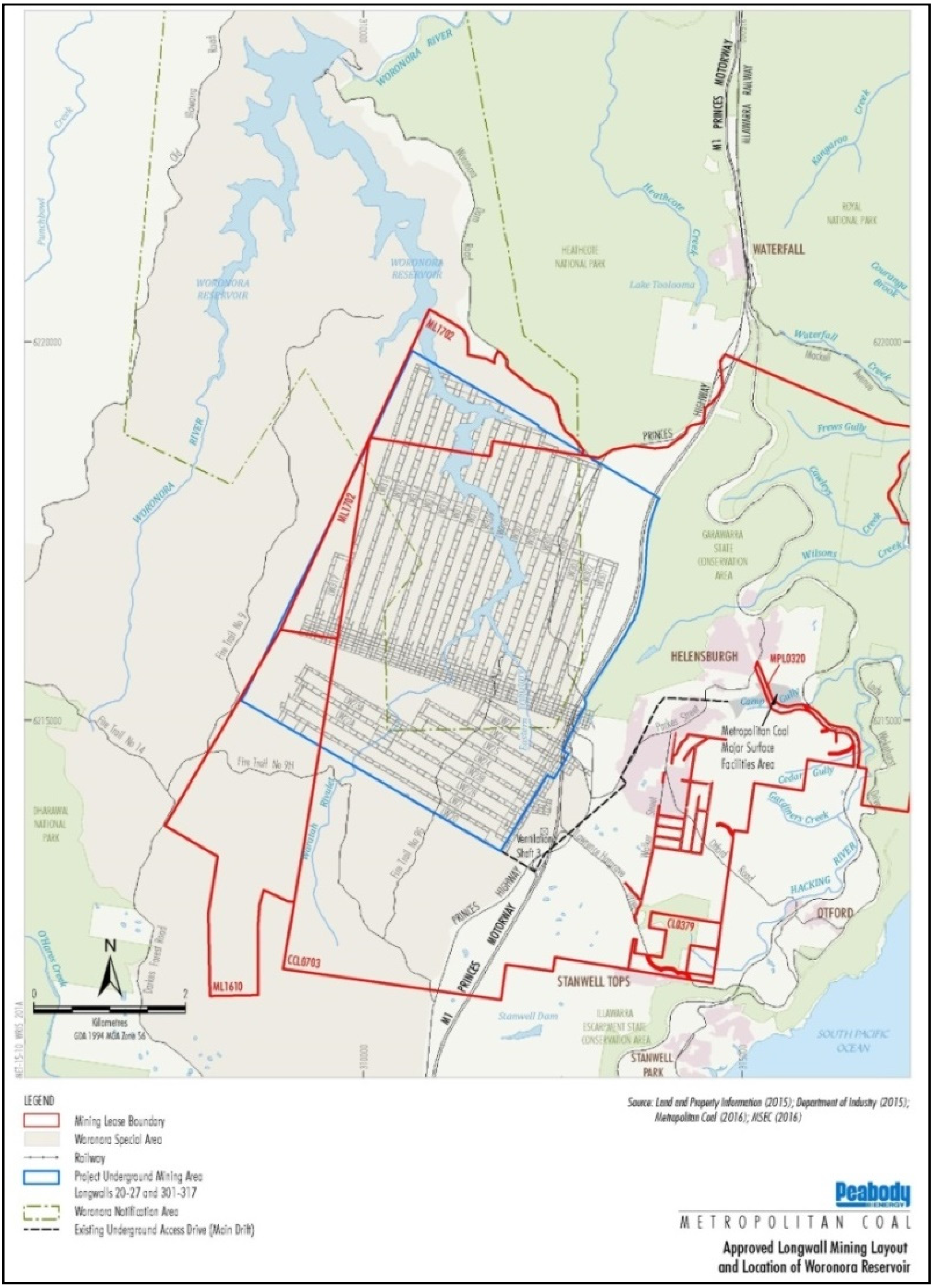

Figure 1.1. Original mining proposal (November 2016)

(source: Metropolitan Coal)

2.0 SUMMARY FINDINGS FROM THE STAGE 1 REPORT

The following is a summary of the main findings and recommendations from the Stage 1 Impact Strategy Report (September 2017). Readers are directed to that report for further, more detailed information.

2.1 Conceptual Metropolitan Coal Groundwater System

The description of the hydrogeological conditions at the Metropolitan site are reproduced here, but updated, based on the recent borehole and VWP piezometer monitoring data from monitoring sites associated with extraction of longwall panel 302 but also from monitoring piezometers at 303 and 304. This level of detail is important to assist in understanding the further results and analysis contained in this Stage 2 Report.

The mining area is situated within a sedimentary rock sequence comprising deeper Permian and shallower Triassic-aged geological strata. The total thickness of all the rock units and formations from the top of the sequence to the bottom is between 400m to 500m with the main geological units comprising from the top to bottom:

- Surficial sediments with some upland swampy conditions
- Hawkesbury Sandstone (170m)
- Newport Formation and Garie Formation
- Bald Hill Claystone, (extensive claystone/shale layer)
- Bulgo Sandstone, (a thick bedded sandstone with shale horizons (175m)
- Stanwell Park Claystone
- Scarborough Sandstone
- Wombarra Claystone
- Coal Cliff Sandstone
- Illawarra Coal Measures (shales and sandstones with 10 coal seams with the Bulli coal seam situated at the top of the Permian Coal Measure sequence).

Figure 2.1 is an idealised cross-sectional view showing the surface topography; the major geological units comprising the overburden above the mining horizon; down to the mining horizon in the Bulli Seam. The diagram (which is not to scale) indicates a conceptual model of the groundwater system above the mining horizon, within this strata sequence.

Groundwater is recharged by infiltration of rainfall at the ground surface over the wider region with flow within naturally occurring fractures at shallow depth and also through the rock matrix, with groundwater flow directed towards lower-lying topography, including the Woronora Reservoir.

At shallow depth, perched water tables can occur within the swamp zones that are not directly connected to deeper groundwater systems. Groundwater flow rate is restricted in the vertical direction downwards by layers of shale and claystone of much lower hydraulic conductivity and lower overall vertical hydraulic conductivity of the entire rock sequence, compared to horizontal hydraulic conductivity. Vertical groundwater flow in the Southern Coalfield within a stratified geological sequence is determined by the layer of lowest hydraulic conductivity in the geological profile.

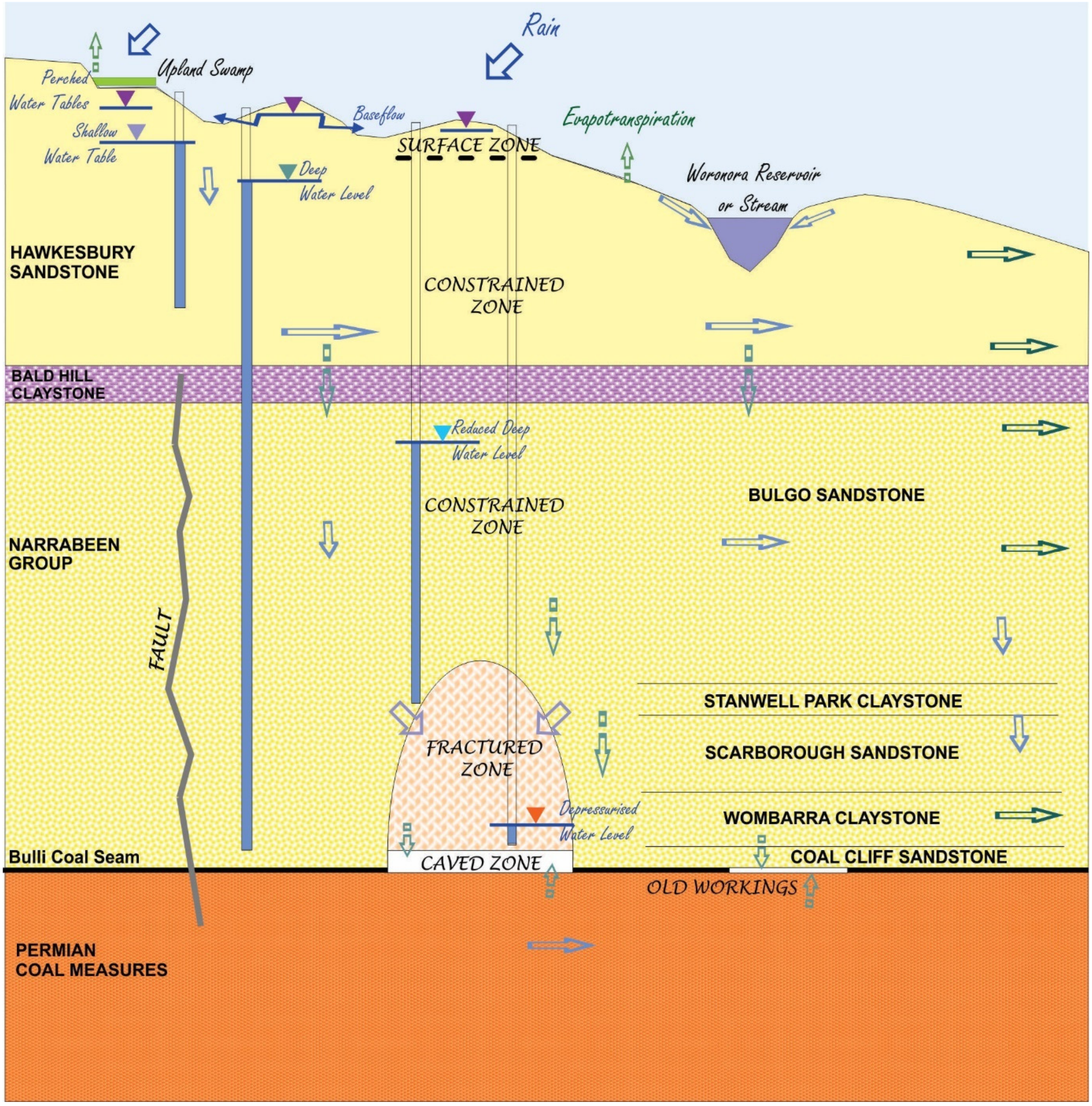

Figure 2.1. Conceptual groundwater system for Metropolitan Coal mining conditions
(not to scale)

Hence groundwater tends to flow horizontally above any impeding horizons and therefore in the Hawkesbury and Bulgo Sandstone predominately flows out into the lower elevation regional groundwater system. Under mining conditions groundwater seepage is directed towards the caved zone above the mined-out seams and the overlying fractured zone and is derived from the adjacent strata. That is, groundwater inflow is predominately horizontal from the in-situ coal seam and also to an extent vertical from the geological layers directly above the coal measure strata and the lower part of the Bulgo Sandstone.

In this conceptual model, under mining conditions, a 'constrained zone' is usually created by the compression within the higher levels of rock above the mined-out panels within the coal seam. This zone tends to maintain the in situ (i.e. pre-mine) vertical permeability[2] of the strata and therefore continues to restrict vertical flow but can display an increase in the horizontal permeability above the parabolic or approximate triangular shaped fracture zone. The constrained zone has little effect on vertical groundwater flow rate due to its low to very low vertical hydraulic conductivity.

The piezometers shown in Figure 2.1 show the pressure head only at the lower end of each piezometer which is open. For example, the water level in the piezometer within the caved zone in Figure 2.1 is near the bottom but this does mean that the groundwater above the fracture zone and higher in the profile along this piezometer has been completely drained. As indicated in Figure 2.1 the water-table above the caved zone piezometer is maintained in the surface zone. Also, while there is reduced pressure head at the base of the adjacent piezometer just above the fracture zone with a corresponding lower water level, there is also no complete drainage of groundwater above this piezometer opening. Similarly, the third piezometer further to the left records much less reduced pressure head at its base and hence there is a much higher water level in the piezometer tube. The corollary is that the piezometer tubes that are open to the groundwater system at their base or within a short interval within the tube have water levels that do not represent the positions of a variable water table depth but only the pressure head at the particular piezometer opening.

Recent monitoring has shown the compression effects in the profile with rising water levels in the piezometers in and around the Bulgo Sandstone down to the Scarborough Sandstone, and less rising pressure levels in the shale/sandstone below the Bald Hill Claystone up into the lower part of the Hawkesbury Sandstone (see section 5.1 and the reasons for these rising pressure levels, discussed in Appendix A).

Hydrosimulations (2017a) has also noted that:

> *"Although geological structures are known to exist in underground workings or are inferred to extend into the approved mining area, there is no definitive evidence of structural control on groundwater levels or flow directions. In general, individual structural features located on the floor of the Bulli Coal Seam have not been identified at surface despite focused searches over the years, nor have individual surface features been successfully projected and proven at the Bulli Coal Seam horizon."*

Due to some ground level subsidence above the mining zone there is the probability of some shallow (< 20m) limited vertical conduits created in the rock with corresponding shallow, horizontally connected bed separation strata cavities beneath the ground surface. These cavities can redirect oxygenated surface run-off into the shallow sub-surface with subsequent reduction of oxygen and re-emergence of this sub-surface flow further down-gradient outside of the subsidence zone and hence result in limited loss of flow volumes. Re-emergence of this flow, which has undergone reducing conditions, into the oxygen rich atmosphere can cause ferrous iron in solution to precipitate into a ferric iron form indicating the sub-surface origin of the temporary shallow sub-

[2] In this document the term permeability is considered to be the same as hydraulic conductivity.

surface flow. The re-emergence of shallow sub-surface flow is confirmed by the iron rich content of the subsequent flowing surface water.

Generally low iron concentration levels are non-toxic within emergent coloured flow although variable, depending on complex redox geochemical and bacterial mechanisms (Cullimore (1993), Appelo & Postma (1993), Alan, Perdue & Brown (1993), Deutsch (1997), Domenico & Schwartz (1998)[3]). These iron concentrations levels at the Metropolitan Coal site area can also be shown to depend on ambient temperature and stream runoff volumes.

2.2 Comparisons with Other Mining Operations

The following comparisons include other cases of mining beneath water bodies from the Southern Coalfield and elsewhere. These are more fully described in the Impact Strategy Stage 1 report but are repeated here for completeness and for readers not familiar with the Stage 1 report contents. There is no suggestion that any of these cases represent similar conditions to Metropolitan – they are referenced here, simply because they also involve mining beneath water bodies.

2.2.1 Dendrobium Mine

Coal mining at Dendrobium Mine has generated some concern with both authorities and the public over recent years. There is a perception that it is a typical example of what can be expected at other mine sites in the region. However, the mining conditions at this site differ considerably to mines elsewhere. In the Strategy 1 report comparisons were made between the mining parameters at Metropolitan and at Dendrobium and are summarised below.

Table 2.1 Comparison of Metropolitan Coal and Dendrobium Area3B Longwall mining parameters (Table prepared by MCPL)

Mining Parameter	Metropolitan Coal Longwalls 301 – 303	Metropolitan Coal Longwalls Beneath Woronora Reservoir	Dendrobium Mine Area 3B
Longwall Void Width	163 m	138 m	305 m
Extraction Ratio *Longwall void width to Depth of Cover*	41% (163 m / 395 m)	35% (138 m / 395 m)	98% *At minimum depth of cover - valley*
Extraction Height	2.7 m to 3.2 m	2.7 m to 3.2 m	3.9 m to 4.6 m
Depth of Cover	395 m to 555 m	395 m to 435 m	310 m to 450 m
Chain Pillar Width	45 m	70 m	45 m
Seam Mined	Bulli Seam	Bulli Seam	Wongawilli Seam
Water make	~0.1 ML/day	~0.1 ML/day	~11 ML/day

In summary, in comparison to Metropolitan, the panels at Dendrobium are much wider; extraction seam thickness greater; depth of cover is less; and at Dendrobium, mining is conducted in a different seam namely the Wongawilli, with Metropolitan extracting coal from the Bulli Seam.

[3] These references only discuss the redox reactions of oxygen charged recharge water and subsequent reactions of oxygen loss, ferrous iron increase and subsequent creation of ferric compounds. They do not discuss specific conditions that might occur in shallow mining cavities and subsequent exit of groundwater into the atmosphere. Nevertheless, the redox processes would be similar in the mining case as is evident by the ferric hydroxide suspended brown and precipitate material in the emerging groundwater. Naturally occurring groundwater seepages, in unmined regions, emerging along valley escarpment fractures and bedding cavities can also due to the same processes, exhibit the formation of iron staining due to and including natural seepage flow from the exposed escarpment faces due to the same processes.

The differences in geometry, extracted seam thickness and therefore height and resultant degree of connected fracturing, have resulted in substantial differences in pressure head propagation and inflow even though the geological profile is very similar to the Metropolitan site conditions. At Dendrobium the panel width to depth of cover ratio (**W/H**) is, for example, in the range **0.68 to 0.98** whilst at Metropolitan the ratio is in the range **0.29 to 0.41** beneath longwalls 301 to 302, and below the Woronora Reservoir in the range **0.32 to 0.35**.

It is reasonable to expect that higher ratios such as those at Dendrobium could have led to increased inflow due to the increased height of vertical fracture propagation. Recent simulations have included likely cracking to the ground surface in some areas to be mined. Dr Mackie in his review of Dendrobium mine site has indicated weak correlation with the presence of rainfall infiltration from the surface in Area 1, but strong correlations in Areas 2 and 3A and, at the time, weak but *"potentially increasing correlations in Area 3B"* at that mining site. In addition, the maximum extraction seam thickness at Dendrobium is 1.4 times greater than the maximum extracted seam thickness at Metropolitan. This will also influence fracture height propagation and the potential of any surface infiltration which is currently not evident at all at Metropolitan.

The reduction of the Metropolitan mining geometry parameters was a direct response to the concerns by stakeholders during the Planning Commission Assessment process about Dendrobium mining conditions.

2.2.2 South Bulli Colliery beneath Cataract Reservoir

In summary, mining was conducted at South Bulli between 1983 and 1986 and again during 1992 and 1999. Panels were 80m wide with 60m pillars and 2.5m of seam extraction at 230m depth beneath the reservoir and 340m under the adjacent plateau. There were no discernible mining effects in the overlying Hawkesbury Sandstone and essentially no inflow from the storage with the mine reported as being 'dry'. Based on these mining parameters the W/H ratio is 80/230m =0.35, and in the adjacent plateau W/H = 0.24. References for this case are available in the Stage 1 Strategy report.

2.2.3 Bellambi West Colliery beneath Cataract Reservoir

From 1993 extensive longwall mining was conducted in the vicinity and beneath the Cataract storage at the Bellambi West Colliery. The initial panels were 100m wide with 66m pillars and mining depth of 320 to 430m and extracted seam thicknesses of 2.5m. The initial two longwall panels were 880m and 1,040m in length. Over 5 years there was loss of groundwater below the Stanwell Park Claystone by vertical fractures. It was estimated that "linked", that is, connected vertical fractures, extended up to 85m above the mined Bulli seam with some head loss in the Bulgo Sandstone after mining moved away. No excessive inflows were recorded that required pumping out with more water pumped into the mine than pumped out (38%). Some shallow horizontal flexed strata were evident at the surface although there were no apparent shallow separation cavities. Consequently, by the end of 1990 a total of 14 panels and pillars were mined successfully with widths of 100m to 150m and pillars 60m to 65m wide and seam thickness in the range 2.5m to 2.7m. Based on these mining parameters the W/H ratios were 100/295m = 0.34; 100/325m = 0.31 and 150/295m = 0.51; 150/325 = 0.46. References for this case are also available in the Stage 1 Strategy report.

2.2.4 Wongawilli near Avon Reservoir

Mining at Wongawilli Colliery was not directly below the reservoir but adjacent to the Avon reservoir. Initially inflow was 0.048 ML/day that increased to 0.69 ML/day with mining adjacent to a 2m wide dyke. Later, when mining was adjacent to a sill, flow increased to 2.4 ML/day before stabilising, but this halted mining. In addition, depth of cover was also limited at this site to less than 140m and absence of 'aquitards' (see Appendix B on discussion about the use of this term to describe a geological unit having low to very low vertical hydraulic conductivity).

The commitment by Metropolitan Coal with regard to the presence of dykes and sills and other structures such as faults that could induce much higher inflows is as follows:

> *"MCPL maintains a register of all geological structures (faults, dykes) identified from underground workings that (if continuous) would intersect the surface within the Dams Safety Notification Zone. The register includes a description of the geological structure, and of relevance here, whether there is any water make associated with the structure, either after initial exposure or with time. To date there has been no geological structures exposed in the underground workings with water make. The register and inspection information is provided to the DSC in a monthly report (Management Status Report for Metropolitan-4 & 2 approvals)".*

2.2.5 Additional Cases

Gale (2008) makes reference to the following cases (cited references available in the Gale report):

- Lake Macquarie longwall panels 150m width successfully extracted under Lake Macquarie with 160m depth of cover. Subsidence in this case was estimated less than 0.6m (Li et al, 2006).
- Hunter Valley (Wollombi Creek) indicates stream flow loss when it was under mined at a depth of 90m but not for depths greater than 120m. Subsidence was typically in the range in the range 1.4-1.6m (Li, 2004).
- A similar situation was noted at Gordonstone and Kestrel Mine with clay rich units under Tertiary sands and Permian strata below that layer. Significant depressurisation in the Permian did not influence the Tertiary sediments.

2.3 Stage 1 Strategy Report: Conclusions & Recommendations

The following sections are extracts from the conclusions and recommendations of the Stage 1 Woronora Reservoir Impact Strategy Report:

2.3.1 Groundwater

1. The extension of mining at the Metropolitan Coal site was previously approved by the Planning Assessment Commission panel that included mining the entire 300 series of longwall panels many of which are located beneath the Woronora Reservoir.
2. Mining already completed at the southern Metropolitan Coal site (up to LW27) adjacent to the Woronora reservoir has indicated low rate of groundwater inflow. Since January 2009 to April 2019, water make has averaged 0.01 ML/day. Given the large fluctuations in daily water usage and the cycle period for water entering the mine and for assessment of environmental performance of the mine, a 20-day average is used by Metropolitan Coal to provide a more

reliable estimate of water make. The 20-day average water make has been below 0.5 ML/day.

3. Comparison of geological strata conditions at the Metropolitan Coal site with previous mining during the 80's and 90's at the South Bulli Mine and Bellambi West Colliery near and below the Cataract Reservoir, with similar geological conditions to Metropolitan, indicate that mining was successfully conducted beneath the Cataract reservoir with very low inflow rates.

4. Comparison of groundwater conditions with relatively much higher groundwater inflow experienced at the Dendrobium mine (~ 11 ML/day) and the very much lower inflows at the Metropolitan site (< 0.5 ML/day) is invalid in one important respect because the geometry of mining parameters is markedly different at the two sites. The ratios of width of panel and depth of cover at the Dendrobium site, are relatively much higher (0.68 to 0.98) compared to the lower ratios at the Metropolitan site proposed at LW301, LW302 and LW303 (0.29 to 0.41); proposed below the Woronora Reservoir LW304 to LW317 (0.32 to 0.35), and also at the successful mining conducted with very low inflow at the South Bulli mine and Bellambi West Colliery below the Cataract Reservoir (0.34 to 0.41).

5. To further confirm suitable groundwater conditions at the Metropolitan site, extensive monitoring is proposed as part of the strategy initiative at Longwall panel footprints LW301 and LW302 and later at LW303 that lie immediately east and outside of the Woronora storage area. Monitoring is to include the deep (down to the mining goaf), central and shallow stratigraphic levels with standard and vibrating wire piezometers. Groundwater level responses will be assessed as these longwalls are mined and at the completion of mining LW301 and LW302 before any mining is conducted at LW303 and below the Woronora Reservoir. The proposed piezometer installation works are outlined in Section 8, Table 8.1 herein.

6. The proposed extensive monitoring at the Metropolitan site at LW301, LW302 and later at LW303 will provide additional validation and comparison of the currently used empirical model analytical equations versus the monitored pressure heads for determination of the 'Height of Fracturing' above longwall mined out panels at the Metropolitan site.

2.3.2 Geotechnical

1. On the basis of current conceptual models and definitions, the term *"height of fracturing"* is used to refer to the region of connective cracking or fracturing which results in significant depressurisation of the strata. Pressure monitoring is therefore used as the primary means of detection of the upper limit of this zone. Height of fracturing of approximately 130m extending just beyond the Stanwell Park Claystone unit was evident from the pressure testing data at the Metropolitan Colliery after extraction of longwall 10 (9HGW0) and in a second hole longwall 22B (9GGW1-3) with a total loss of groundwater at a height of 137.5m above the Bulli Seam, which is quite consistent with the 130m for height of connective fracturing at borehole 9HGW0 above longwall 10.

2. Measurement of pressure heads pre-mining in each new mining region is seen as necessary, including where possible post mining pressure head responses due to initial panels mined, to validate any forward reliance on these empirical models. The contributions in this strategy

report (FK, BH) has emphasized the importance of width to depth ratios (*w/d)* as a simple screening estimate in the Metropolitan site area prior to mining for determining the likely height of *"connective cracking"* as a 'first pass' estimate, that is, validated based on past mining responses of very low inflow in similar strata at Metropolitan Coal site beneath the Cataract Reservoir.

3. There is agreement with the program of groundwater monitoring discussed in Section 5, as a basis to estimate the height of fracturing within the current mining region adjacent to the Woronora Reservoir including surface cavity development if any at Metropolitan site.
4. It has also been observed that far-field or regional bedding plane shear can occur in the near-surface strata, induced by the effects of mining. These bedding plane shears are more likely to be associated with what is termed non-conventional subsidence.
5. It is recommended that a series of inclinometer holes are installed in advance of longwall extraction, in the region between LW301, 302 and the reservoir, in order to detect the presence and horizons of any major shear planes. These inclinometer holes should extend from the surface to a depth that will penetrate into the top levels of the Bulgo Sandstone. Associated groundwater hydraulic testing should also be used in an attempt to determine any changes in strata permeability as a result of such shear movements.
6. Major structural geological features are not dominant in the region between LWs 301/302 and the reservoir. However, it is recommended that any future boreholes drilled in the area – either for exploration, or for instrumentation purposes, also be used to update the structural interpretation for the region.
7. The proposed surface subsidence monitoring program appears to be reasonable and appropriate, given the major limitations of access in some parts of the surface approaching the reservoir (steep slopes and dense vegetation).
8. Further investigations into the use of LIDAR, or InSAR technologies should also be carried out, although their limitations due to increased topographic slopes and vegetation are acknowledged.
9. Bathymetric technology warrants further investigation as a possible means of surveying incremental subsidence effects on the floor of the Reservoir. However, it is firstly necessary to establish the exact vertical accuracy achievable (on a repeatable basis) and also the horizontal accuracy for positioning the images, if they are to be used for repeated surveys to determine movements of the reservoir floor.
10. It is recommended that all monitoring data be available for review after each longwall panel is mined, to inform and update this staged Impact Strategy.

2.3.3 Surface Water

The purpose of the surface water strategy is to assess any impact of mining of longwalls (LW) 301-303 on the surface flows in the small sub-catchments that drain westerly from the area above LWs 301-303. In addition, a water balance analysis of Woronora Reservoir is planned to assess whether there is a loss of water from the Reservoir through seepage due to mining of Longwall 300 series. To achieve these objectives the following actions are in progress or proposed:

1. Installation of two streamflow monitoring stations in the sub-catchments above the foot-print of LW301-303 (to be operative by January 2018).
2. Installation of a pluviometer in the vicinity of the northern end of LW307 (to be operative by January 2018).
3. Implementation of a preliminary water balance of Woronora Reservoir (to be completed June 2018).
4. Depending on the outcome of the preliminary water balance, implementation a more detailed water balance including additional hydrologic monitoring as required (instrumentation to be operative by January 2019 and a water balance to be performed for calendar year 2019)[4].

[4] Note this sentence contains typographical errors, with the correct year being 2018 (not 2019).

3.0 REVIEW OF RECENT SIGNIFICANT LITERATURE

This section of the report provides some summary comments on points of relevance from a number of recent significant publications. These comments are not intended to be a comprehensive review, but to offer high level summary commentary, in relation to matters of interest to the Woronora Reservoir Impact Strategy study.

3.1 PSM Report

The Pells, Sullivan and Meyninck (PSM, 2017) report was commissioned by the Department of Planning and Environment (DPE) to determine the validity of the Height of Fracturing (HoF) concept within the overburden above longwall mining panels, with specific reference to Dendrobium Mine, Area 3B; and how that concept might be related more generally to other longwall mining sites in the region. The concepts and methods used at the time by hydrogeological consultants for determining predicted inflow to longwall mining sub-surface mining were also reviewed by PSM.

After the PSM report was received by the DPE, the Department commissioned two independent experts to review relevant sections of the PSM report related to their areas of expertise, being geotechnical and hydrogeological. These two experts were Emeritus Professor Jim Galvin (geotechnical) and Dr. Col Mackie (hydrogeological). These review reports (Galvin, 2017) and (Mackie, 2017) are also briefly reviewed in the subsequent section 3.2 of this report, in relation to their responses to the PSM Report.

The conclusions from the PSM report are reproduced in full, below, followed by some summary comments:

<u>PSM Conclusions</u>

> The investigations, modelling and monitoring carried out to date in Area 3B and the wider Dendrobium Mine area, have been insufficient for the scale and complexity of the technical issues. This means there are still a number of gaps and uncertainties. Notwithstanding this, it is considered sufficient work has been carried out in the available time to provide answers and guidance on the principal questions posed for this study.
>
> However, at the same time, given the ramifications and importance of the issues raised by this study it is essential that further work is undertaken to confirm the findings.
>
> It is considered the monitoring and investigations of real and potential mining effects and their impacts could have been improved if the overall geological, geotechnical, hydrogeological and mining context was better investigated, modelled and monitored. This would have included detailed geotechnical models followed by numerical modelling of the caving and subsidence behaviour of the rock mass, then validated using the site specific investigations and monitoring data as it became available from each longwall panel or area.

In summary the conclusions from this study are:

1. In general subsidence engineering recognises a zoned fracture model that comprises:
   a) Caved Zone, comprising completely fractured rock of High permeability and porosity.
   b) Fractured Zone, with highly connected cracking that is relatively free drainage, and with enhanced vertical permeability.
   c) Constrained Zone, with a zone of disconnected cracking and negligible enhancement of vertical permeability.
   d) Surface Zone; a zone close to the surface with some deformations and local water impacts.
2. The important elements of this conceptual model for this study are related to two zones:
   a) The Constrained Zone is where deformations of the rock mass are sufficiently low as to cause little depressurisation and pre-mining groundwater pressures are essentially maintained.
   b) The Caved and Fractured Zones, where deformations to the rock mass are sufficient to cause full depressurisation. The rock mass becomes desaturated or fully (100%) depressurised.
3. There has been ongoing debate focussed in part on the accuracy of the height of fracturing models used to predict the height of cracking at Dendrobium. The term cracking implies that intact rock is broken, but it is more instructive to think in terms of cracking, fracturing and or dilation of existing geological defects. This is because even small increases in the aperture of a crack or geological defect are important for groundwater flow.
4. In the height of fracturing models and general subsidence engineering the Constrained Zone was thought to largely isolate the upper layers of strata from the impacts of drainage and depressurisation at depth, thus limiting impacts on ground and surface water.
5. At Dendrobium two height of cracking/fracturing (HoF) models have been applied; Tammetta (2013) and Ditton and Merrick (2014). The Tammetta (2013) model is derived from direct observations from 18 locations worldwide. The Ditton and Merrick (2014) model was derived from examination of 34 observations, 32 of which were from NSW.
6. Both model approaches assume the inputs from these databases are independent variables. These input values have been examined using a matrix scatter plot and show:
   - The Dendrobium longwall geometries are well outside the database;
   - The input parameters are not independent, and
   - Extrapolation beyond the database centroid will see the accuracy and standard deviation of the fit decay significantly leading to over extrapolation.

7. The Tammetta (2013), Ditton and Merrick (2014) and DGS (2016) models all have the following limitations in addition to the above:

- They are empirical models designed to give a best fit to their respective databases;
- The models ignore any site specific geological conditions;
- The models require significant error corrections;
- The prediction error is significant considering the small sample size and relatively large standard deviations; and
- The observations are based mainly on interpretation of extensometer or piezometer responses, which are non-definitive information;

8. A key conclusion regarding all the height of fracturing models is that contrary to predictions the groundwater response at Dendrobium has not exhibited full depressurisation (desaturation) at any height apart from the near surface zone.

9. Investigations were carried out in only one location in Area 3B above LW9 to directly assess the height of fracturing. However it is clear from this investigation that increases in fracturing are evident in all units up to the ground surface. The 'height of fracturing' at least over LW9 is 100% of the cover. The debate then centres on whether this fracturing is or isn't connected. The groundwater data shows that post mining depressurisation is occurring long term right through the vertical profile so the fracturing in the rock mass taken as a whole is connected; at least to a level that allows some depressurisation.

10. The assessment of the deep to intermediate groundwater system in Area 3B shows:

a) Substantial depressurisation (40%) of a major proportion of the stratigraphic profile, from the coal to the upper sandstone, had already occurred before mining started in Area 3B and records indicate this was from at least the start of any mining in Area 2.

b) Groundwater reactions to mining occur due to mining in both Area 2 and Area 3A.

c) As mining in Area 3B starts, depressurisation increases right through the profile but also into the overlying sandstones.

d) Depressurisation is continuing but by the end of mining in Area 3A, this is substantial and ranges from around 30 to 70%.

e) Depressurisation is occurring right through the profile, which shows there is some connectivity.

11. There is no evidence of desaturation, rather the data shows the rocks remain saturated but with very significant depressurisation.

12. The SOW refers to desaturation, complete drainage of the rock mass such that groundwater pressure is close to zero. However groundwater pressures can reduce, but the rock mass may remain fully saturated. Under such conditions there will be a component of downwards vertical flow. Thus ground and surface water losses from the system may still occur.

13. If depressurisation occurs, a portion of the water that infiltrates below the ground surface will eventually report to the major permeable units at depth, the caved and fractured rock mass and the mine. This will occur as pressure pulses, driven by transient pore pressure rises from rainfall recharge events and or reservoir level increases. However the actual transit time of a particle of water entering the system at the surface then exiting into the mine may be very long.

14. There is no widespread evidence of a Constrained Zone limiting effects of mining and impacts on the more shallow ground and surface water systems.

15. The patterns of mine inflow for each area are very different and it is not clear why this should be the case. Comparison of mine inflows for each area with climatic wetting and drying cycles; and rainfall shows:

- Area 2 has a markedly 'peaky' response to all significant rainfalls and broader response to climate patterns with a change after 2010 with the start of mining in Area 3A;
- Area 3A shows a correlation with the climate cycles and or Cordeaux Reservoir level; and
- Area 3B shows a long term increasing inflow, but there is insufficient information available to properly understand the long term increases.
- It is considered likely that Areas 1 and 3B show rainfall recharge responses.
- There are a number of apparent anomalies in the data and these are not readily explained by comparisons of mine inflows with screened rainfall data alone.

16. The pattern of groundwater responses in space and time for many piezometers located close to Cordeaux Reservoir are very different to the general piezometer behaviour throughout the other mining areas. The interpretation from these patterns is that pressure levels in the geological units under the reservoir are being increased and or maintained by recharge through the rockmass. This is as a result of mining induced effects on the rockmass around and probably under the reservoir. This effect dissipates further away from the reservoir. The interpretation is that

effects on the rockmass around and probably under the reservoir. This effect dissipates further away from the reservoir. The interpretation is that

this pattern is consistent with some losses from the reservoir into the groundwater through the rock mass. It is considered that Area 2 and 3A mine inflows are also anomalous and probably reflect some losses, of both ground and surface water, from the catchments and or reservoir. Given the regional depressurisation these losses will eventually report to the lowest pressure point, Dendrobium Mine.

17. Detailed investigation of the height of fracturing has only been carried out at one site at Dendrobium and this is near the start of Area 3B in LW9. Given the scale of mining in Area 3B this is considered insufficient investigation as the results from LW9 need to be confirmed in the remaining part of Area 3B.

The following brief commentary is offered in relation to the above conclusions – excluding any matters that are specific to Dendrobium Mine only:

- It is agreed that there is still a considerable amount of investigation and further monitoring to be carried out in order to develop a reliable level of understanding about the deformation and fracture network within the overburden above longwall mining at Dendrobium (or at any other mine), and its impact on groundwater, surface water and other features. The call for further investigation work is supported.
- Whilst PSM recommends that there should have been more detailed numerical modelling of the caving and subsidence behaviour to assist in understanding – this would be useful but is far from straight-forward. It requires quite specialised numerical coding to be used and needs a good level of calibration to be useful – also requiring further data. Some numerical modelling can appear to be effective and meaningful, but unless it includes appropriate constitutive behavioural representation for rock deformation and failure, and appropriate failure criteria, it can actually be quite misleading.
- Conclusions 1 and 2 adopt the zones discussed previously in the Stage 1 Strategy Report.
- Conclusion 3 refers to the models for prediction of height of fracturing, and rightly asserts that connectivity and impacts on groundwater are not just caused by intact rock fracturing but can also arise due to rock or bedding plane dilation. In addition, bedding plane shear, which is a critical, and ever-present component of subsidence effects from underground mining, can also contribute to increased permeability, and possibly porosity. This has often been overlooked in the past. Bedding plane shear occurs around the edges of the caved and fractured zones, but also in all of the overlying zones through to the surface. However, the extent to which bedding plane shear contributes to increased horizontal permeability is likely to vary considerably depending on the properties of the shear planes, and the nature of any clamping forces acting across the shear planes. Some planes may undergo significant shear but remain quite tightly closed with limited change to permeability or porosity, whilst others may result in considerable horizontal flow pathways and storage.

- Conclusion 4 quotes the concept of a constrained zone being defined to represent a zone which restricts further depressurisation, thereby isolating the above overburden from subsidence-induced depressurisation (and by definition, dewatering). This is considered to be a correct interpretation of the concept model, although the same caution as before is given here – such models are only concepts and should be validated by the groundwater data itself, which is ultimately the means by which we define such zones in the first place. The notion of a complete isolation barrier to flow is probably at one extreme end of likelihood, only if there is a distinct aquiclude strata unit present, otherwise the constrained zone should be regarded more as a transitional zone or significant step-down in vertical permeability, that is an aquitard, in comparison to the strata regions below it.
- Conclusions 5 to 7 discuss the relative features and merits (or otherwise) of the so-called Tammetta and Ditton models for prediction of height of fracturing. PSM points out the limited number of data points in the databases used to develop these empirical techniques, which is a valid criticism. PSM discusses specific Dendrobium data in relation to these databases.
- The issue of mining height is certainly one that is very important in relation to the formation of caving above a longwall (as is panel width), and will clearly impact on height of fracturing, so the lack of a large and broad range of data for these two geometric parameters is a valid criticism of the models, in their present forms.
- Other criticisms by PSM include the fact that the parameters are not independent variables, and also that the models ignore site-specific geological conditions although the Ditton model does to some extent (see dot point below). This conclusion regarding dependency of input parameters (being panel width, depth and mining height) is considered quite inappropriate and incorrect. Firstly, there is a difference between correlation and dependency. Correlations can exist between any disparate datasets, regardless of dependency or otherwise. In the body of the PSM report (p26), PSM states *"These correlations indicate that the input parameters are not necessarily independent but are somewhat correlated to each other. This is not surprising as deeper longwalls are often associated with thicker seams and wider panels due to technological advances …".* Firstly, the observation that deeper longwalls are often associated with thicker seams is an observation that is probably not supported by the evidence – either within Australia or internationally. There are many thick seam operations around the world at relatively shallow depths, and vice-versa. The initial observation is therefore challenged. But more importantly, the assertion that there is a correlation, and then further, a dependency between depth, mining thickness and panel width in the regression equations cannot be accepted. By definition, these are absolutely independent variables or parameters – which may from time to time exhibit some correlations in the broader database, but in themselves, they are totally independent of each other, being functions of the coal seam geology (depth, and to some extent, mining height); and mine operator selected mining geometries (panel width and mining height).
- These conclusions also comment on the lack of site-specific geology considerations in the Tammetta and Ditton models. In fact, the Ditton model does have a fairly simplistic consideration of geology in one version of the model, but it is agreed that the level of local

geological input to the models, especially regarding massive overburden strata units, is limited.

- Conclusions 11 and 12 draw the distinction between desaturation and depressurisation and confirm that only partial depressurisation has occurred, and so this does not result in complete desaturation. They also note that depressurisation is sufficient to result in ground and surface water losses from the system. Conclusion 13 does acknowledge the time factor associated with the depressurisation process, which could continue for years, and notes that the time for a particle of water entering the system near surface to reach the mining, or lower strata horizons may be "very long".

3.2 Galvin and Mackie Peer Reviews of the PSM Report

It is understood that the two independent reviews of PSM by Galvin (2017) and Mackie (2017) were prepared based on a draft version of the PSM report, which has not been sighted by this Strategy Panel. The final PSM report was prepared once the Galvin and Mackie reviews had been provided. However, it is not known how much the PSM report was modified in the light of their review comments.

Galvin (2017) focused primarily on the geotechnical aspects of the study, whilst Mackie focused more on the hydrogeological aspects, although clearly there is a lot of overlapping or common ground. As with the above PSM report commentary, this is not intended to be a detailed review of the documents, but rather a high-level summary of significant issues. As above, comments on matters that are specific to Dendrobium only, are not included here.

3.2.1 Galvin Report

The Panel is in broad agreement with the overall findings of the Galvin review, which, in particular, provides a detailed commentary on the Tammetta and Ditton "H of F" prediction models (Ditton and Merrick 2014) and an equation for height of complete drainage[5] $\boldsymbol{H_d}$ (Tammetta 2013). Galvin poses several basic questions regarding the assumptions and validity of the Ditton equations. These questions relate to the accuracy of the estimates of actual field height of fracturing; and the applicability of the database points to the cases under consideration. With regard to the apparent goodness of fit and the high regression coefficients, he states:

> *"……while high standard deviations are associated with low R^2 values, high standard deviations can also be associated with seemingly good R^2 values. The latter is the situation in regard to the Ditton Zone B models".*

Many of the other points made by Galvin in his review coincide with points addressed in the PSM review comments above. However, there are a number of points on which differences of opinion exist, of relevance to the understanding and prediction of height of fracturing. These are as follows:

- The first point of difference relates to the discussion about factors contributing to height of fracturing, and the higher-level effects and impacts of mining on overlying strata, including groundwater, surface subsidence and surface water impacts. Galvin rightly points out the significance of factors such as Panel Width (W), Mining Height (h), Depth (H) and critical

[5] See Galvin 2016a page 437 equation 10.4.

geological factors. He then argues the importance of considering the ratio of W/H, that is, panel width to depth ratio.

On page 9 of his review report, he writes:

> *"Consideration of panel width, in isolation of consideration of the depth of the panel, and vice-versa, is important but it is also essential that the two parameters are considered together when evaluating rock mass response to mining and its impacts on the subsurface and surface."*

He then goes on to say:

> *"Hence, for a given set of site-specific conditions (geology, stress field etc.), the mode of failure and the extent of disturbance of the overlying strata extent caused by forming an excavation is strongly controlled by the ratio of panel width-to-mining depth, W/H".*

The Panel is in full agreement with regard to the importance of W/H with respect to the overall effect of mining on the overburden through to manifestation of subsidence on the surface. Where the value of W/H is of the order of 1.0 or greater, there is a degree of stress-related interaction between the underground excavation and the surface, with the mining-induced stresses extending from the excavation boundary to the surface (hence resultant potential deformation, fracturing/failure). However, it can be argued that at greater depths, where W/H is below a value of 1, the surface proximity does not significantly influence the mining-induced stress field, and an incremental change in depth, for a given panel width, will only have a minor influence on the "height of fracturing" zone directly above the mining panel (whilst undoubtedly still having a major influence on the higher levels of deformation and surface subsidence). (Note: The value of W/H below which this behaviour changes is only approximate, being a function of the triaxial stress field and the rock materials (geology) involved).

This rock deformation and fracturing behaviour at depth, for a given set of geological, stress and mining height conditions, is likely to be largely dependent on panel width (and mining height) and is relatively independent of small to moderate incremental changes in depth. This is consistent with the conceptual model of Mills (2012), as discussed in the Stage 1 Strategy Report. Of course, prediction of height of fracturing is not simple or straight-forward. Different models make estimates and approximations, but the level of understanding of the formation of such fracture zones is very complex and requires ongoing study, informed by good quality monitoring data, and use of appropriate, calibrated parametric numerical modelling studies, if prediction techniques are to be improved and refined significantly.

- The second point of some difference, but also agreement, relates to the role of empirical models. The current Tammetta and Ditton empirical models are available and in use by the industry. The Panel strongly supports the Galvin view that mechanistically-based models built around a sound understanding of the mechanisms involved, and a good quality database, are far superior to simple statistically-derived empirical models which do not necessarily honour the behavioural mechanisms. Having said that, if an appropriate, improved empirical model is derived, and applied within the database range on which it has been built - with due consideration for the site geology - then this is a very powerful predictive tool and does have a place in forward planning and design. It is worth noting that in the case of Metropolitan Mine, the predictions by both the Tammetta and Ditton models are in reasonably close agreement with each other, and also align approximately with measured data obtained from monitoring above previous longwall panels.

Galvin is highly critical of both the Tammetta and Ditton models, and there are no significant disagreements with his criticisms. However, there is undoubtedly scope to continue working on development of improved empirical predictive models. There is no reason why Dendrobium and other mines should not proceed to develop such improved mechanistically-based models that are also based on, and applicable to, the overburden geology in the Southern Coalfield of NSW.

- In his final paragraph, Galvin then writes:

> *"Numerical modelling of the mechanical and hydrogeological response of the rock mass to mining may also aid in the design, notwithstanding that this approach also has limitations and the need for calibration against field performance."*

There is no disagreement with this statement, and there will be an increasing role for numerical modelling – probably as a complement to empirical modelling rather than a replacement, particularly to conduct comparative parametric studies. However, it is important to place greater emphasis, and hence caution, on recognition of the limitations and simplifications in current modelling being conducted, as well as the importance of good calibration.

3.2.2 Mackie Report

The Mackie (2017) review of the PSM report is primarily focused on hydrogeological matters. The following comments are considered relevant:

- On p2, in discussing the zones of fracturing in the overburden, as defined in the various conceptual models, Mackie notes

> *"I concur that fracture connectivity is best perceived as a continuum migrating from highly connected pathways in lower parts of the fractured zone to weakly connected and disconnected pathways in upper parts of the zone".*

This understanding aligns well with the gradation between zones discussed previously and supports the view that these relatively simplistic conceptual models, while having a role to understand the overburden behaviour, should not be assigned too much importance. It is far more important to interpret the monitored, and/or geomechanical modelling results directly to determine the nature of the effects and impacts of mining within the strata.

- (Section 2, Page 2) Mackie points out the incorrect PSM concepts and calculations with regard to flow velocities that are based on bulk vertical hydraulic conductivity (K_v) values as opposed to fracture K_v values and the conclusions drawn from those calculations by PSM.

- (Section 3, Page 3) Mackie refers to the use of Cumulative Excess Rainfall (CER) and Cumulative Rainfall Deficit (CRD) used by PSM. Mackie, although considering CRD as *"useful",* points out those short periods of heavy rainfall can occur even during a longer term *'drying cycle'*. Whilst we agree with the concerns of Mackie and acknowledge the points he has raised, experience on many projects has indicated that CRD does correspond well with the trend of groundwater levels in the sub-surface over the longer term. Shorter term 'heavy' rainfalls during an extended dry period often do not lead to recharge because evaporation rates are so high that they can readily remove infiltrated water from the soil profile before such infiltrated sub-surface water reaches the water table depending on the water table depth. So overall, during a long-extended period these shorter-term weather conditions are not that critical when assessing longer term events of the effects of weather. However, they could be if permeable pathways already exist from the ground surface via fractures to the underlying mining voids as noted as likely by Mackie at the Dendrobium site.
- (Section 6.1, page 4). In reviewing the height of fracturing models Mackie refers to the Tammetta and Ditton-Merrick models of HoF estimation. Mackie however uses ***H*** to refer to the *"height of cracking"* when this parameter adopted elsewhere and in this report is designated as the **Depth-of-Cover** above the extracted seam. Mackie uses instead the parameters ***d*** and ***t*** to refer to the depth of cover and coal seam mining height (extracted seam thickness). But later under Section 6.1 he re-defines ***H*** as the *"height of desaturation"* when referring to the Tammetta model. It may have been better to define height of cracking as H_c and height of desaturation as H_d .
- With regard to the Tammetta equation Mackie is critical of the use of H_{max} and H_{min} used by Tammetta since Mackie states that *"Any number of equations can be generated with acceptably low errors associated with fitting to the data set and any number of estimates of the height of fracturing can be generated"*. Mackie considers that the PSM report fails to verify and validate the Tammetta data set and *"its absence to be a significant shortcoming of the report".* He also notes that the Mackie parameters **W, t** and **d** (i.e. depth-of-cover) for Dendrobium longwalls *"are mostly beyond the range in values of the data set used by Tammetta to underpin the equation".* That is, Mackie notes that the panel widths and seam extraction heights are greater that the widths and heights in Tammetta's data set.
- Mackie agrees with Galvin and considers that the PSM 'correlation' between depth of coal seam and seam thickness to be spurious. The Woronora Impact Strategy investigators are also of that opinion (see previous commentary on PSM Report).
- (Section 6.1, page 5) Mackie makes the point that complete and significant drainage can occur reasonable quickly if the fracture openings are substantial but may take many years if they are not. This timing is also affected by the mining of subsequent panels. In addition, because piezometers are generally within the footprint [i.e. usually over or close to the centreline of the panel] undermining usually results in failure of those piezometers and relevant data on cracking evolution and drainage subsequently are generally not available post mining.
- Further to the above point on the importance of time, Mackie discusses the role of time-dependant water flow through the fracture networks which may take many years for water

to move through the overburden. He notes that this time effect is not well recognised in some of the existing models and interpretations, as discussed earlier. He also uses a very effective terminology to describe this form of low permeability, but nevertheless, connected fracture network, when he says:

> *"If the network remains connected but has tortuous flow paths with smaller fracture apertures, then drainage may be slowed – complete drainage may take many years".*

The term "tortuous flow paths" is a good one to describe some of these grey areas within and between the simplistic fracture zones of the conceptual models.

- (Section 6.1, page 6) Mackie refers here to the Ditton-Merrick model (2014) equation. He notes that similar zones are used as Tammetta but that the constrained zone is defined by a 'disconnected zone (B) and an elastic zone (C)'. In addition, it also requires an estimated thickness of a more massive strata *"that could notionally be represented by a beam".* The creation of such a "*beam"* is regarded as obscure in meaning. It appears it is an attempt to account for unforeseen or known low permeable units in the profile although the assessment appears to be somewhat approximate.
- Mackie notes, as is the case with the Tammetta equation that *" the longwall geometries are well outside of the Ditton-Merrick (2014) Southern Coalfield data"* and the absence in the PSM review of examining pore pressure responses to the 30 estimates of the height of saturation (A zone) for mine sites located in Australia.
- Mackie concurs with the PSM findings with regard to the limitations of both the Tammetta (2013) and DM (2014) models because:
    - *"They are empirical and are based on the minimisation of fitting errors to specific data sets;*
    - *They ignore site specific geological conditions, the mechanical properties of which, govern the failure regime;*
    - *The applicability (validation) of the two models to conditions at Dendrobium has not been demonstrated."*
- (Section 9, page 7) Mackie refers to the PSM view that shallow fracturing that allows loss of some surface flow and downstream emergence should be questioned with depressurisation that leads to a strong vertical flow component with gradients *"probably in excess of 3".* The first point not considered in the PSM report is that downstream emergence is verified by the presence of iron in solution and deposits in a surface drainage that has been explained in the Stage 1 Strategy report. That is, it is caused by ferrous ions precipitating out of solution when flow emerges into the oxygen rich atmosphere. The contention by PSM that the vertical flow has a gradient of 3 requires explanation since in the fundamental Darcy flow equation (dh/dl) head divided by its flow path would indeed be equal to 1 with flux directly proportional to the vertical hydraulic conductivity and effective unit area of flow.
- (Section 10, page 7) In the concluding statements in his review Mackie offers the following:

  Are the crack regimes and influence on groundwater flow above extracted panels predictable? Mackie's answer to this is that it should be possible to determine this stochastically. Also that *"Computer geomechanical modelling incorporating fluid flow in three dimensions with sub-metre discretisation of the physical domain, supported by field and laboratory measurements of rock properties and flow through fractures is likely to provide a pathway offering reasonable certainty."* The Strategy investigators response to this is that this complex approach would still not however remove all of the uncertainty of modelling assumptions that would still be required in such a complex and time-consuming investigation.

Mackie's response to his own statement quoted above regarding the desirable approach, and as a practising project modelling consultant in the past is also understandable and sensible: *"However, the technology to undertake such a study within a sensible time frame and at reasonable cost is not generally available".* Mackie however does not attempt to provide advice on what might be appropriate for fracture potential assessment in the situation for example where a hydrogeologist and or modelling consultant may be faced with for a given project that would have a modest budget and time limit. While it is agreed that such advice was not required under scope of works prepared by the DPE it nevertheless leaves open an important issue in the Mackie review report as it does in the Galvin review.

Mackie points out that it is evident at Dendrobium that there are weak correlations between rainfall events and mine groundwater inflows in Area 1, strong correlations in Areas 2 and 3A and weak but potentially increasing correlations in Area 3B. These he states infer presence of fracture flow paths from seam to ground surface in these areas. These conclusions are not that surprising given the quite high ***W/H,*** seam extracted thickness ***h*** and ***strain*** that is evident at Dendrobium mining zones with inflow measured at 11 ML/day. This is quite a different situation compared to the Metropolitan Coal longwall mining site where ***W/H***, seam extracted thickness ***h*** and ***strain*** are much less and inflow of up to only so far, 0.5 ML/day.

3.3 Advisian Report

A report was prepared for WaterNSW by Advisian, dated December 2016 (Advisian, 2016). The following are some summary comments relevant to the Woronora Impact Strategy study, primarily in reference to the Advisian Executive Summary.

3.3.1 Geotechnical

- It is claimed that most if not all ACARP and company-sponsored reports are not peer-reviewed. Whilst this may be the case for some such reports, it is certainly not universally true.
- The terminology of systematic as opposed to non-systematic subsidence adopted by Advisian is inconsistent with the terminology more recently adopted by the 2008 Southern Coalfield Inquiry Report (NSW Dept of Planning, 2008) of conventional and non-conventional subsidence, together with anomalous subsidence effects.
- Advisian discusses the concepts of Height of Fracturing (HoF) and Height of Connected Fracturing (HoCF) and states that HoF can include nearer to surface regions of vertical fracturing that are not connected and hence have no impact on permeability. Whilst such fracturing commonly exists, it is not correct to include such fractured regions into what is commonly referred to as HoF.

- Section S2.4 discusses current gaps in knowledge with regard to subsidence effects, impacts and consequences on groundwater and water bodies. The overall recognition of shortcomings in prediction techniques for HoF are valid, although the assessment of available technologies ignores monitoring systems such as inclinometers, which are capable of identifying horizontal movements. The role of microseismic techniques in relation to this topic is questionable. The report also suggests techniques such as LIDAR and DinSAR should be trialled – in fact these techniques have been in use for some time now with promising results under certain conditions.

3.3.2 Groundwater

The groundwater section of the Advisian/WaterNSW report is reported to be a "Literature Review of Underground mining Beneath Catchments and Water bodies" and lists 31 items in Section S3 that deal with 'Effects of Subsidence on Hydrogeological Conditions", 'Impacts and Consequences of Coal Mining' and 'Gaps in Existing Knowledge' which are overall, non-site specific. They deal with coal mining in general even though Section S12 of the report states that *"The Project focuses on the catchments within the Metropolitan and Woronora Special Areas which overlie the coal measures of the Southern Coalfield".*

The discussed items deal with a range of possibilities rather than probabilities and the report does not emphasise that these issues do not necessarily relate to the Metropolitan Coal area but rather purport to relate to coal mining within the region and knowledge gaps of coal mining in general. Many of the statements are qualified with words such as "could", "may" and "potentially", "suspected to increase the risk" and undefined terms such as "substantial water level declines". Consequently, the majority of statements lack examples, evidence, quantitative estimates and/or measurements supporting the claims and conditions listed in the report that weaken the arguments presented.

The Advisian hydrogeological author also makes excessive use of the term *'aquifer'* in the Advisian report when describing particular geological formations such as the Hawkesbury Sandstone and other specific geological units. Although the common perception is that *'aquifer'* is a well-defined hydrogeological term, this is unfortunately not so. Rather than continue with this discussion, reference is made to Appendix E for a more detailed explanation for that conclusion.

With respect to the assumption of zonal layering in models, Advisian authors make the points that:

> *"Galvin (2016*b*) concludes that zoned models may be very useful conceptually; however the end user must be aware of important limitations, being:*
>
> - *None account for the effects of horizontal-to-vertical stress ratio and the important impact this can have on permeability, conductivity and the formation of a constrained zone;*
> - *None account for discontinuous subsidence associated with bridging strata;*
> - *In reality, behaviour types, permeability and the lateral extents of affected areas changes gradationally as depth of mining increases relative to panel width."*

With regard to dot point 1 it is not known why Galvin differentiates between *"permeability"* and *"conductivity".* If permeability (hydraulic conductivity - as it takes account of the fluid as well as material properties) is different to *'conductivity'* then it is not clear what is meant by the reference to *conductivity*.

While it is agreed that the issues indicated in the dot points above are to be considered, the Advisian report does not present any evidence or data for any particular existing longwall mining case where the dot points above are relevant, or the range of change that these factors could have on hydraulic conductivity and the formation of a constrained zone. Neither is there any indication in the Galvin documents to what extent these factors would have under longwall mining conditions or give any particular examples, particularly in the Southern Coalfield.

While the Strategy 2 report consultants acknowledge the presence of layered/geological unit zones in any longwall mining case, models are not used in the assessment of the extent of disturbance in a geological profile. The method of assessment has already been discussed above and reiterated below. Therefore, the first two points raised are of only of secondary concern particularly where data is available on W/H ratios, inflow, strain and extracted seam thickness (e.g. Dendrobium and Metropolitan Coal sites).

It is acknowledged that lateral extent of affected areas increases as depth of mining increases (dot point 3). It would seem that Advisian is unaware that this is included in any groundwater modelling assessment. Uncertainty assessment in such a modelling case would normally, and should, take the range of change of hydraulic parameters into account. However, as noted previously, the assessment is not directly dependent on such modelling outcomes or an assumption of the extent and distribution of particular zonal layers within a profile. They are only taken as a guide in terms of response particularly where there are very low hydraulic conductivity layers present.

The Advisian report also makes comments about the use of the Tammetta and Ditton and Merrick empirical/regression models which they say have the characteristics designed to give the best fit using correlations of simple geometric measures such as height of extraction, panel width and depth of cover. This would seem to downplay these parameters as being of limited application. However, it is clear there is a misunderstanding how these parameters are important in the way they are used.

The authors of this Strategy Stage 2 report are well aware that the *"simple"* mining parameters referred to are not the entire description of all factors affecting subsidence and HoF. But these parameters are quantities usually available and, together with strain estimates and measured inflow at existing mines, do provide direct evidence of conditions that do not rely on any modelling assumptions. They are therefore very useful in making comparisons between mined and unmined areas particularly where geological profiles and conditions are very similar at the mines being compared.

The Advisian report also present conditions of mining using a number of Guidelines developed by Babcock and Hooker (1977) as quoted by these American authors:

> *"1. Any single seam of coal beneath or in the vicinity of any body of surface water may be totally extracted, whether by longwall mining or by pillar robbing, provided that for each 0.3 m thickness of the seam to be extracted, a minimum of 18 m of solid strata cover exists between the proposed workings and the bed of the body of surface water.*
>
> *5. Where a fault which might connect mine workings with a body of surface water and which has a vertical displacement greater than 3m, or an intrusive dyke, having a width greater than 3m, is*

known to exist or is met with during development, no seam should be totally extracted within 15m horizontally on either side of such fault or dyke."

Only item 1 is directly relevant to Metropolitan Coal. Item 5 is also listed here to again emphasise the comment and commitment of Metropolitan Coal as outlined in the Stage 1 Strategy report. We repeat here again the MC commitment:

"MCPL maintains a register of all geological structures (faults, dykes) identified from underground workings that (if continuous) would intersect the surface within the Dams Safety Notification Zone. The register includes a description of the geological structure, and of relevance here, whether there is any water make associated with the structure, either after initial exposure or with time. To date there has been no geological structures exposed in the underground workings with water make. The register and inspection information is provided to the DSC in a monthly report (Management Status Report for Metropolitan-4 & 2 approvals)".

With regard to item 1 for Metropolitan Coal mining of Longwalls 301, 302 the following is relevant:

Seam Extraction of Bulli seam height of up to 3.2m;
Panel Width =163 m;
Pillar width=45m;
Depth of Cover H range = 395m to 555m.

Using the criteria in item 1 we have that 3.2m/0.3m = 10.66 and therefore 10.66 x 18m = 192m minimum depth of cover *H, as* recommended by Babcock and Hooker. That is, there is additional depth of cover available at Metropolitan Coal longwalls 301 to 302 sites in the range 203m - 363m in excess of that recommended by the US authors.

The depth range for longwalls that lie directly beneath the Woronora Reservoir are yet to be determined accurately but would also likely exceed the recommended depth of cover even though somewhat less than for longwalls 301, 302 because of elevation difference of the bed of the reservoir.

It is relevant however that the Width to Depth Ratio at the Longwall sites 301 to 302 is in the range 0.294 to 0.412 with inflow, according to Metropolitan Coal, of up to 0.5 ML/day and on average about 0.01 ML/day. The Metropolitan site mining parameters have already been compared with the Dendrobium Site (see Strategy Stage 1 report) where *W/H* ratios are much higher in the range 0.678 to 0.984 and extraction seam thickness also much higher in the range 3.9 to 4.5m. It is therefore not surprising that connected fracturing at the Dendrobium site extends to the surface with either significant surface or rainfall infiltration or both given that subsidence would also be high. Inflow at that site is currently about 11 ML/day, that is, some 22 times higher than the maximum inflow at Metropolitan Coal. <u>The Dendrobium mining site cannot therefore be validly compared with the Metropolitan site mining conditions, based on current evidence.</u>

3.3.3 Surface Water

Surface water aspects are described in five sections (3.6, 3.7, 6.1, 6.2, 6.3) in the Report. The surface hydrology discussion in the Report focuses on baseflow which is considered by Advisian (2016) to be a key component of the inflow contribution to reservoir storage. Consequently, our comments concentrate on baseflow.

Although titled "Literature Review" very little published literature on baseflow was reviewed in this Report. With the exception of a very short section quoted from Hydrological Recipes (Grayson et al., 1996) and several references noted therein, virtually no peer reviewed literature was assessed. No consideration was given to linear and nonlinear baseflow systems which provide a scientific basis for understanding baseflow (for example, Brutsaert and Nieber, 1977). Many papers have developed and applied this approach, a useful summary and application is Stoelzle et al. (2013).

A generally accepted definition of baseflow is the low flow in a stream resulting from one or more nonlinear storages representing the regional and local groundwater systems. A single linear storage is not usual, although simple models like AWBM make this assumption.

The baseflow index (BFI) is the ratio of the estimate of baseflow divided by the estimate of total flow. Based on a digital filter approach (it is not stated which procedure was used), according to Advisian (2016, p, 31) WaterNSW estimated the baseflow contribution to be 0.2 to 0.4 of the total reservoir inflows. Advisian suggested this estimate is "unrealistically high", because values were estimated using a digital filter. Nathan and McMahon (1990) analysed recession data for 186 streams located in south-east Australia and showed that the BFI values based on a digital filter procedure (Lyne and Hollick, 1979 using a filter parameter equal to 0.925) were highly correlated (R^2 = 0.94 and regression slope of 1.04) with the smoothed minima technique, the procedure developed by the UK Institute of Hydrology (1980) (see also Gustard et al., 1992) and adopted widely at that time for estimating baseflow (see Smakhtin, 2001). Furthermore, for the catchments analysed by Nathan and McMahon which extended from the Macleay drainage basin in northern NSW to the Yarra and Latrobe in the south and Murrumbidgee in the southern NSW, the median BFI for 184 catchments was approximately 0.5. Only 10% of the catchments exhibited BFIs less than 0.1.

Advisian (2016) discussed in some detail the calibrated BFI parameters in the AWBM model. According to Boughton (2010), his BFI parameter is the fraction of total flow that appears as baseflow and, therefore, equivalent to BFI values discussed above. For 214 streams located in eastern Australia, 6% have calibrated BFI values less than 0.1.

3.4 Independent Expert Panel for Mining in the Catchment (IEPMC)

The Independent Expert Panel for Mining in the Catchment (IEPMC, 2018) Report, dated 12 November 2018 (and released in December 2018) focuses on their first Term of Reference which is: *"… to undertake an initial review and provide advice to government focused on the mining activities of Dendrobium Mine and Metropolitan Mine in the Special Areas…".*

The main contents of the Report cover a general discussion of mining-induced ground subsidence effects with particular reference to Dendrobium and Metropolitan mines, and a discussion of groundwater and surface water impacts at the two mines. The Report concludes with a brief discussion of catchment, groundwater and reservoir water balances. The following summary review comments will focus in the main on the Report's applicability to the Metropolitan Mine.

The Strategy Impact Panel notes that this is an important contribution to the description of the groundwater and surface water systems in the Greater Sydney Water Catchments Special Areas. We have reviewed the document in the light of our terms of reference which are to provide *"… a staged plan of action for further investigations and a report into the impacts of mining near the [Woronora] Reservoir".*

Section 7 of the IEPMC Report is reproduced in full, below, to assist in the context of the following review comments.

7 CONCLUSIONS AND RECOMMENDATIONS

In this report, issues have been discussed and conclusions and recommendations have been developed under the relevant specialist discipline headings. Some of these issues were originally envisaged to fall under Term of Reference 2 but have needed to be considered, at least in part, under Term of Reference 1 in order to properly inform the Panel and the reader and to contextualise the Panel's observations and findings. Regard to a range of reports including those specified in the Panel's Terms of Reference is embedded throughout this document.

There is universal agreement that the issues are complex and complete reading of the detail contained in chapters is needed to understand the full range of the Panel's conclusions and recommendations. Therefore, for the benefit of the non-specialist reader, the principal conclusions and recommendations have been extracted and summarised in this chapter under headings that give them context in terms of mine design, mine approval and monitoring and performance.

MAJOR CONCLUSIONS

Mine Design

- The knowledge base regarding mining-induced subsidence and its impacts on groundwater and surface water continues to grow. In some cases, these advances have identified aspects not appreciated at the time of mine approval and may require the originally proposed mine layouts to be revised in order to satisfy performance measures
- The existing development consent for Dendrobium Mine was granted almost two decades ago and expressly allows mining in Areas 1, 2, 3A, 3B and 3C, with LW 14 currently being extracted in Area 3B. The consent conditions only place performance measures on three watercourses and one reservoir and offset provisions are in place to compensate for any exceedance of swamp performance measures. These legacy mine approval conditions are embedded and provide a significant degree of flexibility in mine planning. They provide considerable scope for maximising mining dimensions which, in turn, is reflected in the high percentage extraction of the coal resource, the high level of vertical surface displacement and the significantly higher daily water inflow than at Metropolitan Mine
- There has been a major effort over the last decade by Metropolitan Mine and Dendrobium Mine to employ up to-date 3-dimensional groundwater models and best practice modelling methods undertaken by suitable experts, with expert peer review. The models have improved in accuracy and predictive capacity and peer reviews of the models and modelling have provided valuable direction without which the process may have been less focussed
- The modellers, peer reviewers and the Panel recognise the fundamental limitations of the groundwater models for predicting impacts and consequences of mine subsidence, including those related to grid scales, computation time, and hydrogeologic parameter estimation
- The height of complete groundwater drainage is an important consideration in groundwater modelling and the Tammetta equation and the Ditton equations were developed in Australia for this purpose some 5 years ago. There are significant and fundamental differences between the characteristics of the Tammetta and DGS (Ditton) databases which preordain that, irrespective of the methodologies adopted to process this data, the respective predictions of the height of complete drainage based on the data are likely to be very different

- Field performance at Dendrobium Mine suggests that irrespective of whether the Tammetta equation is predicting the height of complete drainage reasonably accurately, its outputs can be useful as an indicator of the potential for water ingress from the surface

Mine Approval

- The Panel endorses the Department of Planning and Environment's approach for dealing with legacy issues and evolving knowledge bases whereby:
  - the management plans for longwall panels at Dendrobium and Metropolitan mines are being approved on an incremental basis that provides for considering existing and emerging information and knowledge gaps that have the potential to jeopardise compliance with performance measures
  - conditions are attached to approved Subsidence Management Plans and Extraction Plans that require mine operators to undertake a range of investigations and monitoring and engage independent experts to review and prepare advice to address geotechnical and hydrogeological information and knowledge gaps
  - some mining applications are being referred to independent experts and bodies, including the Panel, for advice

Monitoring and Performance

- Although knowledge of the consequences of mining on surface water quantity in the Catchment Special Areas has progressed substantially over the last 10 or so years, limitations in monitoring and modelling mean that it is difficult to verify conclusions by some stakeholders that mining has had negligible consequences on surface water supplies.
- Knowledge of the contribution of swamps to water supplies is particularly undeveloped due to lack of integrated monitoring targeting swamp water balances.
- Supported by its own analysis, the Panel concludes that in the case of Dendrobium Mine:
  - water inflow into all four mining areas (Areas 1, 2, 3A & 3B) exhibits some correlation with rainfall, ranging from weak in Area 3B to strong and rapid for Area 2
  - it is very likely that the high rate of influx is associated with a connected fracture regime that extends upwards to the surface
  - it is plausible that an average of around 3 ML/day of surface water and seepage from reservoirs is currently being diverted into the mine workings
- In the case of Metropolitan Mine:
  - The average daily water inflow of about 0.5 ML/day displays no evidence of a connected fracture regime to surface or correlation with rainfall
  - the potential for water be diverted out of Woronora Reservoir and into other catchments through valley closure shear planes and geological structures including lineaments will require careful assessment in the future because it is planned that most of the remaining longwall panels in the approved mining area will pass beneath the reservoir
- At both the Dendrobium and Metropolitan mines, the nature of surface water TARP triggers is not suited to determining the level of confidence that can be placed in surface water modelling results

- The performance measures for surface flow losses are not explicitly related to materiality of flow losses, limiting the objectivity of performance evaluation.
- In the present situation, TARPs classify the seriousness of events that have already occurred rather than fulfilling their more usual role of early signalling to prompt intervention that prevents escalation of impacts

MAJOR RECOMMENDATIONS

Mine design

- Notwithstanding that uncertainty is associated with both the Tammetta and the Ditton height of complete drainage equations, it is recommended to err on the side of caution and defer to the Tammetta equation until:
    - field investigations quantify the height of complete drainage at the Dendrobium Mine and Metropolitan Mine, and/or
    - alternative geomechanical modelling of rock fracturing and fluid flow is utilised to inform the calibration of groundwater models
- The potential implications for water quantity of faulting, basal shear planes and lineaments need to be very carefully considered and risk assessed at all mining operations in the Catchment Special Areas
- The concept of restricting predicted valley closure to a maximum of 200 mm to avoid significant environmental consequences should be revised for watercourses

Mine Approval

- Government should verify that sufficient entitlements are retained by Dendrobium and Metropolitan mines to cover surface water losses resulting from mining-induced effects.
- The Panel recommends that in future:
    - mine design methodologies and procedures that underpin critical aspects of mining proposals should be supported by robust, independent peer review and/or a demonstrated history of reliability when applications are submitted to government
    - all applications to extract coal within Catchment Special Areas should be supported by independently facilitated and robust risk assessments that conform to ISO 31000 (the international standard for risk management subscribed to by Australia)
    - government needs a sustainable mechanism for accessing objective expert advice when assessing mining applications.

Monitoring and Performance

- In future, mines operating in the Catchment Special Areas need to develop, in consultation and with the agreement of regulators and key stakeholders, a standard for field investigations, data collection, and data processing that provides for and integrates the interests of all stakeholders and facilitates the sharing of the information by being presented on a common platform. This should be canvassed in submissions to inform Term of Reference 2
- This monitoring standard in relation to groundwater should include provision for:
    - Installation of multi-level piezometers on the centreline of panels at Dendrobium and Metropolitan mines in order to monitor pore pressure changes associated with subsidence. These should include at least five transducers per borehole with installation being completed at least two years in advance of being undermined

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- Daily monitoring of local rainfall and mine water ingress from overlying and surrounding strata, and separation of rainfall correlated inflows for base flow volumetric analyses
- Dendrobium Mine and Metropolitan Mine to develop site-specific databases in relation to the height of complete drainage in-lieu of relying on height of drainage equations

- In future, surface water monitoring requirements should include:
  - a distinction between primary watercourse monitoring sites, which are the sites at which performance measures are specified; and secondary watercourse monitoring sites, which will provide additional information identified as necessary as the mine plan evolves
  - a specification of the minimum flow measurement accuracy required at the primary and secondary sites
  - the identification of the primary sites in proposed future mining areas and the installation of flow monitoring at these sites at least four years in advance of mining activities
  - the identification of the secondary sites as the mine plan evolves and the installation of flow monitoring at these sites at least two years in advance of mining activities or a shorter time if approved as part of the mine plan approval
  - paired piezometers in swamp sediments and nearby bedrock, and flow gauges at the swamp exit stream, complemented by soil moisture sensors at selected sites.
  - consistent use of inter-site comparisons using suitable control sites to complement rainfall-runoff modelling
- Surface flow monitoring associated with mining should be required to be continued until the consequences of mining (including any rehabilitation) have stabilised or the mine is considered by the relevant regulatory authorities to be closed. This requires clear metrics of stabilisation
- There is a need for groundwater modellers to address apparent inconsistency in the hydrogeologic parameters used to model Dendrobium and Metropolitan mines as it calls into question the robustness of current model predictions
- Research needs to be progressed into the use of tritium for calculating 'modern' water contributions at Dendrobium Mine, including the potential for results to be affected (skewed) by adsorption
- A reservoir water balance model needs to be developed. A limitation of using either groundwater or rainfall-runoff models as currently applied is that these models do not necessarily correspond to the space or time scales relevant for quantifying water losses to the Sydney drinking water supplies. Water balances should include drought periods and results for these periods should be highlighted
- In setting performance measures, government should have regard for those measures relevant to strategic resources (such as flow to storage) and to sanctions which rapidly prevent escalation of impacts and consequences if there are exceedances, clearly linked to monitoring results. Future consent conditions should clearly specify the acceptable levels of impacts and consequences on catchment resources, and that assessment of these should continue at strategic locations beyond the life of mine
- TARP triggers should be based on meaningful surface water loss performance measures developed in consultation with relevant agencies with oversight and regulatory responsibilities for mining

- TARPs should be related to the desired outcomes (such as maintenance of water flows) and be consistent both within and between mine domains. The TARP triggers for surface and groundwater should be replaced by meaningful flow loss indicators developed in consultation with relevant agencies and authorities with oversight and regulatory responsibilities for mining
- In situations where performance measures of negligible or minor environmental consequences are set by government, mine planning should incorporate appropriate factors of safety to avoid marginal situations associated with gaps in the current knowledge base.

3.4.1 Mining, Geotechnical and Related Hydrogeological Issues

The following summary comments are provided in the order in which the related issues appear in the body of the IEPMC Report. The order of the comments therefore does not necessarily reflect any priority of issues.

1. Introduction

- P10 - It is noted that the IEPMC is tasked to consider, but not be confined to, risks to the total water quantity and holding capacity of both surface and groundwater systems.
- P10 - This is an initial report and further consideration will be given to feedback received from stakeholders prior to finalising conclusions in the next report.
- P13 - The importance of consideration of cumulative impacts from past, present and future mining (and other land uses) is stated and this view is supported. However, in doing so, the difficulty of securing accurate and meaningful data – especially with respect to past impacts, should be recognised. The report also recognises difficulties associated with future impacts due to potentially long timeframes that can be involved. This point is also supported.
- P14 - Discussion is provided on the trend towards use of outcomes-based regulation, as opposed to the more traditional, previous prescriptive approach. Overall, it is agreed that this is a more appropriate and manageable approach, and one where Australia is considered a leader, internationally. It is noted by the IEPMC that approvals or development consents are now typically defined by conditions which include outcome-based targets, or performance measures, specifying acceptable levels of adverse impacts which must then be managed by the mine. This brings with it a challenge for the approval agencies to deliver specific, meaningful and measurable acceptance targets, which has not always been the case in the past. It is also noted that in addition to outcome-based assessment, approvals have become more iterative. This is also considered reasonable, provided the significant lead-times and all related timeframe issues associated with a major mining operation are recognised and the approval process does not incur excessive delays that can jeopardise responsible mine planning and implementation processes.
- P16 - The final sentence in paragraph one refers to the factors which can influence the extent of caving, fracturing and subsidence, listing mining dimensions and geology. This list of factors should also include depth, especially with regard to surface subsidence.

2. Mining-Induced Ground Subsidence Effects

- P23 - The acceptance and ongoing adoption of the terms – effect, impact and consequence – associated with mine subsidence, as defined by the 2008 Southern Coalfield Report, is commended. Consistency in terminology is important in this field where there is often unnecessary confusion and at times contradiction created by use of alternative terminologies by different parties.

- P24, Fig. 6 - It is acknowledged that this Figure is a direct extract from a Hydrosimulations 2016 report. However, it is considered that the extreme exaggeration of the vertical scale in this diagram may create some misconceptions by some lay-readers about the extent of variable surface topography relative to seam and strata horizons. It may be more beneficial to replace or at least supplement this diagram with a more regular vertical scale with little or no vertical exaggeration.
- P25 - The comments regarding the roles of geological defects or discontinuities is quite appropriate and correct. It is suggested to add the term "structural discontinuities" as another term used to describe these. In relation to the final sentence of the second last paragraph, it is important to acknowledge that it is not just the opposing "face rocks" that can impact on the permeability or otherwise of the structures, but also, very importantly, the properties of any in-fill gouge or intrusion material.
- P26 - An important point is made regarding excavation span. This is that *"when the width of an excavation (or panel) is small, the immediate roof strata will bridge across it and there is negligible disturbance of the surrounding strata".* This point is certainly important in some mining contexts where there are current misconceptions that any mining excavation will lead to strata fracturing/disturbance of overlying strata and hence potentially also groundwater impact. This is clearly an incorrect perception, as is made clear by this statement from the Panel.
- P26 and following, Section 2.3.1 - There is discussion here about the various forms of conceptual models for zones of fracturing and constraint above extraction panels. In discussion (p27), the Panel notes that these zones *"are not based on groundwater response to mining but rather on rock deformation inferred from surface and underground observations".* In many reported instances, whilst this might be a desirable means of determining such zones, it is not commonly carried out in this manner, but if it is, the geotechnical data from which zones are inferred is extremely limited and not necessarily regionally representative. For this reason, and for the more common use of such zones to infer groundwater impacts, it is more common to use groundwater data to infer the presence and boundaries or transitions between such zones. In this case, it is now considered more appropriate to move away from referring to this important parameter as height of fracturing, and instead, use the term height of depressurisation (see later discussion on terminology).
- P28 - Reference is made to classical subsidence theories and performance from Britain and Europe. It seems remiss not to acknowledge specifically the extensive work of the National Coal Board (NCB) in Britain, and in particular, the NCB's "Subsidence Engineer's Handbook (1975)" which was the basis for much of the early international subsidence engineering experience and original prediction capabilities.
- P29 - The discussion on conventional subsidence includes reference to horizontal bedding plane shear occurring between different strata layers (which may or may not be "basal planes"). It is noted that such shear movement *"may or may not significantly enhance horizontal permeability"*. This statement is correct but could be extended further. In fact, it is reasonable to say that it may not enhance horizontal permeability at all – depending on a range of factors such as confining stresses, geological properties, geometry etc.

  The issue of bedding plane shear has gained significant attention in recent years as a potential source for groundwater movement and hence possible water loss. Whilst this may be a hypothetical possibility, the fact is that there has been very little investigation to date to either substantiate or contradict this hypothesis. Clearly this is a matter for further investigation. In the interim, caution should be exercised to give too much credence to this hypothetical scenario until there is compelling evidence to support it or otherwise.

- P32 - Discussion and data is presented regarding empirical predictions of maximum subsidence above mining panels having a particular width (W) at a depth (H), hence the important W/H ratio. The classical curves used by many are presented in Figure 12 – although the vertical axis showing maximum surface subsidence as V_z is more commonly referred to as S_{max}. This discussion should make clear that such curves are for single panels only, and not the cumulative effect of multiple adjacent panels. This point is made later in the text but it would be beneficial to be included earlier, for clarification.
- P33 - Section 2.3.3 introduces the concept of Non-Conventional Subsidence, including valley closure, valley floor uplift (or upsidence) and other effects including basal bedding plane shears (see earlier comment – these are not always just basal bedding planes). The section title introduces an alternative terminology of "site-centric subsidence". The terminology of both conventional and non-conventional subsidence was introduced and accepted following the Southern Coalfield Report in 2008. As with other terminology discussed earlier, it is important to stay with consistent terminology. For this reason, the unusual and rather confusing "site-centric" terminology included here is discouraged from further use.
- P34 - Two issues already referred to above are covered on this page. Firstly, the statement that *"basal shear planes can enhance hydraulic conductivity"* is made. However, as previously stated, there is only very limited data available, to date, to verify this claim, and so it should be couched in a less definitive manner and a comment made to indicate that there is limited data at present. If the IEPMC has substantial and convincing data to support this claim, then it should be included in the report. (This same issue is also referenced on P35). Secondly, the use of the term *"site-centric"* is again questioned.
- P35 - The term "unconventional" subsidence should be replaced with "non-conventional" subsidence, to be consistent with the accepted terminology.
- P35 - The role of geological structures is discussed, and examples given of up to 30% above predicted subsidence occurring in the presence of lineament zones at Springvale Colliery in the Western Coalfield. Lineaments are major surface topographic features or surface manifestations of major structural defects (such as valleys, gorges or cliff lines), usually caused by underlying regional geological structures. The IEPMC suggests that investigations should address the potential similar role and impact of lineaments on subsidence in the Southern Coalfield. This is a reasonable recommendation, but caution should be exercised.

  There is no argument about the impact of lineaments in the Western Coalfields on strata behaviour generally, including not just subsidence, but major zones of adverse underground mining conditions when mining through such zones. However, the lineaments in the Western Coalfields are believed to have their origins in the underlying igneous basement rock which, in the west, lies at quite shallow depths below the sedimentary coal seam strata (tens of metres). However, in the Southern Coalfield it is understood that the basement rocks are some hundreds of metres below the coal seams and therefore the mechanisms and scale of behaviour involved are likely to be quite different between the two regions. There is also believed to be far less evidence of underground impact of lineaments on mining conditions at mines in the south. Caution is therefore recommended in making direct comparisons between the impact of Western Coalfield lineaments and similar features (if they exist at all) in the Southern Coalfield. Nevertheless, it is appropriate to investigate this issue further.

- P36 - Section 2.3.5 is discussing the rock mass response to underground mining with respect to individual panel geometries. A list of five bullet point factors is provided. There is no argument with four of the five but point 4 states that *"as depth of mining increases, surface subsidence over panels of the same W/H ratio increases".* The basis of this statement is challenged. It is contrary to the fundamental principles of the role of W/H ratio, as was presented in Figure 12 of the IEPMC Report which shows that maximum subsidence over a panel is a function of mining height and W/H ratio, but for a given geology, the value of subsidence at a constant W/H is constant for a particular mining height. What is true is that the surface area, and underlying volume of rock influenced by subsidence will increase, as depth increases for a constant W/H ratio – since panel width must increase by a commensurate amount to the depth increase, to maintain a constant value for W/H, but the maximum value of subsidence will not increase.
- P37 - The report returns to the issue of hydrogeological models and rightly points out that zones which often provide hydrological barriers between the model zones – especially what is referred to as the constrained zone – more likely consist of aquitards rather than aquicludes.
- P38 - The IEPMC emphasises and supports the view previously stated regarding the conceptual nature of the zones above longwall mining panels. They stated that:

  > *"models of sub-surface behaviour zones can be useful for conceptualising the impacts of mining on the surrounding rock mass and groundwater system but it is important to appreciate their limitations. In particular, while it is convenient to divide subsurface behaviour into a series of zones with distinct physical and/or hydrogeological characteristics, in reality changes in ground behaviour and fracturing, permeability and the lateral extent of affected areas occur gradationally rather than as step changes. The so-called 'fractured zone' is a misnomer. Fracturing still develops above this zone and may be connected."*

  In fact, from a groundwater perspective, water flow and hence depressurisation or dewatering can also occur not just through fractured rock but also if geological structures such as bedding planes, joints, faults etc are impacted by mining and dilate, resulting in increased permeability. Hence, linking zones of groundwater behaviour solely to fracture zones can be quite misleading, apart from the problems of measuring such fracture zones.

3. <u>Ground Subsidence Effects at Dendrobium Mine and Metropolitan Mine</u>

- P40 – It is noted that a value of 200mm valley closure has been widely used as an upper acceptable limit in order to avoid significant impacts, although it was an empirical value derived from early work at a number of mines in the Southern Coalfield. It is understood that this prediction methodology has evolved over time as additional data has been acquired and analysed.

4. <u>Groundwater Impacts at Dendrobium Mine and Metropolitan Mine</u>

- Pp58, 59 – The IEPMC is discussing modes of flow from near-surface groundwater systems by means of horizontal flow along bedding planes into valley sides, and cites the evidence presented in Figure 10 which showed seepage from a very shallow bedding plane in the exposed strata of a railway cutting over the Dendrobium lease (less than 5m of cover depth). This is a reasonable example, but it should not be used to form a generalised model of flow along bedding planes, where at greater depths there will be significant vertical confinement/clamping of bedding planes due to overburden weight, which will no doubt reduce the permeability and hence flow paths available along bedding planes.

- P60 – The discussion has returned to the conceptual models of zones above a mined panel or goaf region – this time in relation to hydrogeological parameters. There is no dispute here with the content other than suggesting that the first dot point on P60 should also include the role of joints and other structures on potential flow paths, rather than just fracture surfaces and bedding planes.
- P60 – The desire and value of using groundwater monitoring along panel centrelines through systems such as borehole piezometers – both pre- and post-mining – is supported, although the difficulties in establishing and maintaining such boreholes and instrumentation should not be under-estimated. However, reliance on centreline data in isolation, may lead to an incomplete understanding of the groundwater regime and mining-induced fracture network above the whole of the mining-affected overburden zone. The IEPMC has acknowledged the difficulties of obtaining such data. The IEPMC has acknowledged this as well as the difficulties of dealing with knowledge gaps between different monitoring installation systems.
- P64 – The IEPMC refers here and subsequently to a "height of complete drainage". This is certainly more appropriate than using the term "height of fracturing" or "height of connective cracking", but the use of the term "complete drainage" can lead to a perception of total dewatering and lack of any residual groundwater. Once again, the argument is put forward to use the term "height of depressurisation" instead, which can be defined to represent significant reduction in water head levels, approaching zero, without the implication of no water present at all.
- P64 – The IEPMC notes that theoretically, coupled solutions incorporating both geomechanically behaviour and groundwater models can be adopted. It then cites computing power, especially when attempting true 3D modelling, as the major limitation. This is certainly true as being one major limiting factor, but it is important to note also that there remain other ongoing difficulties – at least with the geomechanical models – in developing appropriate constitutive behaviour models to represent the appropriate rock response to stress; and further, to represent the rock mass in a meaningful and sufficiently detailed manner on this scale, including the complex discontinuity regime, to a level that can realistically be linked to groundwater flow modelling. This is ideally the route to follow, but we are still a long way from having meaningful modelling capacity to achieve these objectives.
- P64 and following – There is an extended discussion of the available empirical prediction equations, namely the Tammetta model and the Ditton or DGS model. It is not intended to conduct a detailed analysis of the documented Panel analysis here. Suffice to say that the overall content of the Panel report on this issue is supported.
- Pp68, 69 – The IEPMC returns to the conceptual model of zones above a mining panel and reinforces the Mackie concept of "tortuous flow" being particularly applied to the region above the "fractured zone" into a region where mining-induced fractures are isolated and unconnected. The IEPMC also agrees that the definitions used by the Woronora Reservoir Strategy Report – Stage 1 (2017) are consistent with their views, i.e.:

  "… the term "height of fracturing" is used herein to refer to the region of connected fracturing which results in significant depressurisation of the strata.

  The constrained zone tends to maintain the in situ (i.e. pre-mine) vertical permeability of the strata and therefore continues to restrict vertical flow but can display an increase in horizontal permeability within and above the parabolic fracture zone that has however little effect on vertical groundwater flow rate".

- P74 – As part of the analysis of the Tammetta equation, Galvin and Mackie are quoted by the Panel as re-analysing the available database and reducing the Tammetta equation to a simpler form, being:

  $H_{cd} = 0.3 * h * W^{'}$ (m)

  where:
  H_{cd} is the Height of complete drainage (or preferably now referred to as the Height of depressurisation) (m);
  h is the mining height (m);
  $W^{'}$ is the effective panel width, reaching a maximum defined by the critical width for maximum subsidence (assume to be approximately 1.4 H, where H is depth (m))

  If this equation derived by Galvin and Mackie is accepted, it confirms that the height of depressurisation is essentially a function of mining height and panel width and is largely independent of depth or W/H (apart from setting an upper value for effective panel width). This outcome is supported, although it is in contrast to the previous position expressed in the response to the PSM Report by Galvin on this issue[6].

- P88 – In the conclusions from this section of the report, the IEPMC notes the following significant findings which are fully supported:

  "Based on the partial analysis of the Tammetta and DGS databases undertaken by the Panel, a full analysis of the evidentiary databases as originally requested of PSM by DPE would prove very challenging and may not yield useful outcomes"

  "The Panel considers that it would be quicker and more productive for Dendrobium Mine and Metropolitan Mine to develop their own site-specific databases".

  This second conclusion cited appears to lend support for the value of an empirical prediction approach, appropriately developed and calibrated, rather than relying on the use of numerical modelling as had been previously implied by some authors following the PSM Report.

- P90 – A significant recommendation from this section of the report relates to standards for field investigations and data collection, analysis and reporting. The IEPMC stated:

  "In future, mines operating in the Catchment Special Areas need to develop, in consultation and with the agreement of regulators and key stakeholders, a standard for field investigations, data collection, analysis and reporting that provides for and integrates the interests of all stakeholders and facilitates the sharing of the information by being presented on a common platform".

  This is a commendable recommendation, in principle, although the ability for it to be implemented is questionable, with a requirement for all key stakeholders to agree on all of these aspects of the proposed standard. Certainly, input from key stakeholders is of value, as is the subsequent reporting/communication using a common platform. However, the requirement for all parties to agree on every aspect of investigation and data collection and analysis may prove to be an unworkable objective.

- The subsequent discussion on P91 about groundwater monitoring focuses on adequate advance data, prior to mining commencement, but it appears to neglect the all-important post-mining data collection.

[6] It should be noted however that this equation can have differences of fracture height between the Tammetta equation of between 4% and 30% difference compared to the Tammetta equation.

- P91 – Further in the recommendations of this section of the report, the IEPMC notes that it will defer to the use of the Tammetta equation until further monitoring at each of the mines quantifies the height of complete drainage, and/or a coupled geomechanical modelling of rock fracturing and fluid flow model is utilised to inform the groundwater models. Both of these findings are supported, albeit that each of these end-point objectives are difficult to achieve – at least in the short-term, and there is no recommendation with respect to specific modelling approaches or codes.

<u>Conclusions and Recommendations</u>

This section of the IEPMC report was reproduced in full in section 3.4 above, for easy reference.

- <u>Major Conclusions – Mine Design</u>
    - There has been continuing growth in knowledge of subsidence and groundwater/surface water impacts – agreed.
    - There has been significant improvement in groundwater modelling capabilities over the last decade, but there are a number of limitations that are recognised by all parties – agreed.
    - The Tammetta and DGS (Ditton) equations for prediction for height of complete drainage (depressurisation) have a number of fundamental differences which result in different prediction outcomes, but the Tammetta model does provide a useful indicator for consideration of potential water inflow from the surface – agreed. (As noted previously, both the Tammetta and Ditton models predicted similar results for Metropolitan Mine – in close agreement with measured data) depending on the "beam" thickness adopted in the Ditton equation.
- <u>Major Conclusions – Mine Approval</u>
    - The IEPMC endorses the current DPE approach to approval, utilising an incremental basis, with conditions attached, and independent review of some mining applications. This approach is considered reasonable, provided the DPE and other government agencies recognise the critical time factors involved in making appropriate mine planning and operational decisions and hence approval processes must function in a timely manner accordingly.
- <u>Major Recommendations – Mine Design</u>
    - Height of complete drainage prediction equations – defer to Tammetta until other criteria achieved (see earlier discussion) – agreed
    - Potential implications for water quantity of faulting, basal shear planes and lineaments all need to be considered and risk assessed – agreed (suggest basal shear planes be described as bedding plane shears)
    - Concept of using a 200mm limit for valley closure for avoiding significant environmental consequences should be revised for watercourses – agreed that this should be further investigated. It is understood that this concept and model are under constant review as more data becomes available.
- <u>Major Recommendations – Mine Approval</u>
    - Mine design methodologies and procedures that underpin critical aspects of mine proposals should be supported by robust and independent peer review and/or demonstrated history of reliability – agreed

- Applications to extract coal in the Catchment Special Areas should be supported by independently facilitated and robust risk assessments – agreed.

- Major Recommendations – Monitoring and Performance
  - Need for a standard for field investigations, data collection, analysis and reporting – agreed to establish and implement a standard, but as discussed earlier, the expectation of requiring approval by all stakeholders may prove unworkable. As a minimum, a consultation with key stakeholders should be required. Groundwater monitoring instrumentation along panel centrelines should also address requirements for post-mining monitoring.
- Overall, the IEPMC Report is considered to be a sound document which provides positive confirmation of many key issues and useful conclusions and recommendations.
- Other issues worthy of special mention include the following:
  - The importance of adopting consistent and appropriate terminology is emphasised. In relation to subsidence terms, the terminology adopted by the 2008 Southern Coalfield Report should be retained and used at all times.
  - The importance issue of what has been referred to as "height of fracturing" requires special mention again here.
    - In terms of terminology, the term "height of fracturing" or "height of connective cracking" is potentially misleading and inappropriate when referring to impact of mining on groundwater. A preferred term would be "**height of depressurisation**". This is favoured over the term used by the IEPMC of "height of complete drainage" which, whilst technically correct, has connotations of totally dewatered strata with no water present at all, which is not considered appropriate.
    - It is acknowledged that there is no unique term that perfectly defines the region of overburden where groundwater impacts are occurring above a mining excavation. Depressurisation does not, of itself, mean desaturation, and does not necessarily acknowledge the vertical downward flow that may be occurring within fracture lineaments within the matrix. None of these terms give clear and appropriate recognition to the time-dependent effect of groundwater flow through fractured overburden strata.
    - The IEPMC has acknowledged that the zones often described in these fracturing/groundwater models are only conceptual and caution should be used in treating them too literally; or regarding the transitions between zones to always be distinct horizons. These models or concepts are only artefacts and should be regarded as such, to aid in understanding, rather than as literal and distinct regions within the overburden.
    - The value of empirical models such as the Tammetta model have been recognised by the IEPMC, somewhat in contrast to earlier opinions expressed by some IEPMC members. This is not to say that they are adequately developed or are accurate representations at the present time, but they are a reasonable starting point for estimating the height of depressurisation. The IEPMC rightly acknowledges that this is a very complex field and is difficult to obtain comprehensive and reliable validation data. However, they also acknowledge that there is value in the mines continuing to develop empirical prediction models calibrated to their own mining and geological conditions.

- The IEPMC report makes multiple references to leakage or enhanced water flow along strata bedding planes, specifically referring to basal shears. Any bedding plane, basal or otherwise, has the potential to either remain intact and resistant to permeability at all, or allow for horizontal permeability, in either a virgin condition or when subjected to mining-induced shearing. However, there is very little data available at present to validate the nature and extent of such water flow. Caution should therefore be exercised in moving to premature conclusions about this mode of water flow/loss, without further quality data and analysis being available to substantiate such claims. Any initiatives to gather such data is encouraged.
- The IEPMC also makes multiple references to the potential role of surface lineaments associated with zones of major structural disturbance as being potential sources of water loss, and also potential sources of increased subsidence effects. Reference is made to experience from the Western Coalfield (Springvale Mine), with an unsubstantiated observation that the increased subsidence seen at Springvale associated with lineaments might be repeated in the Southern Coalfield. Whilst this issue warrants further investigation, it is inappropriate to draw or even infer such connections in the absence of any reported evidence. The potential different mechanisms associated with the existence of the lineaments in the Western Coalfield, understood to be mechanistically driven by the very close proximity of the underlying Basin basement igneous rocks, needs to be carefully considered. Caution should be exercised in making assumptions about the impact of lineaments on either subsidence or groundwater flow in the Southern Coalfield until substantiating evidence is available.

3.4.2 Surface Water Impacts and Water Balance (Sections 5 and 6)

In reviewing the current state of knowledge about the consequences of long wall mining on surface water supplies in the Special Areas, the IEPMC identified four limitations in quantifying knowledge: ability to accurately monitor water balance components, ability to quantify flow consequence especially in the swamps due to lack adequate monitoring, ability to unambiguously identify the hydrological (and geomechanical) processes, and the inadequacy of current modelling and monitoring technologies to accurately predict future streamflow. We concur with these observations and suggest that little progress will be made towards their solution unless there is a major integrated research effort focused initially on understanding the hydrology of the catchments including the swamps in the Special Area.

Monitoring of climatic and hydrologic variables underpins our understanding of the impact of longwall mining on surface water inflows to Woronora Reservoir. The Impact Strategy Panel has reviewed the hydrologic monitoring required to assess the potential influence of mining of LW panels 301-303 on the Woronora Reservoir. This review resulted in the installation by Metropolitan Mines of an additional pluviometer and two special flumes in 2018, and the Panel identified the need for an additional stream gauging station on one of the ungauged tributaries flowing eastward towards Woronora Reservoir. The need and location of this station are subject to the outcome of the Woronora water balance study, recommended by the Panel. At this stage we see no need for additional local surface water monitoring.

The Panel notes the IEPMC observations (p. 108) regarding the accuracy of surface water models at Dendrobium. However, a more general issue that has never been addressed in the context of surface hydrology associated with longwall mining is whether the AWBM model is the most suitable model of those available. A further confounding issue relates to the adoption of a daily time-step rather than a more appropriate sub-daily time-step for small catchments. These are research questions that should be addressed in a research environment and, until that can be done, the AWBM model should continue to be used to model the hydrology at the Metropolitan mine site.

The IEPMC (p. 114) questioned how the water level and streamflow data measured in flumes located in sub-catchments I and K would be applied given a short baseline period. We understand the fact that the baseline period maybe inadequate in a temporal sense, but what is important is goodness of fit of the relationship between the data (water levels and discharge) collected at I (and K) and equivalent data at another suitable location. Analysis of baseflow recessions can also be used to assess exogenous impacts.

The IEPMC (p. 118) recommends that a *"…good practice guide or standard should be referred to so that it is clear what standards are being followed"*. A recent paper by Nathan and McMahon (2017) may meet at least some of the requirements of the IEPMC.

The need for uncertainty estimates in the observational data (e.g. water levels in streams) and any resulting variables (e.g. discharge from a rating curve and water level) is highlighted in the Report. Procedures to carry out such analysis have not been readily available. A recent paper by McMahon and Peel (2019) presents a procedure to estimate uncertainty in discharge estimates within the gauged range.

Under application of water balances, the IEPMC (p. 122) outlines the steps in applying the rainfall-runoff process. These include model calibration and after model validation using independent data, the model is "… then used to simulate watercourse flows in the post-mining period", i.e. the model parameters are stationary. This assumption may not necessarily hold. A recent study by Saft et al. (2015) of 228 catchments from south-eastern Australia found that there was a significant shift in the rainfall-runoff relationship for ~50% of the catchments as a result of an extended dry period.

3.5 Tammetta (2018) report

The Tammetta 2018 Report (Tammetta, 2018) develops and applies a methodology to assess *"… potential mining-induced surface water losses for a number of small catchments overlying longwall panels at four mines (three in Australia and one in the US)"*, one of which is the Metropolitan Mine at Helensburgh. The author rightly observed the study is a preliminary one as it is based on a number of identified limitations. The Panel agrees with this and notes that in its present form the Report is unsuitable and hence not yet ready for public distribution.

The approach assumes that a void excavation created by longwall mining will over time fill with groundwater, recharged from the overlying surface catchment. It is proposed that the influence on the streamflow can be quantified by an analysis of the disturbance of flow in the stream above the void. In developing a conceptual model to represent and quantify this process, Tammetta (2018, Figure 4) identified two types of stream gauges – Type 1 gauge is within the surface disturbance zone of the mine and the other, Type 2 gauge, is located beyond, yet as close as possible, to what is called the "affection distance" (which is defined as the horizontal distance at ground surface from the edge of the mining area to the limit of surface deformation).

In order to take into account of the effects of the variability of climate between the pre- and the post-mining period, Tammetta (2018) adopted the standard hydrology approach of a control period and an assessment (target) period. During the control period a relationship is established that can be used to estimate the flow at the Type 2 gauge during the post period that would have occurred if the mining had not taken place. Three models were explored to develop such a relationship: a rainfall-runoff model, a streamflow-streamflow correlation approach, and a baseflow separation technique. Tammetta (2018) concluded from his preliminary analysis that the streamflow-streamflow correlation approach provided the best performance of the three methods.

The Panel endorses the general approach proposed in the Report to assess the potential long-term impact of longwall mining on streamflows. However, there is more analysis required to ensure the correlation technique is the most suitable of the three models considered. This would include an analysis of several rainfall-runoff models other than the AWBM model, a less restrictive application of the correlation method by incorporating non-linearity of the streamflows in log space, and a broader review of the baseflow separation techniques including digital filter approaches. Application of the adopted method to an area known to have no mining nor other exogenous impacts would provide some assurance that the method is not unreliable assuming there were no statistically significant flow changes identified.

Given the importance of the analysis we concur with Tammetta (2018) regarding the importance of uncertainty analysis. Furthermore, an uncertainty analysis undertaken to assess residuals between modelled and observed flows during a control (pre) or a target (post) period must ensure the residuals or their transformed values are normally distributed, homoscedastic and independent. Unless these three criteria are satisfied, a null hypothesis test of no difference between the pre and post streamflows is severely compromised and probably invalid.

In relation to the potential mining-induced surface water losses, the Report makes the following statement *"No statistically significant flow difference could be found for the Metropolitan Mine gauges with analytical methods used herein, although results for catchment yield and comparison with control gauges suggested a possibility that an increase in flow may have occurred."*

4.0 GEOTECHNICAL ISSUES AND RESULTS AT METROPOLITAN COAL

The following sections discuss the main issues, current geotechnical monitoring results and associated interpretations – since the publication of the Stage 1 Impact Strategy Report.

4.1 Height of Depressurisation

Knowledge of the detailed nature of rock deformation and failure above any form of large-scale underground mining is always going to be limited to interpretation from a very incomplete set of data. It is extremely difficult, if not impossible, to directly measure the detailed nature of the rock failure, fracture networks and deformational behaviour above an extracted mining area. Limited techniques such as borehole extensometry can provide some evidence of relative or incremental deformation in the direction of the borehole (usually vertical). However, such data cannot assist below the horizon where full caving has caused major rotation and dislocation of rock blocks and effectively destroyed the instrumentation borehole. Above such a horizon, the data is only valid along the axis and in the direction of the borehole, and to the level of detail defined by the extensometer anchor spacing intervals.

Other direct measurement techniques include borehole inclinometers which can assist with measuring shearing across the line of the instrumentation borehole, usually, but not always associated with bedding plane horizons. Coupled with an extensometer to provide movements in the borehole axis direction, the combination of extensometers and inclinometers provides a "coarse" level of deformation measurement along the axis of the instrumentation borehole. This direct borehole monitoring data can also be complemented by down-hole geophysical and calliper logging to provide further fracturing information along the axis of the borehole, together with various forms of borehole wall inspection or scanning devices. However, none of these different borehole techniques assist with detection of the laterally dispersed deformation and failure taking place away from the individual instrumentation boreholes. The result is therefore a very incomplete dataset that relies heavily on in-fill estimation and interpretation.

Why then is there a need for an improved knowledge of such regional deformation and failure above the mining location – in particular, above underground longwall mining panels? The answer can relate to a number of important issues:

(a) To consider the effect of mining taking place at one horizon on a higher horizon within the overburden (either mined previously, or planned to be mined in the future);

(b) To assist in developing predictive models for estimating surface subsidence;

(c) To develop an understanding of, and predictive model for the impact of underground mining on groundwater present within the overburden.

It is this third issue that has taken on increased importance in recent years. In fact, the reason for trying to define regions of fracturing above a longwall panel is not typically about defining the deformation and fracturing specifically, but actually about interpreting the impact of such deformation and fracturing on the groundwater regimes.

Furthermore, at the present time, it is often the measurement of groundwater data which is used to infer the different fracture zones – so the whole argument becomes a circular one. We measure groundwater pressures and related data to infer overburden fracture zones in order to estimate groundwater impact levels and regions. Why not simply refer to the parameters we can measure – groundwater pressures and properties – rather than making arbitrary distinctions regarding the level of rock fracturing that is not clearly defined.

However, there is often a desire to assess a number of rock deformation and fracturing parameters in the overburden above longwall mining, specifically:

- The height of connective cracking (or fracturing);
- Extent of surface cracking;
- Potential connections with horizontal partings.

It is therefore important to have a clear understanding of what is meant by these terms and how they relate to each other and to the mining process.

Firstly, fracture patterns associated with overburden rock strata subjected to longwall mining can be extensive and quite variable, ranging from complete rock failure in the immediate caving zone above the coal seam, through to some level of near-surface tensile cracking within the subsidence impacted zones of curvature. These two extremities of the fracturing regime are normally isolated from each other, and subject to quite separate or independent mechanisms. It is not possible to fully analyse or characterise all fracture patterns throughout the overburden – either pre- or post-mining. It is considered more important to focus on what is commonly referred to as the *"height of connective cracking, or height of fracturing",* which are widely-used terms. The issue of surface cracking is also of interest and such cracking can inter-connect with the lower region of connective cracking, under some circumstances of shallower depths and higher W/H values, but the surface cracking regime is more generally a separate fracture region within the overburden, as noted above.

Even the concept of height of fracturing is difficult to fully and accurately *"analyse and characterise"* and remains a subject of some debate amongst the geotechnical and hydrogeological community (see PSM (2017), Galvin (2017) & Mackie (2017)). However, it is accepted as being very important to gain a meaningful understanding and best-estimate analysis of such a region of fracturing and *"connective cracking"* within the overburden.

It is important when discussing the height of fracturing zone to establish some common and consistent terminology. The actual nature of the fracturing above a longwall panel cannot be directly measured but can generally only be inferred from indirect observations and measurements, as discussed above. The conceptual model of the fracture zone has been discussed internationally by many authors through the use of a number of simplified conceptual models which describe a series of zones of different types of rock failure, fracturing and deformation above longwall panels.

Figure 4.1 is one such conceptual model (previously included in the Stage 1 Report), quite widely-accepted, for representing or describing the zones of fracturing above a single longwall panel. In this model, four major, different zones are identified (note – this diagram is not necessarily to scale, with respect to the height of the different zones). Other models, from both Australia and internationally, similarly describe four, or sometimes five different zones.

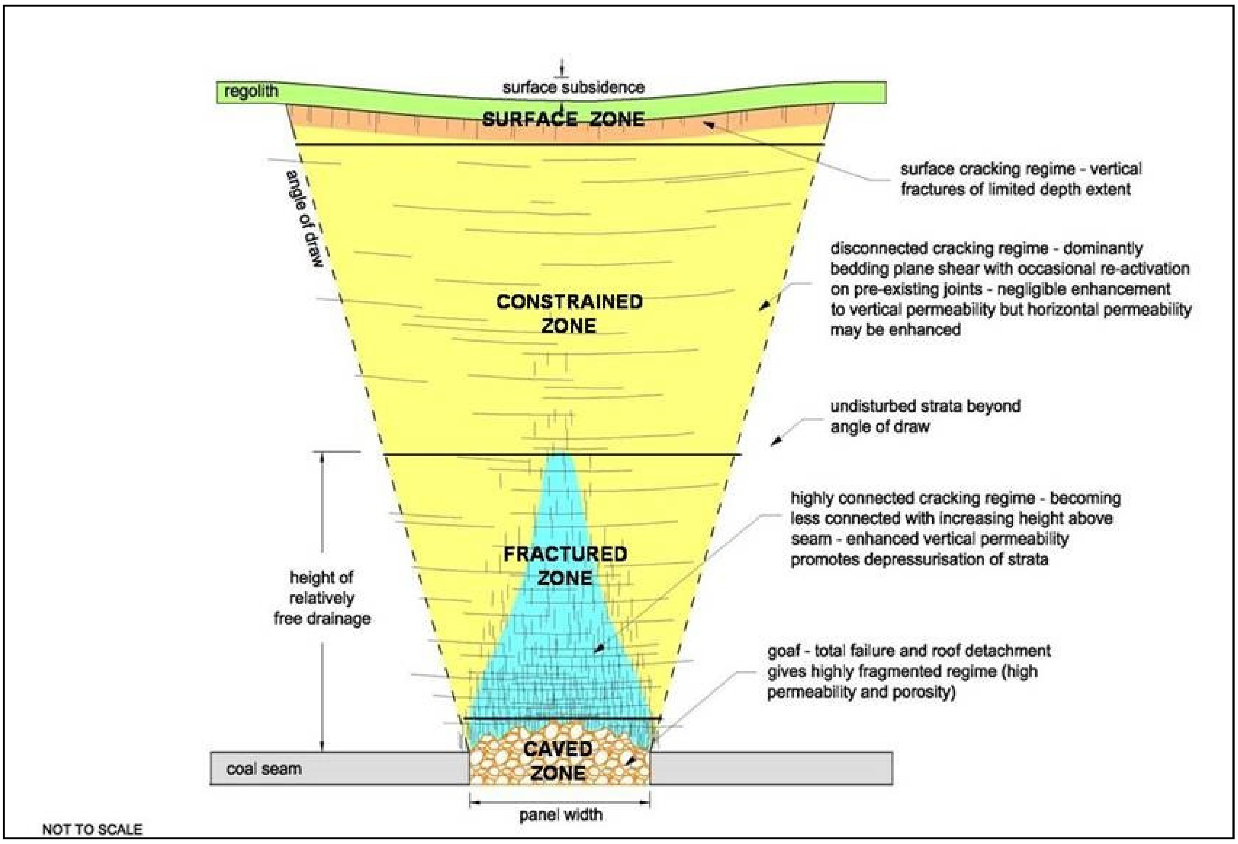


Figure 4.1 "Height of Fracturing" concept.[7]
(source: NSW Dept of Planning, 2008)
(original source: Dr C Mackie)

- **caved zone** – where there is complete rock failure and large-scale downward movement and some rotation of rock blocks, resulting in a significant amount of void space. There is obviously complete groundwater depressurisation and dewatering/drainage from within this zone. The height of this zone is affected by the type of immediate roof above the coal seam, and mining height, which will define the available void space created by mining.
- **fractured zone** – where the rock has undergone significant vertical and horizontal deformation, with dilation of some discontinuities (bedding planes and joints) and also incurred connective cracking of intact rock. The result is a fractured rock mass that allows increased permeability permitting depressurisation and desaturation of groundwater in this zone (Height of relatively free drainage' – as shown in Figure 4.1). The term "height of fracturing" refers to the height above the mined seam to the top of this zone, where there is enhanced vertical permeability due to the fracturing, allowing groundwater depressurisation and desaturation. It is also understood that within this fractured zone there may be

[7] While Figure 4.1 displays the commonly quoted main four zones that can often occur in the geological profile above longwall mining panels, some features shown are not necessarily correct. This includes the horizontal line across the figure labelled as the *'height of relatively free drainage"* and the inverted *"wine glass" "fracture zone"* coloured blue. The height of *"free drainage"* maybe quite irregular and it may not necessarily occur on either of the far sides of the fracture zone peak as suggested by the horizontal line. Also the *"fracture zone"* most often has an inverted parabolic shape. It should be noted that there is also a six zone configuration proposed by Mills (2012), as was referenced in the Stage 1 report.

increased porosity due to the fracture network, which may also contribute to depressurisation. (see also footnote 7 above).

- **constrained zone** – contains deformation, but significantly less cracking, without extensive connective fracturing occurring, such that depressurisation does not occur to a significant extent. The deformation includes a significant extent of bedding plane shear as the layers of rock strata bend. (In some conceptual models the constrained zone is divided into two different zones where the upper region consists of much more simple strata unit bending, without any major fracturing, but also with shear movement on bedding planes).
- **surface zone** – the near-surface region where cavities associated with tensile fractures open up as the surface strains create a limited depth of open vertical fractures and horizontal cavities in the shallow strata. These cavities are often said to lie within a zone 10m to 20m below ground level (this should be validated on a site by site basis).

On the basis of this form of conceptual model and definitions, the term *"height of fracturing"* is used by most investigators as the region of connective fracturing and structural deformation (bedding planes, joints etc) leading to increased permeabilities which will result in significant depressurisation and progressive desaturation over time of the groundwater in the strata. For this reason, groundwater pressure monitoring can be used as a means of detecting the upper limit of this fracturing zone at some point in time, rather than relying on direct, but limited deformation and fracture monitoring, which as discussed above, is extremely difficult.

Some important summary points to note in relation to the above concepts:

- These are concepts only, representing hypotheses regarding the nature of fracturing above an extracted longwall panel. They have been developed as hypotheses or conceptual models, in order to describe the type of deformation and fracturing of the overburden strata, and how it is made up of different zones or different types and intensities of deformation and fracturing.
- These conceptual models have been developed based only on indirect or very incomplete data sets, and use data, if available, from geotechnical monitoring, groundwater monitoring and/or numerical and physical modelling.
- The gradation from one zone to another in any of these models, whilst appearing distinct within the concept diagrams, may well be quite gradual and transitional, rather than distinct boundaries, and may be highly impacted by localised geological factors such as specific strata units present, or other structural defects including bedding planes, joints and major structures (faults, dykes etc.).

Based on the above points, these model concepts, should be used with caution, together with significant qualification, and/or detailed analysis of the relevant data. The breakdown of the overburden into distinct zones should only be regarded as a hypothesis and conceptual model as an aid in conceptual understanding, rather than an exact description of what is occurring in the geological profile.

It is further proposed that there should be a change in the terminology used in future – for all of the reasons discussed above, relating to both the nature of the deformation and fracturing characteristics; as well as the means of measurement or estimation. For use of this concept for groundwater impacts, it is proposed that the term ***"height of depressurisation"*** be adopted in future, rather than the terms *height of fracturing*, or *height of connective cracking* (acknowledging the limitations and minor inconsistencies that exist with the use of this or any other single term for this zone of overburden, as per earlier discussion). This proposed terminology is directly linked to the application of the term for groundwater purposes, as well as being directly linked to the means of measurement or estimation. It is also consistent with the findings of the 2017 PSM Report discussed earlier – see PSM conclusion 3.

It is also noted that some authors are making reference to this zone as a height of drainage. However, the use of this term is discouraged. Whilst it is acknowledged that some increased level of free drainage will occur in this zone (to enable depressurisation to occur), the word drainage can sometimes be interpreted to refer to total dewatering, which is not always the case within the depressurisation zone. From a groundwater perspective, the height of drainage where complete dewatering is always expected would more commonly occur in the lower caved zone, as illustrated in Figure 4.1.

In the Stage 1 Report, previous data from Metropolitan Coal recorded a height of depressurisation of between 130m and 140m above the Bulli Seam (from longwalls 10 and 22B). These results confirmed the significant extent of the overlying constrained zone preventing hydrogeological interaction between seam pressure head decline and the ground surface. Piezometer monitoring of boreholes over the centreline of longwalls 301 and 302 has been conducted at the Metropolitan mine site. Results of these measurements are discussed further in section 5 of this report.

4.2 Bedding Plane Shear Movements

The above concept discussion also highlighted the importance and ever-present role of bedding plane shear movement throughout the overburden above and immediately adjacent to a longwall extraction panel. As demonstrated in the Stage 1 report, based on experience elsewhere (e.g. Dendrobium Mine and Sandy Creek Waterfall), borehole inclinometers can be a very effective monitoring instrumentation device to detect such shear movements (in both magnitude and direction) at multiple depths down a vertical borehole.

The Stage 1 report recommended the installation of a number of borehole inclinometers in order to identify the presence and nature of bedding plane shears induced by mining; and also to assess the distance from mining at which such shear movements commence, in order to make some preliminary predictions about the extent of overburden above and adjacent to a mining operation that is affected by bedding plane shear. It was proposed that these installations should penetrate below the Bald Hill Claystone horizon, into the top of the Bulgo Sandstone. This region of overburden would correspond to the "surface zone" and the upper section of the "constrained zone', using the concept model illustrated in Figure 4.1.

Figure 4.2 shows the locations of two such installations – TBS02 and TBS03 – installed above the centreline of LWs 302 and 303 respectively – prior to the approach of the LW302 face. (Note: There was insufficient lead time to install an inclinometer ahead of LW301). This installation was one of the deepest such inclinometer sites in Australia, to date.

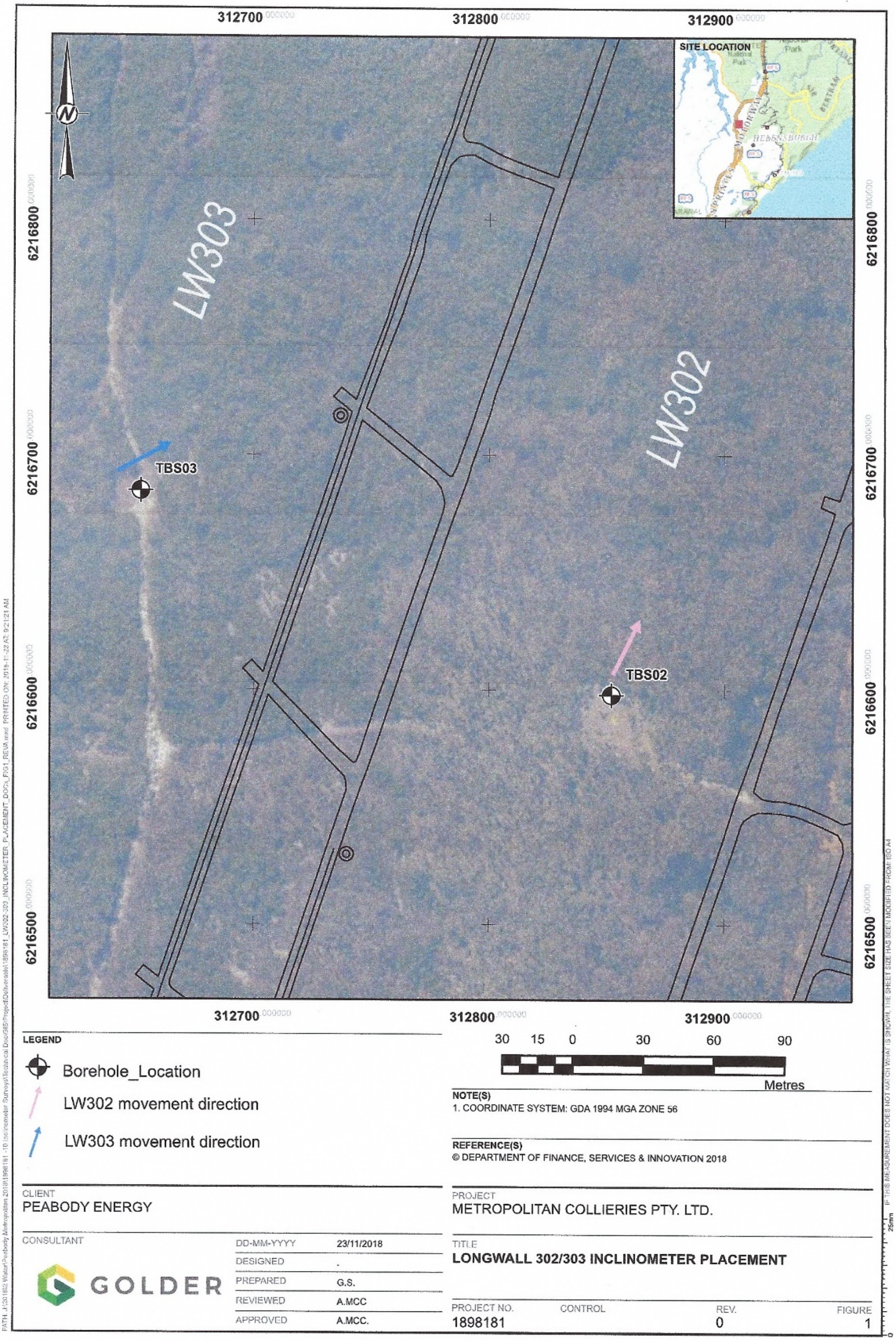


Figure 4.2 Location of borehole inclinometers TBS02 and TBS03

(source: Golder Longwall 302 TBS02, TBS03 Results)

Figure 4.2 also includes an arrow associated with each borehole site indicating the predominant direction of overburden movement detected by each instrument, as the mining of LW302 took place – in both cases, the movement was directly towards the approaching longwall face.

Both instruments TBS02 and TBS03 were installed prior to commencement of extraction of LW302. Figure 4.3 shows the results obtained from site TBS02 located in the centre on LW302. These results show the movement detected at seven different time epochs after installation. All movement shown is relative to the bottom of the borehole (at approximately 230m depth in this case). The accuracy or error band of the results increases from zero at the base of the borehole to a level of approximately 10 - 15mm at the top of the hole. These results are clearly well outside such an error band and are therefore valid results reflecting real ground movement.

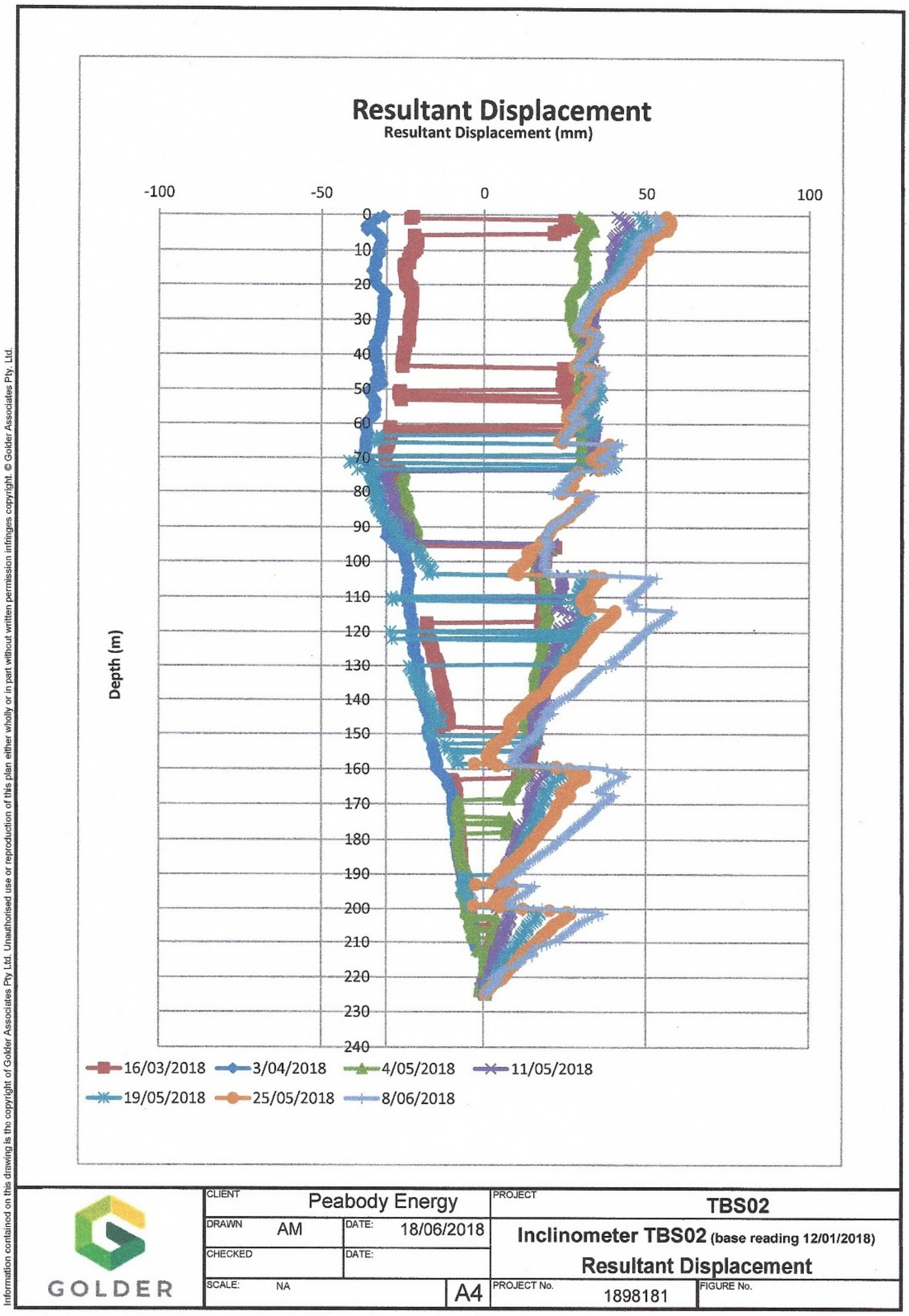
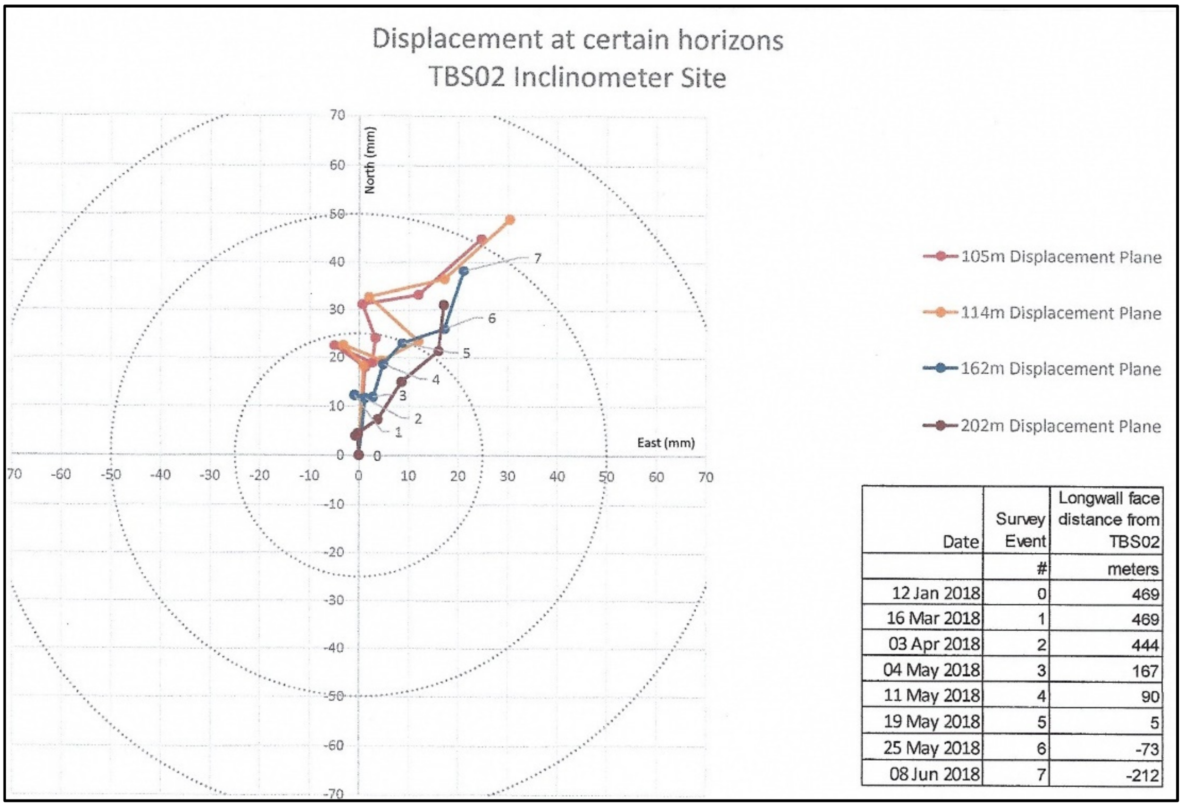


Figure 4.3 Borehole inclinometer TBS02 results

(source: Golder Longwall 302 TBS02, TBS03 Results)

The results clearly show bedding plane shear movement (evident as discontinuous steps in the displacement graphs) at depths of 105m, 114m, 162m and 202m below surface. These higher bedding planes correspond to planes within the Hawkesbury Sandstone while the 202m bedding plane is at approximately the top interface of the Bald Hill Claystone, which could also be referred to as a basal shear plane. The extent of shear movement at each horizon differs slightly but is in the range of at least 20mm – 50mm.

Figure 4.4 is a plot of the movements at these key bedding plane shear horizons from TBS02, indicating the direction and magnitude of movement with time. The inclinometers can resolve movement using two orthogonal axes to provide this directional data. These results show a very consistent shear movement of each bedding plane horizon in a north-easterly direction, which, as was indicated on Figure 4.2, corresponds to movement towards the approaching LW302 face or goaf.



Date	Survey Event	Longwall face distance from TBS02
	#	meters
12 Jan 2018	0	469
16 Mar 2018	1	469
03 Apr 2018	2	444
04 May 2018	3	167
11 May 2018	4	90
19 May 2018	5	5
25 May 2018	6	-73
08 Jun 2018	7	-212

Figure 4.4 Inclinometer TBS02 – direction of movement for selected bedding plane horizons

(source: Golder Longwall 302 TBS02, TBS03 Reports)

The table included in Figure 4.4 also lists the distance from the instrumentation site to the longwall face for each measurement epoch. The initial distance was 469m. Whilst there is some evidence of small-scale movement even between the first two epochs (1 and 2), it was still well within the error band of the instrument. It was only when the third and subsequent epochs were recorded once the face was within 167m of the site that substantial, real movement was recorded. This provides an approximate indication of initial influence distance being within the range of 167m to 444m based on this data. It is also interesting to note from these results that the bedding plane shear movement continued in the same direction, even after the longwall face had passed beneath the site (epochs 6 and 7).

Figure 4.5 is a plot of the TBS03 inclinometer results – installed in a corresponding position above the centreline of LW30 (see Figure 4.2). Whilst the extent of shear movements is less than for TBS02, as would be expected) there is evidence of activation of shear planes within the 140m to 190m depth range, in the epochs recorded in May 2018 and subsequently, representing the time when the

LW302 passed adjacent to the site. (LW302 commenced extraction on 3 April 2018 and passed the sites in early May 2018, when the closest distance to TBS03 was 138m).

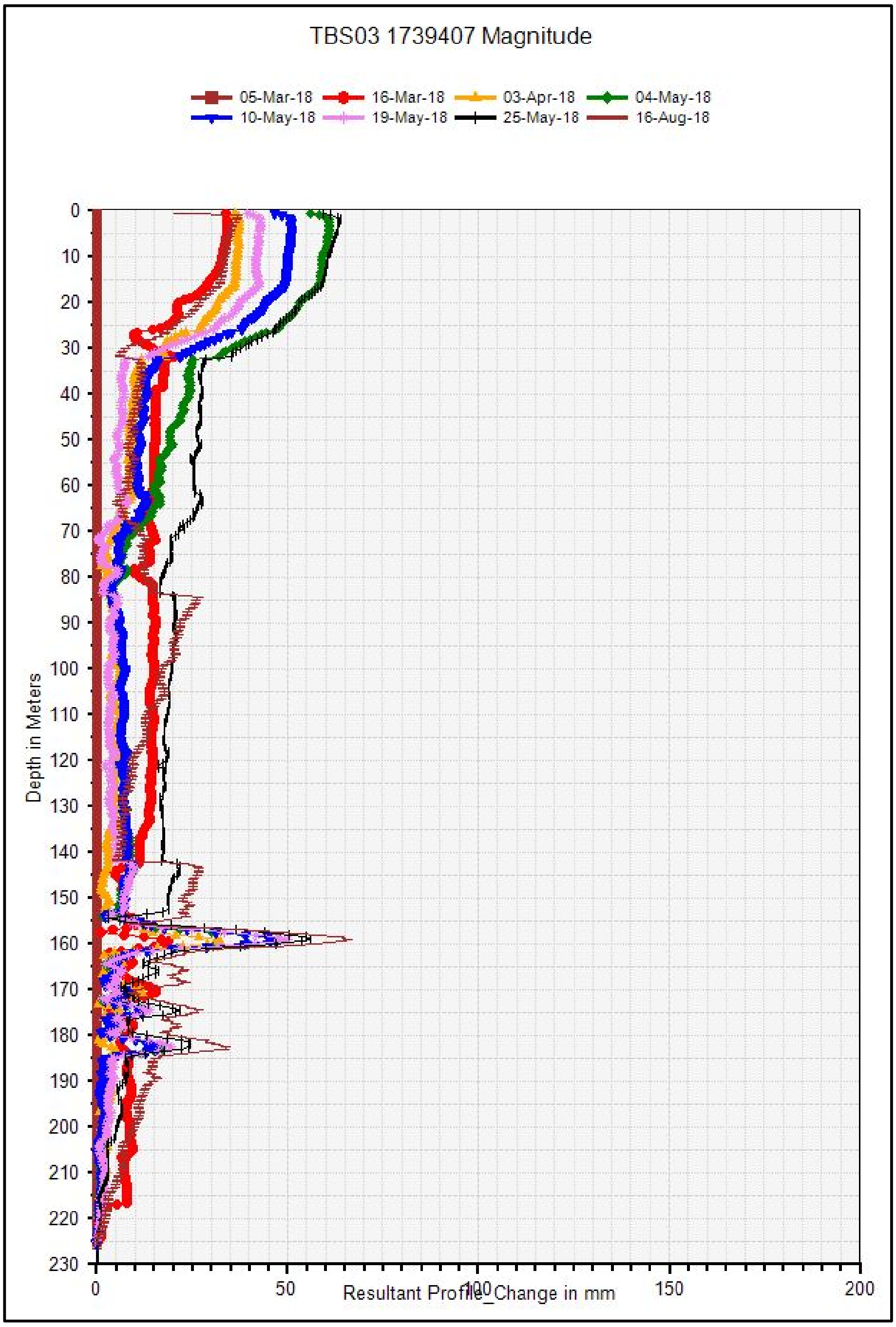


Figure 4.5 Borehole Inclinometer TBS03 results

(source: Golder Longwall 302 TBS02, TBS03 Reports)

The above data is a valuable contribution to understanding the nature and behaviour of bedding plane shear and confirms that it is directly linked to proximity to the mining extraction process. Based on this monitoring data, such shear plane activation is restricted to a region of <400m from the edge of the goaf or edge of extraction.

Additional very useful results from this monitoring work is available from the associated hydrogeological packer test work conducted at the same location as the TBS02 inclinometer. Figure 4.6 shows the horizontal hydraulic conductivity test results determined from packer testing at a number of the horizons where the bedding plane shears were detected by TBS02 inclinometer (reference Figure 4.3). These results show both pre-mining and post-mining conductivity results. The inclinometer detected significant shear movement at depths of 105m, 114m, 162m and 202m below surface. However, inspection of Figure 4.6 shows only very small differences in conductivity for the 105m, 114m and 162m horizons, but a dramatic increase in conductivity for the 202m shear horizon at the top of the Bald Hill Claystone. Once again, these are only a limited dataset, to date, but they are quite unique and of great value in developing an understanding of the role played by bedding plane shear on potential water flow paths. The results confirm the view that whilst shear can occur on multiple horizons, not all horizons represent increased flow paths.

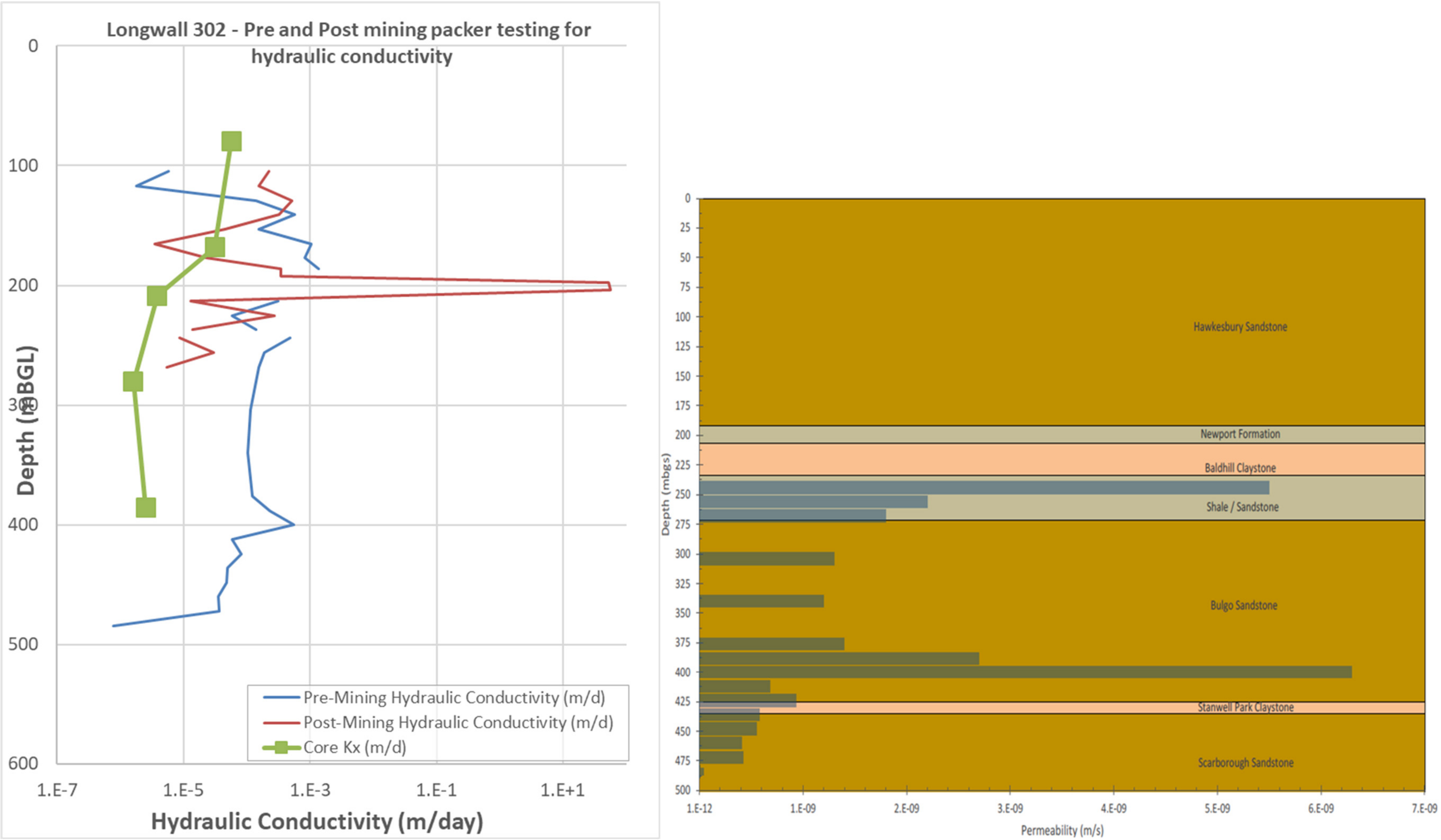


Figure 4.6 LW302 overburden conductivity test results – pre- and post-mining

(source: HydroSimulations presentation – February 2019)

4.3 Structural Geology

In response to the IEPMC report on the potential role of surface lineaments on groundwater flow through overburden above mining operations, Metropolitan Coal has independently conducted a formal risk assessment on this issue for the Longwall 304 Extraction Plan. It is not intended to discuss the results of the risk assessment in this report, other than to note that it has taken place and has been reported to DPE separately.

However, in discussion of the IEPMC Report (see section 3.4.1 above), caution was urged in making any direct comparisons of similarities between behaviour observed at Springvale Colliery in the Western Coalfield, and the Southern Coalfield. At Springvale, the IEPMC states that some lineaments were linked to water flow paths accounting for loss of surface water due to mining. However, in the review of the IEPMC Report it was pointed out that the structural geology with regard to lineaments in the Western Coalfield is linked to structural features in the granite basement rock that lies beneath the sedimentary Sydney Basin sediments, at depths ranging from as low as 30m, up to about 100m beneath the coal seams (Shepherd, 1980), (Sheffield, 2019). These are reported as often leading to the presence of continuous and quite distinct discontinuities running from the basement through to the ground surface.

In contrast, the basement rocks in the Southern Coalfield are many hundreds of metres deeper, and so there is no reason to expect that similar mechanisms would exist to link all lineaments with overburden-penetrating discontinuities, as they do in the west.

To support this important distinction, Metropolitan Coal has sourced a geological section from their lease that extends through to the basement rocks. This is reproduced in Figure 4.7. This shows the basement rocks at a depth of 2,280m below the surface borehole collar, or 1,755m below the Bulli Seam.

This is clear evidence of a quite different geological setting to that which exists in the Western Coalfield – hence the call for caution in drawing any conclusions regarding the role of surface lineaments on surface or groundwater behaviour at Metropolitan Coal.

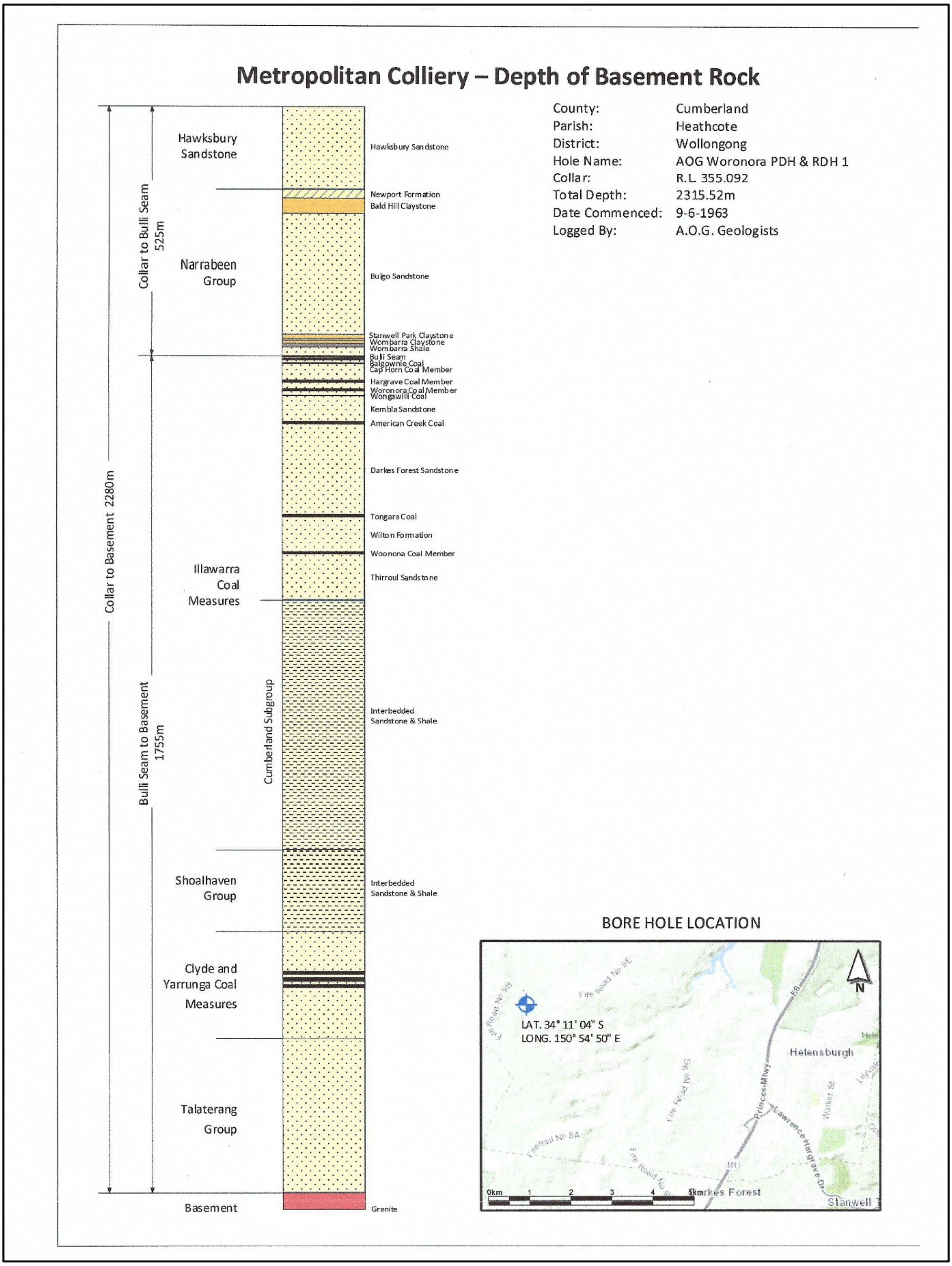


Figure 4.7 Surface to basement geological section – Metropolitan Coal

(source: Metropolitan Coal)

4.4 Surface Subsidence Monitoring and Prediction

Metropolitan Coal, through their subsidence consultants, Mine Subsidence Engineering Consultants (MSEC), has continued the extensive subsidence monitoring program, as previously discussed in the Stage 1 Report. After initial subsidence monitoring took place associated with LW301, the MSEC prediction model was re-calibrated for use with subsequent longwalls. Figure 4.8 shows the correlation of LW301 and 302 results, relative to previous Metropolitan site data (LW1 to LW27).

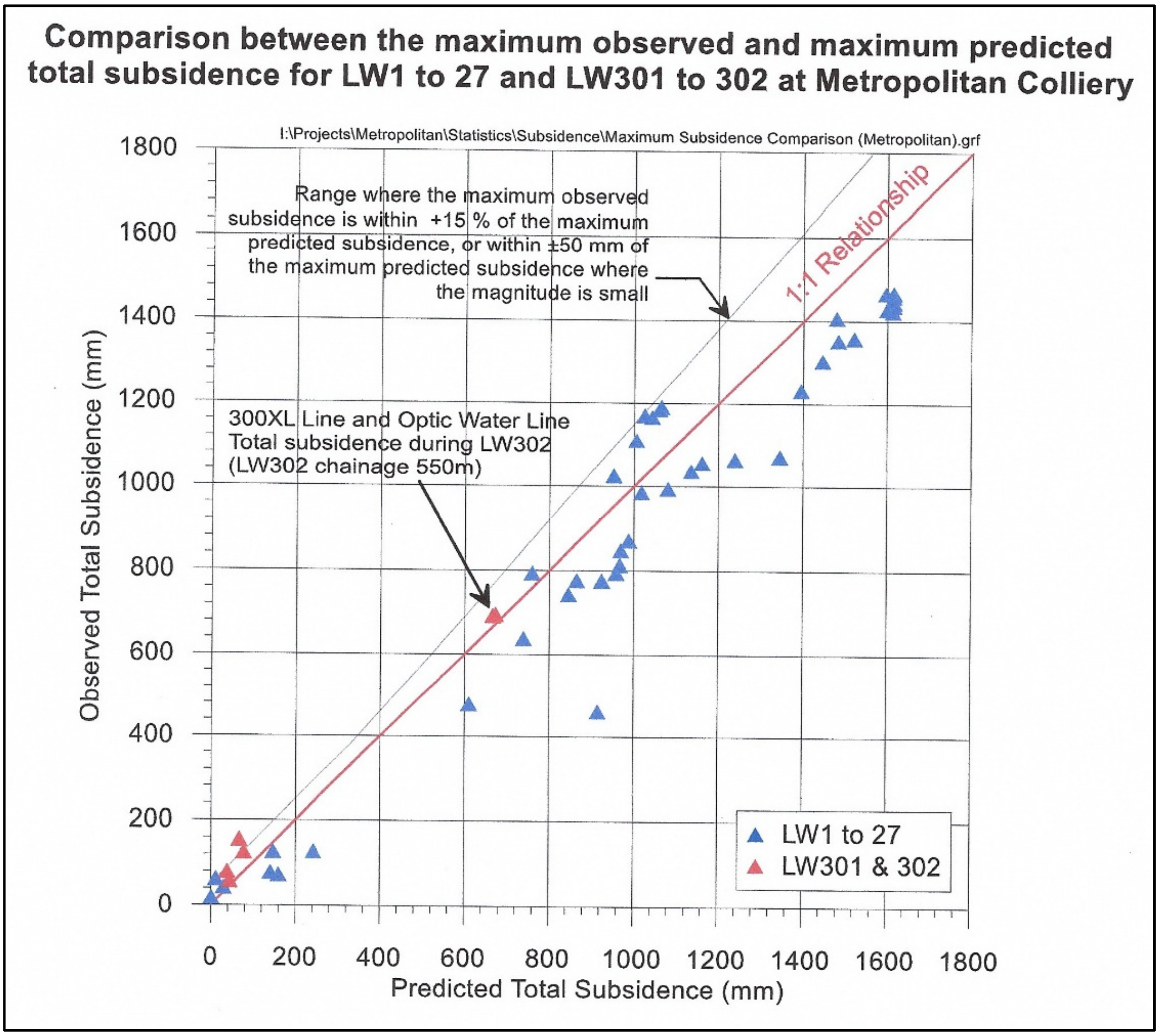


Figure 4.8 MSEC Observed v Predicted subsidence data for Metropolitan Coal

(source: MSEC)

Figure 4.9 shows the monitoring results for LW302, for the 300XL cross line, relative to predictions, with very good correlation, giving a high level of confidence in future predictions for this region of the mine.

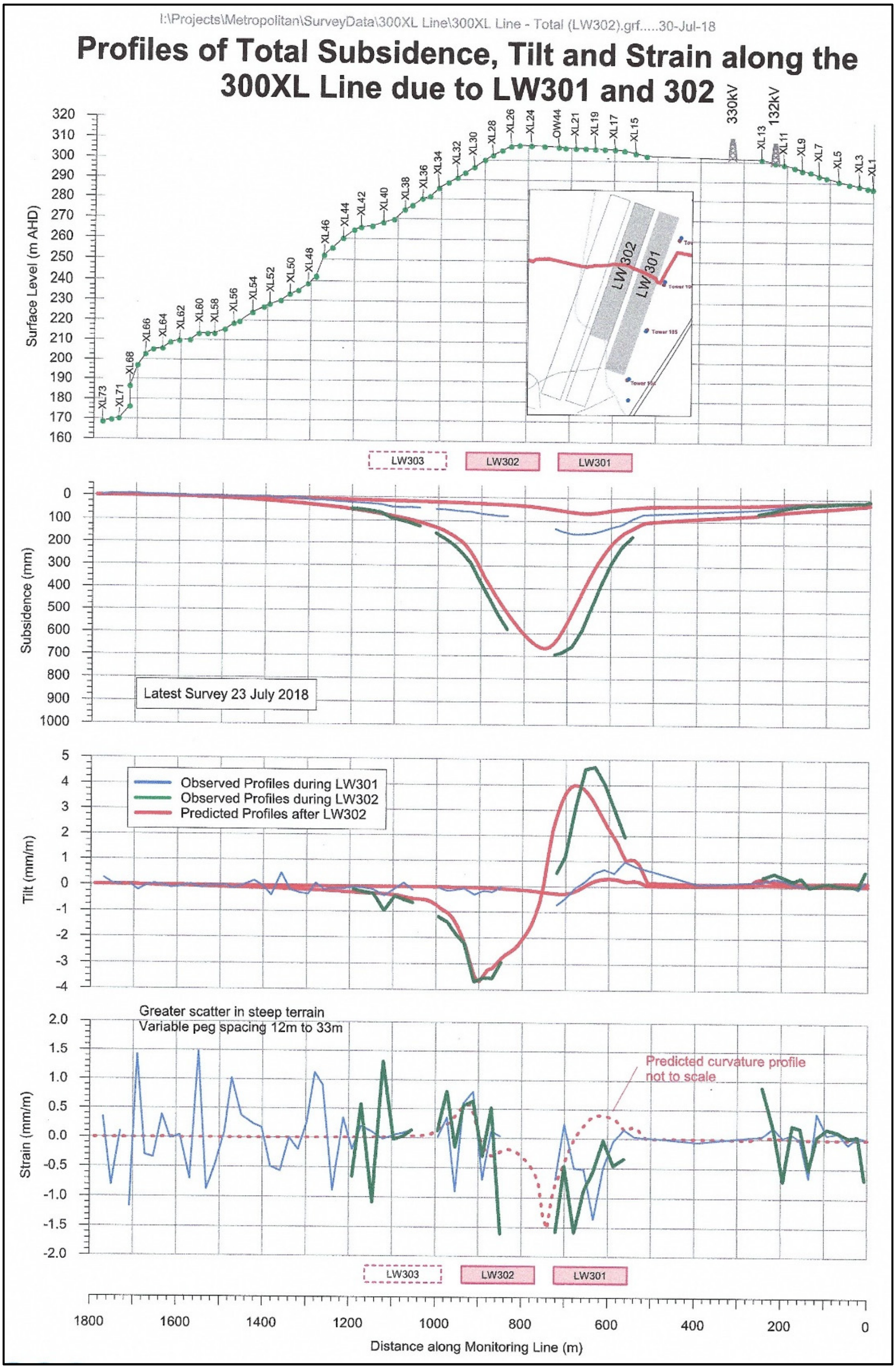


Figure 4.9 MSEC Observed v Predicted subsidence data – LW301, 302

(source: MSEC)

In response to the Stage 1 Report, the DPE requested provision of a more regional prediction of subsidence across the full set of proposed longwall panels that run beneath the Woronora Reservoir, in the 301 to 317 panel series.

MSEC has now produced such a prediction suite, using the latest calibrated prediction model referred to above. Figures 4.10 and 4.11 show these predictions, including total subsidence both as contours and a cross-sectional profile, together with tilt and curvature. The subsidence-reducing influence of the narrower panels and wider chain pillars beneath the reservoir is evident in these results, with maximum subsidence reduced by at least 50% under the Reservoir area.

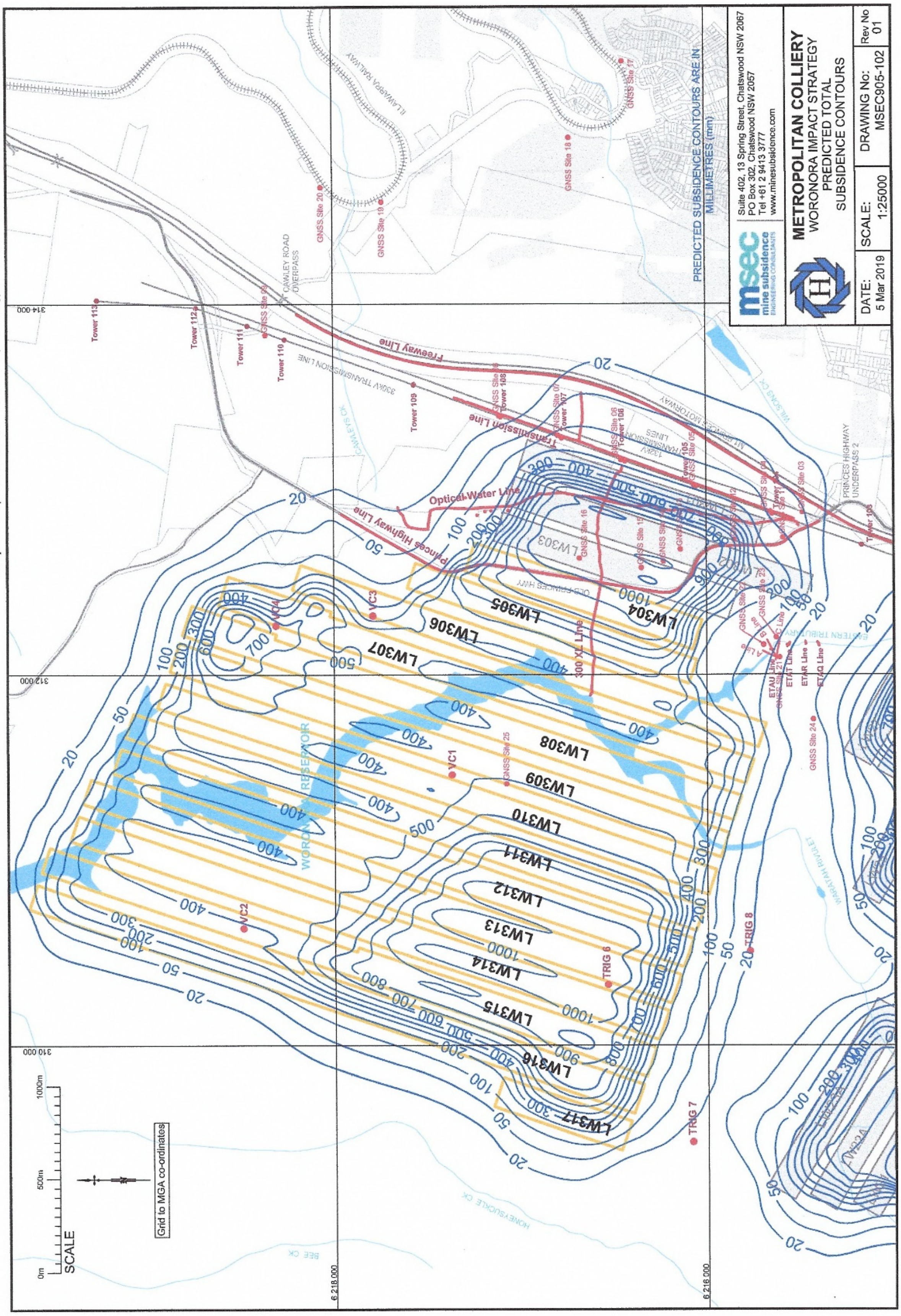


Figure 4.10 Predicted subsidence contours – LWs 301 to 317

(source: MSEC)

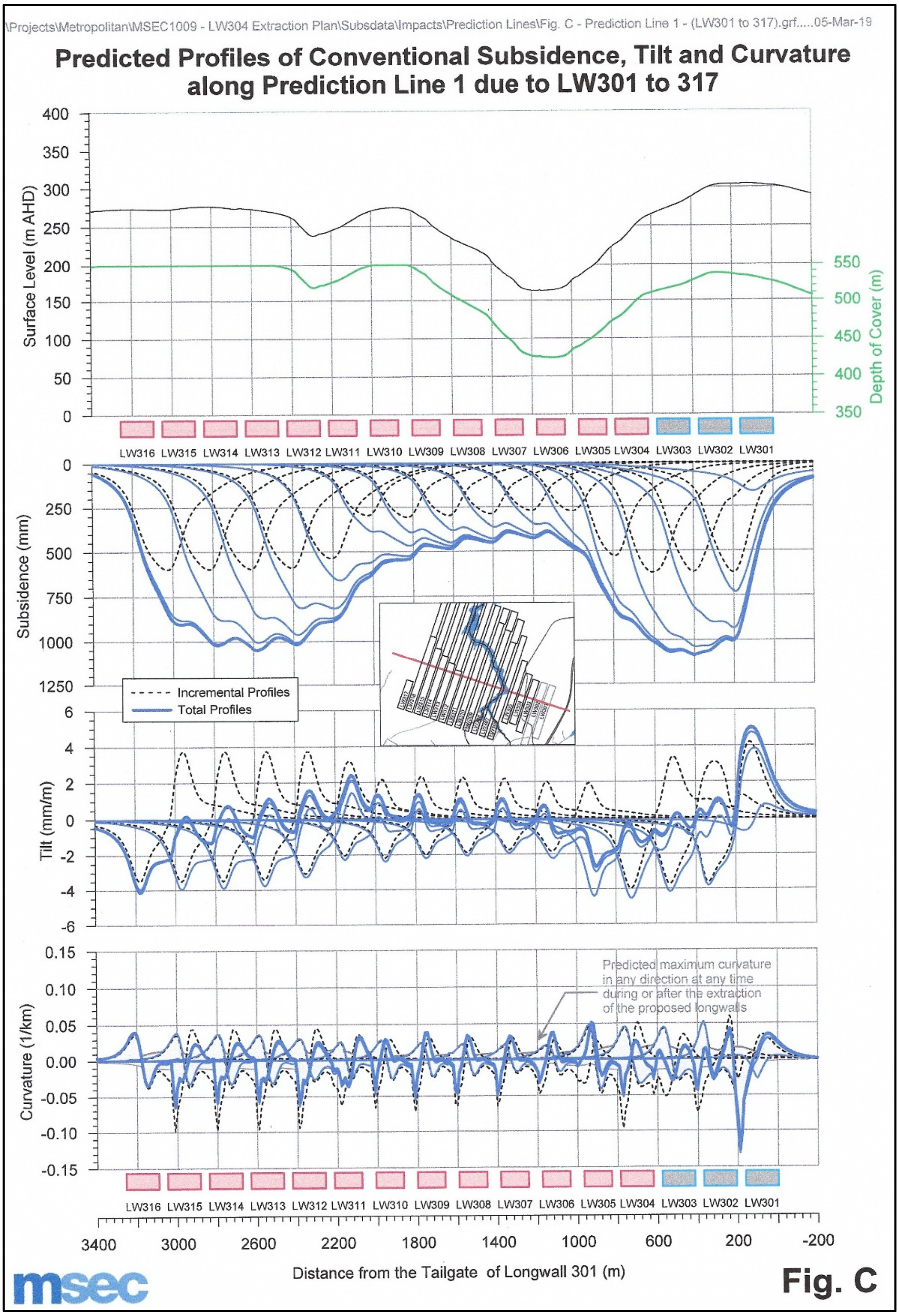


Figure 4.11 Predicted subsidence along a centreline cross-section – LWs 301 to 317

(source: MSEC)

4.5 Future Monitoring Systems and Technologies

The Stage 1 Report discussed a number of future technologies that could assist in monitoring different aspects of subsidence effects and impacts. MCPL made a commitment to continue with evaluation of these various new technologies. The technologies listed at the time were:

- InSAR satellite subsidence monitoring
- LIDAR aerial survey subsidence monitoring
- Bathymetric surveillance of underwater ground surface profiles beneath the Woronora Reservoir.

A further trial and evaluation of InSAR technology was conducted by MCPL during 2018. However, the shortcomings previously discussed – namely, great difficulty in achieving acceptable resolution in regions of high surface vegetation and steep terrain/slopes – have been confirmed as problems with this technology for this particular location. It has been decided not to pursue the technology further at this time, and this decision is supported by the Strategy study team.

On the other hand, LIDAR has proven a useful technology – not to replace some of the conventional survey techniques, but to supplement it. The benefit of LIDAR is that it can provide an image of vertical subsidence across 100% of the area surveyed, rather than just at nominated measurement stations. Figure 4.12 shows LIDAR images taken after completion of each of LWs 301 and 302. These clearly show the growth in the development of the subsidence bowl with the extraction of LW302.

The quoted accuracy of LIDAR at present is ± 100mm which is not as good as can be achieved with some conventional and alternative single station technologies, but to provide an overall survey of the development of subsidence, LIDAR is clearly a valuable complementary technique and MCPL have indicated they will continue to use it, at least at the completion of each panel. Once again, this decision is endorsed.

A further opportunity related to the use of LIDAR is to move from the use of fixed-wing aircraft to fly LIDAR surveys, to the use of drone technologies. MCPL has already commenced trials of this option with very promising results – not only in improved levels of survey accuracy, but significant cost savings.

The third technology previously under consideration was bathymetric surveys of the reservoir floor using a boat on the water surface. Whilst some initial investigations were made following the Stage 1 report, unfortunately, water level drops in the reservoir have resulted in the relevant arm of the Reservoir now being virtually empty of water and so no further actions have been taken to pursue bathymetry at this time. (However, access to the reservoir floor is available by conventional means for some time to come).

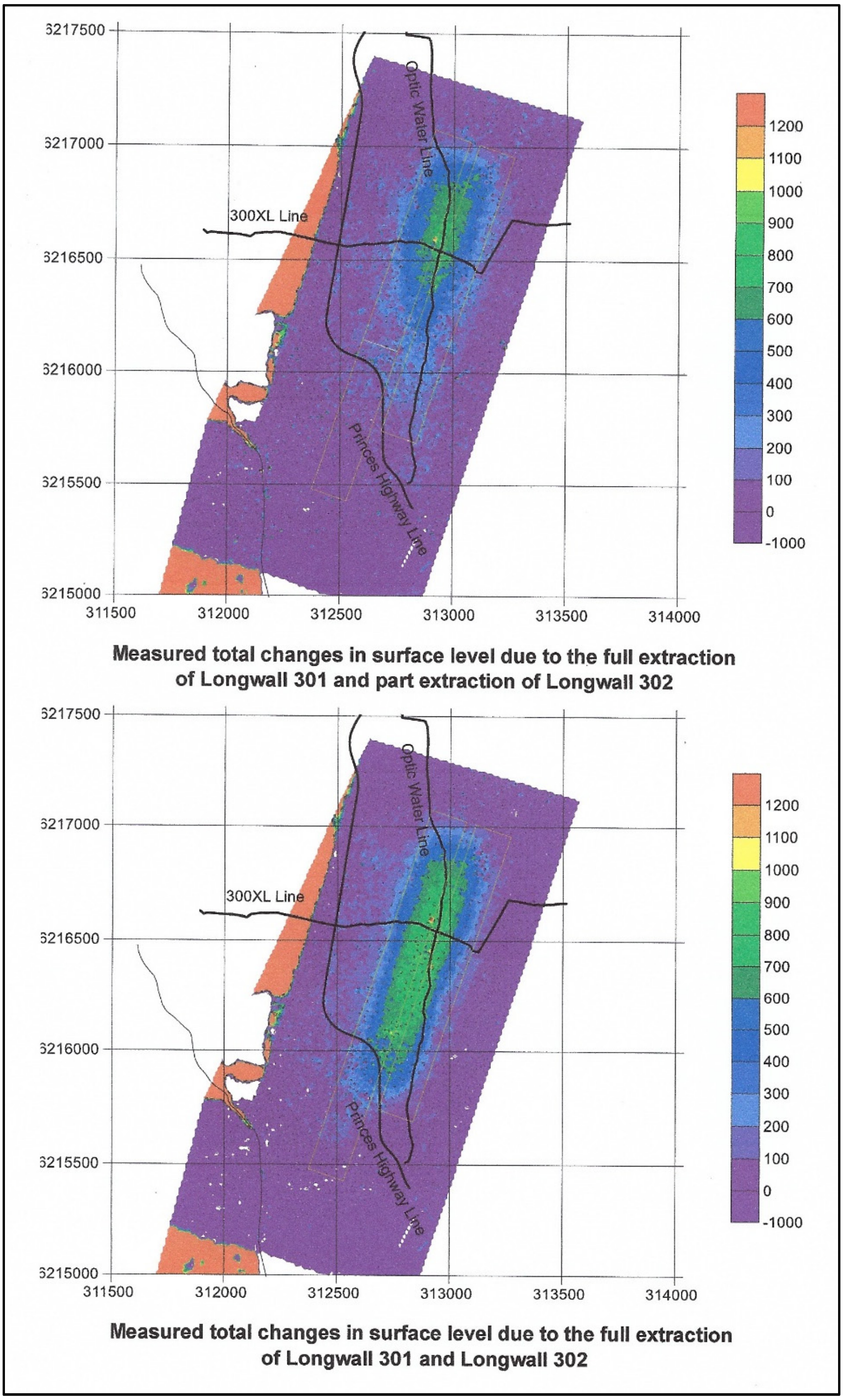


Figure 4.12 LIDAR survey results after LW301 and LW302

(source: MSEC)

Since the Stage 1 Report was released, two further promising survey measurement techniques have been trialled and are now in use by MCPL. These are the use of GNSS survey stations; and the use of high precision cross-valley survey lines.

GNSS (Global Navigation Satellite System) stations are effectively a further extension of previous GPS monitoring stations. They can provide full 3D movement data on a continuous basis, with a quoted accuracy presently of ±10mm. Figure 4.13 is a plan of the currently installed array of GNSS stations over the LW301 – 303 region of the mine plan. These stations are providing valuable data, particularly, continuous horizontal movement (magnitude and direction) data relative to the current longwall face movement.

It is recommended that this GNSS array be further deployed on both sides of the Reservoir at the earliest opportunity to provide more regional coverage, with installations well ahead, and hence, distant from current mining locations, to provide accurate and absolute regional movement data which can also be used to inform valley closure analysis, at different levels of the valley sides.

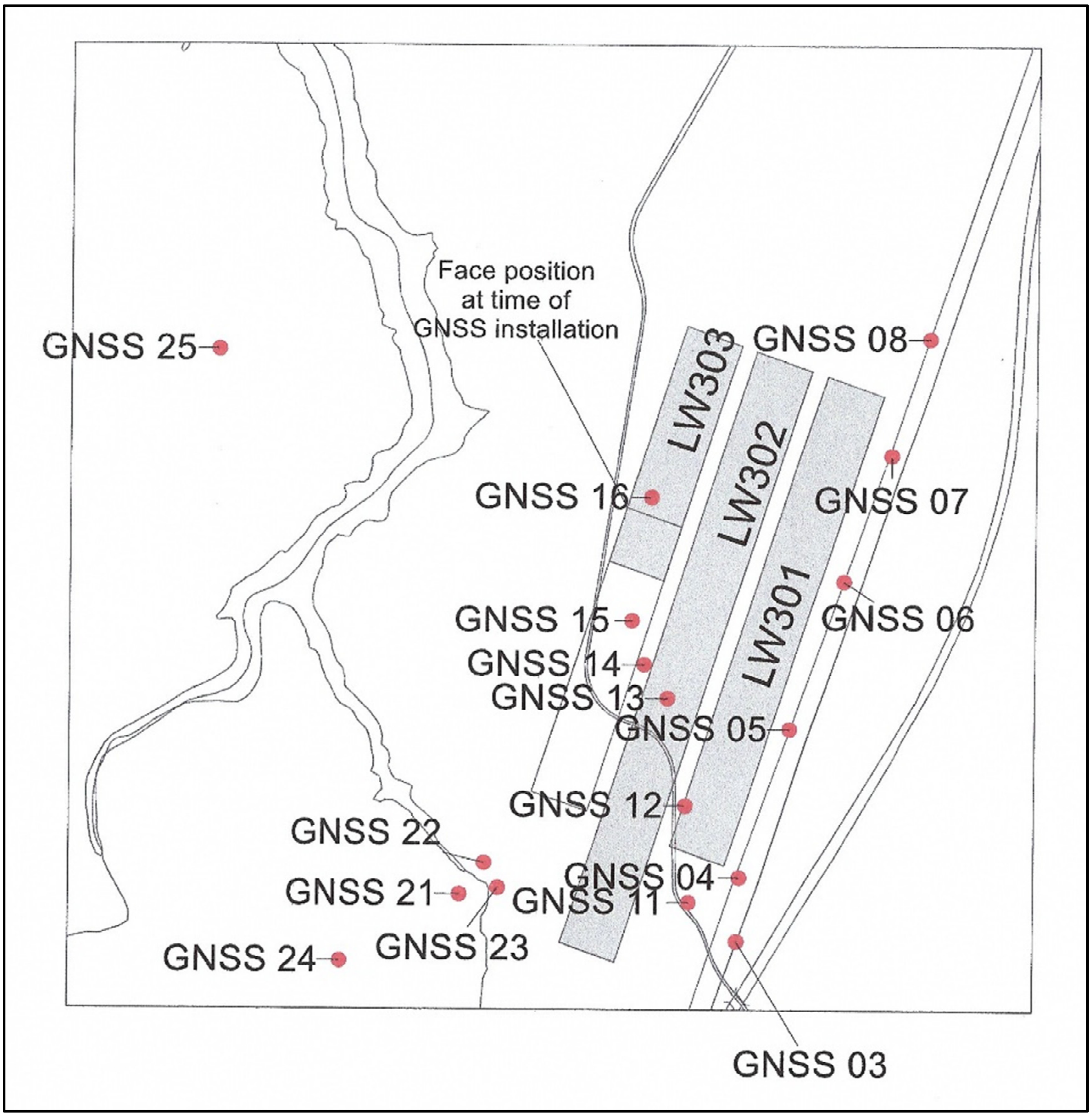


Figure 4.13 GNSS survey station array installed around LWs 301 – 303

(source: MSEC)

The second promising new technique is the use of high precision survey lines across selected valley locations using precision survey equipment. These require a physical survey to be undertaken for each survey epoch, and results can be influenced by climatic conditions, but under good conditions, are capable of distance measurements (such as valley closure) of ± 1mm accuracy which is quite remarkable.

This technology was previously used by Dendrobium Mine for the Sandy Creek Waterfall project investigation. Metropolitan Coal has now implemented it to monitor closure across the rock bars of the Eastern Tributary due to the approaching LW303 goaf. Figure 4.14 shows the deployment of these survey lines over Eastern Tributary.

It is recommended that greater use of this technology be used in future – particularly across the Reservoir at a number of locations and elevations, subject to access and limitations of line lengths and line of site/visibility issues.

Figure 4.14 High precision survey lines across Eastern Tributary

(source: MSEC)

5.0 GROUNDWATER AT METROPOLITAN COAL

5.1 Piezometer/Borehole and Packer Results

In accordance with the recommendation works listed in the Strategy 1 report a series of piezometers and boreholes were constructed above the proposed 302 longwall panel footprint at the Metropolitan Coal site during late 2017/early 2018. The locations are shown in Figure 5.1 whilst a section with the distances between piezometers across LW302 is shown in Figure 5.2.

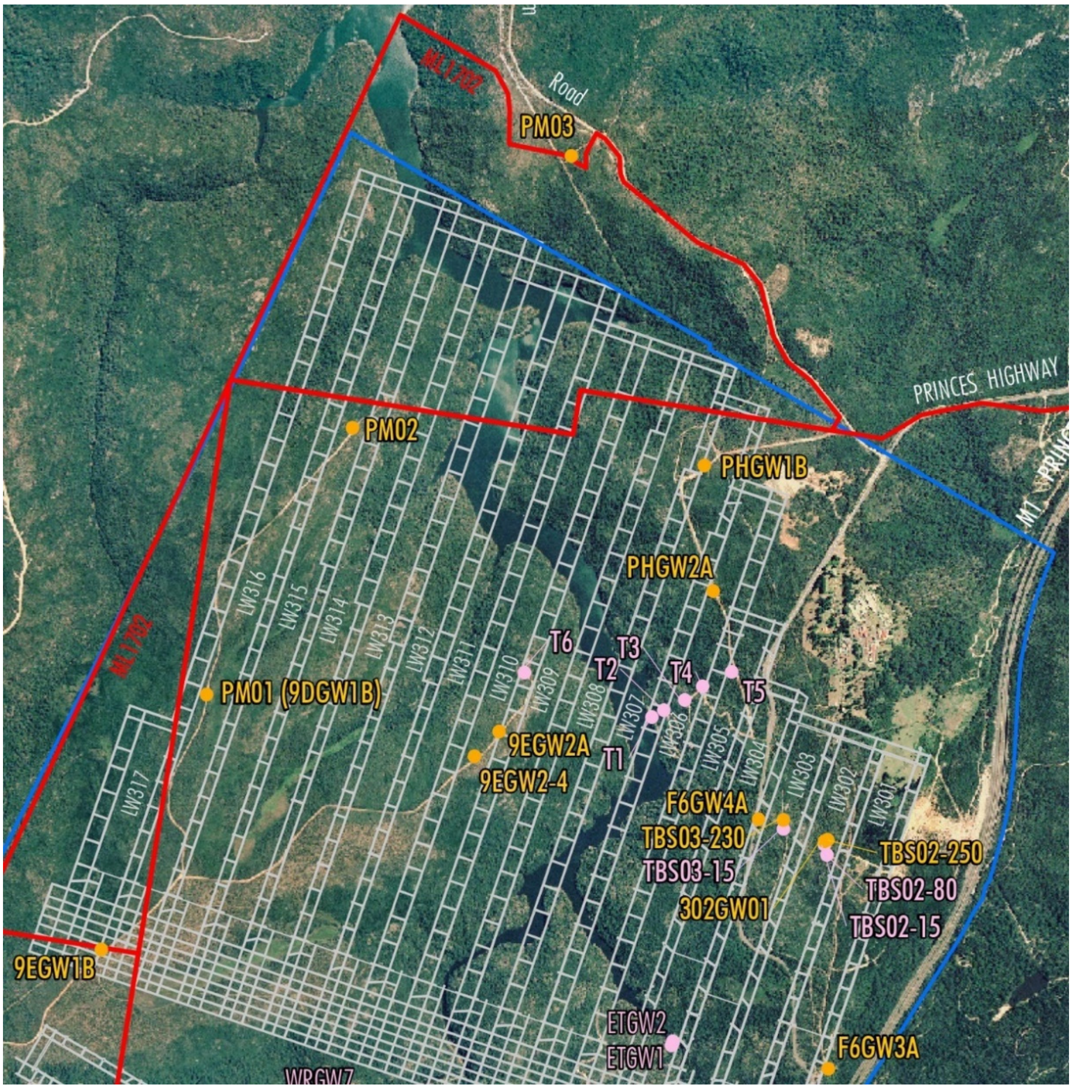


Figure 5.1 LW 302 VWP locations

(With regard to Figure 5.1 yellow dots are VWP's and white dots with pink notation are standpipes).

(source: Metropolitan Coal)

In Figure 5.2 piezometers marked with black dots are VWP's 1 to 5 extending from the bottom to the top whilst the Fibre optic piezometers 1 to 4 are marked with red dots that extend from top to bottom. Piezometers VWP 1 and 2 in TBS02 extend from bottom to the top. An inclinometer was also established at the bottom of borehole TBS02 at a depth of 247.8m.

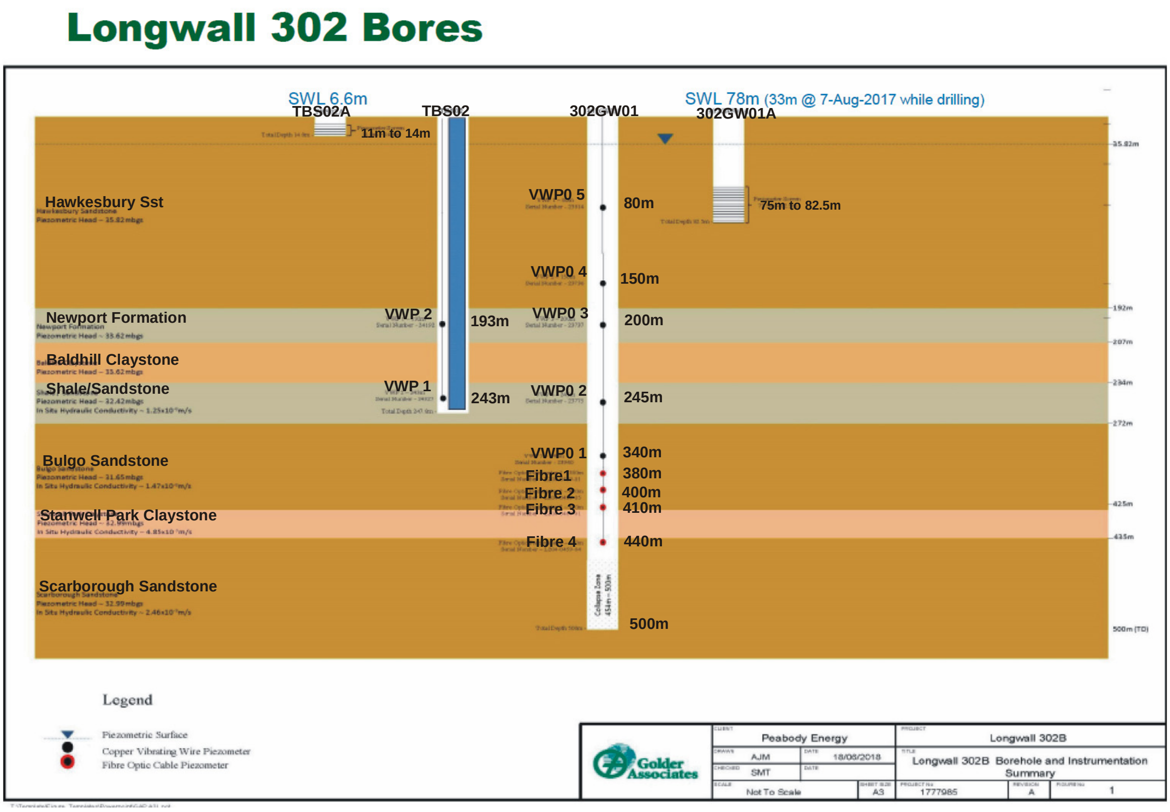


Figure 5.2 Longwall 302 borehole and Instrumentation

(source: Golder, 2018)

Figure 5.3 below shows the pressure head graphs at VWP0's (1 to 5), fibre optics (1 to 4), TBSO2 VWP's (1 and 2) and TBS03 VWP's (1 and 2 at 162m and 213m respectively); piezometer notation, depths and geological units. TBS03 is situated above LW303.

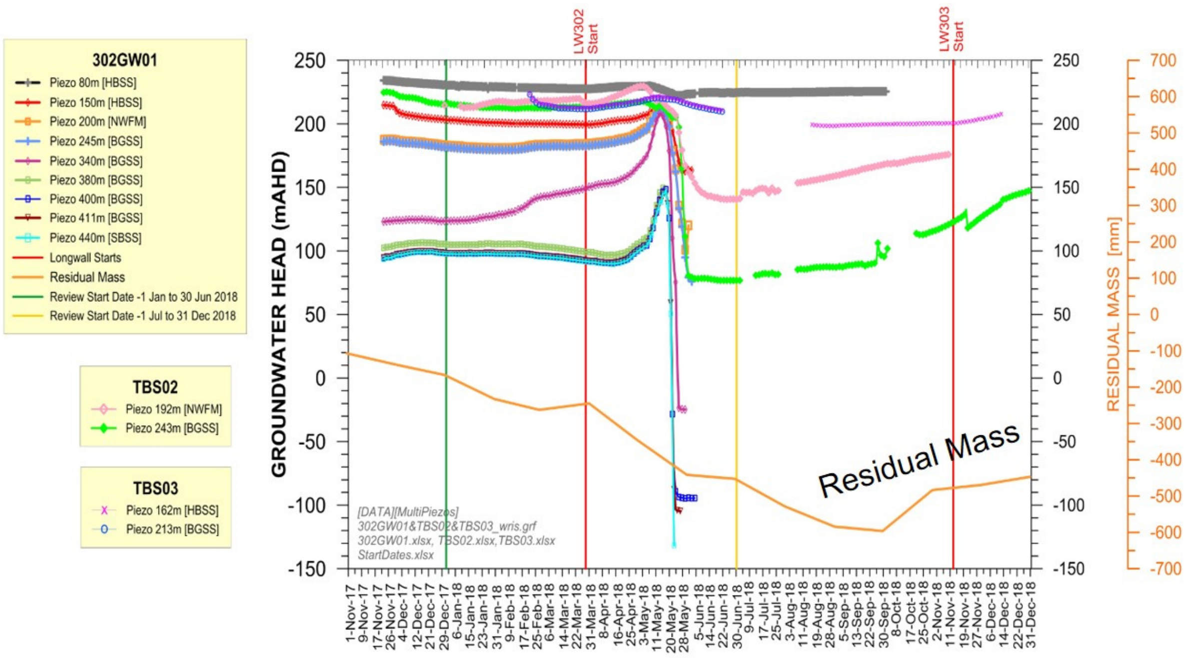


Figure 5.3 Pressure head graphs prior to, during and post longwall mining 302GW01

(source: HydroSimulations, 2019)

Figure 5.3 indicates a number of deeper VWP's that display a slow rise over a couple of weeks in pressure followed by a relatively sudden rise within several days or so in pressure levels, followed in turn by a substantial decline of the pressure head as the longwall mining passes these piezometers. The slow initial rise seems likely due to mining of LW301. The probable cause for the main sudden rise in pressure is that it is due to compression effects of fine grained, low permeability strata. This effect has been noted in other environments in the literature. Further detail on this phenomena is provided in Appendix A herein. In summary an initial temporary rise rather than a pressure decrease (i.e. substantial pressure decline) is thought to be caused in the relevant piezometer by poro-elastic effects, that is by compression of low permeable and fine-grained layers (possibly by claystone strata within the Stanwell Park Claystone unit in particular) but also by other such low permeable layers present in the geological profile close to the caved zone. It is relevant for example that the Bulgo Sandstone Formation is comprised of layers of fine to medium-grained quartz lithic sandstone with lenticular shale interbeds.

Less pressure effect is evident in piezometers with increasing height above the caved zone as the longwall panel is removed. There is very little rise effect at 150m depth and virtually almost none at 80m below ground surface (bore 302GW01 in Figure 5.3). According to Hydrosimulations (2019) pressure pulses at bore F6GW4 (located between longwalls 303 and 304) display *"cusps-like features on the Hawkesbury Sandstone",* and *"sustained rises in the upper to middle Bulgo Sandstone".*

The pressure levels that show major pressure decline are the deeper fibre optic piezometers (2 to 4) and VWP01 as longwall 302 was mined. Following the sharp decline in pressure head as shown in Figure 5.3 three shallower piezometers have displayed some pressure head recovery. The rainfall residual mass curve for this period indicates that the head recovery is not due to rainfall recharge. Recovery of pressure head following the passing of an excavated longwall panel is not unusual and recorded in the literature at a number of mining sites. It is quite possible this is due to migration of higher surrounding pressure head in the profile to lower pressure head zones.

However, the question arises whether it is possible to analyse the pressure declines observed in Figure 5.3 to determine the state of connective fracture network developed in the geological profile. While this is not entirely straightforward the following is a possible result of such analysis. Connective fracturing would induce desaturation and possible complete or ongoing draining of groundwater immediately above the extracted seam. Hence by selecting those piezometers that displayed substantial decline of pressure head, the extent of possible connective fracturing was determined. For assessment the piezometers with openings at depths of 440m, 411m 400m and 340m that show substantial pressure head decline were selected. Adopting the depth of the extracted Bulli seam at a depth of 535m (based on MSEC seam contours)[8], then 535m – 340m = 195m. That is, the possibility exists that substantial to significant fracturing extends up to 195m above the Bulli extracted seam.

There is of course evidence of decrease in pressure in the piezometers in TBSO2 at depths of 243m, TBSO2 at 193m and 200m in 302GW01 bore. Additional monitoring was conducted into 2019 as shown below in Figure 5.4 indicating the extended recovery of piezometers in TBSO2 at depths of 243m and 193m. Unfortunately the VWP in TBSO2 at 193m failed in late 2018. However, some new

[8] MSEC 2018 Longwall 301 to 303 depth of cover contours. Drawing No MSEC984-05 Rev A. Metropolitan Colliery. 1 Sept.

VWP's were installed as depicted in Figure 5.4 at the depths shown in that figure. These results indicate virtually no subsequent pressure head response at depth of 80m, 90m and 180m and minor response at a depth of 190m.

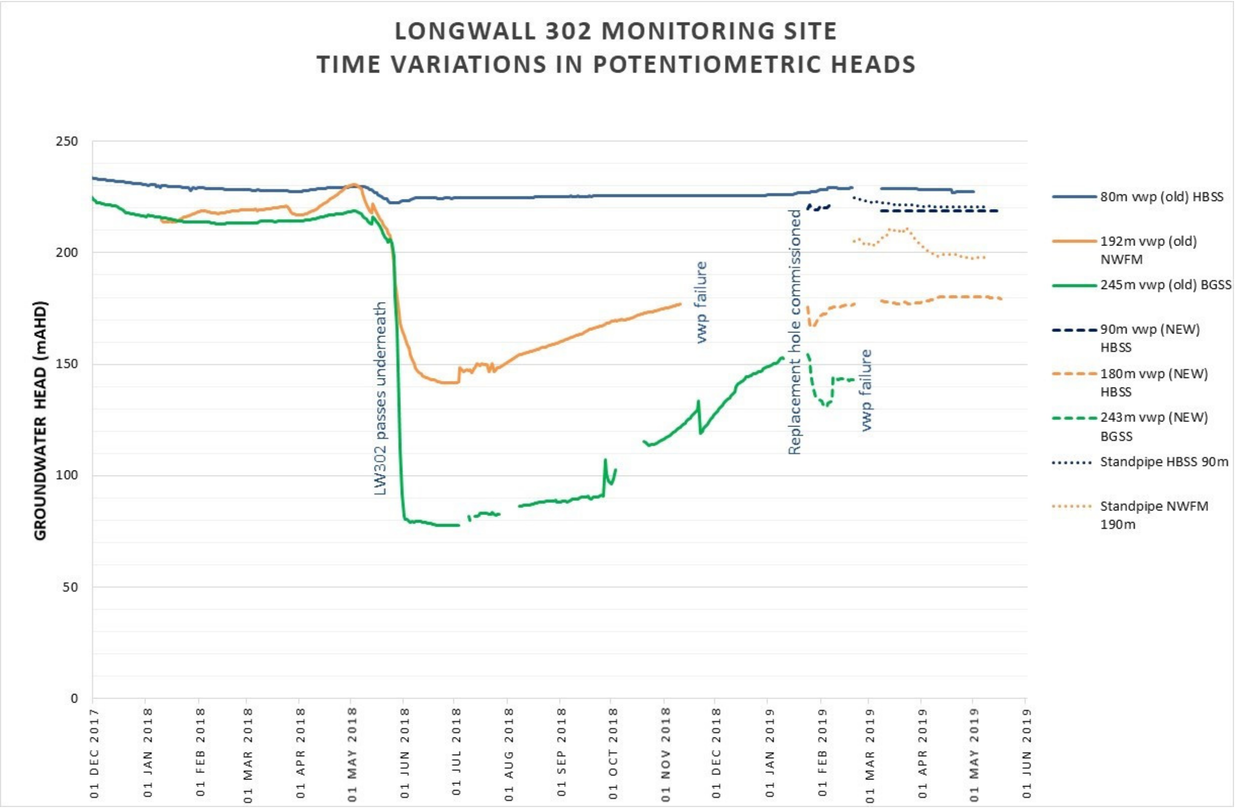


Figure 5.4 Extended piezometer pressure heads recovery in older 2018 and newer VWP's in 2019

(source: Metropolitan Coal, 2019)

A comparison of the main declines in piezometer pressure head was conducted with an available regression equation. For that assessment the Tammetta (2012) equation was used first to determine the possible extent of connective fracturing. Despite criticism levelled at this regression approach and the basis of this equation, it has nevertheless recently been suggested that it could provide a suitable "conservative" determination of such connective fracturing in a profile. For this determination the following parameters were used W=163m; Cutting height= 3.2m and Depth of Cover = 535m. These parameters yield 173m. For a cutting height (t) of 2.7m with the same Depth of Cover and Panel Width yields 138m. The Ditton equation using a beam thickness of 20m, that the authors of that equation consider appropriate, yields for W=163; Cutting height=3.2 and depth of cover = 535m a fracture height of 174m. It is interesting that for the same parameters but a beam thickness of 15m yields a height of 195m while a beam thickness of 30m yields a height of 148m.

The piezometer analysis yields the possible substantial to significant fracturing to 195m above the extracted seam whilst the Tammetta equation yields a height of such fracturing at a height of 173m from the extracted seam. This is similar to the Ditton equation (174m) if the beam thickness of 20m is adopted. These heights correspond to depths of 340m and up to 362m respectively from the surface. Based on the results of other piezometers it is quite possible that the height of 195m should be considered as a "conservative" estimate and include a zone of upper depressurisation. But as noted above even at this height there remains a considerable rock profile depth of 340m above that height estimate.

At site TBSO3 two additional VWP's were installed at that site after failure of earlier piezometers. The monitoring results are shown in Figure 5.5 for piezometers at depths of 162m, 213m, 245m and 265m.

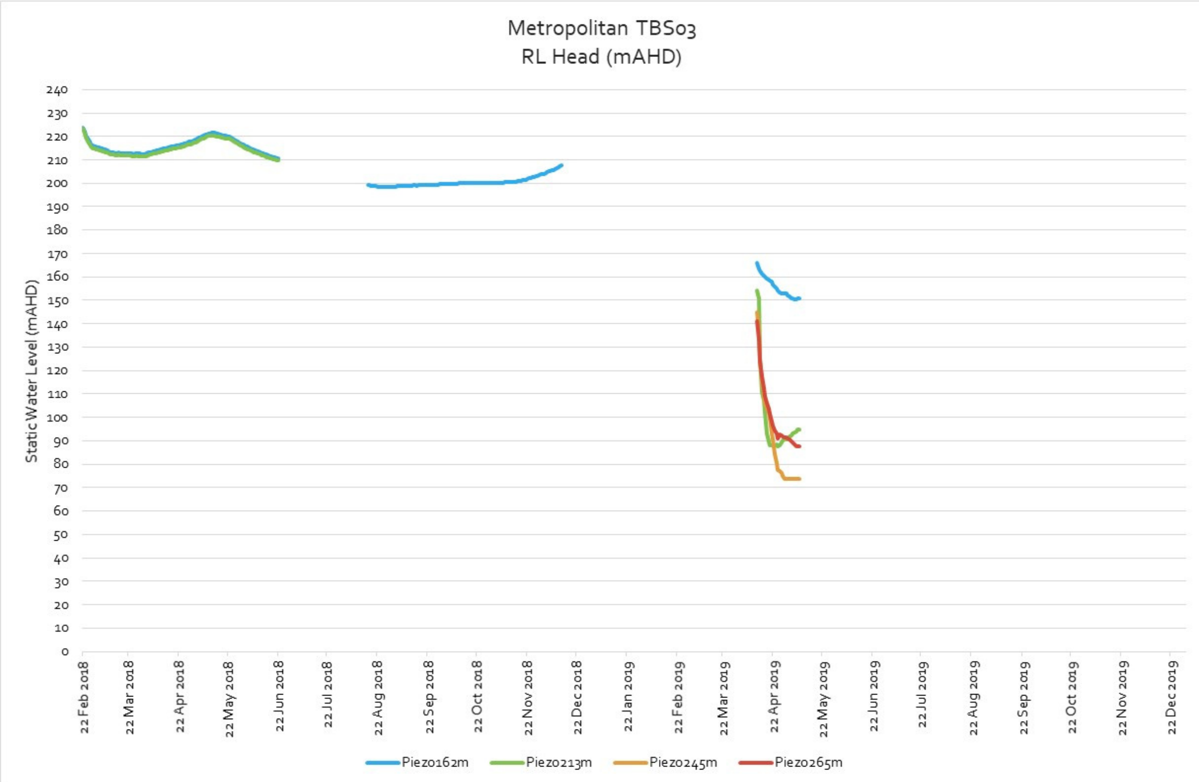


Figure 5.5 TBSO3 piezometer static water levels

(source: Metropolitan Coal, 2019)

The piezometers at depths of 245m and 265m were placed within the Bulgo Sandstone. Longwall panel passed under the site on the 14 January 2019 with the first data available on the 12 April 2019. These piezometers do not display any major declines in pressure. Based on the MSEC contours the piezometers are situated at heights of 270m and 250m respectively above the mining zone.

In relation to longwalls 303 and 304 a borehole F6GW4 has been previously constructed between these longwall panels and has had levels recorded since 2013 as shown below.

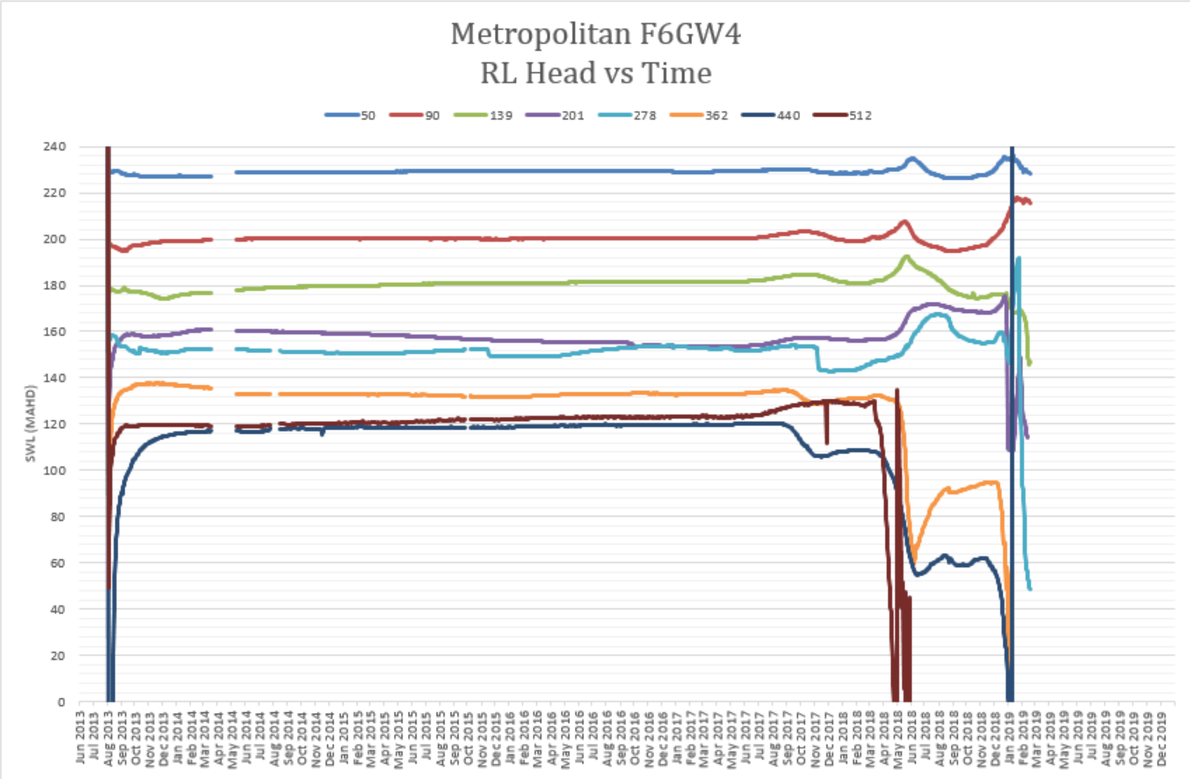


Figure 5.6 Piezometer levels over the period 2013 to early 2019 at borehole F6GW4

(source: HydroSimulations, 2019)

The monitoring results indicate that the piezometer at 512m is displaying collapse, while piezometers at 362m and 440m display substantial decline in pressure. These piezometers are respectively at heights of 143m and 65m above the mining zone for a mining zone depth of cover of about 505m (based on MSEC 2018 contours).

It should be noted that presentation and discussion of a number of piezometer results in more distant locations in and around the proposed and mined longwalls are given in Merrick (2019), in a workshop presentation prepared on 19 February 2019.

As part of the Longwall 304 Water Management Plan Metropolitan Coal has indicated that it will install a post-mining multi-level bore over Longwall 305. The bore will extend to the fracture zone and will assess permeability below the Bald Hill Claystone.

5.2 Packer Tests and Core Samples and Hydraulic Conductivity

In addition to pressure measurements, packer tests and core samples for determining insitu horizontal and vertical hydraulic conductivities were also conducted at locations in the section shown in Figure 5.2 for borehole 302GW01 as described in Appendix C. The four zones that were packer tested are shown as black vertical bars in Figure 5.7. Packer test results are also listed in Appendix D for borehole TBSO2.

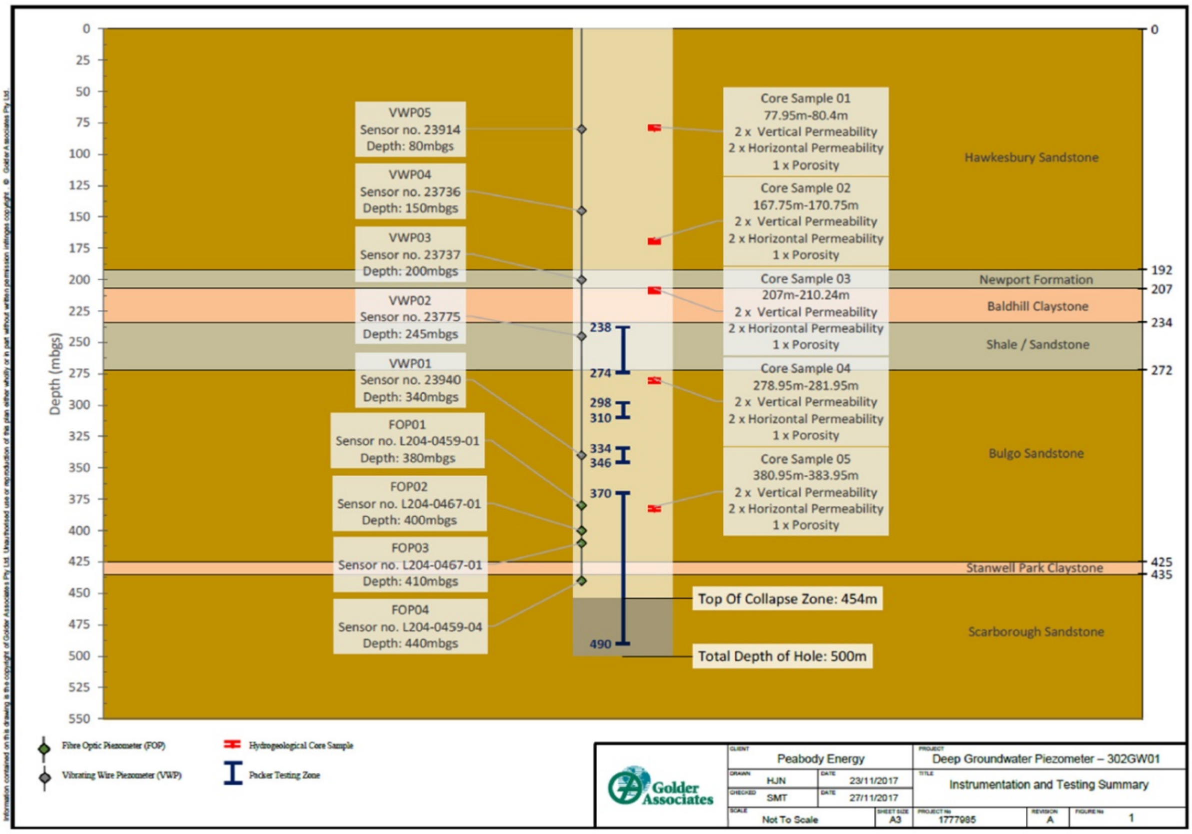


Figure 5.7 Packer tests and Hydraulic conductivities of Core Samples

(source: Golder, 2017)

6.0 CURRENT SURFACE WATER RESULTS AT METROPOLITAN COAL

6.1 Monitoring Program and Results

In response to a recommendation in the Woronora Reservoir Strategy Report - Stage 1, two streamflow monitoring stations in sub-catchments I and K to the west of Longwalls 301-303 and a pluviometer in the vicinity of the northern end of Longwall 307 were installed in May 2018 and January 2018 respectively. The locations of the streamflow monitoring stations are shown in Figure 6.1. Figures 6.2 and 6.3 show the measuring flume at sub-catchment I. The location of the pluviometer (PV8) is shown in Figure 6.4.

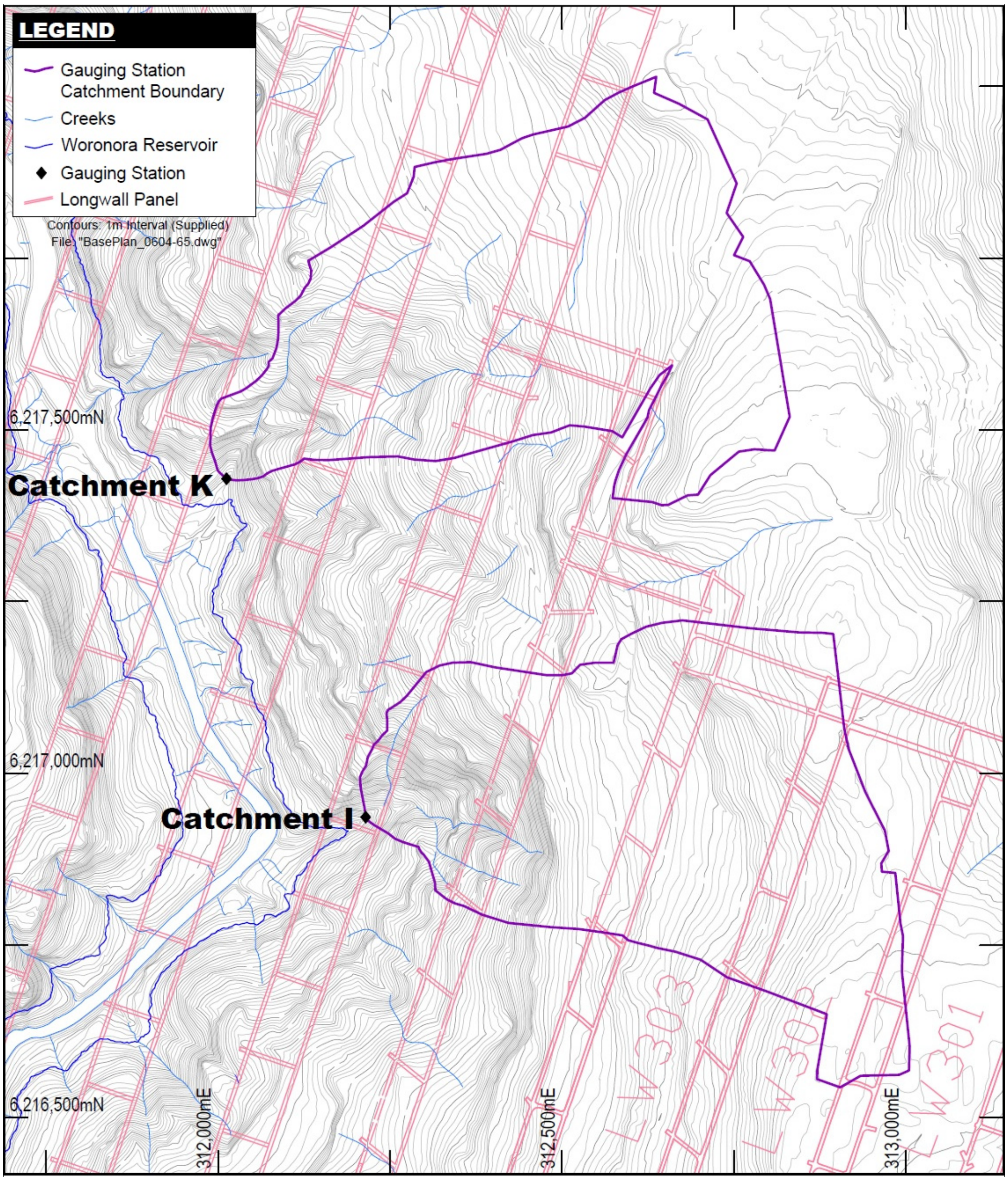


Figure 6.1 Location of the newly installed streamflow monitoring stations I and K
(source: Hydro Engineering & Consulting)

Figure 6.2 Sub-catchment I Flow Gauge
(source: Metropolitan Coal)

Figure 6.3 Sub-catchment K Flow Gauge
(source: Metropolitan Coal)

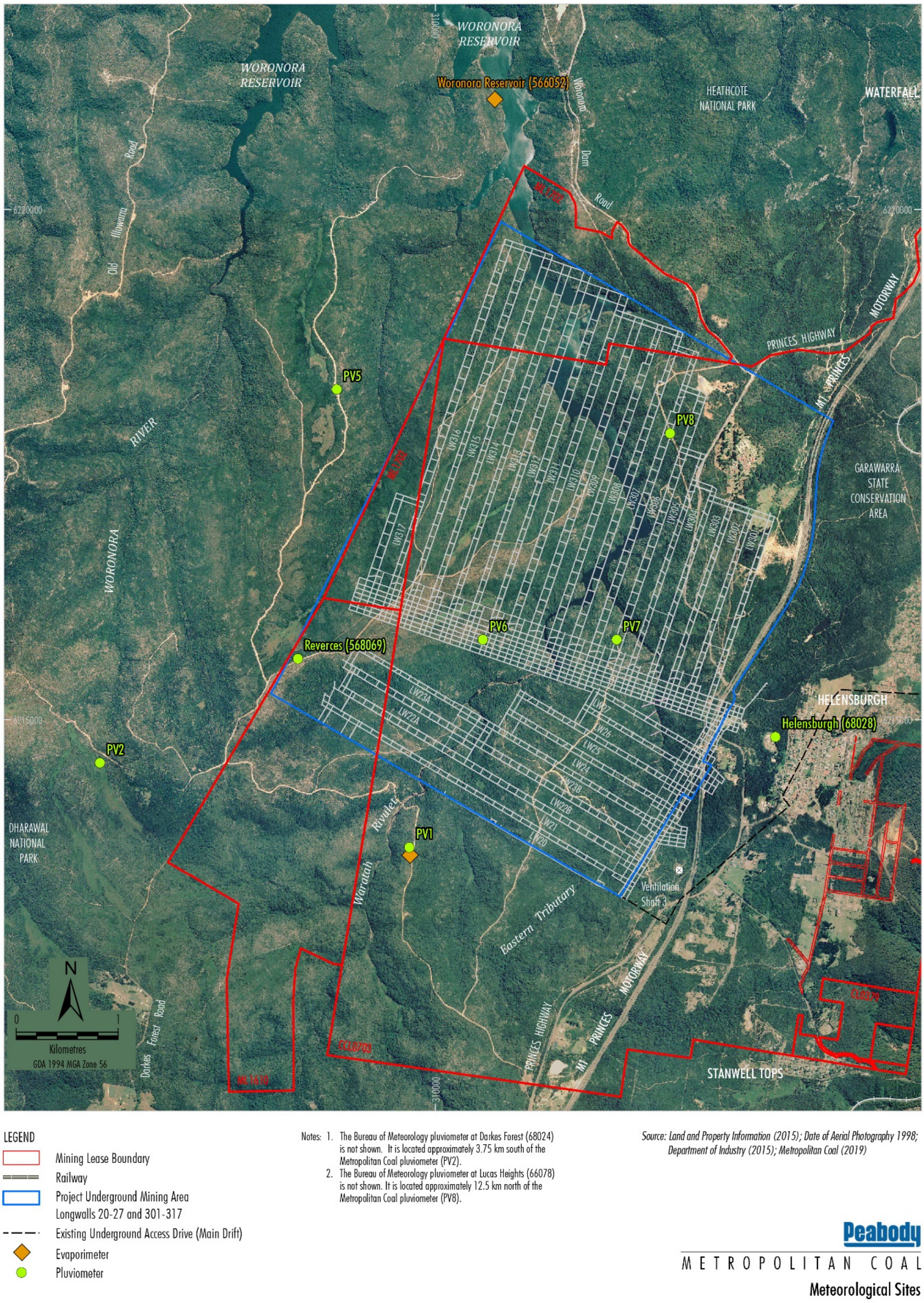


Figure 6.4 Location of the newly installed pluviometer (PV8)

(source: Metropolitan Coal)

Flow data measured in the flumes for the period June 2018 to mid-January 2019 are presented in Figure 6.5. A preliminary analysis of the data has been summarised in the Longwall 304 Management Plan, page 33 as follows: *"In comparing the recorded recessionary behaviour of sub-catchment I with the control on sub-catchment K it is evident that mining activity over the period has not resulted in any noticeable change in recessionary behaviour in sub-catchment I that is also not evident in sub-catchment K. That is, mining in the upper reaches of sub-catchment I has not impacted on flows recorded at the flume further downstream, consistent with the results of monitoring of the quantity of water resources reaching the Woronora Reservoir for the Waratah Rivulet and Eastern Tributary".*

The Panel concurs with this summary observation and recommends a further analysis of the recessions that cover at least the initial 12-month period.

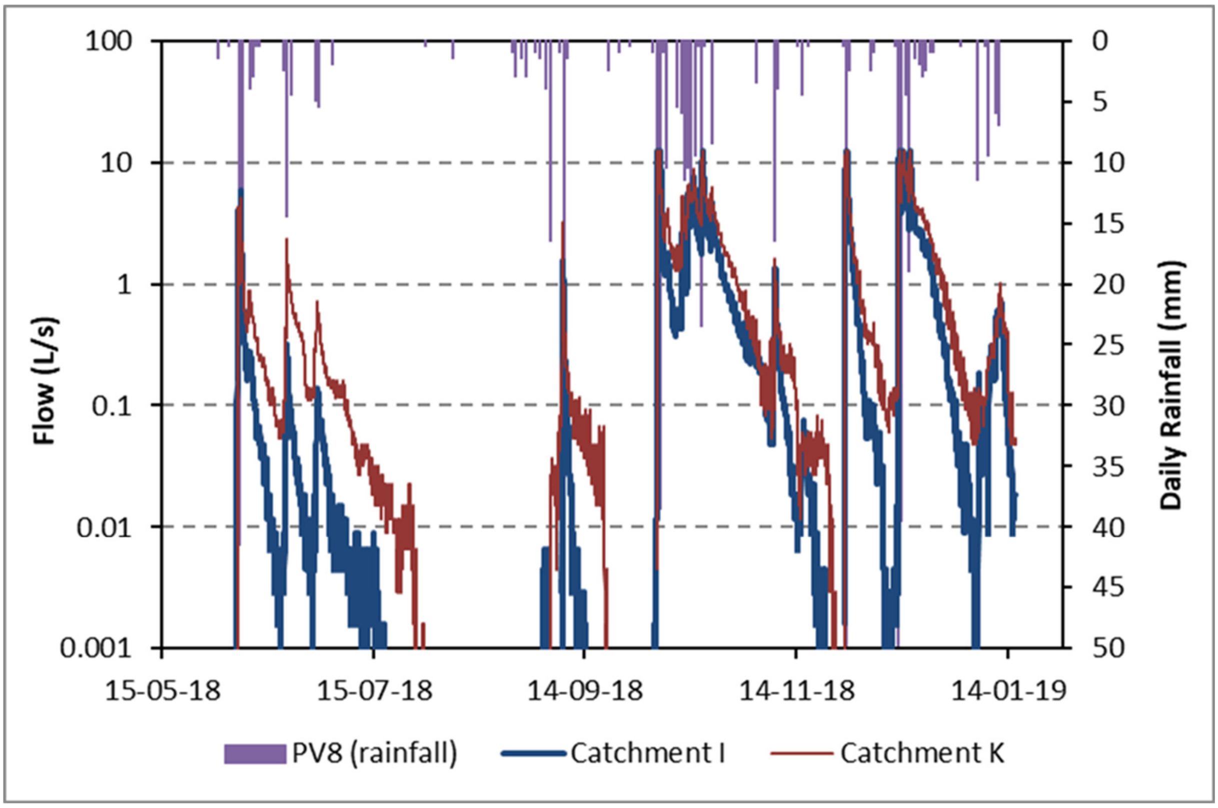


Figure 6.5 Measured hydrographs at flow monitoring stations I and K and observed rainfall at station PV8

(Mining of LW301 was completed February 2018, LW302 was completed November 2018 and LW303 is due for completion late May/early June 2019)

6.2 Woronora Water Balance

In the Stage 1 Impact Strategy Report, it was recommended that a preliminary water balance of the Woronora Reservoir be carried out after which a recommendation would be made whether or not a more detailed water balance should be embarked on. The primary purpose of the water balance was to establish whether the inputs to and outputs from the reservoir could be measured sufficiently accurately to identify whether there was a loss through the bed of the reservoir because of longwall mining being undertaken in the catchment and/or from other activities that may affect the water balance. The following material presents the outcome of the preliminary water balance study and includes some details about the data, the applications of a deterministic and a stochastic model, and an associated uncertainty analysis.

6.2.1 Background and model

Woronora Reservoir is located on the Woronora River and commands a catchment of 74.1 km^2. At full supply level (FSL), the reservoir has a capacity of 81,643 ML and there is an ungated spillway. At FSL, the reservoir surface area covers 3.996 km^2.

Although rainfall on the reservoir provides some input water, most of the input is from three sub-catchments (Waratah Rivulet gauged at 20.57 km^2, Woronora River gauged at 12.43 km^2, and an ungauged area[9] of 41.13 km^2). Also, there is a small inflow to the reservoir from regional groundwater. Most of the water in the reservoir is released downstream for environmental flows and, separately, by pipeline to a nearby water treatment plant. Both these outflows are monitored. A very small contribution of seepage water is monitored at the base of the dam wall. Reservoir evaporation, which is not directly measured, is another output. There is also an unknown outflow from the reservoir through groundwater flow under the dam wall to downstream. The analysis is carried out at a daily time-step covering an approximate six-year period.

The adopted water balance equation (Equation 6.1 below) incorporates all the above inputs and outputs, and a variable representing potential bed loss which is to be estimated.

$$V_t = V_{t-1} + (R_t + SWa_t + SWo_t + SUg_t + GI_t) - (E_t + DWS_t + LF_t + WTP_t + GO_t + Sp_t + PL_t) \quad (6.1)$$

where V_t and V_{t-1} are respectively the reservoir volumes at end of day t and $t-1$, R_t is daily rainfall over the surface water of the reservoir, SWa_t and SWo_t are, respectively, the estimated inflows for Waratah Rivulet and Woronora River, SUg_t is the streamflow estimated from the ungauged area, GI_t is the regional groundwater inflow to the filled portion of the reservoir, E_t is the evaporation from the surface water of the reservoir, DWS_t is the dam wall seepage, LF_t is the low flow (environmental) release, WTP_t is the water treatment plant release, GO_t is the groundwater outflow to downstream of the dam wall, Sp_t is the uncontrolled spillway flow, and PL_t is the potential loss through bed of the reservoir, all during day t. However, as noted later, the groundwater outflow to downstream of the dam wall (GO_t) and the potential loss through bed of the reservoir (PL_t) are combined as the groundwater loss (CL_t) from the reservoir ($CL_t = GO_t + PL_t$).

Reservoir volume simulations are based on two approaches: a deterministic historical model and a stochastic approach. In the case of the deterministic model in addition to examining the full 2112 days of historical data, six windows of consecutive daily data were examined in detail. These were used to estimate the magnitude of the combined groundwater losses from the reservoir.

[9] Two Metropolitan Coal streamflow gauging stations are located in the Woronora Reservoir catchment, one on Honeysuckle Creek and one on Eastern Tributary and record streamflow rates from a small portion of the Woronora Reservoir catchment which is not gauged by the Waratah Rivulet and Woronora River gauging stations (Appendix G).

6.2.2 Data

A key aspect of the analyses reported herein relates to the availability and accuracy of data. The water balance analyses were carried out at a daily time-step covering an approximate six-year period from 21 March 2012 to 31 December 2017. A large effort was expended by the staff of Hydro Engineering & Consulting Pty Ltd (HEC) who were responsible for collating and preparing the data and ensuring the input data for the modelling were the most reliable within the time-frame and resources available. However, if modelling were to proceed to a Stage 2 phase, all data would require further verification.

Figure 6.6 is a map of the Woronora Reservoir catchment and gauged sub-catchments and shows the location of the stream gauging stations, the rainfall stations, the meteorological stations, and the Class-A evaporation pans.

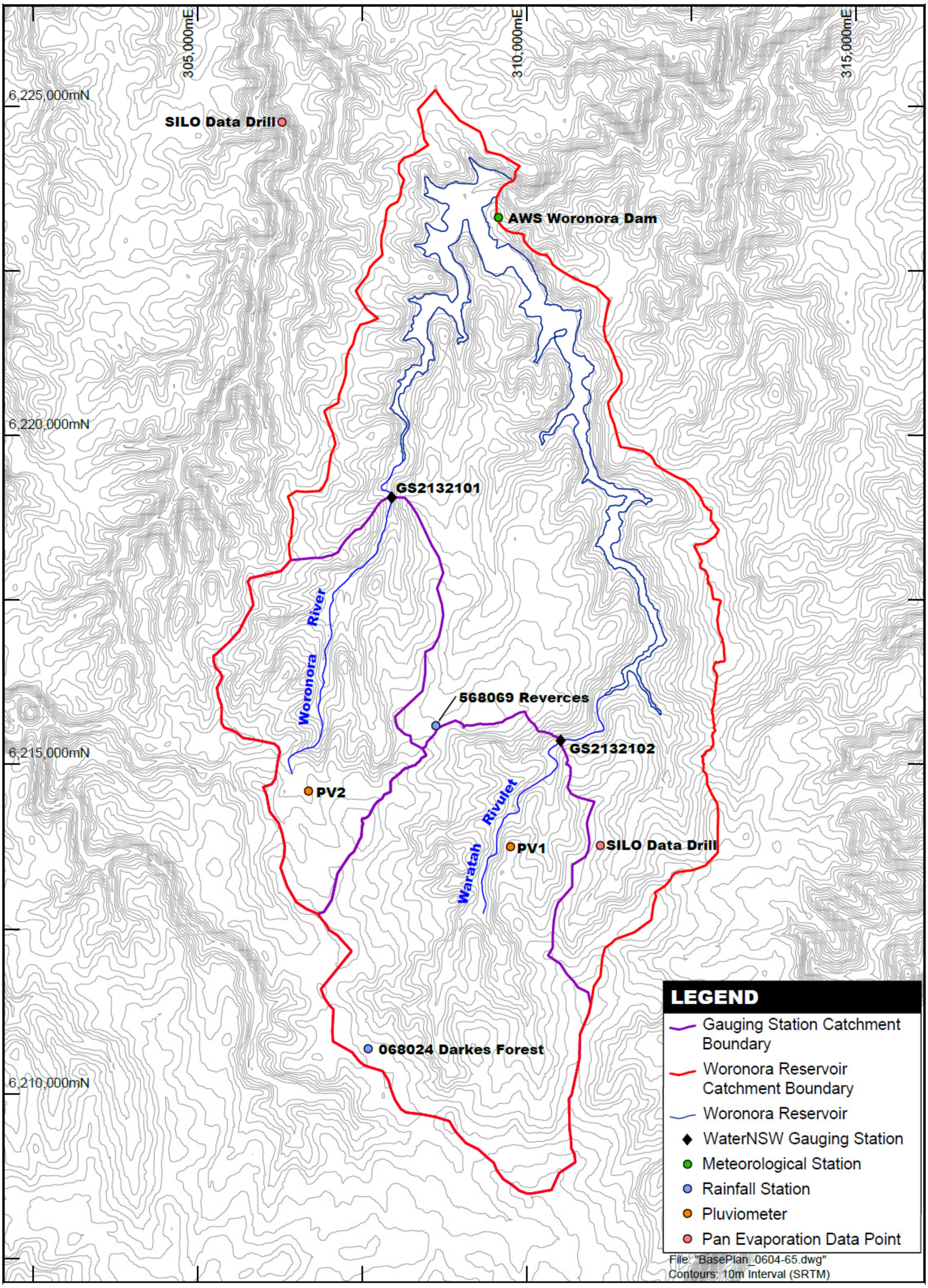


Figure 6.6 Map of Woronora catchment

(source: Hydro Engineering & Consulting)

Reservoir water volume (V)
Based on water level observations, estimated daily reservoir water volumes were provided by WaterNSW in ML.

Rainfall (R)
Daily rainfalls recorded at Woronora Dam (site code 566052) were provided by WaterNSW for the simulation period. The units of rainfall were in mm/day and these were converted to ML/day by applying the surface area of the reservoir for the day in question.

Streamflow (SWa, SWo, SUg)
Three separate sources of inflow were estimated – Waratah Rivulet (SWa), Woronora River (SWo) and the ungauged area inflow (SUg). The first two sources are gauged estimates for Waratah Rivulet at station 2132102 and for Woronora River at station 2132101. The Waratah station was gauged to a maximum discharge of 1,478 ML/day and Woronora station to 205 ML/day. Thus, 16% of the estimated mean annual streamflow is gauged at Waratah and 38% at Woronora. Although these percentages are not particularly high, they permit a reasonably accurate estimate of non-flood flows at these stations during the windows of analysis in estimating potential groundwater losses.

The flows in the ungauged area, which is 56% in area of the Woronora Reservoir catchment, were estimated as follows. The flows were based on a modified AWBM model (Gilbert & Associates, 2015), which had been calibrated previously using Waratah Rivulet data (February 2007 – December 2009). The revised model was used to estimate runoff from 2012 to 2017. The runoff values were adjusted for the known catchment area which depends on the water level in the reservoir. The flows from ungauged area are a major source of uncertainty.

Groundwater (GI)
Groundwater inflows to the reservoir were estimated under steady state conditions using a pseudo-2D section of the reservoir integrated along the two storage arms using the observed variation in hydraulic conductivity in the profile. (Data provided by Dr F Kalf, 31 October 2018 – see Appendix E.)

Evaporation (E)
Estimating evaporation from a deep reservoir is not straightforward. Two methods were explored to do this – Kohler and Parmele (1967) and Vardavas and Fountoulakis (1996), both incorporate the stored energy in the reservoir. The following daily or monthly data were used in applying these methods: rainfall, solar radiation, air temperature, humidity, wind speed/run, water temperature, inflow temperature, temperature of released water, reservoir depth, and Class A pan evaporation.

In Figure 6.7, estimates of monthly lake evaporation for Woronora Reservoir are plotted for the procedures of Kohler and Parmele (1967) and Vardavas and Fountoulakis (1996), along with Class A pan data derived from the SILO Data Drill evaporation record. (The figure also shows the Kohler and Parmele estimate increased by 37%, which was the adjusted value adopted in applying the water balance to estimate the potential loss – see Section 6.2.3 for details.)

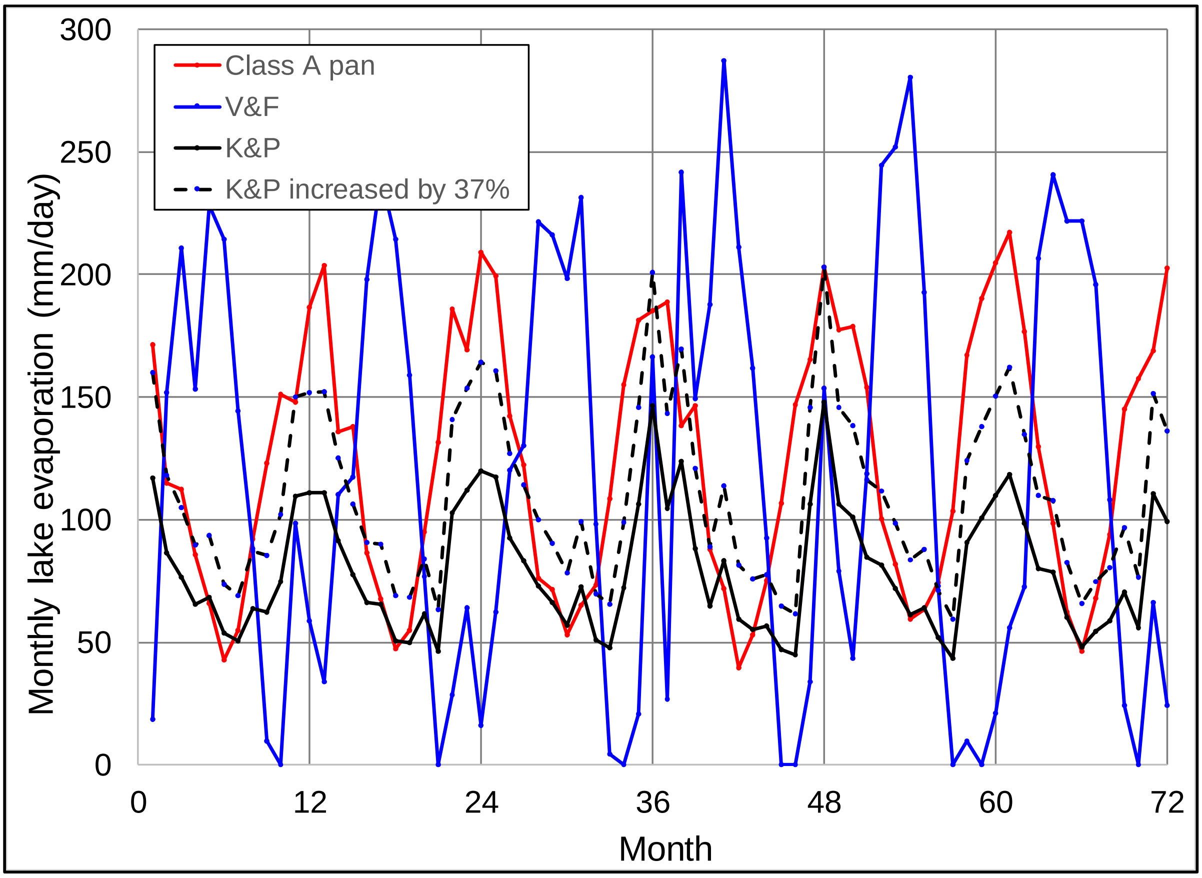


Figure 6.7 Estimates of monthly lake evaporation (V&F: Vardavas and Fountoulakis (1996) and K&P: Kohler and Parmele (1967)) compared with Class A pan SILO DD estimates for Woronora Reservoir

Because of the erratic pattern of the monthly evaporation and the excess number of zero or near zero values, the more consistent monthly values of Kohler and Parmele (1967) were adopted over those of Vardavas and Fountoulakis (1996). However, the Kohler and Parmele (1967) values are low compared to the pan data and to Vardavas and Fountoulakis (1996) monthly estimates. Hoy and Stephens (1979), Weeks (1982) and Kotwicki (1994) together provide Class A pan coefficients for 16 reservoirs or lakes across Australia (McMahon et al., 2013, Table S12) in which the average pan coefficient is 0.83, the range is 0.66 to 1.0, and the 75-percentile value is 0.89. These data would suggest the Kohler and Parmele (1967) lake evaporation values need to increase by 27% for Woronora to evaporate at a rate equivalent to the average reservoir (or lake) pan coefficient (0.83) estimated from McMahon et al., 2013, Table S12. A 27% increase in Kohler and Parmele (K&P) was initially adopted in the base-case analysis but for the loss analysis K&P was increased to 37% to ensure a water balance as noted above and discussed in Section 6.2.3. This analysis suggests that estimates of reservoir evaporation are uncertain.

Dam wall seepage (DWS), Environmental or low flow releases (EF) and Water treatment plant releases (WTP)

Low flow release and water treatment plant release data were provided by WaterNSW in ML/day. Dam wall seepage rates (ML/d) were calculated based on daily measurements of seepage depth through a v-notch weir. The v-notch weir water level measurements and flow rate formula were provided by WaterNSW.

Groundwater discharge below dam wall (GO)

Because a groundwater model that extended downstream beyond the dam wall was not available, it was not possible to estimate the groundwater flow downstream under the dam wall. In view of this, we have combined in the water balance model the unknown GO_t with PL_t, the potential loss through bed of the reservoir which is to be estimated. If modelling were to proceed to Stage 2, a groundwater model would need to be developed that could be used to estimate groundwater flows downstream. We note there is no grout curtain below the wall.

Spill (S)

The reservoir reached the FSL on one occasion during the six-year period, and a small spill (1,342 ML) over a 7-day period was recorded. Data were provided by WaterNSW.

Bathymetry data

The bathymetry data, which was used to estimate the relationship between reservoir surface water area, reservoir depth and reservoir volume, were provided by WaterNSW.

6.2.3 Deterministic model and potential groundwater loss[10]

Deterministic model

As noted above, the unknowns in Equation (6.1) have been combined and unless otherwise noted the following discussion relates to the combined loss (CL_t). Equation (6.1) is the basis of the deterministic model and applied on a daily time-step starting on 21 March 2012 with an initial reservoir volume (V_t) of 70,931 ML. As each day's data were routed through the reservoir, the variables relying on reservoir water surface area were adjusted using the known surface area-volume relationship, noting that area for the ungauged catchment also needed to be adjusted. The results of applying the model assuming no losses (base-case) are presented in Table 6.1 (middle columns) and the simulation for the base-case is shown in Figure 6.8. The small out-of-balance balance (defined as the final modelled reservoir volume less observed volume) was achieved by adopting the Kohler and Parmele (1967) lake evaporation estimate increased by 27% (see discussion above).

[10] This Panel member (TAM) acknowledges the helpful discussions about the water balance analysis held with the staff of Hydro Engineering & Consulting Pty Ltd.

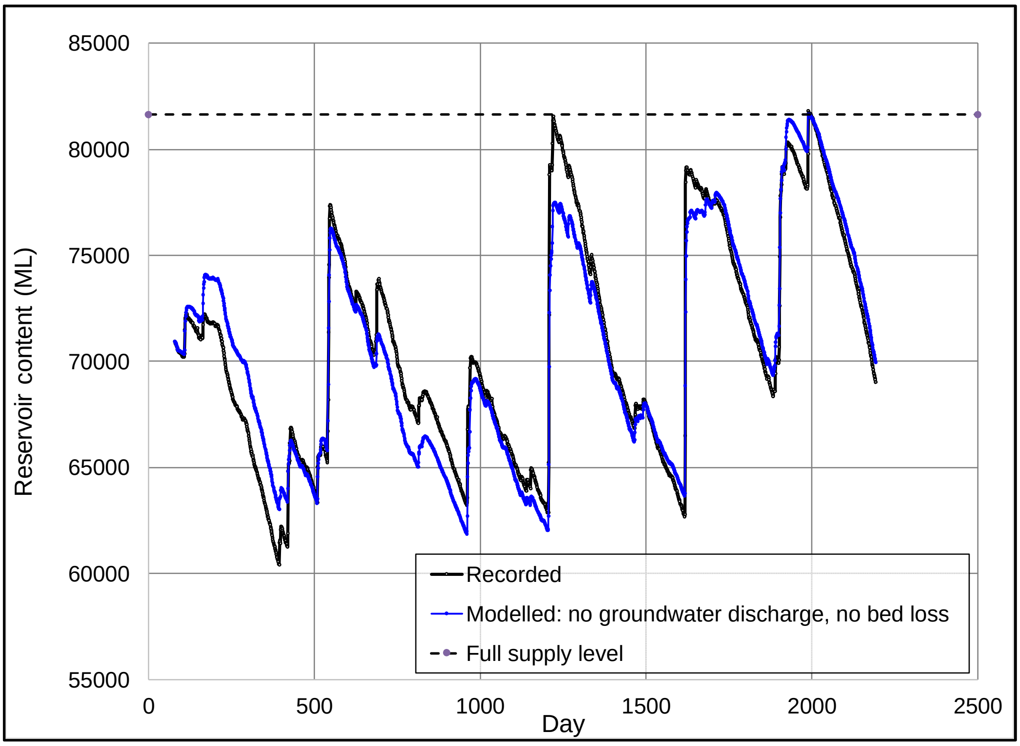


Figure 6.8 Woronora reservoir behaviour diagram for the period 21 Mar 2012 to 31 Dec 2017 for two conditions: (a) Recorded reservoir volume (b) Modelled reservoir volume assuming no combined groundwater loss and Kohler and Parmele lake evaporation increased by 27% (base-case simulation)

The base-case simulation, shown in Figure 6.8, suggests that except for the peaks and the period from day 1624 (11 Jun 2016) to day 1684 (10 Aug 2016) the model mimics the recorded reservoir volumes satisfactorily. During days 1624 to 1684, the model predicts an increase in reservoir volume whereas the monitored reservoir volumes fell. This suggests the mis-match may be due to data errors in variables other than inflow. In Table 6.1 (middle columns) we note that about 86% of the inputs to the reservoir are streamflow of which 58% is from the ungauged area. There are three major sources of output: lake evaporation 16%, low flow downstream release 21%, and WTP releases 62%.

As noted above there appear to be two major sources of uncertainty in the model as listed in Table 6.1 – the ungauged area inflows and the actual lake evaporation. The importance of these uncertain variables is discussed later.

Table 6.1 Water balance simulation based on the deterministic model using daily data for the period 21 March 2012 to 31 December 2017

		Base-case analysis. Assumed no loss.		Combined loss estimated. 7,900 ML added to ungauged area inflow to achieve minimal out-of-balance.	
Variable		ML/year	%	ML/year	%
Inputs to reservoir					
Rainfall		3,425	12.1	3,444	11.7
Flow	Waratah (20.57 km^2)	7,621	27.0	7,621	25.8
	Woronora (12.43 km^2)	2,612	9.2	2,612	8.8
	Ungauged (41.13 km^2)	14,016	49.6	15,299	51.8
Groundwater		583	2.1	579	2.0
Total input		28,257	100.0	29,556	100.0
Outputs from reservoir					
Evaporation		4,325	15.5	4,694	15.8
Dam wall seepage		116	0.4	116	0.4
Low flow release		5,889	21.1	5,889	19.9
WTP release		17,404	62.2	17,404	58.7
Spill		232	0.8	457	1.5
Groundwater outflow		0	0.0	1,068	3.6
Loss through bed		0	0.0		
Total output		27,966	100.0	29,628	100.0
Out-of-balance (ML)*		922		146	

*Final modelled reservoir volume less observed volume

Potential Groundwater Loss

In estimating the combined groundwater loss from the reservoir, we use Equation (6.1) with CL_t (the combined loss) being the dependent variable which was estimated from the six reservoir volume recessions shown in Figure 6.9. These periods were chosen because the inflows were relatively low and, therefore, the effects of unreliable inflow estimates were minimised. The six recessions varying in length from 41 to 115 days covered a total of 502 days. If there were no losses and the model was perfect, the slope of a modelled recession would be the same as the slope of the recorded recession. This feature was exploited in the following way.

For a specified combined loss, a daily water balance was carried out across the approximately six years of simulation and then, separately, for each recession the out-of-balance between the total inputs and total outputs was computed. Although the net difference varied across the individual recessions, the combined loss was adjusted to ensure there was no difference between the inputs and outputs summed over the six periods. To ensure there was minimal out-of-balance of the reservoir volume at the end of the 2112-day simulation, the inputs to the model were adjusted to offset the losses. This was achieved by adding two additional flows to the ungauged inflow volumes of 4,900 ML on day 689 and 3,000 ML on day 1209. However, it was also necessary to increase the lake evaporation by a further 7.9% to partly offset the additional flood volume. This adjustment resulted in the Woronora lake evaporation being equivalent to a Class A pan coefficient of 0.89, a value in the range discussed above and reported in McMahon et al. (2013) where a value of 0.98 is listed for Cataract Reservoir.

The results of this analysis are presented in Figure 6.9, as a simulation of the modelled reservoir volumes compared with the recorded reservoir volumes, and in Table 6.1 (right side columns) where the results can be compared to the base-case. Based on the analysis, a combined average groundwater loss of 2.9 ML/day was estimated. Table 6.1 shows that the optimized loss is offset by an increase in inflow to achieve a no out-of-balance condition of the final state of the reservoir volume and an increase in lake evaporation. The two days in which the flood inflows were increased are identified in Figure 6.9. But what is important in the figure is the ability of the model, which incorporates an estimated combined loss, to follow very closely the slope of the recorded recessions suggesting the model performed satisfactorily.

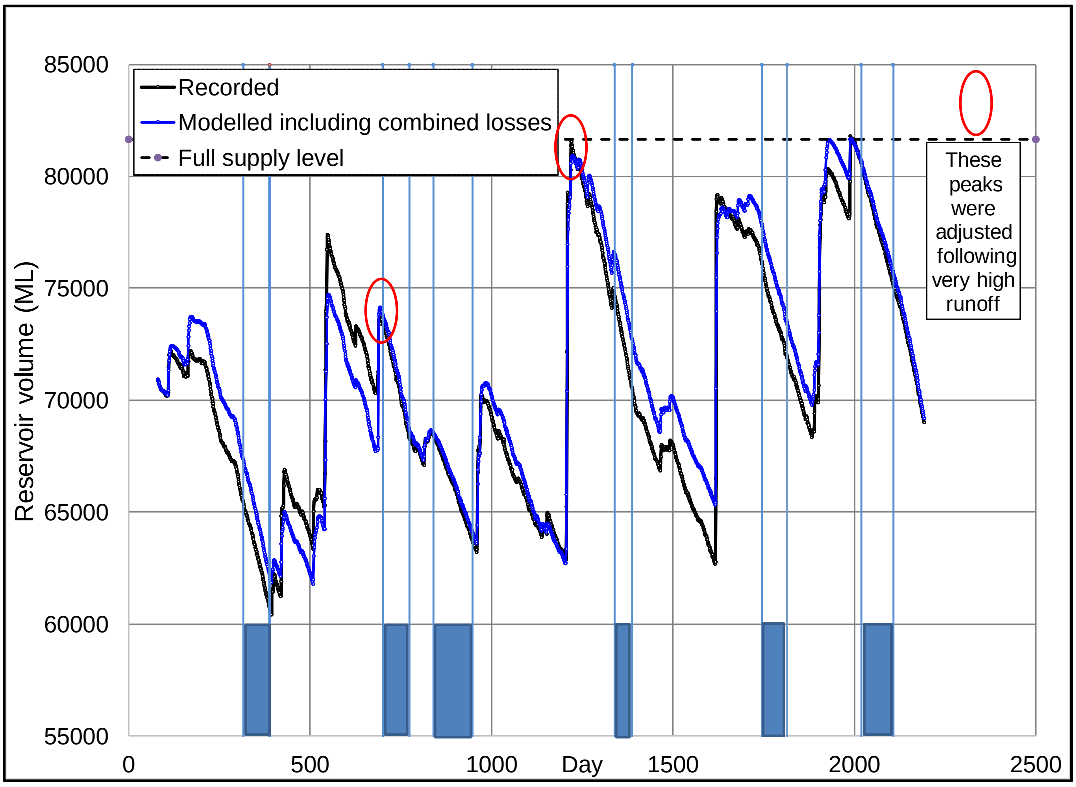


Figure 6.9 Woronora reservoir behaviour diagram for the period 21 Mar 2012 to 31 Dec 2017 for two conditions: (a). Recorded reservoir volume (b) Estimated volumes using water balance model adopting base case inputs and outputs and incorporating a daily combined groundwater loss of 2.9 ML/day and increasing two flood volumes (day 689 by 4900 ML and day 1209 by 3000 ML)

The estimated groundwater losses as a function of changes in lake evaporation are presented in Table 6.2. Lake evaporation for three class A pan coefficients (0.80, 0.89 and 0.98) were explored. The evaporation factor of 1.37, equivalent to a pan coefficient of 0.89, was applied to the K&P daily evaporation estimates and is used in the loss modelling above. The pan coefficient of 0.98 (Cataract Reservoir) is the second highest value of the 16 reservoir and lake pan coefficients listed by McMahon et al. (2013, Table S12). Table 6.2 illustrates the importance of lake evaporation in estimating potential losses; for example, for a ±10% change around a pan coefficient of 0.89, the combined groundwater loss varies from 1.6 ML/day to 3.9 ML/day.

Table 6.2 Estimate of the combined groundwater loss* (ML/day) as a function of changes in lake evaporation

Equivalent class A pan coefficient	0.80	0.89	0.98
Evaporation factor (× K&P)‡	1.27	1.37§	1.50
Combined groundwater loss (ML/day)	3.9	2.9	1.6

** The combined groundwater loss is equal to the sum of the groundwater outflow to downstream of the dam wall plus the potential loss through bed of the reservoir. ‡ K&P is the Kohler and Parmele (1967) lake evaporation estimate. §Factor adopted in the water balance modelling*

Based on the above deterministic simulation of the behaviour of Woronora Reservoir the combined average groundwater loss is estimated approximately 2.9 ML/day, from which we can conclude that the average potential loss through the bed is no more than approximately 2.9 ML/day and probably less depending on the groundwater outflow to downstream of the dam wall.

In summary, the average groundwater loss from Woronora Reservoir was estimated to be less than 2.9 ML/day through the application of the water balance equation in a deterministic way ensuring there was minimal out-of-balance of the reservoir between modelled and recorded volumes. To achieve this, flow from the ungauged area was increased and lake evaporation was also increased. These requirements point to the inadequacy of estimates of both the flow from the ungauged area and lake evaporation.

6.2.4 Reducing bias and uncertainty

Bias

In this investigation bias is considered indirectly. For example, in relation to inflows from the ungauged area it was necessary to increase on two occasions the daily inflows by substantial amounts to achieve a reservoir volume balance. Also, again to achieve a balance, the initial evaporation estimates by the Kohler and Parmele procedure were increased by 37%. This issue of bias is different to the uncertainty represented by the standard error in a variable.

It was observed during the simulations that bias in the estimates of rainfall and inflow makes only a small difference in the estimate of groundwater loss due to their high daily variability but do affect the out-of-balance of the reservoir volume. In terms of variability, the coefficients of variation (Cv) of daily rainfall and inflows vary from 3.5 to 6.0 which are very large compared to the Cv for groundwater inflow of 0.1 and for the releases from the WTP of 0.4. As a result, an upward bias of 6% in WTP releases is sufficient to reduce the potential groundwater loss to zero. Alternatively, increasing the lake evaporation equivalent to a pan coefficient of 0.98 (the same as Cataract Reservoir) would result in a potential combined average groundwater loss of 1.6 ML/day. This brief analysis highlights the importance of using data in the water balance that has minimal bias.

Bias will also be affected by the extrapolation of the rating curves for Waratah and Woronora gauging stations, and by unreliable estimates of inflow from the ungauged area.

Uncertainty

In this analysis, uncertainty is defined as the standard error in each variable. Reducing the uncertainty of the key variables will be difficult. Where uncertainty information is based on a literature search, for example rainfall, a more detailed search is required especially reports from government agencies. We have already noted the importance in bias of extrapolation of rating curves and the estimation of flow from the ungauged area and the unsatisfactory estimation of lake evaporation. The uncertainty in these latter variables is a major issue and a more complete analyses of the standard errors are required. Understanding the uncertainty in bathymetry is important in estimation of uncertainty in reservoir volume estimates that are used in the model along with uncertainty in the reservoir area–volume relationship.

To estimate the uncertainty in the combined groundwater loss, we examined 18 independent samples of modelled and recorded reservoir volumes, each of 25 consecutive days extracted from the 502 days of recession described in Section 6.2.3 and identified in Figure 6.9. The sample mean of the combined groundwater loss ranged from 5.7 ML/day to -11.2 ML/day with a standard deviation of 5.4 ML/day. This translates to a standard error in the combined groundwater loss estimate of 1.3 ML/day with a 95% confidence range of 0.4 ML/day to 5.4 ML/day.

The issue of uncertainty is explored further in Table 6.3 which is based on the analysis provided for each variable in Appendix F. Here the effective variance is estimated as a percentage in each variable and confirms the two largest sources of uncertainty in the water balance are the inflow from the ungauged area and lake evaporation, the latter mainly due to the very high autocorrelation (0.94) in the daily data. In the analysis, the standard errors for the two gauged inflows were for the rated portion of the rating curves, and for the ungauged area were for values less than the mean estimated flow. In the table the variance was adjusted for autocorrelation using Equation (6) in Appendix F and the weightings were based on the magnitude of each variable in the water balance equation.

Table 6.3 Identifying key variables in the water balance

Variable	Standard error (ML/day)	Auto-correlation (ρ)	Variance adjustment for ρ	Variance weightings based on MLs	Effective variance	Percentage effective variance
R	2.3	0.35	11	0.06	0.7	0.3%
SWa	2.4	0.54	19	0.13	2.5	1.2%
SWo	1.9	0.52	12	0.04	0.5	0.3%
SUg	23.6	-0.01	547	0.26	143.6	68.2%
G	0.25	-0.14	0.0	0.01	0.0	0.0%
E	4.9	0.94	781	0.08	61.5	29.2%
DWS	0.01	0.54	0.0	0.00	0.0	0.0%
LF	0.24	0.86	0.8	0.10	0.1	0.0%
WTP	0.64	0.86	6	0.30	1.6	0.8%
Vo, Vn	19			0.00	0.0	0.0%

R is daily rainfall;

SWa and SWo are, respectively, Waratah Rivulet and Woronora River inflows;

SUg is ungauged area inflow;

GI is regional groundwater inflow;

E is reservoir evaporation;

DWS is dam wall seepage;

LF is low flow (environmental) release;

WTP is water treatment plant release.

6.2.5 Stochastic model

This section dealing with the stochastic model is based on an independent analysis[11] prepared by Hydro Engineering & Consulting Pty Ltd (HEC) which is reported in detail in this Report as Appendix G. The stochastic model analysis complements the deterministic model and uncertainty investigation described above.

The stochastic modelling approach adopted by HEC was to simulate the Woronora water balance on a daily time-step using the GoldSim® software package within a Monte Carlo framework incorporating a random error (uncertainty) for each variable. The uncertainty values were based on Appendix F (which is included as Appendix A in the HEC Report). The stochastic simulation provided 1000 independent realizations of the daily model incorporating uncertainty of each individual variable covering the period from 21 March 2012 to 31 December 2017. The 1000 replicates were then used to assess the overall uncertainty in the modelling of the Woronora Reservoir water volumes.

It is noted the HEC analysis is based on the same data set (collated by HEC) as adopted in the deterministic model analysis described above. Compared with the discussion about the data set in Section 6.2.2, the description of the data is more complete in Appendix G.

[11] This Panel member (TAM) provided comments to HEC at various stages of their analysis.

The results of the stochastic analysis are succinctly summarised in Table 5, and Figures 10 and 11 of Appendix G. The uncertainties reported in Table 5 are not inconsistent with those summarised in Table 6.3 in that the latter deal with the effective variance in the variables whereas the uncertainties in Table 5 consider separately the range of values across the 1000 replicates. Table 5 supports the earlier observation that the ungauged streamflow and evaporation are associated with the largest uncertainties. The table shows that there are considerable uncertainties in the rainfall and groundwater inflow estimates. The significance of the large uncertainty in the inflows from the ungauged area is illustrated by the comparisons in Figures 10 and 11 where, in the latter figure, no error in the ungauged area is included and the uncertainty in the reservoir volume estimates are greatly reduced.

Based on their stochastic approach, HEC offer the following conclusions:

> *"… the magnitude of bias and uncertainty evident in the stochastically simulated reservoir volume indicates that the water balance model, in its current form, is unsuitable for use as a baseline against which potential low (i.e. mine related) rates of loss from the reservoir may be assessed."*
>
> *"In order to increase the potential for the water balance model to be used as a baseline, the ungauged streamflow and evaporation data adopted in the model would need to be significantly improved. Establishment of a number of additional streamflow gauging stations would be required in the currently ungauged catchment to provide more reliable estimates of streamflow rate. The method for estimating evaporation from the reservoir water surface would also require further investigation and monitoring, particularly with respect to factoring of the evaporation rates."*

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Geotechnical

- The ongoing subsidence monitoring program at Metropolitan is proceeding satisfactorily, with good levels of confidence achieved in the prediction model used by MSEC and a comprehensive array of monitoring stations and survey technologies in use.
- A prediction model has now been produced covering all of the proposed longwall panels (through to LW317) beneath and adjacent to the Reservoir. This prediction model is regarded as being of a high standard, with good confidence in the predictions based on the LW301, 302 calibration experience. The predictions clearly show the benefit of narrower panels and wider pillars beneath the reservoir, in terms of significant reductions in predicted subsidence.
- The bedding plane shear monitoring using borehole inclinometers has been very successful (unfortunately TBS03 inclinometer ceased to function after the longwall passed beneath it). These results have clearly identified multiple planes of shear both within the Hawkesbury Sandstone and at the top of the Bald Hill Claystone. The shears have initiated at a distance of less than 400m from the approaching longwall face, with strata movements in the direction towards the approaching goaf.
- A particularly valuable, and possible unique set of results has linked bedding plane horizontal hydraulic conductivity measurements, both pre- and post-mining, with the identification of these shear planes ahead of LW302. These results have demonstrated that not all shear planes demonstrate increased conductivity, even though they have exhibited significant shear (20mm – 50mm).
- Evidence from previous boreholes demonstrates that the basement rocks are over 1,700m below the Bulli Seam at Metropolitan, in contrast to less than 100m below the working seam at Springvale Colliery. Hence, comparisons of impacts of surface lineaments on water flow, as suggested by the IEPMC, whilst worthy of investigation, should be treated with caution.
- The following new technologies have been evaluated for monitoring subsidence-related effects and impacts, with varying success:
  - InSAR – not being pursued due to limitations with application under prevailing surface conditions at Metropolitan.
  - LIDAR – very useful technique for total coverage assessment of vertical subsidence. Opportunity to use with drones provides greater benefits and applications.
  - Bathymetry – currently on hold due to lack of water in the Reservoir.
  - GNSS – very useful, precise, continuous 3D positioning system, now implemented over LWs301 – 303.
  - High precision survey lines – excellent tool for monitoring of valley closure, subject to suitable installation locations.
- The current subsidence monitoring regime should be continued with regular updating of observed versus prediction results, to maintain confidence levels in future predictions.

- Further predictions of closure across the Reservoir should be provided, in response to the proposed undermining panels.
- Continued use of bedding plane shear monitoring should be pursued if possible, if more cost-effective technologies can be found, especially with consideration given to installation of one or more measurement sites at further distant borehole locations on one or both sides of the Reservoir. (The significant cost of inclinometer installations is recognised, hence the desire to find alternative, more cost-effective solutions to deliver similar bedding plane behavioural data).
- It is strongly recommended that the GNSS array network be extended at the earliest opportunity to both sides of the Reservoir to establish a more comprehensive regional array of these monitoring stations.
- Consideration should be given to whether some high precision survey lines can be installed across the Reservoir valley, closer to the valley floor, in conjunction with the extended GNSS array.

7.2 Groundwater

- The groundwater pressure head results at LW302 indicate that there was virtually no pressure head propagation beyond about 80m from the surface and very little above 150m from the surface.
- The substantial decline of piezometer pressure head indicates that it is likely that depressurisation and desaturation of both the fracture network and possibly the associated rock matrix has occurred and is occurring in the upper part of the deeper geological profile.
- No response to water levels was observed due to mining in TBS02A and 302GW01A observations bores (Figure 5.2) validating that no fracture network propagated to the Hawkesbury Sandstone shallow groundwater system.
- Analysis of the substantial decline of piezometer pressure head in borehole 302GW01 has yielded possible extended fracturing and/or matrix depressurisation above the caving zone within a height of 195m. It suggests possible extended fracturing and depressurisation up to a depth of 340m below the ground surface. The Tammetta equation for comparison has yielded a drainable or at least a depressurisation/desaturation fracture extent of 173m above the caving zone for a cutting height of 3.2m. The Ditton equation produces a similar height (174m) if a "beam" thickness of 20m is adopted.
- Further research has determined the following about the ratio ***W/H*** (Panel Width/Depth-of-Cover). Although the ratio ***W/H*** is not directly related to Height of fracturing (HoF) it is nevertheless an important and useful ratio for the purposes of determining the extent of possible vertical fracturing in most geological profiles that occur in practice with due consideration given to subsidence and mining height. This has been validated at Dendrobium mine site. There is however a condition where this ratio becomes less relevant at shallow depth when ***W/H*** is purported to be greater than about 1 (according to our geotechnical consultant) and when it would possibly approach or start to interact with the shallow fracture zone. However, this can just mean that connective cracking, the important issue, can occur close to ground surface. **But this is not relevant at the Metropolitan Coal site.**

Some investigators have stated that Panel Width (***W***) combined with mining height ***t*** to be a more suitable relation. The Strategy 1 and 2 authors nevertheless stand by the use of the ***W/H*** ratio in the Strategy 1 report when comparing that ratio at the Dendrobium and Metropolitan Coal sites as a "screening" device. As noted previously the Dendrobium mining parameters used and hence the overall consequences of mining there should not be used as a "blueprint" for mining conditions that currently occur and in the future at the Metropolitan site.

- Whilst it has been thought (in some cases incorrectly) that the placement of piezometers in the centreline of the extracted Longwall panel fracture parabola would capture the full extent of fracturing (e.g. the somewhat stylised conceptual model Figure 4.1 herein), this is not necessary the case. Shear fracturing that occurs at the margins of such a parabola can also propagate in a vertical direction under certain conditions.
- At borehole F6GW4 situated between longwalls footprints 303 and 304 substantial pressure decline occurred in piezometers at 362m and 440m at a height of up to 143m above the mining zone with the mining zone at a depth of cover of about 505m. However, F6GW4 is situated between LW303 and LW304 and may not therefore represent the profile response in the central part of the panel.
- With regard to Longwall 305 access for establishing piezometers will be the difficult but as noted above *"As part of the Longwall 304 Water Management Plan Metropolitan Coal has indicated that it will install a post-mining multi-level bore over Longwall 305. The bore will extend to the fracture zone and will assess permeability below the Bald Hill Claystone."*
- It is understood that MODFLOW-SURFACT code is still currently in use by SLR (formerly HydroSimulations). It is therefore suggested that SLR update and calibrate their MODFLOW model for representing all the current mining outcomes.
- Model derived cross sections should be generated to display the pressure head profiles before and after mining specific panels with the zero pressure heads clearly displayed. Such sections will become more important in demonstrating the mining consequences of longwall extraction beneath the Woronora Reservoir in the future.
- At the current Metropolitan Coal site it would useful to see modelling conducted using the 'stacked drain' approach that would not only be more conservative but provide much improved numerical stability and convergence that has been experienced in the recent simulations conducted elsewhere by HydroSimulations (now SLR).

7.3 Surface Water

Following a recommendation in the Woronora Reservoir Strategy Report - Stage 1, two streamflow monitoring stations were installed in sub-catchments to the west of Longwalls 301-303. Based on preliminary analysis of discharge data from the stations it was observed that "… mining in the upper reaches of sub-catchment I has not impacted on flows recorded at the flume further downstream, consistent with the results of monitoring of the quantity of water resources reaching the Woronora Reservoir for the Waratah Rivulet and Eastern Tributary". The Panel concurs with this summary observation and recommends a further analysis of the recessions that covers at least the initial 12-month period be conducted as soon as feasible.

The primary purpose of the water balance analysis was to establish whether the inputs to and outputs from the Woronora Reservoir could be measured sufficiently accurately to estimate a loss through the bed of the reservoir because of longwall mining being undertaken in the catchment and/or from other activities that may affect the water balance. All the inputs (rainfall, stream inflow and groundwater inflow) and outputs (evaporation, dam wall seepage, low flow release, water treatment release, spill) except for groundwater outflow below the dam wall were either estimated or measured. Because the groundwater outflow under the dam wall could not be adequately estimated, the potential loss of water through the bed was combined with the groundwater outflow as the unknown variable in the water balance equation. Based on a daily water balance analysis, the combined average groundwater loss was estimated over a window of 502 days within 2112 days of simulation as 2.9 ML/day.

The combined average loss of 2.9 ML/day is subject to a 95% uncertainty band between 0.4 ML/day to 5.4 ML/day, in which ungauged inflows to the reservoir and reservoir evaporation are the major contributors to the uncertainty. An independent stochastic analysis of the water balance of Woronora Reservoir water volumes by Hydro Engineering & Consulting Pty Ltd confirmed these inadequacies. A further complication in estimating the potential loss of reservoir water through the bed is the proportion of loss that can be attributed to groundwater flow under the dam wall. Even if this could be estimated through the application of a more complete groundwater model extending beyond the whole reservoir, the uncertainty associated with the outflow estimate would be large. The issues identified in the current water balance suggest that the magnitude of bias and uncertainty in the data used in the analysis is such that it is of doubtful that the water balance values provide a satisfactory baseline for assessing the potential loss of reservoir water through the bed. Also, it may not be possible to improve sufficiently data collection to enable reliable estimates of future mine induced losses to be identified or quantified unless they are relatively large, for example, larger than say 5.4 ML/day).

Taking into account the facts that groundwater outflow could not be adequately modelled, that there are problems in stream gauging a large proportion of the current ungauged area, and there are difficulties in estimating reservoir evaporation, it is recommended that a Stage 2 water balance study be not undertaken. However, if it were to proceed, all data used to develop the input and output components of the water balance would require detailed reassessment. In this context we note that if a more rigorous water balance analysis was carried out, we caution that the conclusions from such an assessment would inevitably be limited.

8.0 REFERENCES

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Appendix A – Piezometers Rising Pressure

The phenomena of rising water levels in observation bores during a pumping test conducted on a production bore were first noted in the Netherlands at a location Noordbergum (i.e. North-Bergum). Since then it has been referred to as the *"Noordbergum effect".* The rise effect was however in the centimetre range as have subsequent observations at other pumping sites in the world in "aquifer/aquitard" sediments.

Since then the effect observed has been directly attributed to poro-elastic effects in the overlying or adjacent "aquitard(s)" (i.e. very much lower hydraulic conductivity of the groundwater system) due to compressibility during bore pumping and drawdown in the pumped groundwater system.

Since then it has also been noted in fractured rock environments (Schweisinger et.al. 2011 in gneiss). Gellasch et.al. (2014) have noted rises that have been confirmed at tens of metres vertically and distances horizontally of up to 300 metres (Note: due only to a single pumping bore). Such transmission could only have been caused by the poro-elastic effects being directed through fractures at relatively rapid rates, with the rise(s) transmission ahead of the drawdown pressure front (Gellasch et. al. 2014). The rising pressure response has also been confirmed by modelling conducted by Slack et.al. (2013) using slug tests in fractured biotite gneiss. Slack comments that conventional analysis of the slug test:

> *"…uses a simplified approach to evaluate how pressure changes deform the solid framework of the aquifer. In this approach, pressure change, effects aquifer deformation, but the deformation does not affect the pressure change. A more representative account of this coupling considers the effect of the deformation of the solid on the fluid pressure, which results in a source term in the equation governing fluid pressure.*
>
> $$\Delta(K\Delta p) = S\frac{\partial p}{\partial t} - \gamma R \qquad (1)$$
>
> *Where K is the hydraulic conductivity [L/T], S is the specific storage [1/L] and γ is the unit weight of water [M/(L^2T^2). The source term R[1/T] in equation 1 couples pressure diffusion to the strain rate of the solid. For example, R is negative when the solid contracts or when the walls of a fracture are displaced inward. This effect causes the pore pressure to increase, according to equation 1."*

Since pumping bores only create localised drawdown in the higher hydraulic conductivity zone, considerable differences would very likely exist for a single longwall panel and/or multiple panels where extensive 'constant' head drawdowns are created in the caving zone with poro-elastic effects transmitted from fine grained lithology and low hydraulic conductivity layers through the fracture zone(s) created by the mined-out seam.

It would therefore seem possible because of the wide extent of this 'constant' drawdown in the caving zone that the subsequent rising pressure effect would be particularly large in the vertical direction.

Appendix B – Limitations of Definitions of the terms Aquifer and Aquitard

"If you wish to converse with me, you need to define your terms"
Voltaire

As noted in the main text it was stated that the term *'aquifer'* is not well-defined. This is because in nearly all textbooks it depends on undefinable terminology of being a formation where a "*usable" (Bouwer 1978), "economic" (Groundwater and Wells 2007)* or *"significant quantities of water" (Walton 1970), (Freeze1979), Bear (1979),* is available or moves through the formation[12] It depends on the user's interpretation. For most in the community, it has been often found from KA experience, that an *'aquifer'* is where the community would expect to find a *'potable'* supply of groundwater from a bore that clearly may not be accurate. The excessive use of the term in the **Advisian report** is misleading. Such an 'aquifer' water supply could be for example be 0.5 L/sec or less, or 5 L/sec or more as an example. For private domestic pumping 0.5 L/sec, or even somewhat less than that, could indeed be considered as being usable or significant, but for an investigator seeking a town water supply from a bore it would not. In addition such a term does not indicate the quality of the groundwater supply. It gives the impression to many folk that every formation designated as 'aquifer' is pristine and therefore needs to be protected. For example even the Illawarra Coal Measures are described in the **Advisian report** as follows: *"These deeper rocks form a succession of minor aquifers, low permeability water bearing zones and aquitards."* There is no acknowledgement that the groundwater system described is brackish to saline and unsuitable for most purposes and certainly not 'pristine'. The description that the Coal Measures comprise a *"succession of minor aquifers"* is certainly misleading. But interestingly the report states that *"These rocks have little or no productive groundwater resource potential across Special Areas".* Then why would they be considered as 'aquifers'?

The Hawkesbury Sandstone can indeed produce quite variable yields in test bores in the range of yields indicated above that may be suitable for certain domestic purposes but inadequate for use as a town or irrigation bore water supply as the Advisian's hydrogeological author is no doubt aware. This poorer yield potential applies to the Hawkesbury Sandstone around the Woronora area as the Advisian report has clearly noted and also to alluvium and colluvium which are not well developed in that region but supports the swampy conditions at certain elevated surface locations.

The term *'aquitard'* also suffers from the same ill-defined terminology as *'aquifer'* since its impediment of groundwater flow is not adequately defined by the rates of the restricted flow magnitudes under natural or mining conditions in these units.

The Advisian report adds that: *"In mined areas the presence of both small scale and larger extensional faults and any movement along these defects in the rock mass, <u>is suspected to increase the risk</u> of vertical flow from shallow groundwater systems to deep mining voids".* While this is the

[12] Interesting that Bear (1979) indicates other terms often used are 'groundwater reservoir' and 'water bearing zone or formation'.

case at certain locations (e.g. Wongawilli mine described in the Strategy report 1 it is not generally the case. To suggest that this is a very possible occurrence is misleading.

Advisian also describes the basalt lava flow as an *"aquifer"* which is not particularly accurate given that the water bearing zones are thin at the base of the lava flows together with basal sands underlain by low yielding shale formations that are both saline and iron rich.

In the Metropolitan mining area there is no basalt and hence calling that formation regional is not correct. Hawkesbury Sandstone, Upper, Middle and Lower lies immediately below the swampy colluvial sediments at Dendrobium, for example HS (2018).

A comprehensive hydrogeological textbook by Kresic (2007, 807 pages) also questions the ill-defined nature of the word *'aquifer'* in the Section *'Aquifers and Aquitards':*
"An aquifer is a geologic formation, or group of hydraulically connected geologic formations, storing and transmitting significant quantities of potable groundwater. Although most dictionaries of geologic and hydrogeologic terms would have a very similar definition, it is surprising how many interpretations of the word exist in every day's practice, depending on the circumstances. The problem usually arises from the lack of common understanding of the following two terms that are not easily quantifiable: ***significant and potable.*** *For example, a well yielding 2 gpm may be very significant for an individual household without any other available sources of water supply. However, if this quantity is at the limit of what the geologic formation could provide through individual wells, such* [an] *"aquifer" would certainly not be considered as a potential source for any significant public water supply. Another issue is the question of groundwater quality. If the groundwater has naturally high total dissolved solids (TDS), say 5000 mg/L, it would disqualify it from being considered as a significant source of water supply, regardless of the groundwater quantity".*

Thus geological formations can have yields even in the same formation that are very small or very large and can act as continuum regionally in geological units with very low and very high hydraulic conductivity. Hence while the terms *'aquifer'* and *'aquitard'* continue to be used by hydrogeologists, they do remain in a sense 'generic'. It therefore should be kept in mind that the terms may not be strictly correct in describing actual hydrogeological conditions in a geological profile at the Metropolitan and Dendrobium sites.

It is best therefore to refer to a particular layer having a *groundwater system* that is of high or low hydraulic conductivity and if possible to qualify its potential yield with a likely maximum and minimum yield estimate and water quality.

Appendix C – (Golder 2018a)

Table C1 Borehole 302GW01 Packer Test Results. Borehole 302GW01 was drilled to a depth of 500 mbgs with several packer tests within four zones as shown in this report in Figure 5.7. That is, 14 tests overall within the four zones. (To convert from m/s to m/day divide by 86,400 e.g. 5.5 x10-9 m/s = 4.72 x 10-4 m/day)

Table 2: Permeability testing summary and results

Section Top (mbgs)	Section Bottom (mbgs)	Formation	Hydraulic Conductivity (m/s)	Solution Method
238	250	Interbedded Shale & Sandstone	$5.5x10^{-09}$	Bouwer – Rice (Confined Aquifer)
250	262	Interbedded Shale & Sandstone	$2.2x10^{-09}$	KGS Model (Confined Aquifer)
262	274	Interbedded Shale & Sandstone	$1.8x10^{-09}$	KGS Model (Confined Aquifer)
298	310	Bulgo Sandstone	$1.3x10^{-09}$	KGS Model (Confined Aquifer)
334	346	Bulgo Sandstone	$1.2x10^{-09}$	KGS Model (Confined Aquifer)
370	382	Bulgo Sandstone	$1.4x10^{-09}$	KGS Model (Confined Aquifer)
382	394	Bulgo Sandstone	$2.7x10^{-09}$	KGS Model (Confined Aquifer)
394	406	Bulgo Sandstone	$6.3x10^{-09}$	Bouwer – Rice (Confined Aquifer)
406	418	Bulgo Sandstone	$6.8x10^{-10}$	KGS Model (Confined Aquifer)
418	430	Bulgo Sandstone / Stanwell Park Claystone	$9.3x10^{-10}$	KGS Model (Confined Aquifer)
430	442	Stanwell Park Claystone / Scarborough Sandstone	$5.8x10^{-10}$	KGS Model (Confined Aquifer)
442	454	Scarborough Sandstone	$5.5x10^{-10}$	KGS Model (Confined Aquifer)
454	466	Scarborough Sandstone	$4.1x10^{-10}$	KGS Model (Confined Aquifer)
466	478	Scarborough Sandstone	$4.2x10^{-10}$	KGS Model (Confined Aquifer)
478	490	Scarborough Sandstone	$8.9x10^{-12}$	KGS Model (Confined Aquifer)

Table C2 Borehole 302GW01 sampled horizontal and vertical hydraulic conductivity at five locations. (see Figure 5.7)

Formation	Sample Top (mbgs)	Sample Bottom (mbgs)	Porosity (%)	Dry Density (t/m^3)*	Horizontal Permeability (m/s)	Vertical Permeability (m/s)
Hawkesbury Sandstone	79.24	80.24	10.5	2.31	6.0×10^{-10}	1.3×10^{-09}
					7.0×10^{-10}	9.6×10^{-10}
	167.75	168.65	14.7	2.25	2.4×10^{-10}	2.3×10^{-09}
					4.7×10^{-10}	8.5×10^{-10}
Baldhill Claystone	208.18	209.14	5.4	2.71	2.7×10^{-11}	1.5×10^{-11}
					6.0×10^{-11}	2.9×10^{-11}
Bulgo Sandstone	278.95	281.95	9.5	2.35	2.7×10^{-11}	2.9×10^{-11}
					1.0×10^{-11}	8.3×10^{-12}
	383.95	386.95	6.2	2.52	4.3×10^{-11}	4.3×10^{-11}
					1.5×10^{-11}	3.8×10^{-11}

*Dry density values have been quoted from analysis during porosity testing

Appendix D – (Golder 2018b)

Table D1 Borehole TBS02 drilled to 247.8mbgs. Packer tests at 12 locations

Table 1: In-situ permeability results

Section Top (mbgs) †	Section Bottom (mbgs)†	Formation	Hydraulic Conductivity (m/s)	Solution Method
99	111	Hawkesbury Sandstone	6.6×10^{-11}	KGS Model (Unconfined Aquifer)
111	123	Hawkesbury Sandstone	2.1×10^{-11}	KGS Model (Unconfined Aquifer
123	135	Hawkesbury Sandstone	1.6×10^{-09}	KGS Model (Unconfined Aquifer
135	147	Hawkesbury Sandstone	6.6×10^{-09}	KGS Model (Unconfined Aquifer
147	159	Hawkesbury Sandstone	1.8×10^{-09}	KGS Model (Unconfined Aquifer
159	171	Hawkesbury Sandstone	1.2×10^{-08}	KGS Model (Unconfined Aquifer
171	183	Hawkesbury Sandstone	9.6×10^{-09}	KGS Model (Unconfined Aquifer
183	195	Hawkesbury Sandstone	1.6×10^{-08}	KGS Model (Unconfined Aquifer
195	207	Newport Formation	6.9×10^{-09}	KGS Model (Unconfined Aquifer
207	219	Baldhill Claystone	3.6×10^{-09}	KGS Model (Confined Aquifer
219	231	Baldhill Claystone	6.7×10^{-10}	KGS Model (Confined Aquifer
231	243	Shale / Sandstone	1.6×10^{-09}	KGS Model (Confined Aquifer

† metres below ground surface

(Details of the inclinometer instrumentation in TBS02 is provided in the geotechnical section in this Strategy 2 report).

Appendix E – Detailed Woronora Water Balance Flow Components

The section model below (Figure E1) was developed by Dr Kalf from a request by Prof. Tom McMahon for a calculation of the groundwater seepage rates into the Reservoir for different water levels. The model seepages rates were determined for the section model and integrated along the two arms of the Woronora storage.

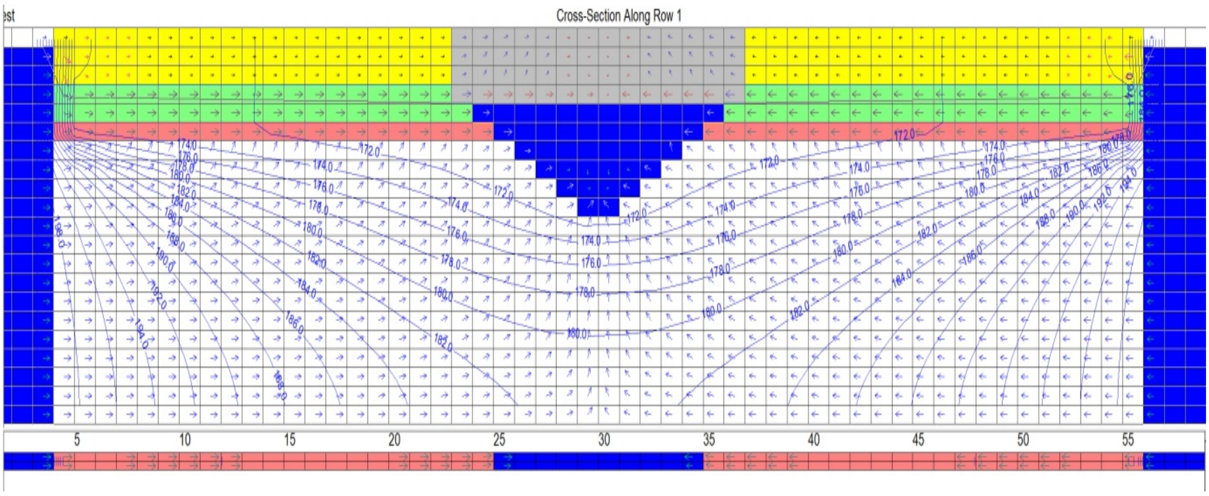

Figure E1. 2D 10 m thick idealised layered section with variable saturation MODFLOW numerical model with variable hydraulic conductivity with depth and Woronora Reservoir indicating flow vectors and hydraulic head contours.

Appendix F - Estimating uncertainty for Woronora water balance

As an input to the Woronora water balance model, we require estimates of uncertainty for each daily variable in the model namely rainfall, streamflow, lake evaporation, reservoir water level, groundwater inflow, dam wall seepage, releases for environmental water and releases to the water treatment plant. As there are only minor flows over the spillway and as this variable is not used in the recession analysis of groundwater discharge, the uncertainty in the spill variable is not considered.

F.1 Rainfall

There are two forms of error (uncertainty) that need to be considered with respect to rainfall: systematic errors and random errors.

Systematic errors

Systematic errors relate to the loss of rain to a gauge because of wind, wetting and emptying losses, evaporation, and splash in and out of the gauge. WMO (1994, Table 1) provides the following systematic error equation:

$$P_k = k\left(P_g + \Delta P_1 + \Delta P_2 + \Delta P_3 \pm \Delta P_4\right) \qquad (1)$$

where P_k is the adjusted precipitation, k is loss due to wind, P_g is measured precipitation (mm/day), ΔP_1 + ΔP_2 are combined wetting and emptying losses respectively, ΔP_3 is loss due to evaporation from the gauge, and ΔP_4 is the splash in and out of the gauge. In Table F1, values of the WMO (1994) parameters are listed with comments, resulting in an adjustment due to systematic errors of $P_k = 1.051P_g$ which is applied to daily rainfalls. The effect of this systematic error was examined in the Hydro Engineering & Consulting Pty Ltd Report (Appendix G) that describes, inter alia, the stochastic water balance modelling of Woronora Reservoir. Figure 9 in Appendix G shows the simulated reservoir volume with and without the systematic error and it was concluded that the -error is unrealistic and, therefore, was not used to adjust rainfall in our analysis. This is an issue that would require further investigation if the modelling were to proceed to a Stage 2 phase.

Random errors

Several references were available to estimate the random error in the rainfall input to the reservoir. In the analysis, we adopted a rain gauge density of 4 km^2/gauge on the basis that one rainfall station is used to estimate the rain input to the reservoir surface of 4.0 km^2 at FSL. Various estimates of the random error as uncertainty estimates from our literature search are presented in Table F2. McGuinness's (1963) proposed an equation, based on data from a small watershed in Ohio, relating average absolute deviation to gauge density and daily rainfall. Steiner (1996) suggested a simple error relationship $(\frac{30}{T})^{0.5}$, where T is days, yielding an uncertainty estimate of 5.5% over the time-step adopted. Based on a 135 km^2 catchment in UK, Wood et al. (2000) estimated the uncertainty of daily rainfall for a single gauge as a function mean rainfall (their Figure 10).

Figure F1 is a plot of the data in Table F2 and presents the uncertainty as a standard error, expressed as the uncertainty estimate in daily rainfall, for a range of daily rainfalls. The uncertainty estimate is given by:

$$\sigma_P = 0.14P^{0.71} \quad (2)$$

where σ_P is uncertainty estimate as a standard error of daily rainfall (mm/day), and P is daily rainfall (mm/day).

F.2 Streamflow

The key uncertainties in the Waratah and the Woronora gauged data used in the water balance modelling relate to the uncertainty in the extrapolations of the rating curves which are unknown. The low flow estimates of discharge are, overall, satisfactory as indicated by the gauging data versus rating curve plots presented in Figure F2. (Analysis follows McMahon and Peel 2019). In view of this, to estimate uncertainty we adopted a simple procedure based on the standard deviation of the residuals (that is the standard errors) computed as the differences between the gauged discharges and the adopted rating curves. For Waratah and Woronora gauging stations, the adopted standard errors were respectively as σ_{Wa} = 2.4 ML/day and σ_{Wo} = 1.9 ML/day.

Regarding the ungauged area, as the flows were estimated using a rainfall-runoff model calibrated for a nearby catchment and upscaled to the area of the ungauged catchment, there is considerable uncertainty in the estimates of flow. To assess uncertainty, the standard deviation of the residuals was adopted which were computed as the differences between the daily discharges estimated from the rating curve and the concurrent estimated discharges from the calibrated model upscaled to reflect the ungauged area. Because of the large errors associated with the large flows, the standard error for the flows from the ungauged area was estimated using only flows less than the mean flow resulting in σ_{Ug} = 8.8 ML/day.

Because of the shortcomings noted above and as the method does not account the skewed nature of the discharges, the procedure to estimate streamflow uncertainty requires detailed analysis if a Stage 2 water balance is carried out.

F.3 Lake evaporation

In his 1986 paper Morton (1986) compared estimates of annual and monthly lake evaporation using his CRLE procedure with those estimated using a water balance for 17 reservoirs in the Canada and the United States. Annual evaporation data were also available for four Australian reservoirs from Vardavas and Fountoulakis (1996) who estimated monthly lake evaporation based on Penman (1948) approach and compared their results with Garrett and Hoy (1978). To estimate uncertainty, we assumed the water balance evaporation estimates used by Morton and those by Garrett and Hoy are correct against which we tested the adequacy of the CRLE Morton procedure. To account for the effect of autocorrelation in estimating a daily estimate of uncertainty of lake evaporation from the monthly and annual standard errors, we applied the Kotz and Neumann (1963, Equation 12) which accounts for autocorrelation. For Woronora daily Class A pan evaporation (https://legacy.longpaddock.qld.gov.au/silo/datadrill/), the autocorrelation is 0.70. The Kotz and Neumann equation is:

$$\sigma_n^2 = \sigma^2\left[n + \left(\frac{2\rho}{1-\rho}\right)\left(n - \frac{1-\rho^n}{1-\rho}\right)\right] \quad (6)$$

where σ_n^2 is the variance of the sum of n consecutive values, σ^2 is the variance of the values assumed to be independent, and ρ is the autocorrelation. For example, in estimating a daily variance from an annual variance, n is 365. The analyses of the annual and monthly data resulted in an estimate of standard error of daily lake evaporation of 1.7 mm/day and 1.4 mm/day based on monthly and annual data respectively. Of the two estimates, it is likely the one based on the annual data is more accurate than the monthly one (see Morton, 1986, page 385).

In the lake evaporation component of the water balance analysis, two complex procedures (Kohler and Parmele, 1967; Vardavas and Fountoulakis, 1996) that account for the stored energy in a reservoir were assessed. Although neither was wholly satisfactory, we adopted the Kohler and Parmele method to provide preliminary monthly lake evaporation estimates. However, for the purposes of assessing evaporation uncertainty we based our analysis, described above, on Morton (1986). A standard error of lake evaporation of 1.4 mm/day was adopted.

F.4 Reservoir water level

No information had been received regarding water level measurements of Woronora Reservoir by the time the water balance report had been finalized. In view of this, an uncertainty estimate was developed as follows. Two factors need to be considered: uncertainty in a water level observation, and uncertainty introduced due to wind setup. We assume water levels are observed or recorded with an uncertainty (standard error) of 0.002 m, the value adopted for stream gauging in Section 2. An additional potential uncertainty results from wave setup affecting the gauge measurement. Pelikan and Koutny (2016) provide an equation to estimate the characteristic wave height, H_0, (trough to crest) as a function of wind speed and fetch as follows:

$$H_0 = 0.0026 \frac{u_{10}^{106} F_{ef}^{0.47}}{g^{0.53}} \qquad (7)$$

where u_{10} is wind speed (m/s) at 10 m reference level, F_{ef} is the effective fetch length (m) (adopted here as 1000 m), and g is the gravitational constant (m/s^2) (9.81 m/s^2). To adjust wind speed measured at 2 m to 10 m, we use (Ladson, 2008, Equation 3.61)

$$u_Z = u_2 \frac{ln\left(\frac{Z}{z_0}\right)}{ln\left(\frac{2}{z_0}\right)} \qquad (8)$$

where u_Z is wind speed at height z, equal to 10 m in Equation 7, and z_0 is the roughness height for water = 0.001 m (McMahon, 2013, Table S2). For a median daily wind speed (2 m height) of 0.78 m/s for Woronora, H_0 = 0.019 m from Equation 7 which results in an uncertainty value of 0.005 m (0.019/4). Combining this with the measurement uncertainty of 0.002 m, an estimate of standard error or uncertainty estimate for reservoir water level is calculated as 0.0054 m.

F.5 Groundwater inflow

Based on a pseudo-2D numerical groundwater model of a section across the reservoir, groundwater inflows were estimated for three capacities. It was assumed for each case in the model the groundwater would flow to an inundated area equivalent to that at FSL. Taking this into account, the estimated groundwater inflows are as follows:

Reservoir water level (and percent full)	70 m (96% capacity)	58 m (50% capacity)	37 m (10% capacity)

Estimated groundwater flow to reservoir	1 ML/day to 2 ML/day	1.5 ML/day	1.2 ML/day

To estimate uncertainty in the groundwater flow, in consultation with Dr F Kalf, the range of error in the model is adopted as 1 ML/day. If we assume a Normal distribution of errors, this is equivalent to a standard error of 0.25 ML/day.

F.6 Dam wall seepage

The dam wall seepage was estimated by the Vee-notch weir formula:

$$Q = CH^{2.5} \quad (9)$$

where Q is discharge, C is the weir coefficient, and H is the water level in the notch. From Equation 9 the following error function is derived:

$$\frac{\Delta Q}{Q} = 2.5\frac{\Delta H}{H} \quad (10)$$

As no information is available about the uncertainty in H, we have adopted the water level error, ΔH, as ±0.003 m (Bos, 1989, page 363). Assuming a Normal distribution, the water level error is equivalent to a standard error of 0.0015 m. Thus, for a gauge height of 0.1 m, the uncertainty estimate is 3.8%.

F.7 Environmental release

We have been advised by WaterNSW that both the environmental flow and water treatment releases were made using electromagnetic flow meters. Based on field testing of seven meters by Hydro Environmental in 2007, Lowe et al. (2009) reported that the errors extended from -2.3% to 3.3%, a range of 5.6%. This is not inconsistent with WaterNSW's estimate of 0% to 5% (phone discussion on 5 December 2018 between Dave Tomlinson, WaterNSW and Tony Marszalek, HEC Pty Ltd) which is a range of 5%. A range of 5.6 % translates to a standard error of 1.4%.

F.8 Release to the water treatment plant

We adopt an uncertainty estimate of 1.4%, based on the discussion in Section F.7.

Table F1. Adopted values of systematic error components in estimating rainfall

Reference/Adoption	k	ΔP_1	ΔP_2	ΔP_3	ΔP_4
WMO (1994)	2% – 10%	Combined 2% -10%		Assume tipping bucket – no loss	1% - 2%
Adopt	Average wind speed ~ 1m/s, k = 5%	Wetting loss ΔP_1 = 2.5%	Assume tipping bucket, ΔP_2 = 0	ΔP_3 = 0	But WMO (2006) does not include splash ΔP_4 = 0

Table F2. Uncertainty estimates (mm/day) in daily rainfall

Reference	Method	Daily rainfall (mm/day)				
		2.5	12.5	25	75	125
McGuinness (1963)	McGuinness Equation 1	0.30	0.72	1.05	1.90	2.51
Steiner (1996)	Steiner Equation 1	0.14	0.68	1.37	4.11	6.85
Wood et al. (2000)	Experimental data	0.52	1.37	2.07	4.00	5.44

Table F3. Error information available in Spank et al. (2013, Table 2) and uncertainty estimates. Spank et al.'s estimates are bolded, and our subsequent uncertainty estimates are shown as normal type. In Spank et al. paper, errors are listed as an intercept (B) and a slope (A), which we have converted using the mean of the variables to individual errors and have combined into a single error estimate for each variable without regard to the distribution.

Variable (average values for Woronora)	Systematic error (uniformly distributed)	Uncertainty estimate	Random error (normally distributed)	Uncertainty estimate	Adopted Uncertainty estimate
Global radiation* (Average solar radiation 22.6 MJ/m^2/day)	**A: 0.95–1.05** Range¥: 2.26	0.56	**A: 0.90–1.10** Range: 4.52	1.13	σ_R = 1.31 MJ/m^2/day
	B: ±0.4 MJ/m^2/d	0.20	**B: ±0.6 MJ/m^2/d**	0.30	
Air temperature‡	**B: ±0.1 K**	0.05	**B: ±0.5 K**	0.25	$\sigma_{Tres} =$ 0.25 °C
Wind speed (0.85 m/s)	**A: 0.98–1.02** Range: 0.034	0.0085	**A: 0.98–1.02** Range: 0.034	0.0085	$\sigma_u =$ 0.14 m/s
	B: ±0.2 m/s	0.10	**B: ±0.2 m/s**	0.10	
Relative humidity (72%)	**A: 0.97-1.03** Range: 4.32%	1.08	**A: 0.97–1.03** Range: 4.32%	1.08	σ_{RH} = 3.2%
	B: ±2.5%	1.25	**B: ±5%**	2.5	

* Assume errors in solar radiation are of the same magnitude as global radiation measurements.

‡ Assume uncertainty in reservoir temperature change is approximately the same as dry bulb temperature.

¥ The range is scaled by applying the slopes (A) to the mean value of the variable, and then the range is divided by 4 (recommended by Hozo et al. (2005) for a Normal distribution) to provide an approximate uncertainty estimate (on the basis that 4 standard deviations account for 95% of the area under a Normal distribution).

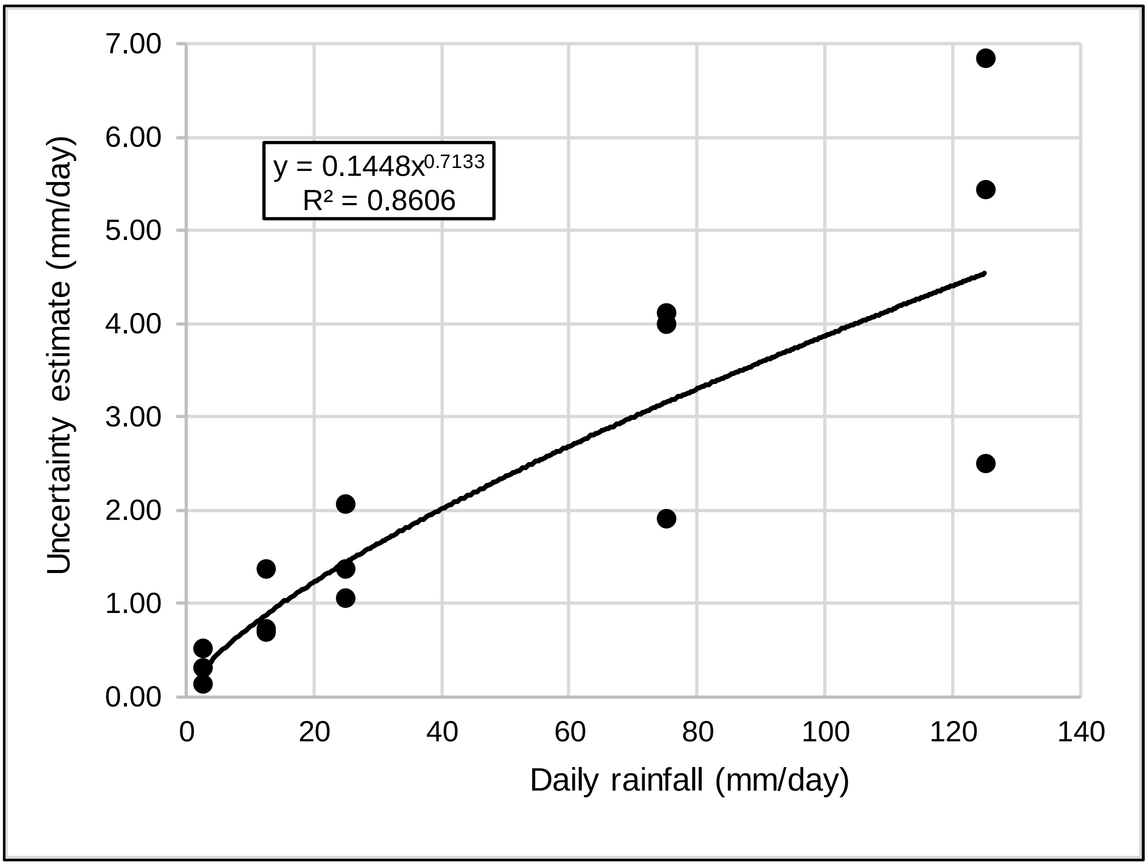

Figure F1. Uncertainty estimates (standard error) based on daily rainfall estimates from Table F2

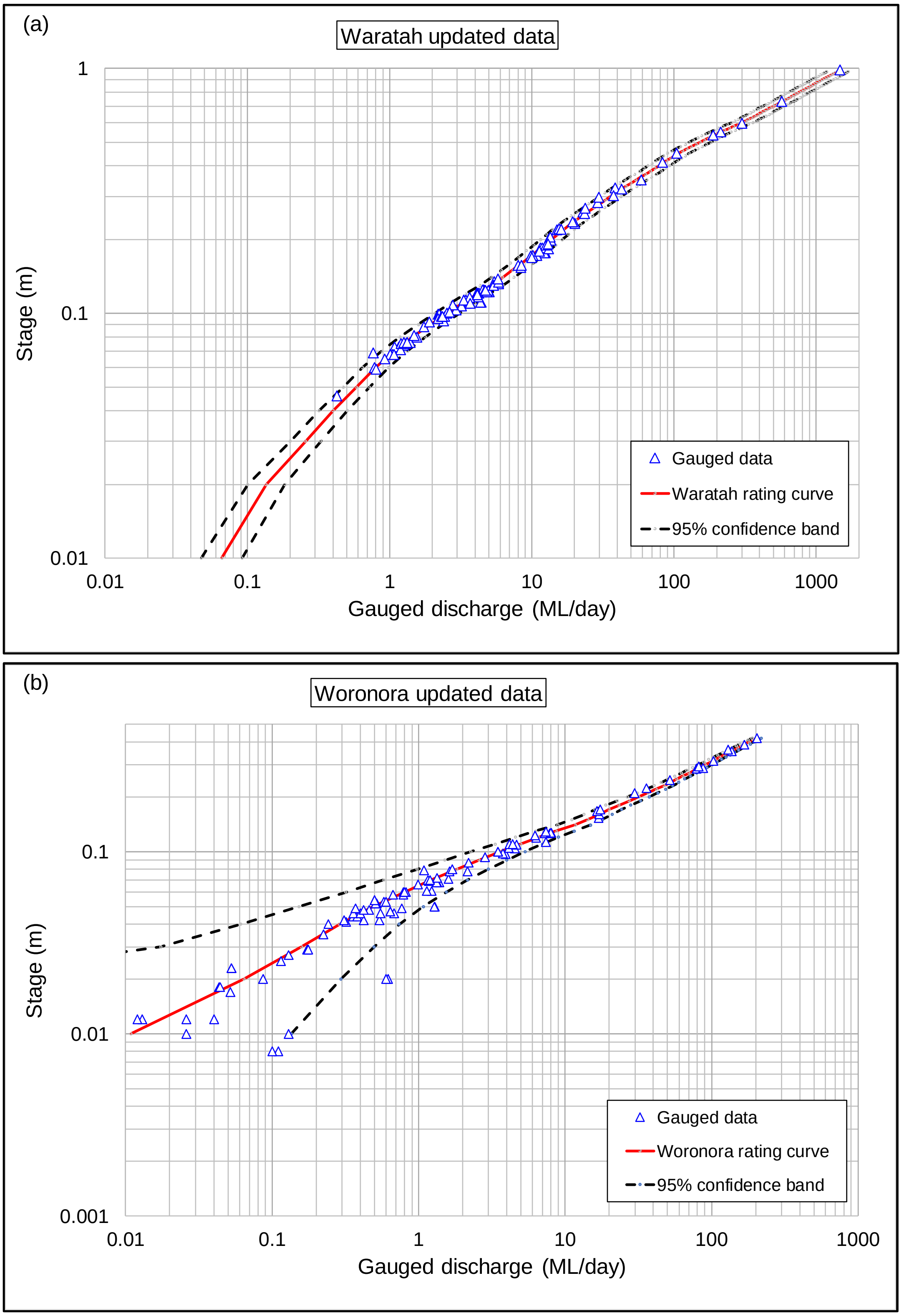

Figure F2. Rating curve for (a) Waratah Rivulet (GS2132102) and (b) Woronora River (GS2132101) showing the 95% uncertainty band

Appendix G – Report by Hydro Engineering & Consulting Pty Ltd (HEC)

HYDRO ENGINEERING & CONSULTING PTY LTD

REPORT

Metropolitan Coal
Woronora Reservoir
Water Balance Assessment

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d	Final	CAW	LMG / TSM	TSM	21/05/2019

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1.0 INTRODUCTION AND SCOPE

The Woronora Reservoir is located approximately 50 kilometres from Sydney, NSW and provides water supply for Sydney's southern suburbs and the northern portion of the Illawarra region. Metropolitan Coal undertake longwall mining in the Woronora catchment.

The *Woronora Reservoir Strategy Report – Stage 1* (Hebblewhite et al., 2017) recommended the development of a preliminary water balance of the Woronora Reservoir as a means of identifying loss of stored water in the reservoir due to longwall mining in the catchment. Additionally, the report recommended that the potential uncertainties in each component of the water balance be assessed.

Subsequently, Hydro Engineering & Consulting Pty Ltd (HEC) have been engaged by Metropolitan Coal to undertake a preliminary water balance assessment of the Woronora Reservoir. This report summarises the assumptions, methodology and outcomes of the water balance review.

A water balance model has been developed using the GoldSim® software package to simulate the Woronora Reservoir water balance. Two approaches to the model simulation were adopted: a deterministic simulation and a stochastic simulation.

The deterministic simulation was undertaken to assess the capability of the model to simulate reservoir volumes consistent with recorded reservoir volumes. The deterministic simulation was then utilised to ascertain if the model could enable assessment of potential loss through the bed and embankment of the reservoir, with loss through the bed potentially associated with mine related effects. The deterministic simulation also comprised an assessment of systematic rainfall error on the reservoir water balance.

The stochastic simulation was undertaken for the same historical period as the deterministic simulation and comprised the application of random error (uncertainty) to the historical model inputs. The stochastic simulation was undertaken to reflect potential inaccuracies in the input data and calculations used to simulate each component of the reservoir water balance. The stochastic simulation was used to quantify the potential range of predicted uncertainty in the water balance and to assess the associated constraints of the analysis to identify potential loss through the bed and embankment of the reservoir.

1.1 BACKGROUND

Woronora Reservoir is a regulated water storage located on the Woronora River as illustrated in Figure 1. The catchment area of the reservoir is approximately 74 square kilometres and is largely undisturbed. The catchment area is comprised of two major surface water systems: the Woronora River and Waratah Rivulet. Metropolitan Coal has undertaken longwall mining in the catchment of Waratah Rivulet, with mining occurring to the south of Woronora Reservoir prior to January 2018. Post January 2018, longwall mining of panels commenced in the vicinity of the upper reaches of the Woronora Reservoir, as illustrated in Figure 1.

At Full Supply Level (FSL), the reservoir has a capacity of 81,643 ML and covers a surface area of approximately four square kilometres. The reservoir is constructed with an uncontrolled spillway at RL 168.88 m AHD (i.e. FSL).

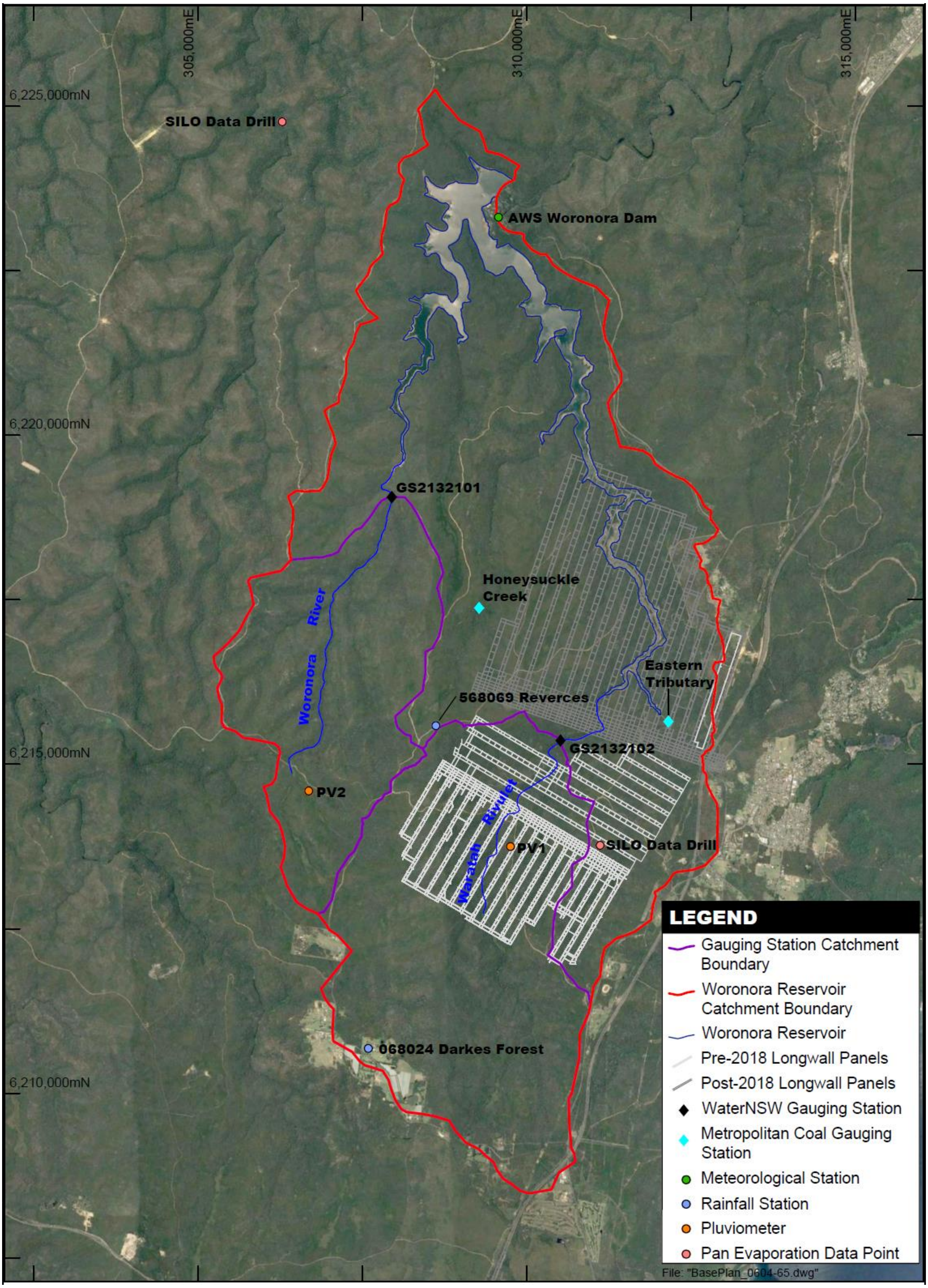

Figure 1 Woronora Reservoir Sub-Catchment Boundaries and Monitoring Locations

The reservoir component inflows and outflows are illustrated in Figure 2. Inflows to the reservoir comprise catchment runoff, groundwater discharge from the upstream catchment and direct rainfall on the reservoir water surface area. Outflows from the reservoir comprise low flow release for environmental flow purposes, release to a Water Treatment Plant (WTP), overflow from the dam spillway, seepage through the dam embankment and evaporation from the water surface area. The out-of-balance between inflows, outflows and stored water volume is considered an unaccounted for 'loss' from the reservoir.

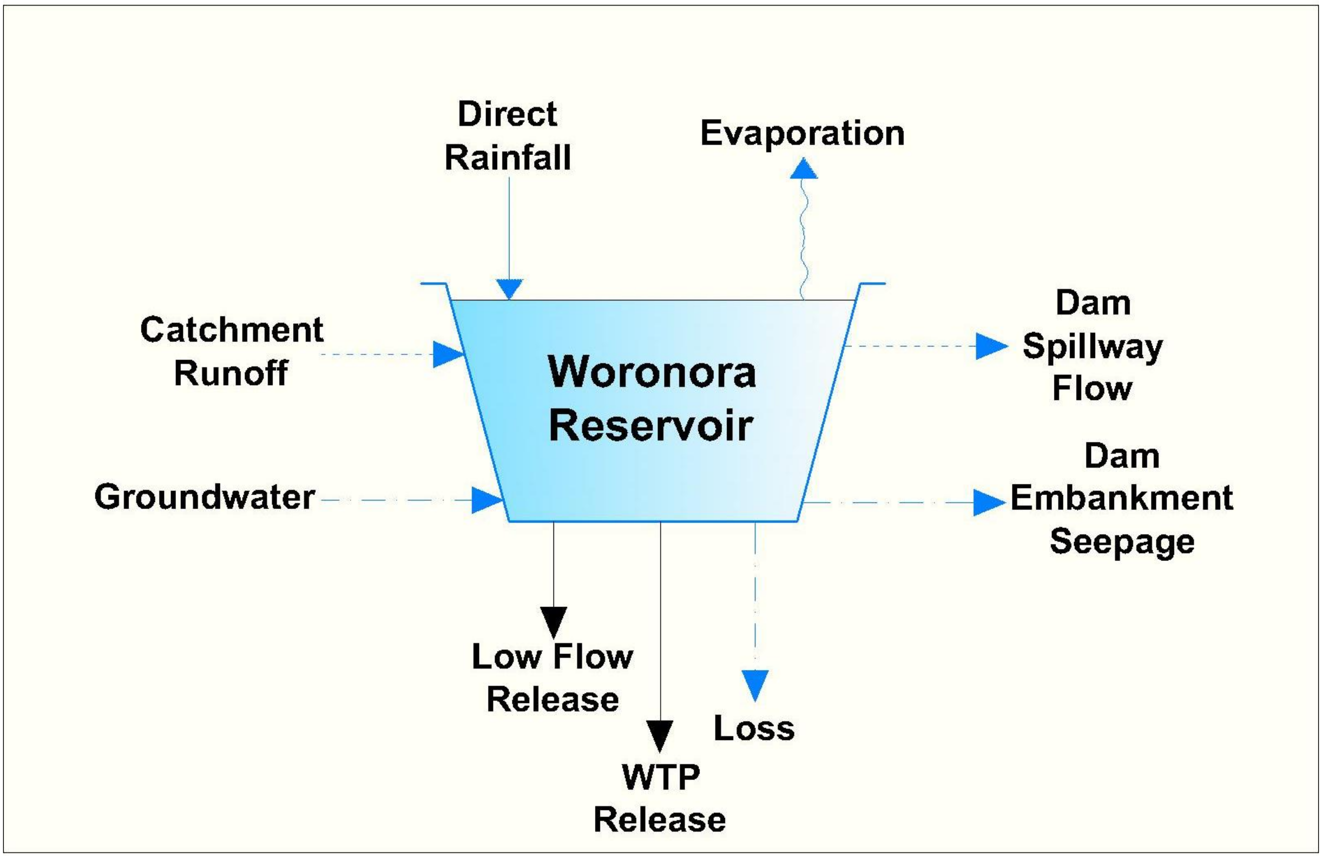

Figure 2 Water Balance Schematic

The water balance analysis detailed in this report aimed to predict the volume of unaccounted for loss from the reservoir based on historically monitored data and with consideration to uncertainty relating to the input data and calculations used to simulate each component of the reservoir water balance.

2.0 WATER BALANCE MODEL DEVELOPMENT

2.1 MODEL DESCRIPTION

A GoldSim® water balance model was developed for the Woronora Reservoir to simulate:

Change in Storage = Inflow – Outflow

Where:

Inflow includes direct rainfall on the reservoir surface, catchment rainfall runoff (including baseflow) and groundwater inflow.

Outflow includes evaporation from the water surface area, seepage through the dam embankment, release to the WTP and environmental flow, spillway overflow and unaccounted for loss comprising potential flow to the downstream groundwater system, potential flow to the underground mine and unaccounted for errors in input data.

2.2 MODEL ASSUMPTIONS AND DATA

A summary of key model assumptions and underpinning data are provided in the sub-sections that follow.

2.2.1 Model Simulation Period

The reservoir water balance model operates on a daily time step and is simulated for 2,112 days from 21 March 2012 to 31 December 2017 for the deterministic and stochastic simulation, equivalent to the period of reliable historically recorded input data.

2.2.2 Reservoir Storage and Catchment Areas

The relationship between the reservoir water level, surface water area and volume were derived from bathymetric survey data provided by WaterNSW. The catchment area contributing to the reservoir was estimated using 10 m interval topographic contours obtained from the NSW Government Department of Finance, Services and Innovation (DFSI) Spatial Services[1]. The area of each sub-catchment contributing to the total catchment of the reservoir is listed in Table 1 and illustrated in Figure 1.

Table 1 Catchment Areas

Catchment	Total Area (km^2)
GS213101 on Woronora River	12.4
GS213102 on Waratah Rivulet	20.6
Ungauged Catchment	41.1
Total Catchment	**74.1**

2.2.3 Rainfall Runoff Simulation

Daily rainfall data recorded at Woronora Dam (AWS Woronora Dam in Figure 1) was provided by WaterNSW and used to simulate direct rainfall on the reservoir surface.

Two streamflow gauging stations are located in the reservoir catchment: GS213101 on Woronora River and GS213102 on Waratah Rivulet, as illustrated in Figure 1. Daily streamflow data was provided by WaterNSW for the model simulation period and is plotted in Figure 3 for Waratah Rivulet and Figure 4 for Woronora River. This data was adopted as direct catchment runoff (added to the reservoir on each simulated day) from the two gauging station catchments.

[1] http://spatialservices.finance.nsw.gov.au/

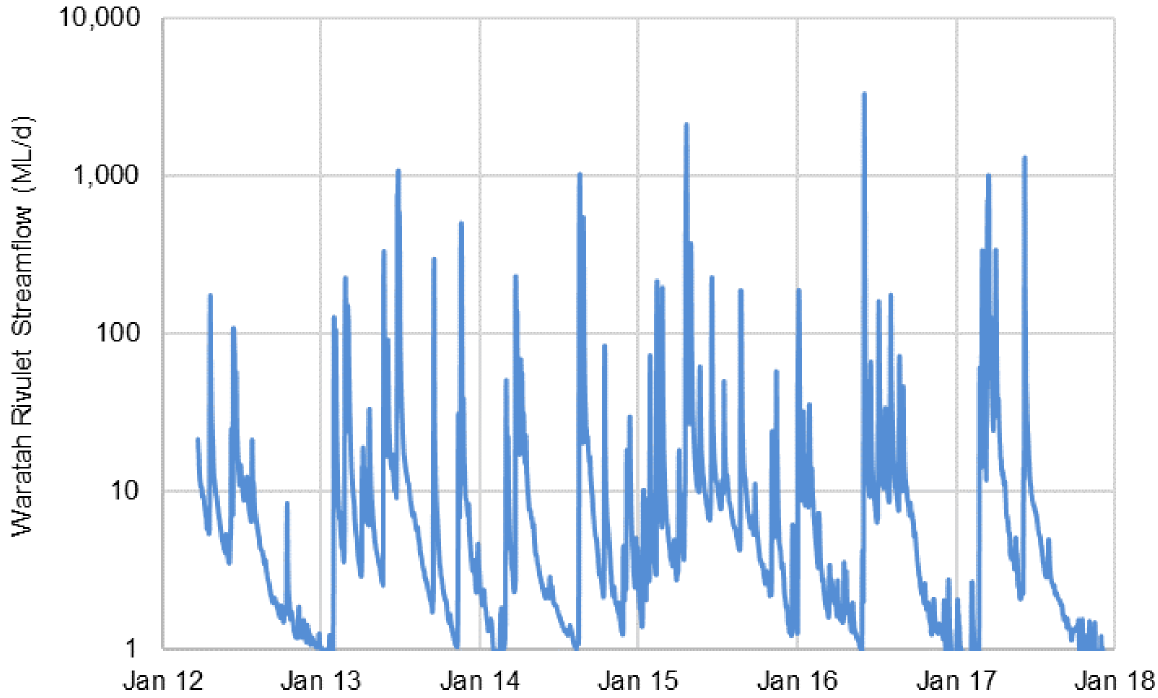

Figure 3 Waratah Rivulet Gauged Streamflow

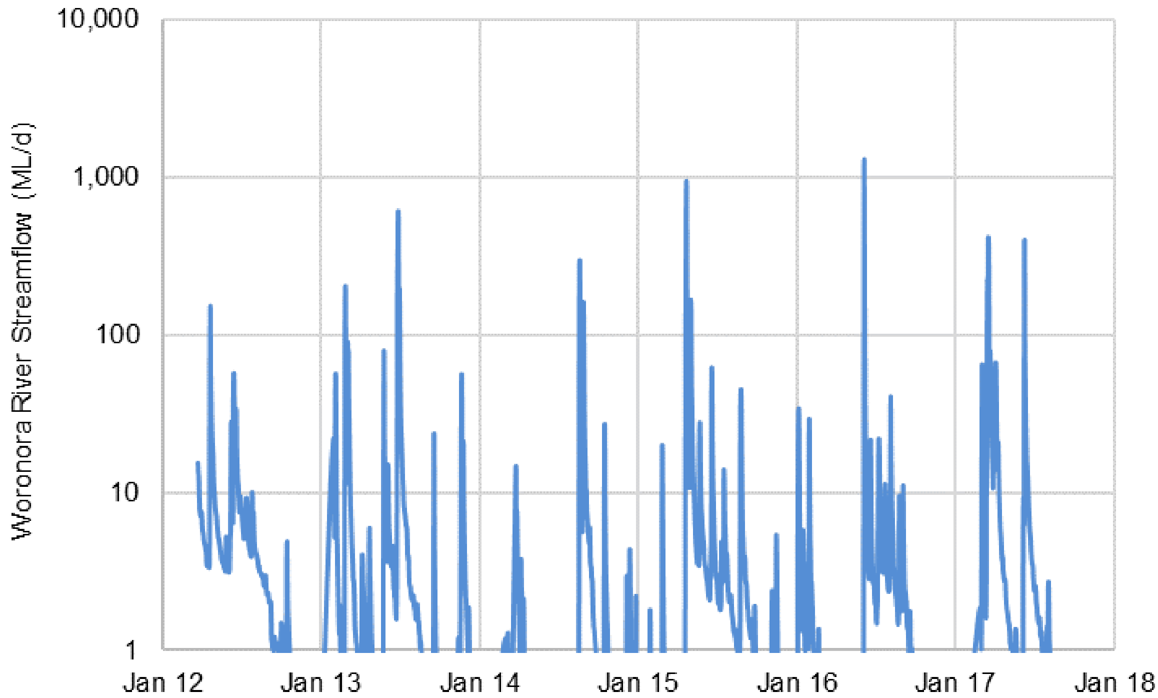

Figure 4 Woronora River Gauged Streamflow

Two Metropolitan Coal streamflow gauging stations are located in the Woronora Reservoir catchment, one on Honeysuckle Creek and one on Eastern Tributary as shown in Figure 1. The gauging stations record streamflow rates from a small portion of the Woronora Reservoir catchment which is not gauged by GS213101 and GS213102 (referred to as 'ungauged catchment' herein). The gauging stations were designed to record low streamflow rates only, which do not contribute significantly to the reservoir volume. Additionally, the Honeysuckle Creek gauging station has been observed to leak and as such the recorded streamflow rates from this station are not accurate.

Consequently, the streamflow rates from the catchment area downstream of GS213101 and GS213102, representing an area of 41 km^2, were simulated using a modified version of the Australian Water Balance Model (AWBM) detailed in Gilbert & Associates (2016). The AWBM is a nationally-recognised catchment-scale water balance model that estimates catchment yield (flow) from rainfall and evaporation. Inflow from the ungauged catchment was simulated using AWBM with model parameters derived from a calibration of the AWBM undertaken for the Waratah Rivulet gauging station (GS2132102). The AWBM was calibrated to streamflow gauging records for the period 1 June 2007 to 31 December 2009 as detailed in Gilbert & Associates (2016).

For calculation of flows from the ungauged catchment AWBM, rainfall comprising the average of the daily rainfall record from the Woronora Reservoir and PV1, (refer Figure 1) was adopted while the Penman equation (Penman, 1948) was used to estimate daily potential evaporation from the catchment. The Penman equation uses daily mean temperature, wind speed, air pressure and solar radiation as inputs. The meteorological data recorded at Woronora Dam (AWS Woronora Dam Figure 1) which was provided by WaterNSW was utilised as input to the Penman equation. The area of the ungauged catchment was varied daily based on the water surface area of the Woronora Reservoir (i.e. catchment area decreased with increased water surface area).

2.2.4 Groundwater Inflow

Groundwater inflow from the catchment to the reservoir was estimated using a steady-state, pseudo-2D groundwater model of the reservoir integrated along the two contributing surface water systems. Modelling was undertaken by Dr F Kalf. The predicted groundwater inflow rates as provided by Dr F Kalf on 31 October 2018 are summarised in Table 2. The groundwater inflow rates were interpolated between tabulated values based on the simulated reservoir depth as it was assumed that groundwater inflow rates would vary linearly on the basis of reservoir depth.

Table 2 Groundwater Inflow Rates

Reservoir depth (percent capacity)	70 m (96% capacity)	58 m (50% capacity)	37 m (10% capacity)
Estimated groundwater flow to reservoir	1 ML/day to 2 ML/day	1.5 ML/day	1.2 ML/day

2.2.5 Evaporation from Reservoir Water Surface

To estimate evaporation rates from the reservoir water surface, two methods were assessed as documented in Kohler and Parmele (1967) and Vardavas and Fountoulakis (1996). The estimated evaporation rates were compared against pan evaporation from SILO Data Drill[2] for the reservoir area in order to assess the applicability of each method. Figure 5 provides a comparison of the estimated evaporation rates against the SILO Data Drill pan evaporation.

[2] The SILO Data Drill is a system which provides synthetic data sets for a specified point by interpolation between surrounding point records held by the BoM. Refer https://legacy.longpaddock.qld.gov.au/silo/

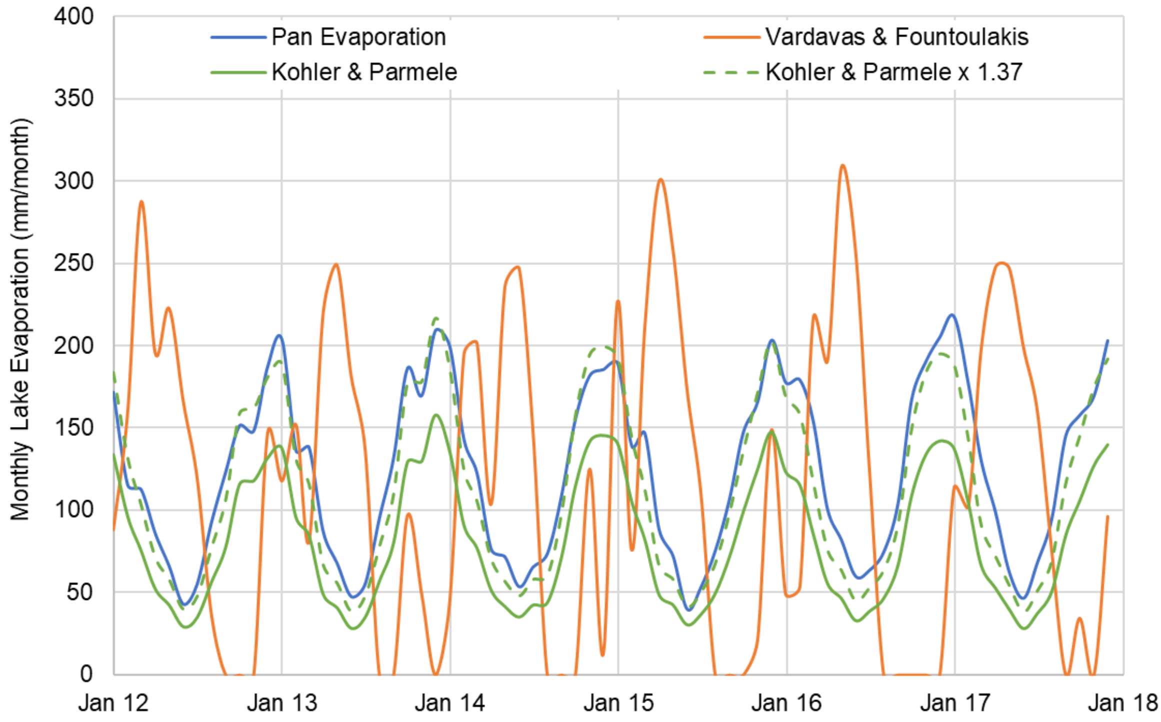

Figure 5 Comparison of Evaporation Rates

The Vardavas and Fountoulakis (1996) equation resulted in an erratic pattern in monthly evaporation rates with a large number of zero or near zero values. Therefore the Kohler and Parmele (1967) method was adopted as the monthly trend in values was more consistent with estimated pan evaporation.

The Kohler and Parmele (1967) equation was developed to estimate evaporation from deep lakes and is based on the Penman equation with an additional relationship to account for water advected energy and heat storage. The equation uses lake temperature, surface water inflow temperature, rainfall temperature, rainfall rate, surface water inflow rate, surface water outflow rate and reservoir volume as inputs. All input data was provided by WaterNSW for the Woronora Reservoir excepting rainfall temperature. As rainfall temperature was unknown, it was assumed to be equivalent to the surface water inflow temperature.

Although the trend in the monthly Kohler and Parmele (1967) estimated evaporation rates was consistent with estimated pan evaporation, the monthly totals were significantly less than that of Vardavas and Fountoulakis (1996) and the estimated pan evaporation rates. Therefore, the Kohler and Parmele (1967) estimated values were increased to match the pan evaporation rates with a pan factor coefficient applied as recommended by Professor Thomas McMahon (pers. comm. 15/04/19). Hoy and Stephens (1979), Weeks (1982) and Kotwicki (1994) provide Class A pan coefficients for 16 reservoirs or lakes across Australia (McMahon et al., 2013, Table S12) in which the average pan coefficient is 0.83 and the range is 0.66 to 1.0, and the 75th percentile value is 0.89. A pan factor coefficient of 0.89 was adopted for the Woronora Reservoir, as recommended by Professor Thomas McMahon (pers. comm. 15/04/19), resulting in a 37% increase in the Kohler and Parmele (1967) estimated evaporation rates.

2.2.6 Embankment Seepage

The depth of water seepage from the dam embankment, measured downstream via a v-notch weir, was provided by WaterNSW and converted to an equivalent seepage rate using the v-notch weir formula as follows:

$$Q = CH^{2.5}$$

where Q is discharge in megalitres per day, C is the weir coefficient (3.76992E-6), and H is the water level in metres upstream of the v-notch.

The average seepage rate over the simulation period based on v-notch water level records provided by WaterNSW was 0.3 ML/d, with a minimum rate of 0 ML/d and a maximum rate of 2.4 ML/d.

2.2.7 Release to WTP and environmental flow

Release from the reservoir to the WTP and for environmental flow purposes (low flow release) were provided on a daily basis for the model simulation period by WaterNSW. Data is summarised in Figure 6 and Figure 7 respectively.

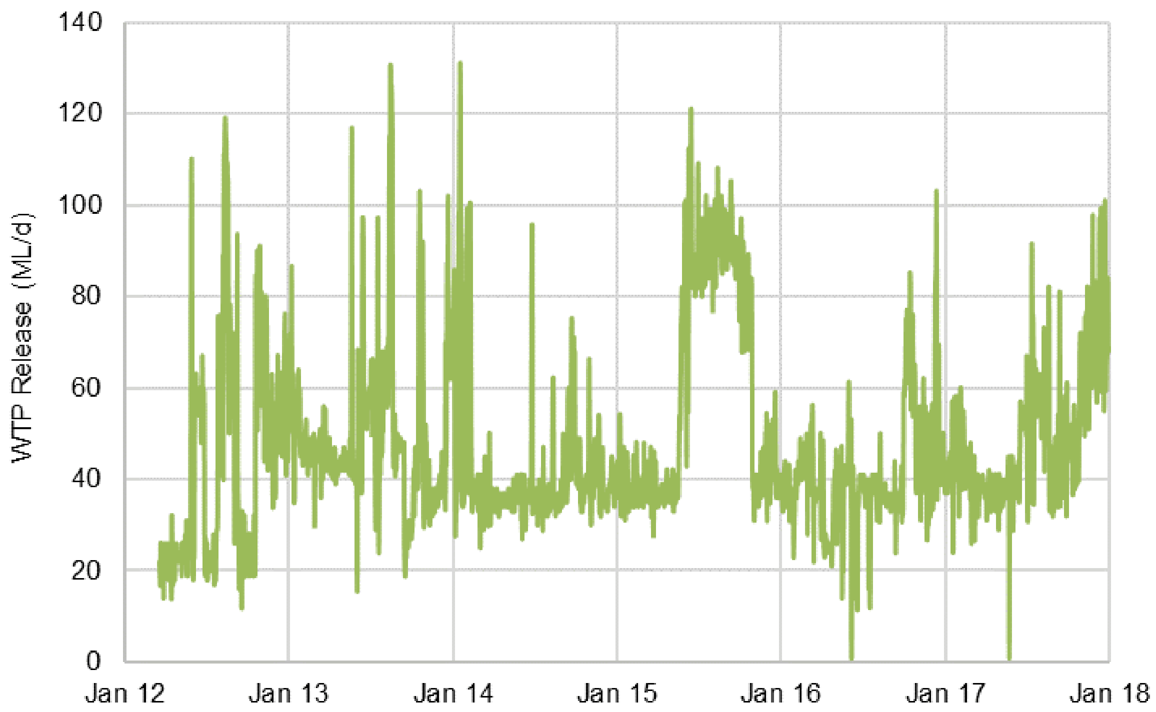

Figure 6 Recorded WTP Release

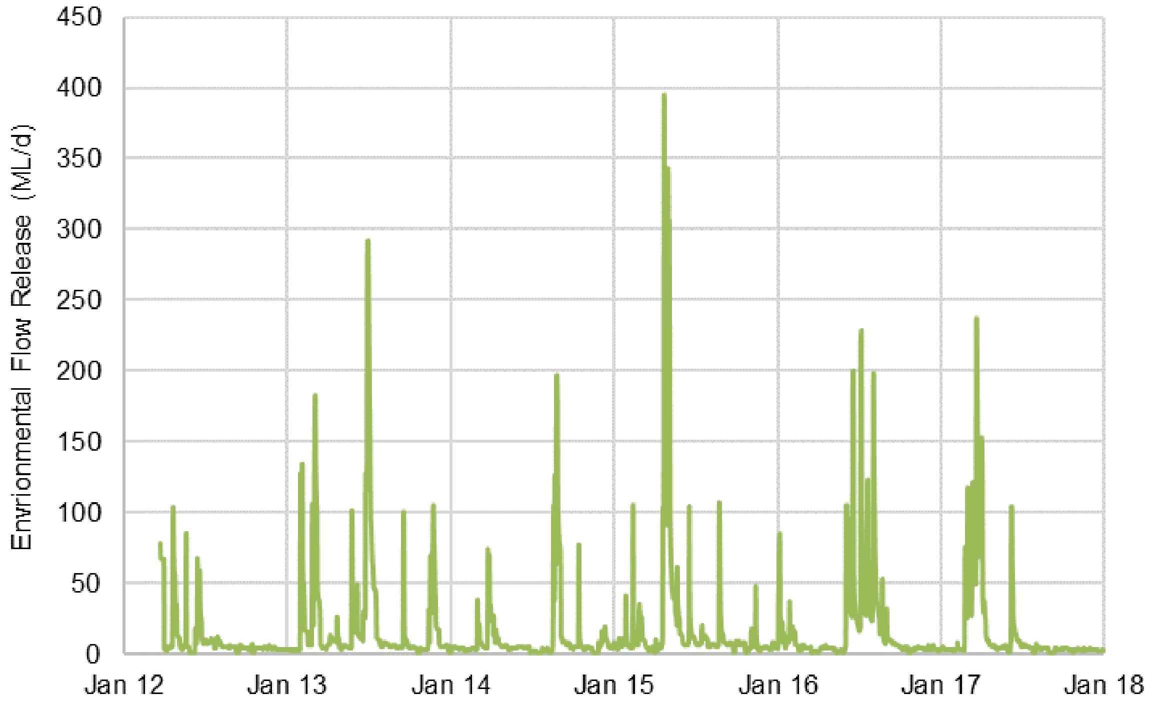

Figure 7 Recorded Environmental Flow Release

2.2.8 *Dam Spillway Flow*

Overflow rates from the dam spillway were provided by WaterNSW for the model simulation period. The data was provided as daily records of overflow rate. A total spillway overflow volume of 1,342 ML was recorded during the simulation period and occurred in June 2017 during one event.

The spillway level was also specified in the model to allow for calculation of overflow if the simulated reservoir water level reached or exceeded the dam spillway level. A spillway rating curve was not specified in the model, rather the simulated volume above the spillway level was reported as spillway overflow and was assumed to occur on one day.

2.2.9 Reservoir Volume

Daily records of reservoir water level were provided by WaterNSW for the simulation period and converted to a volume using the bathymetric survey data provided by WaterNSW. The initial reservoir volume at the commencement of the simulation period was set in the model and the recorded volumes compared against subsequent model simulated volumes.

2.3 UNCERTAINTY ANALYSIS

To account for error (uncertainty) in the model input data and calculations, an uncertainty analysis was undertaken. Two forms of error were assessed: systematic error and random error. The effect of a potential systematic error in the rainfall data, relating to the loss of rain to a gauge due to wind, wetting and emptying losses, evaporation and splash in and out of the gauge, was assessed (refer Appendix A). The assessment of systematic rainfall error was applied to the deterministic model simulation.

The assessment of random error was undertaken through a stochastic model simulation. Table 3 lists the water balance components for which random error was assessed and summarises the predominant mechanisms in which random error is introduced to each model component.

Table 3 Model Component Random Error

Model Component	Random Error Mechanism
Rainfall	Error associated with the distance of the rain gauge to the location in which the rainfall data is applied (density of rain gauges in a catchment).
Gauged streamflow	Uncertainty associated with the difference between gauged discharge and rating curve discharge within the gauged range
Ungauged streamflow	Difference between the recorded streamflow rate used for model calibration and the model simulated streamflow rate.
Lake evaporation	Difference between model estimated evaporation and recorded evaporation.
Reservoir water level	Uncertainty associated with water level measurement and introduced through the effect of wave movements on the gauge measurement (a function of wind speed).
Groundwater inflow	Error associated with model predictions which is a function of model input data, assumptions, methodology and interpretation.
Dam embankment seepage	Error associated with the method adopted for recording water level measurements.
Environmental flow release	Error associated with the measurements recorded by the electromagnetic flow meter.
WTP release	Error associated with the measurements recorded by the electromagnetic flow meter.

Appendix A details the method adopted for estimating the random error of each water balance component. The random error was applied as a normal distribution in the water balance model for all model components except streamflow in which a cumulative distribution function of error was adopted. A normal distribution represents the deviation from the mean value, with 50% of values being less than the mean and 50% of the values being greater than the mean. A cumulative distribution function represents the probability that a random value will be less than or equal to the value under evaluation.

The stochastic simulation was undertaken using the Monte Carlo method with Latin Hypercube sampling. The Monte Carlo method uses repeated sampling to obtain the statistical properties of a particular phenomenon while Latin Hypercube sampling is a statistical method for generating a near-random sample of parameter values (McKay et al., 1979). The model was simulated for 1,000 realizations with the uncertain parameters for each model component sampled (near) randomly on each timestep (day) of each realization. A large number of separate and independent results were then generated representing the possible range of values of each model component. The results of the independent system realizations were assembled into probability distributions representing the water balance of the Woronora Reservoir with consideration to the model component uncertainties.

3.0 WATER BALANCE MODEL RESULTS

3.1 DETERMINISTIC MODEL SIMULATION

The average yearly water balance for the Woronora Reservoir based on the deterministic model simulation is summarised in Table 4.

Table 4 Average Yearly Water Balance

Inflows (ML/year)	
Direct rainfall	3,385
Woronora River streamflow	2,611
Waratah Rivulet streamflow	7,618
Ungauged catchment streamflow	14,099
Groundwater inflow	586
TOTAL	**28,299**
Outflows (ML/year)	
Evaporation	4,629
Environmental Flow Release	5,886
WTP Release	17,396
Seepage	115
Spillway Overflow	459
TOTAL	**28,486**

Table 4 illustrates that the major inflow to the Woronora Reservoir comprises catchment streamflow. Streamflow from the ungauged catchment area specifically represents 50% of the total inflow to the Woronora Reservoir. The predominant outflow comprises the release to the WTP, representing 61% of the total outflow from the Woronora Reservoir.

Figure 8 presents a comparison of the deterministic model simulated volume with the recorded volume for the Woronora Reservoir.

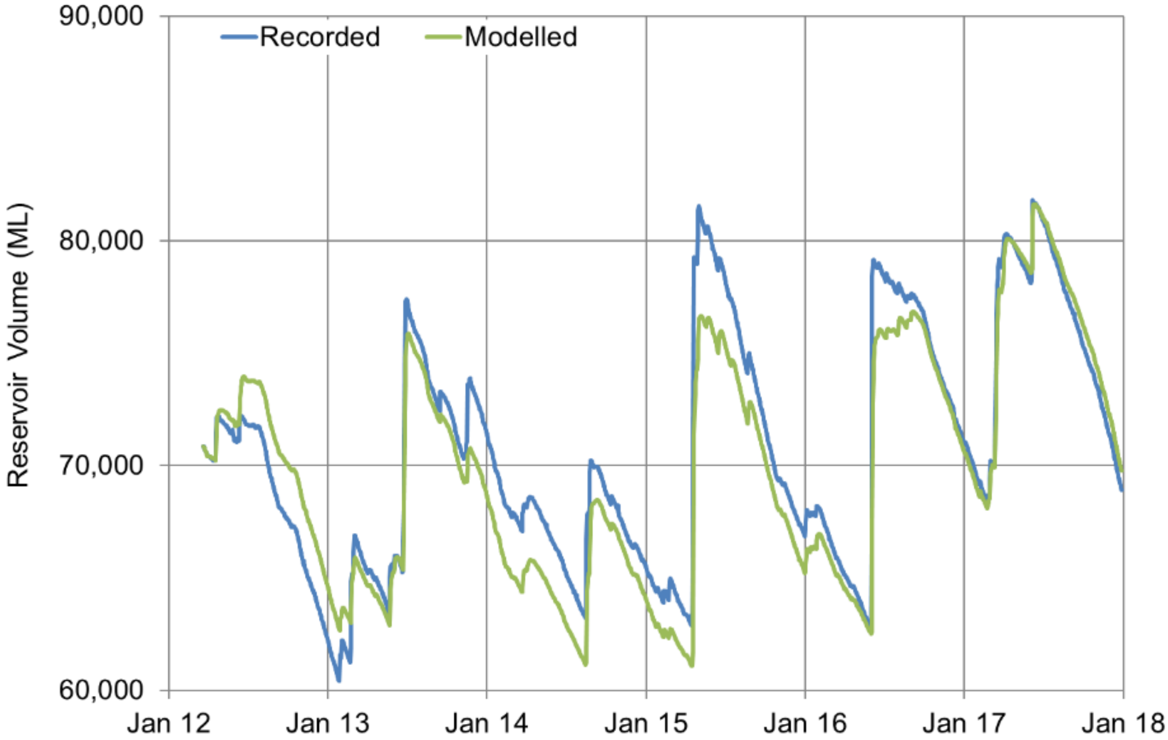

Figure 8 Comparison of Simulation Reservoir Volume and Recorded Reservoir Volume

Figure 8 illustrates a good fit between the recorded reservoir volume and model simulated volume, with a R-squared value of 0.90. The largest differences occurred during periods of peak volume. In 2012, the peak simulated volume exceeded the recorded volume, while the recorded volume exceeded the simulated peak volume in 2013 to 2017. The general pattern of reservoir volume increase and decrease was relatively well matched by the model simulation, except for the period June to September 2016 in which the simulated volume increased while the recorded volume decreased. As the simulated reservoir volume predominately rose during this period while the recorded volume predominately declined, this suggests an error in input data other than streamflow rates alone. Figure 6 illustrates that, during this period, the recorded WTP release rates were generally less than that recorded in other periods. As such, the difference in simulated and recorded reservoir volumes during this period may be indicative of an error in the recorded WTP release rates.

The difference in recorded and simulated reservoir volume at the end of the simulation period (31 December 2017) was 858 ML and is within 1.2% which constitutes a reasonable match between simulated and recorded volumes. The total recorded spillway overflow was 1,342 ML while the model simulated total spillway overflow was 2,656 ML constituting an additional 1,314 ML difference in recorded and simulated overflow volume for the simulation period.

The deterministic model was also used to assess the effect of systematic rainfall error on the reservoir water balance with an overall increase of 5.1% in rainfall (refer Appendix A). Figure 9 presents the simulated reservoir volume with systematic rainfall error in comparison with the recorded reservoir volume.

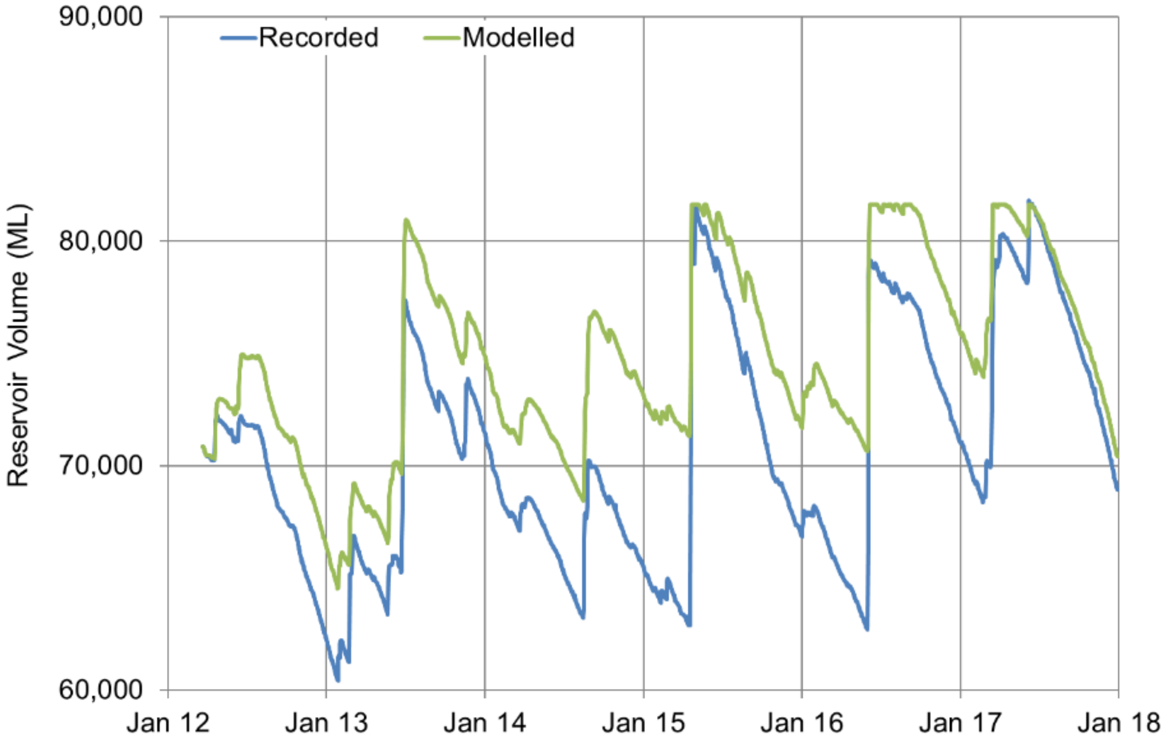

Figure 9 Simulated Reservoir Volume with Systematic Rainfall Error

Figure 9 illustrates that the systematic rainfall error has a large effect in increasing the simulated reservoir volumes with the simulated volumes far exceeding the recorded reservoir volumes. The large variance between simulated and recorded reservoir volumes suggests that the systematic rainfall error has been overestimated. Consequently, the systematic rainfall error has not been included in the stochastic model simulation so as not to skew the results of the stochastic simulation.

3.2 STOCHASTIC MODEL SIMULATION

The stochastic model simulation was undertaken by applying random error estimates to each component of the water balance as summarised in Section 2.3 and detailed in Appendix A. The stochastic model simulation was undertaken for the same period as the deterministic simulation. Figure 10 presents the simulated reservoir volume incorporating uncertainty in the water balance components. The minimum, 2.5 percentile, median, 97.5 percentile and maximum of the simulated Woronora Reservoir volume has been presented.

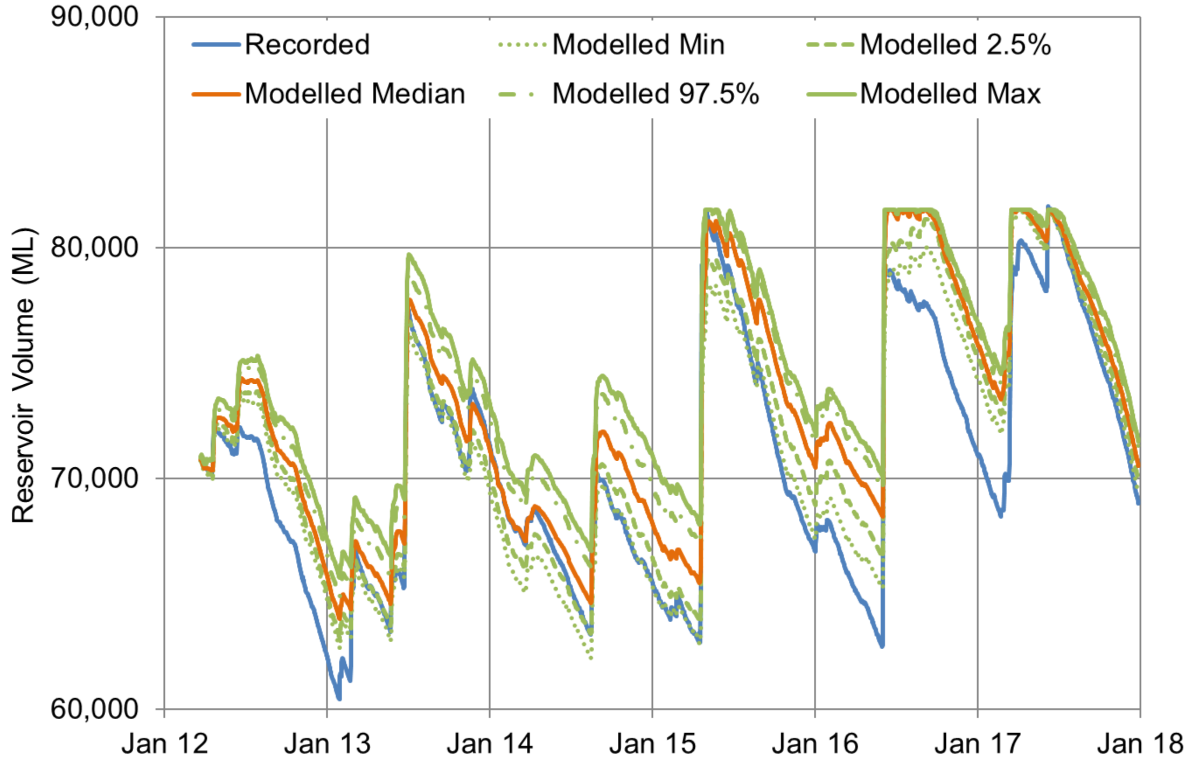

Figure 10 Woronora Reservoir Volume Uncertainty

Figure 10 illustrates that the range of uncertainty in the model inputs is large thereby resulting in a divergence in simulated reservoir volume of up to 5,719 ML (the difference between the maximum and minimum simulated volume). The uncertainty analysis results in the simulated reservoir volume generally being skewed higher than the recorded volume and the deterministic simulation volume.

Although the deterministic simulation represents a good fit between modelled and recorded reservoir volumes (R-squared of 0.90), the magnitude of bias and uncertainty evident in the stochastically simulated reservoir volume indicates that the water balance model, in its current form, is unsuitable for use as a baseline against which potential low (i.e. mine related) rates of loss from the reservoir may be assessed.

Table 5 presents the stochastic simulated minimum, median and maximum total volume for each model component over the model simulation period. The percentage variance between the median and maximum stochastically simulated total volume is presented for comparison.

Table 5 Total Volume of Model Components Based on Stochastic Simulation

Model Component	Total Volume over Simulation Period (ML)			Percentage Difference between Maximum and Median Total Volume
	Minimum	Median	Maximum	
Direct Rainfall	19,774	20,299	20,602	4.1%
Woronora River streamflow	15,138	15,196	15,258	0.8%
Waratah Rivulet streamflow	44,015	44,079	44,149	0.3%
Ungauged streamflow	86,319	89,907	93,392	7.9%
Groundwater inflow	3,235	3,292	3,352	3.6%
Evaporation	27,141	27,927	28,694	5.6%
Environmental Flow Release	33,968	34,051	34,135	0.5%
WTP Release	100,536	100,638	100,746	0.2%
Seepage	666	668	670	0.6%

Table 5 illustrates that the uncertainty in the ungauged streamflow rates has the greatest influence on the water balance with a difference of 7.9% between the median and maximum simulated total volume. The uncertainty in the evaporation data also has a large influence on the simulated water balance with a difference of 5.6% between the median and maximum stochastically simulated total volume.

To illustrate the influence of the ungauged streamflow variability on the simulated reservoir volume, the ungauged streamflow variability has been excluded from the simulation presented in Figure 11.

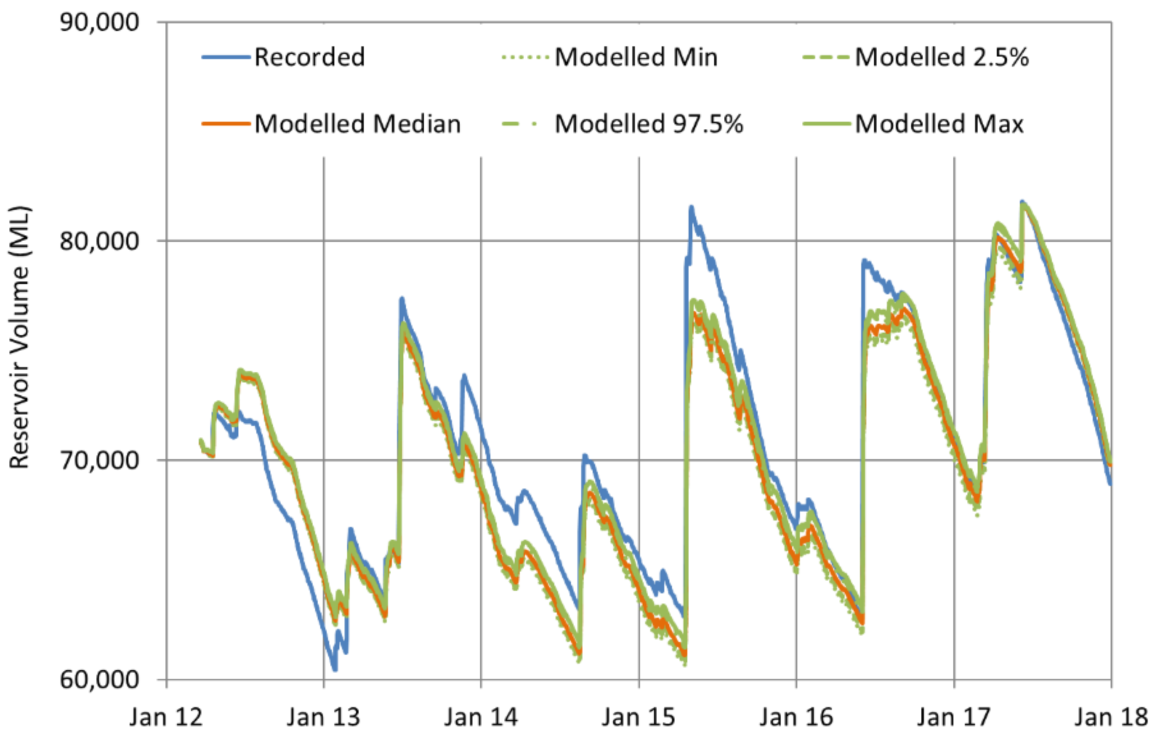

Figure 11 Woronora Reservoir Volume Uncertainty Excluding Ungauged Streamflow Uncertainty

Figure 11 illustrates that the range of uncertainty in the simulated reservoir volume is significantly reduced when the ungauged streamflow uncertainty is excluded from the assessment (deterministic ungauged streamflow rates adopted). Rather than a divergence in simulated reservoir volume of up to 5,719 ML (the difference between the maximum and minimum simulated reservoir volume), the divergence was 1,437 ML.

In addition, the uncertainty associated with the ungauged streamflow rates is positively skewed rather than normally distributed resulting in the simulated total reservoir volume being skewed higher than the recorded volume, as observed in Figure 10. Exclusion of the uncertainty associated with the ungauged streamflow rates results in the uncertainty band of the simulated reservoir volume being more closely aligned with the recorded reservoir volume, as observed in Figure 11.

4.0 CONCLUSIONS AND RECOMMENDATIONS

The Woronora Reservoir deterministic water balance simulation illustrated a good match between the recorded reservoir volume and model simulated volume except for periods of peak volume (R-squared value of 0.9 over the simulation period). However, the stochastic simulation highlighted the magnitude of variability in the model inputs, specifically the uncertainty associated with the ungauged streamflow and evaporation rates adopted in the water balance.

Although the deterministic simulation represents a good fit between modelled and recorded reservoir volumes (R-squared of 0.90), the magnitude of bias and uncertainty evident in the stochastically simulated reservoir volume indicates that the water balance model, in its current form, is unsuitable for use as a baseline against which potential low (i.e. mine related) rates of loss from the reservoir may be assessed.

In order to increase the potential for the water balance model to be used as a baseline, the ungauged streamflow and evaporation data adopted in the model would need to be significantly improved. Establishment of a number of additional streamflow gauging stations would be required in the currently ungauged catchment to provide more reliable estimates of streamflow rate. The method for estimating evaporation from the reservoir water surface would also require further investigation and monitoring, particularly with respect to factoring of the evaporation rates.

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APPENDIX A – ESTIMATING UNCERTAINTY FOR WORONORA WATER BALANCE

Estimating uncertainty for Woronora water balance

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Date: 01/05/2019

As an input to the Woronora water balance model, we require estimates of uncertainty for each daily variable in the model namely rainfall, streamflow, lake evaporation, reservoir water level, groundwater inflow, dam wall seepage, releases for environmental water and releases to the water treatment plant. As there are only minor flows over the spillway and as this variable is not used in the recession analysis of groundwater discharge, the uncertainty in the spill variable is not considered.

1. Rainfall

There are two forms of error (uncertainty) that need to be considered with respect to rainfall: systematic errors and random errors.

Systematic errors

Systematic errors relate to the loss of rain to a gauge because of wind, wetting and emptying losses, evaporation, and splash in and out of the gauge. WMO (1994, Table 1) provides the following systematic error equation:

$$P_k = k\left(P_g + \Delta P_1 + \Delta P_2 + \Delta P_3 \pm \Delta P_4\right) \quad (1)$$

where P_k is the adjusted precipitation, k is loss due to wind, P_g is measured precipitation (mm/day), ΔP_1 + ΔP_2 are combined wetting and emptying losses respectively, ΔP_3 is loss due to evaporation from the gauge, and ΔP_4 is the splash in and out of the gauge. In Table A1, values of the WMO (1994) parameters are listed with comments, resulting in an adjustment due to systematic errors of $P_k = 1.051P_g$ which is applied to daily rainfalls.

Random errors

Several references were available to estimate the random error in the rainfall input to the reservoir. In the analysis, we adopted a rain gauge density of 4 km^2/gauge on the basis that one rainfall station is used to estimate the rain input to the reservoir surface of 4.0 km^2 at FSL. Various estimates of the random error as uncertainty estimates from our literature search are presented in Table A2. McGuinness's (1963) proposed an equation, based on data from a small watershed in Ohio, relating average absolute deviation to gauge density and daily rainfall. Steiner (1996) suggested a simple error relationship $(\frac{30}{T})^{0.5}$, where T is days, yielding an uncertainty estimate of 5.5% over the time-step adopted. Based on a 135 km^2 catchment in UK, Wood et al. (2000) estimated the uncertainty of daily rainfall for a single gauge as a function mean rainfall (their Figure 10).

Figure A1 is a plot of the data in Table A2 and presents the uncertainty as a standard error, expressed as the uncertainty estimate in daily rainfall, for a range of daily rainfalls. The uncertainty estimate is given by:

$$\sigma_P = 0.14P^{0.71} \quad (2)$$

where σ_P is uncertainty estimate as a standard error of daily rainfall (mm/day), and P is daily rainfall (mm/day).

2. Streamflow

The key uncertainties in the Waratah and the Woronora gauged data used in the water balance modelling relate to the uncertainty in the extrapolations of the rating curves which are unknown. The low flow estimates of discharge are, overall, satisfactory as indicated by the gauging data versus rating curve plots presented in Figure A2. (Analysis follows McMahon and Peel 2019). In view of this, to estimate uncertainty we adopted a simple procedure based on the standard deviation of the residuals (that is the standard errors) computed as the differences between the gauged discharges and the adopted rating curves. For Waratah and Woronora gauging stations, the adopted standard errors were respectively as σ_{Wa} = 2.4 ML/day and σ_{Wo} = 1.9 ML/day.

Regarding the ungauged area, as the flows were estimated using a rainfall-runoff model calibrated for a nearby catchment and upscaled to the area of the ungauged catchment, there is considerable uncertainty in the estimates of flow. To assess uncertainty, the standard deviation of the residuals was adopted which were computed as the differences between the daily discharges estimated from the rating curve and the concurrent estimated discharges from the calibrated model upscaled to reflect the ungauged area. Because of the large errors associated with the large flows, the standard error for the flows from the ungauged area was estimated using only flows less than the mean flow resulting in σ_{Ug} = 8.8 ML/day.

Because of the shortcomings noted above and as the method does not account the skewed nature of the discharges, the procedure to estimate streamflow uncertainty requires detailed analysis if a Stage 2 water balance is carried out.

3. Lake evaporation

In his 1986 paper Morton (1986) compared estimates of annual and monthly lake evaporation using his CRLE procedure with those estimated using a water balance for 17 reservoirs in the Canada and the United States. Annual evaporation data were also available for four Australian reservoirs from Vardavas and Fountoulakis (1996) who estimated monthly lake evaporation based on Penman (1948) approach and compared their results with Garrett and Hoy (1978). To estimate uncertainty, we assumed the water balance evaporation estimates used by Morton and those by Garrett and Hoy are correct against which we tested the adequacy of the CRLE Morton procedure. To account for the effect of autocorrelation in estimating a daily estimate of uncertainty of lake evaporation from the monthly and annual standard errors, we applied the Kotz and Neumann (1963, Equation 12) which accounts for autocorrelation. For Woronora daily Class A pan evaporation (https://legacy.longpaddock.qld.gov.au/silo/datadrill/), the autocorrelation is 0.70. The Kotz and Neumann equation is:

$$\sigma_n^2 = \sigma^2 \left[n + \left(\frac{2\rho}{1-\rho}\right)\left(n - \frac{1-\rho^n}{1-\rho}\right)\right] \quad (6)$$

where σ_n^2 is the variance of the sum of n consecutive values, σ^2 is the variance of the values assumed to be independent, and ρ is the autocorrelation. For example, in estimating a daily variance from an annual variance, n is 365. The analyses of the annual and monthly data resulted in an estimate of standard error of daily lake evaporation of 1.7 mm/day and 1.4 mm/day based on monthly and annual data respectively. Of the two estimates, it is likely the one based on the annual data is more accurate than the monthly one (see Morton, 1986, page 385).

In the lake evaporation component of the water balance analysis, two complex procedures (Kohler and Parmele, 1967; Vardavas and Fountoulakis, 1996) that account for the stored energy in a reservoir were assessed. Although neither was wholly satisfactory, we adopted the Kohler and Parmele method to provide preliminary monthly lake evaporation estimates. However, for the purposes of assessing evaporation uncertainty we based our analysis, described above, on Morton (1986). A standard error of lake evaporation of 1.4 mm/day was adopted.

4. Reservoir water level

No information had been received regarding water level measurements of Woronora Reservoir by the time the water balance report had been finalized. In view of this, an uncertainty estimate was developed as follows. Two factors need to be considered: uncertainty in a water level observation, and uncertainty introduced due to wind setup. We assume water levels are observed or recorded with an uncertainty (standard error) of 0.002 m, the value adopted for stream gauging in Section 2. An additional potential uncertainty results from wave setup affecting the gauge measurement. Pelikan and Koutny (2016) provide an equation to estimate the characteristic wave height, H_0, (trough to crest) as a function of wind speed and fetch as follows:

$$H_0 = 0.0026 \frac{u_{10}^{106} F_{ef}^{0.47}}{g^{0.53}} \qquad (7)$$

where u_{10} is wind speed (m/s) at 10 m reference level, F_{ef} is the effective fetch length (m) (adopted here as 1000 m), and g is the gravitational constant (m/s^2) (9.81 m/s^2). To adjust wind speed measured at 2 m to 10 m, we use (Ladson, 2008, Equation 3.61)

$$u_Z = u_2 \frac{ln\left(\frac{Z}{z_0}\right)}{ln\left(\frac{2}{z_0}\right)} \qquad (8)$$

where u_Z is wind speed at height z, equal to 10 m in Equation 7, and z_0 is the roughness height for water = 0.001 m (McMahon, 2013, Table S2). For a median daily wind speed (2 m height) of 0.78 m/s for Woronora, H_0 = 0.019 m from Equation 7 which results in an uncertainty value of 0.005 m (0.019/4). Combining this with the measurement uncertainty of 0.002 m, an estimate of standard error or uncertainty estimate for reservoir water level is calculated as 0.0054 m.

5. Groundwater inflow

Based on a pseudo-2D numerical groundwater model of a section across the reservoir, groundwater inflows were estimated for three capacities. It was assumed for each case in the model the groundwater would flow to an inundated area equivalent to that at FSL. Taking this into account, the estimated groundwater inflows are as follows:

Reservoir water level (and percent full)	70 m (96% capacity)	58 m (50% capacity)	37 m (10% capacity)
Estimated groundwater flow to reservoir	1 ML/day to 2 ML/day	1.5 ML/day	1.2 ML/day

To estimate uncertainty in the groundwater flow, in consultation with Dr F Kalf, the range of error in the model is adopted as 1 ML/day. If we assume a Normal distribution of errors, this is equivalent to a standard error of 0.25 ML/day.

6. Dam embankment seepage

The dam embankment seepage was estimated by the Vee-notch weir formula:

$$Q = CH^{2.5} \quad (9)$$

where Q is discharge, C is the weir coefficient, and H is the water level in the notch. From Equation 9 the following error function is derived:

$$\frac{\Delta Q}{Q} = 2.5\frac{\Delta H}{H} \quad (10)$$

As no information is available about the uncertainty in H, we have adopted the water level error, ΔH, as ±0.003 m (Bos, 1989, page 363). Assuming a Normal distribution, the water level error is equivalent to a standard error of 0.0015 m. Thus, for a gauge height of 0.1 m, the uncertainty estimate is 3.8%.

7. Environmental release

We have been advised by Water NSW that both the environmental flow and water treatment releases were made using electromagnetic flow meters. Based on field testing of seven meters by Hydro Environmental in 2007, Lowe et al. (2009) reported that the errors extended from -2.3% to 3.3%, a range of 5.6%. This is not inconsistent with WaterNSW’s estimate of 0% to 5% (phone discussion on 5 December 2018 between Dave Tomlinson, WaterNSW and Tony Marszalek, HEC Pty Ltd) which is a range of 5%. A range of 5.6 % translates to a standard error of 1.4%.

8. Release to the water treatment plant

We adopt an uncertainty estimate of 1.4%, based on the discussion in Section 7.

Table A1. Adopted values of systematic error components in estimating rainfall

Reference/Adoption	k	ΔP_1	ΔP_2	ΔP_3	ΔP_4
WMO (1994)	2% – 10%	Combined 2% -10%		Assume tipping bucket – no loss	1% - 2%
Adopt	Average wind speed ~ 1m/s, k = 5%	Wetting loss ΔP_1 = 2.5%	Assume tipping bucket, ΔP_2 = 0	ΔP_3 = 0	But WMO (2006) does not include splash ΔP_4 = 0

Table A2. Uncertainty estimates (mm/day) in daily rainfall

Reference	Method	Daily rainfall (mm/day)				
		2.5	12.5	25	75	125
McGuinness (1963)	McGuinness Equation 1	0.30	0.72	1.05	1.90	2.51
Steiner (1996)	Steiner Equation 1	0.14	0.68	1.37	4.11	6.85
Wood et al. (2000)	Experimental data	0.52	1.37	2.07	4.00	5.44

Table A3. Error information available in Spank et al. (2013, Table 2) and uncertainty estimates. Spank et al.'s estimates are bolded, and our subsequent uncertainty estimates are shown as normal type. In Spank et al. paper, errors are listed as an intercept (B) and a slope (A), which we have converted using the mean of the variables to individual errors and have combined into a single error estimate for each variable without regard to the distribution.

Variable (average values for Woronora)	Systematic error (uniformly distributed)	Uncertainty estimate	Random error (normally distributed)	Uncertainty estimate	Adopted Uncertainty estimate
Global radiation* (Average solar radiation 22.6 MJ/m^2/day)	**A: 0.95–1.05** Range¥: 2.26	0.56	**A: 0.90–1.10** Range: 4.52	1.13	σ_R = 1.31 MJ/m^2/day
	B: ±0.4 MJ/m^2/d	0.20	**B: ±0.6 MJ/m^2/d**	0.30	
Air temperature‡	**B: ±0.1 K**	0.05	**B: ±0.5 K**	0.25	$\sigma_{Tres} =$ 0.25 °C
Wind speed (0.85 m/s)	**A: 0.98–1.02** Range: 0.034	0.0085	**A: 0.98–1.02** Range: 0.034	0.0085	σ_u = 0.14 m/s
	B: ±0.2 m/s	0.10	**B: ±0.2 m/s**	0.10	
Relative humidity (72%)	**A: 0.97-1.03** Range: 4.32%	1.08	**A: 0.97–1.03** Range: 4.32%	1.08	σ_{RH} = 3.2%
	B: ±2.5%	1.25	**B: ±5%**	2.5	

* Assume errors in solar radiation are of the same magnitude as global radiation measurements.
‡ Assume uncertainty in reservoir temperature change is approximately the same as dry bulb temperature.
¥ The range is scaled by applying the slopes (A) to the mean value of the variable, and then the range is divided by 4 (recommended by Hozo et al. (2005) for a Normal distribution) to provide an approximate uncertainty estimate (on the basis that 4 standard deviations account for 95% of the area under a Normal distribution).

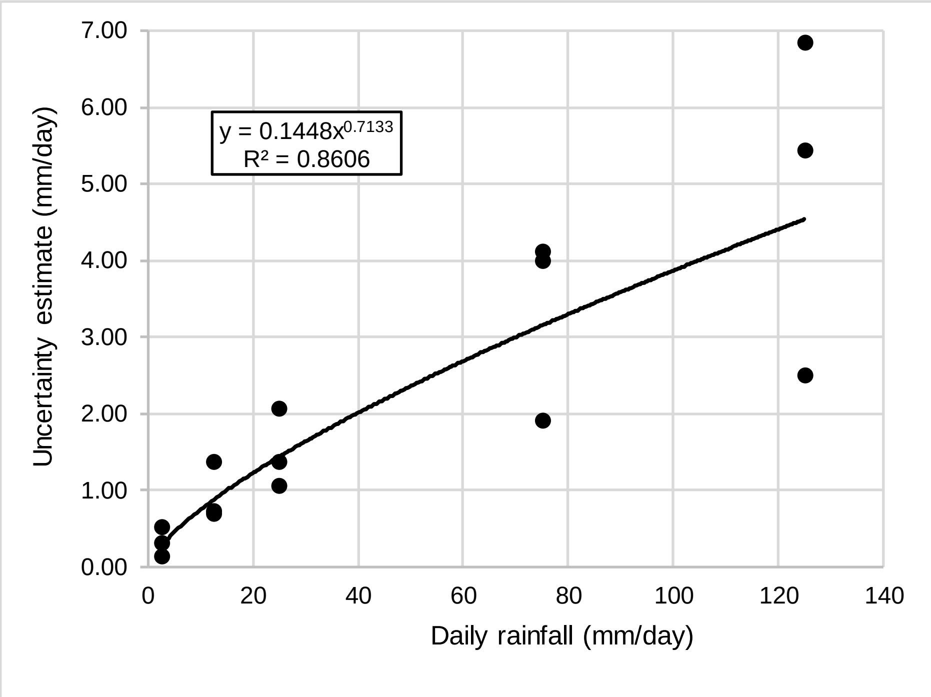

Figure A1. Uncertainty estimates (standard error) based on daily rainfall estimates from Table A2

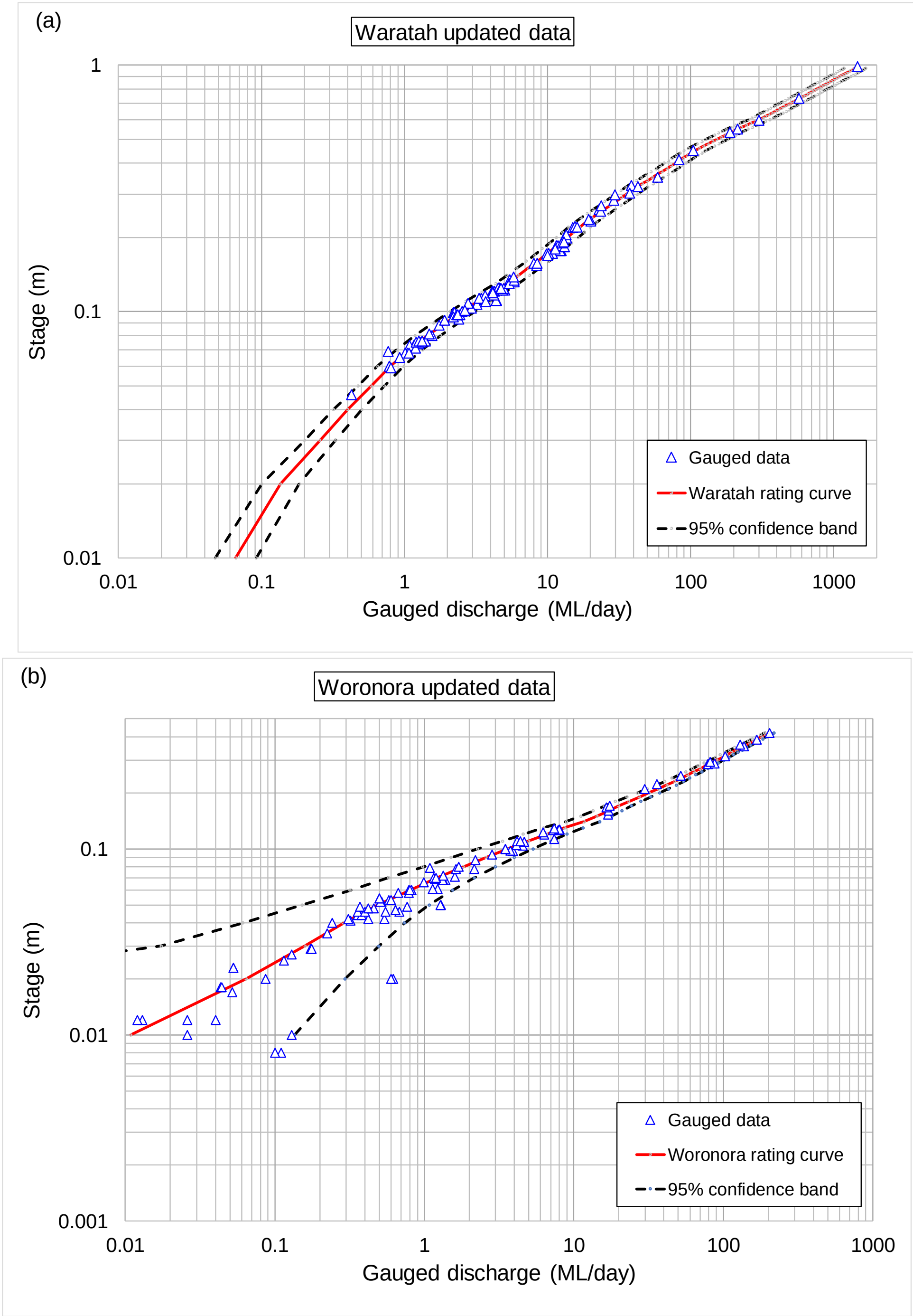

Figure A2. Rating curve for (a) Waratah Rivulet (GS2132102) and (b) Woronora River (GS2132101) showing the 95% uncertainty band

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