Watermark Coal Project Groundwater Model: Audit of specific storage coefficients

WRL TR 2018/33 | January 2019

By D J Anderson and D Howe
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## Project details

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Executive summary

This report was prepared by the Water Research Laboratory (WRL) of the School of Civil and Environmental Engineering at UNSW Sydney following the peer-reviewed article published in the Journal of Geophysical Research: Earth Surface by Rau et al. (2018). The study objective was to audit the confined aquifer specific storage (Ss) values used within the Watermark Coal Project EIS groundwater model (the EIS model). This report is written for a technical audience.

Specific storage (Ss) is a property that describes how much water is released from storage in a pressurised aquifer for each metre decline in hydraulic head.

Rau et al. (2018) reviewed poroelastic theory to calculate an upper limit for Ss for fine grained sands, clays and rocks of approximately $1.3 \times 10^{-9} \text{ m}^{-1}$ and a lower limit of $2 \times 10^{-7} \text{ m}^{-1}$. This equates to the release of just 2.64 to 0.04 US teaspoons of water per cubic metre of aquifer per metre decline in head. Their subsequent review of two models of groundwater flow on the NSW Liverpool Plains by Price and Bellis (2012), and McNeilage (2006) identified that both models made some reliance on Ss values greater than the acceptable upper limit (up to $1 \times 10^{-4} \text{ m}^{-1}$) to provide prediction of the aquifer behaviour. Analysis of cross-hole seismic, barometric, earth tide and associated data by Rau et al. (2018) and Acworth et al. (2017) shows that the shallow smectite and sandy/gravelly clays at Quirindi on the NSW Liverpool Plains near the proposed Watermark Coal Project have Ss in the range of $1 - 5 \times 10^{-6} \text{ m}^{-1}$, one (1) to two (2) orders of magnitude lower than the values used in the Price and Bellis (2012) and McNeilage (2006) models.

This study extended the comparative work of Rau et al. (2018) by contrasting measurements of specific storage at Quirindi to:


2. A data set of specific storage values estimated by WRL from the storativity interpretations made by GHD (2012) following analysis of the field pumping test data collected at Breeza as part of the Watermark Coal Project.

The Ali et al. (2004) model was created to study land subsidence in the Lower Namoi Alluvium. The Nicol et al. (2014) model was utilised to support decision making for the proposed BHP Caroona Coal Project (the mine lease was subsequently relinquished by BHP). The AGE (2013) model was utilised to support decision making for the proposed Shenhua Watermark Coal Project EIS. It may also have been used to support detailed mine design, including water management and monitoring plans which must protect water assets, water sensitive ecosystems and cultural assets.
This study identified that several Ss values in the Watermark Coal Project (AGE, 2013) and the Caroona Coal Project (Nicol et al., 2014) models are substantially inconsistent with the data-driven analyses of Ali et al. (2004), GHD (2012) and Rau et al. (2018).

Specifically, this audit found that 66% of the layers within the Watermark Coal Project EIS model were assigned values of Ss up to three (3) orders of magnitude larger than the available field measurements and the upper limit of poroelastic theory. These assigned values of Ss were typically also higher than the one used in other groundwater models of the NSW Liverpool Plains, including some layers of the BHP Caroona Model (Nicol et al., 2014).

The article by Rau et al (2018) concludes that groundwater flow models developed using values of Ss outside the aforementioned physical limits of $2 \times 10^{-7} \text{ m}^{-1}$ to $\sim 1.3 \times 10^{-5} \text{ m}^{-1}$ lead to an incorrect representation of groundwater flow processes which in turn significantly underestimate both leakage between surface and groundwater and the interconnectivity between aquifer units. As explored further by Anderson et al. (2018), an inappropriate selection of Ss values produces significantly incorrect results in models when the Ss values are not within the range of physical plausibility.

For example, if a cubic metre of aquifer can only produce $2 \times 10^{-7} \text{ m}^{-1}$ (0.2 US teaspoons per metre decline in head) but the modeller has assumed 203 teaspoons (one litre) due to the use of wrong Ss values, then 99.9% of the water required to explain the mass balance has been unaccounted for. This misrepresentation of processes leads to inaccurate prediction of groundwater response to changes in recharge or abstraction as will typically occur due to nearby mining or CSG projects.

Since the storage coefficients used in the Watermark Coal Project EIS Model are unrealistically high, the EIS hydrogeological conceptual model, its calibration methodology and its numerical model predictions are considered fundamentally flawed. Rau et al. (2018) calls for the re-appraisal of all conceptual and numerical models of groundwater flow that do not incorporate values of Ss consistent with poroelastic theory.

A primary concern is that the EIS model may significantly underpredict the rate and extent of drawdown during times of drought and the volume of water lost from connected water sources. This concern may be understood by considering fundamental hydrogeological concepts discussed by various authors including Theis (1935), Bredehoeft (1997), Bredehoeft (2002), Bredehoeft (2005), Bredehoeft and Durban (2009) and Leake (2011). Anderson et al. (2018) provide some examples of the severity of under-prediction that can result from the adoption of incorrect values of specific storage for groundwater abstraction from both hard rock and alluvial aquifers.
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1 Introduction

This report was prepared by the Water Research Laboratory (WRL) of the School of Civil and Environmental Engineering at UNSW Sydney. The study objective was to audit the specific storage values adopted by AGE (2013) during the environmental impact assessment to predict the groundwater impacts of the Watermark Coal Project; a proposed open cut mining development to be situated at Breeza on the NSW Liverpool Plains. The audit was undertaken in response to a recent peer reviewed publication in the Journal of Geophysical Research: Earth Surface by Rau et al. (2018).

This study compares the modelled values of specific storage in each of the Watermark Coal Project EIS model layers to:

1. The limits from poroelastic theory as described by Rau et al. (2018);
2. Field measurements at numerous sites near the proposed Watermark Coal Project site as reported by various authors GHD (2012), Acworth et al. (2017) and Rau et al. (2018); and
3. The groundwater model developed for the nearby adjacent BHP Caroona Coal Project as reported by Nicol et al. (2014) and the groundwater model of the Lower Namoi Alluvium constructed by Ali et al. (2004).

This report is structured as follows:
- Section 2: The Liverpool Plains
- Section 3: Audit of EIS Model Specific Storage
- Section 4: Recommendations for re-assessment
- Section 5: Conclusion

Section 2 provides a brief introduction to the Liverpool Plains which are located in northern NSW. This section briefly overviews the value of agricultural production in the region, the geology, hydrology, key groundwater sources and the proposed Watermark Coal Project. Section 3 presents the audit of the specific storage values utilised in the groundwater flow model for the Watermark Coal Project and briefly discusses the implications of the findings. The end of Section 3 summarises additional modelling and environmental impact assessment issues that were identified in the course of undertaking the specific storage audit. Recommendations are provided in Section 4. Conclusions are provided in Section 5.
2 The Liverpool Plains

The Liverpool Plains in northern New South Wales contain some of the best agricultural land in Australia and are underlain by extensive smectite clay-dominated soils sourced from weathering the alkali basalts of the Liverpool Ranges (Acworth et al., 2015). The valley sediments typically provide high yields of reasonably good quality groundwater. The location of the NSW Liverpool Plains is indicated in Figure 1. The map shows the location of three UNSW field research stations (Cattle Lane, Breeza Research Farm and Norman’s Road).

Figure 1: Location diagram
2.1 Social and economic values

The NSW Liverpool Plains region has the highest agricultural productivity in NSW, with an exclusive combination of volcanic soils, rainfall reliability, climate (sunshine hours, moderate temperature and protection from hot westerly weather) and availability of surface and groundwater. The black earth and chernozem soils found in the Liverpool Plains are classified as some of the most fertile in Australia. These fertile soil types are rare in Australia, making up just 0.7 per cent of the nation’s surface area (NSW Government, 2012, p. 16) and are therefore important for agricultural production for future generations.

2.2 Alluvial geology

The Upper Namoi Alluvium is a complex, valley-fill distributary fluvial sequence (DFS) of sands, gravels, silts and clays. These valley-fill DFS are so complex, and the quality of geological logs and water well driller reports so variable that a detailed geological model of the sediment distribution within the Upper Namoi Alluvium has not been published. To illustrate the complexity of valley-fill DFS aquifers, Figure 2 reproduces a plan view and cross-section model of a valley-fill DFS aquifer in Arizona prepared by Trendell et al. (2012).

Figure 2: Conceptual model of a distributary fluvial system in Arizona (Trendell et al., 2012)
The majority of sediment deposition in the Namoi Alluvium occurred during high-energy, wetter climate periods (Kelly et al., 2014) in association with the weathering of the Liverpool Ranges’ Tertiary Basalts. There is a gap in the dated sedimentological record for the Upper Namoi Alluvium between about 2.58 Ma to 150 ka (Acworth et al., 2015). Some of these sediments may have been transported north, down the valley to form the Lower Namoi Alluvium, however, there are other possible explanations.

Some authors (e.g. Gates, 1980) have proposed that a relatively simple two-layer geological model might explain the complex depositional sequence described above. In this model the underlying Cenezoic sequence with salt-rich clays of the Narrabri Formation of about 20 m thickness overlies sands and gravel aquifers comprising the Gunnedah Formation. Extensive groundwater modelling based upon this simple conceptualisation has been used in water management plans proposed by the mining industry for many years. However, detailed examination of geological core data by Acworth et al. (2015) from Cattle Lane at Quirindi, including grainsize, cation-exchange capacity, X-ray diffraction, X-ray fluorescence and microscopic examination, has failed to detect any evidence of a boundary between the hypothesised Narrabri and Gunnedah formations to 31.5m depth. Rather, the data reveals a gradual change in the dominance of clays and silts over sands and gravels embedded in a clay-rich matrix.

## 2.3 Groundwater

Productive groundwater in the Upper Namoi Alluvium is extracted from sand and gravel belts deposited within a clay matrix. A number of prominent researchers and industry practitioners were approached for photographs of undisturbed aquifer material below 31.5 m where the majority of groundwater is extracted, and to the best of the knowledge of the authors these are not available. The current understanding is that no cores have been collected to study undisturbed sediments from these depths.

Timms et al. (2018) provide several interesting ‘photo-micrographs’ derived from the clay matrix of the top 22 m of the Upper Namoi Alluvium that were studied to reveal:

- Various mineral sediment grains washed from the clay matrix including calcrete (i.e. sea shells) and quartz (Figure 3);
- Preferential flow of water and dye through clay core samples (Figure 4);
- Total porosity in the range of 43 – 47%;
- Total porosity of fluid and gas filled pores of about 15%;
- Mobile porosity (subset of fluid and gas filled pores) in the range of 4% to 8%.
These observations support the earlier work of Acworth and Timms (2009) who observed rapid circulation of irrigation water from surface applications at Breeza Farm to depths of 16 m and 34 m below ground (as evidenced by a freshening of pore water). PHREEQC geochemical models compiled by Acworth and Timms (2009) indicated that a significant proportion of porewater in the shallow aquifer was replaced by recharge water during the irrigation season. PHREEQC is a USGS computer program for calculating water chemistry speciation, batch-reaction, one-dimensional transport and inverse geochemical calculations. Acworth and Timms (2009) concluded that the clays could not be considered to isolate the underlying aquifer from overlying irrigation and associated contamination.

![Figure 3: Photographs of sediment grains in Upper Namoi Alluvium (Timms et al., 2018)](image-url)
2.4 Hydrology

A geo-hydrological centric conceptual model of the Liverpool Plains prepared by Nicol et al. (2014) is reproduced as Figure 5 to provide an introduction of the topography and surficial geology of the region. The conceptual model shows the location of the Caroona Coal Project exploration lease now purchased back by the NSW Government and the Watermark Coal Project area.

A not-to-scale conceptual model cross-section through the SMA provided in the EIS is reproduced in Figure 6. The figure depicts that groundwater pressure disturbances from the proposed mining activity will first need to travel anywhere between 150 m to 3.8 km through bedrock (depending on depth) to have a direct impact on groundwater pressure levels within the Namoi Alluvium. Note this conceptual model was adapted from the model proposed by Gates (1980) and subsequently dismissed by Acworth et al. (2015). Note also the thickness of the ‘Narrabri Formation’ in the figure is misleading as it appears substantially greater than 20 m and is therefore also inconsistent with the conceptual model developed by Gates (1980). Model layer elevation files from the EIS are of insufficient resolution and the geological log interpretation reports are not publicly available. Recommendations to address this limitation are provided in Section 3.5.
Figure 5: Conceptual model of the NSW Liverpool Plains Upper Namoi Region
(Source: Nicol et al., 2014)
2.5 Watermark Coal Project

As part of the Watermark Coal Project proposal, three open cut mining pits into outcrops of Tertiary, Jurassic, Triassic and Late Permian age rocks are to be developed to a depth of approximately 110 m below the level of the adjacent floodplain at Breeza on the NSW Liverpool Plains. There are three mining pits known as the Eastern Mining Area (EMA), the Southern Mining Area (SMA) and the Western Mining Area (WMA). The EMA is proposed to be mined first, followed by the SMA and then the WMA. The duration of mining is proposed to last approximately thirty (30) years.

Figure 6: Simplified schematic cross-section of the Watermark Coal Project
(Source: AGE, 2013)

Figure 7 presents a hydrogeological conceptual model cross section through the proposed EMA as prepared by GHD (2012). This figure shows the rock layers that would be intersected by mining dipping down underneath the Namoi Alluvium. Note that this conceptual model has 13 geological layers while the numerical model utilised by AGE (2013) to predict groundwater impact has 11 numerical layers. The reasons for these differences were not clearly stated in the EIS. Given this apparent uncertainty in knowledge of the geological structure, it would be precautionary to create multiple numerical models of the geology to understand how subjective interpretations of both alluvial and hard rock geology influence the predictions of groundwater impact. The draft guidelines on uncertainty analysis in groundwater modelling (Middlemis and Peeters, 2018) provide recommendations for the assessment of geological uncertainty. It is recommended that future groundwater impact modelling for the Watermark Coal Project follow these guidelines.
Figure 7: Cross Section through the proposed Eastern Mining Area (Source: GHD, 2012)
3 Audit of EIS model specific storage

Specific storage (Ss) values presented in the Watermark Coal Project EIS have been compared to:

1. Poroelastic theory;
2. Field data from the NSW Liverpool Plains collected within the model domain; and
3. Other numerical groundwater flow models of the NSW Liverpool Plains.

3.1 Pells Diagram

Two modified Pells Diagrams have been prepared to summarise the results of the comparative audit. Figure 8 presents the inputs utilised for the EIS base case model to predict the impacts of the project. Figure 9 presents the mean value of the inputs into the EIS uncertainty analysis.

A Pells Diagram is a bivariate plot of rock modulus versus specific storage (or vice versa). The diagram is derived directly from poroelastic theory using the established definitions of rock modulus and specific storage. These definitions have been reported previously, e.g. Wang (2000), Cooper (1960) and Jacob (1940). The lines on the Pells Diagram show valid values of rock modulus for chosen values of specific storage (or vice versa) for different values of porosity and Poisson’s ratio.

The very first Pells Diagram was presented at the NSW IAH and AGS Symposium on Recent Developments and Experiences with Groundwater and Excavation in Sydney on 13 November 2015. That work made reference to an earlier publication by Pells and Pells (2009) entitled “Hydrogeologists and Geotechnical Engineers – Lost without Translation”. This paper highlighted fundamental disconnects between hydrogeology and geotechnical engineering practice and the importance of documenting and testing heuristics in groundwater assessment.

The following introduction to the modified Pells Diagrams is provided:

- The horizontal axis is specific storage (m⁻¹ or mL/m³/m);
- The vertical axis is Young’s modulus (MPa). Young’s modulus is a parameter familiar to geotechnical engineers. It describes rock or sediment strength (and indirectly compressibility). Typical literature values of Young’s modulus for different geological materials are summarised to the left of the figure;
- The grey diagonal lines represent valid values of specific storage and bulk modulus for undrained Poisson ratios (ν) of 0.15, 0.30 and 0.48. The lower limit of Poisson ratio is about 0.15 (Pells, 2009). EMM (2018) reports a 50th percentile of Poisson’s ratio of 0.31 for
tests on rock core samples beneath the NSW Southern Highlands for Hume Coal. Poisson's ratio of an undisturbed rock mass is likely to be lower than that of a core sample. A value of 0.48 is representative of the smectite clays at Cattle Lane, Quirindi (Rau et al., 2018);

- Diverging from the diagonal lines described above are the constraints on specific storage and Young’s modulus for different values of sediment or rock porosity assuming a Poisson’s ratio of 0.48 (i.e. smectite clay at Breeza);
- Circular dots represent the measurements of Ss obtained by GHD (2012) around the Watermark Coal Project exploration lease area from pumping test interpretation. Values for alluvium have been arbitrarily plotted with $\nu = 0.48$ and values for bedrock with $\nu = 0.30$;
- Orange-shaded regions represent UNSW measurements of specific storage (Acworth et al., 2017; Rau et al., 2018) for smectite clays and sandy clays from 5-30 m below ground surface at Cattle Lane, Quirindi immediately to the south of the proposed mine;
- The green shaded area highlights specific storage values from poroelastic theory. Values larger than (i.e. to the right of) these limits are not physically possible and imply inelastic response and/or a source of leakage that has not been accounted for;
- The original Pells Diagram was truncated at a specific storage value of $1 \times 10^{-5}$ m$^{-1}$ which is the upper limit of specific storage from poroelastic theory as shown in the peer reviewed publication by Rau et al. (2018). For the purposes of this report the diagram is extended to an unrealistic specific storage value of 0.01 to show the full range of ‘inelastic’ specific storage values simulated in the Watermark Coal Project EIS model;
- The large, yellow shaded region represents the range of specific storage values assigned in the EIS model to represent the Namoi Alluvium (model layers 1 and 2);
- The vertical lines that project upwards from the x-axis represent the specific storage values of bedrock adopted in the EIS model for the hypothesised model layers 3 to 11. Blue, red, black and purple lines represent Tertiary, Late Permian (Black Jack Group), Early to Late Permian (Millie and Bellata Group) and Jurassic / Triassic rocks, respectively.
1. No evidence to support deep Permian rocks being more compressible than shallow fractured rocks.

2. Physically impossible values of specific storage.

3. Sandstone, basalt and Permian rocks are not more brittle than coal.
Values larger than $1.3 \times 10^{-5} \text{ m}^{-1}$ imply inelastic response, and/or leakage.

1. Physically impossible values of specific storage.
2. Sandstone, basalt and Permian rocks are not more brittle than coal.
3.2 Comparison to poroelastic theory

Table 1 reproduces Table 9.2 of Appendix T of the Watermark Coal Project EIS which summarises the hydraulic properties applied to the EIS model to predict groundwater impact. Figure 10 presents the distribution of specific storage modelled within the Namoi Alluvium. Table 2 presents the error statistics utilised as inputs into the EIS predictive uncertainty analysis as reproduced from Table A.5 of AGE (2013). The upper and lower 95% confidence intervals have been added for context.

The rows highlighted in Table 1 in orange (by WRL for emphasis) are those associated with geological units that were simulated with values that exceed the limits of poroelastic theory. These geological units can be found in layers 1 to 7 of the numerical model and account for more than 66% of the geological units represented within the model. The geological units include:

- The Upper Namoi Alluvium (Gunnedah and Narrabri Formation nomenclature);
- The Tertiary basalts;
- The Jurassic/Triassic interburden rocks;
- The Pilliga Sandstone; and
- The Clare Sandstone.

For the EIS model base case, within the Upper Namoi Alluvium (Gunnedah), there are no areas where specific storage is below the theoretical limit of $1.3 \times 10^{-5}$ m$^{-1}$. Within NSW water management zones 7 and 8 around the southern periphery of the proposed mining area (Figure 10), specific storage is at least one order of magnitude too high. Along the eastern model boundary which partially aligns with the Mooki Thrust Fault (simulated as a no flow boundary condition) specific storage has been set at least two orders of magnitude too high.

Red-italics in Table 2 indicate values of specific storage in the groundwater model uncertainty analysis that are significantly exceeding the limits of poroelastic theory. Note that the uncertainty analysis base (mean) case is biased significantly too high compared to poroelastic theory. This is inappropriate. The uncertainty analysis needs to be redone with appropriate specific storage inputs. Furthermore, to avoid generating unrealistic predictions, the uncertainty analysis should be ‘calibration constrained’ (Doherty, 2015) to ensure the selection of appropriate values of hydraulic conductivity and groundwater recharge for each selection of specific storage.

It can also be inferred from Table 2 that uncertainty analysis outputs clustered around the lower 86% to 99% confidence interval may have appropriate specific storage values with the exception of model layers 1, 2 and 4. However, the EIS describes that scenarios outside the 95% prediction
interval were discarded and that these uncertainty analysis predictions were not ‘calibration
constrained’. Therefore the EIS uncertainty analysis provides biased predictions of impact.
Table 1: Watermark Coal Project EIS Groundwater Model – Hydraulic parameters
(Source: EIS Appendix T, page 150; AGE, 2013)

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<td>5.0 x 10^7 m^-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clare Sandstone</td>
<td>Horizontal Hydraulic Conductivity</td>
<td>2.0 x 10^3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vertical Hydraulic Conductivity</td>
<td>2.0 x 10^3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Specific Yield Sy</td>
<td>1.2 x 10^2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Specific Storage Ss</td>
<td>5.0 x 10^7 m^-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permain Interburden</td>
<td>Horizontal Hydraulic Conductivity</td>
<td>1.0 x 10^3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vertical Hydraulic Conductivity</td>
<td>1.0 x 10^3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Specific Yield Sy</td>
<td>5.0 x 10^7 m^-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hoskssons Coal Seam</td>
<td>Horizontal Hydraulic Conductivity</td>
<td>5.0 x 10^3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vertical Hydraulic Conductivity</td>
<td>5.0 x 10^3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Specific Yield Sy</td>
<td>2.2 x 10^3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Specific Storage Ss</td>
<td>1.7 x 10^7 m^-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Melvilles Coal Seam</td>
<td>Horizontal Hydraulic Conductivity</td>
<td>5.0 x 10^3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vertical Hydraulic Conductivity</td>
<td>5.0 x 10^3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Specific Yield Sy</td>
<td>3.0 x 10^3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Specific Storage Ss</td>
<td>1.5 x 10^5 m^-1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Horizontal Hydraulic Conductivity (Kh) is in m/day
      Vertical Hydraulic Conductivity (Kv) is in m/day
      Specific Yield is a percentage (unconfined storage) (%)
      Specific Storage (Ss) is in m³

All specific storage values highlighted in orange are substantially inconsistent with poroelastic theory
Figure 10: Watermark Coal Project EIS Groundwater Model - Upper Namoi Alluvium: specific storage values (Source: EIS Appendix T; AGE, 2013)
Table 2: Watermark Coal Project EIS Groundwater Model – specific storage “measurement error” statistics utilised for uncertainty analysis (Source: EIS Appendix T)

<table>
<thead>
<tr>
<th>Model Layer</th>
<th>Lower 95% confidence Interval</th>
<th>Mean</th>
<th>Upper 95% confidence Interval</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(m/d)</td>
<td>(m/d)</td>
<td>(m/d)</td>
<td>(log10)</td>
</tr>
<tr>
<td>1</td>
<td>3.8E-07</td>
<td>1.0E-05</td>
<td>2.6E-04</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>3.8E-05</td>
<td>1.0E-03</td>
<td>2.6E-02</td>
<td>0.71</td>
</tr>
<tr>
<td>2</td>
<td>3.8E-07</td>
<td>1.0E-05</td>
<td>2.6E-04</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>3.8E-05</td>
<td>1.0E-03</td>
<td>2.6E-02</td>
<td>0.71</td>
</tr>
<tr>
<td>3</td>
<td>5.6E-06</td>
<td>5.6E-05</td>
<td>5.6E-04</td>
<td>0.50</td>
</tr>
<tr>
<td>4</td>
<td>5.0E-05</td>
<td>5.0E-04</td>
<td>5.0E-03</td>
<td>0.50</td>
</tr>
<tr>
<td>5</td>
<td>5.0E-06</td>
<td>5.0E-05</td>
<td>5.0E-04</td>
<td>0.50</td>
</tr>
<tr>
<td>6</td>
<td>5.0E-06</td>
<td>5.0E-05</td>
<td>5.0E-04</td>
<td>0.50</td>
</tr>
<tr>
<td>7</td>
<td>5.0E-06</td>
<td>5.0E-05</td>
<td>5.0E-04</td>
<td>0.50</td>
</tr>
<tr>
<td>8</td>
<td>1.7E-06</td>
<td>1.7E-05</td>
<td>1.7E-04</td>
<td>0.50</td>
</tr>
<tr>
<td>9</td>
<td>1.0E-07</td>
<td>1.0E-06</td>
<td>1.0E-05</td>
<td>0.50</td>
</tr>
<tr>
<td>10</td>
<td>1.5E-06</td>
<td>1.5E-05</td>
<td>1.5E-04</td>
<td>0.50</td>
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<tr>
<td>11</td>
<td>1.0E-07</td>
<td>1.0E-06</td>
<td>1.0E-05</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Specific storage values highlighted in red are substantially inconsistent with poroelastic theory.

3.3 Comparison to field data

The specific storage values in the EIS model have been compared to interpretations of field data collected by UNSW at the Cattle Lane Research Station at Quirindi. This site falls within the domain of the EIS model. The data has also been compared to interpretations of field data collected for Shenhua by GHD (2012) within the Watermark Coal Project Exploration Lease (EL). These comparisons demonstrate that the specific storage values modelled in the EIS are up to three orders of magnitude too high for smectite clay and sandy/gravelly smectite clay.

3.3.1 UNSW Cattle Lane Research Station

UNSW Connected Waters Initiative have collected groundwater level, cross-hole seismic and core data from the Namoi Alluvium down to a depth of 38m at Cattle Lane in Quirindi, 30km to the south of Watermark. Acworth et al. (2016), Acworth et al. (2017) and Rau et al. (2018) report analysing this data using various methods to calculate the specific storage of smectite clays, and sands and gravels embedded in the clay matrix to be 1-5 x 10^-6 m^-1. Note that Acworth et al. (2017) and Rau et al. (2018) present specific storage calculated as a function of both ‘free’ moisture and ‘total’ moisture. The values of specific storage based on free moisture are the correct values to utilise for elastic deformation because water physically bound to the clay cannot be released.
In contrast, for the impossible scenario of the clay being instantaneously consolidated to rock (i.e. making the total porosity available), the specific storage may be calculated from the total moisture content. In that case the ‘inelastic’ specific storage is estimated to decrease with depth from $1.7 \times 10^{-4} \text{ m}^{-1}$ at 5 m depth to $5 \times 10^{-6} \text{ m}^{-1}$ at 30 m depth. Between 30 and 40 m depth the sediments contain sand and gravel and specific storage is $7 \times 10^{-8} \text{ m}^{-1}$ irrespective of the method.

### 3.3.2 Watermark Coal Project lease

During the course of the Watermark Coal Project environmental assessment, GHD (2012) reported undertaking a number of pumping tests and analysing this data to determine values of at least aquifer transmissivity and storativity. As part of this study the aquifer test interpretation data-sheets produced by the practitioners using AQTESolv software were reviewed for adequacy. These data-sheets were attached to Appendix T of the EIS.

For each aquifer test interpretation, the reported transmissivity, storativity and saturated thickness at the pumping/observation well were noted and the bulk average aquifer hydraulic conductivity, specific storage and hydraulic diffusivity values calculated. Table 3 summarises the aquifer test interpretation data that were accepted for use in this report.

For this study, aquifer test interpretations by GHD (2012) were ignored if:

1. Modelled drawdown responses were a poor fit to the pumping test data; and/or
2. The interpretation yielded a specific storage value substantially inconsistent with poroelastic theory (i.e. much too low or too high) because an appropriate interpretation model incorporating a leaky aquitard solution or more complex aquifer geometry was not utilised.

Revised interpretations of the aquifer test data could be made with more appropriate aquifer models to arrive at improved estimates of aquifer properties. This is discussed further in Section 3.3.3.

Table 4 presents the comparison of the aquifer test data to the values simulated within the EIS groundwater flow model. The comparison highlights that compared to field-scale aquifer test data, the EIS groundwater model simulates specific storage in:

- Coal seam formations at 50 m depth approximately one (1) order of magnitude too high (and hydraulic diffusivity at least one (1) order of magnitude too low);
- Fractured rocks at 50 m depth too high by approximately one (1) order of magnitude (and hydraulic diffusivity potentially up to four (4) orders of magnitude too low);
- Upper Namoi Alluvium too high by up to three (3) orders of magnitude (and hydraulic diffusivity potentially up to six (6) orders of magnitude too low).
### Table 3: Summary of 'accepted' interpretations of aquifer test data on the NSW Liverpool Plains (Source: compiled from EIS Appendix T, including GHD, 2012)

<table>
<thead>
<tr>
<th>Geological Description</th>
<th>Pumping Bore</th>
<th>Screen Depths (m bgs)</th>
<th>Flow Rate (L/s)</th>
<th>Obs Bore</th>
<th>EIS Model Layer</th>
<th>Aquifer Test Datasheet Reference</th>
<th>Analysis Method</th>
<th>Modelled Saturated Thickness at Observation Bore (m)</th>
<th>T (m²d⁻¹)</th>
<th>S (m³)</th>
<th>K (m²)</th>
<th>Ss (m³)</th>
<th>D*K/Ss (m²s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Namoi Alluvium (Gunnedah Formation)</td>
<td>90BL2548422</td>
<td>33-36 39-45 48-54</td>
<td>18</td>
<td>WM0093A</td>
<td>2</td>
<td>pg.763</td>
<td>Dougherty-Babu</td>
<td>33</td>
<td>195.3</td>
<td>1.2E-05</td>
<td>5.9</td>
<td>3.5E-07</td>
<td>193.2</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>WM0093B</td>
<td>2</td>
<td>pg.765</td>
<td>Cooper-Jacob</td>
<td>20.9</td>
<td>168.8</td>
<td>8.5E-06</td>
<td>8.1</td>
<td>4.1E-07</td>
<td>230.0</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>WM076</td>
<td>2</td>
<td>pg.766</td>
<td>Dougherty-Babu</td>
<td>20.9</td>
<td>162.0</td>
<td>8.6E-06</td>
<td>7.8</td>
<td>4.1E-07</td>
<td>218.4</td>
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<tr>
<td>Fractured interburden</td>
<td>GW967044</td>
<td>?</td>
<td>76</td>
<td>WM0563</td>
<td>2</td>
<td>pg.769</td>
<td>Hantush</td>
<td>32</td>
<td>851.0</td>
<td>5.5E-05</td>
<td>26.6</td>
<td>1.7E-06</td>
<td>178.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>WM0036C</td>
<td>4</td>
<td>pg.770</td>
<td>Neuman-Witthespoon</td>
<td>32</td>
<td>851.0</td>
<td>5.5E-05</td>
<td>26.6</td>
<td>1.7E-06</td>
<td>178.0</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>WM0329</td>
<td>4</td>
<td>pg.781</td>
<td>Cooper-Jacob</td>
<td>53</td>
<td>19.9</td>
<td>2.0E-04</td>
<td>0.9</td>
<td>3.8E-06</td>
<td>1.14</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>WM0329</td>
<td>4</td>
<td>pg.782</td>
<td>Hantush</td>
<td>53</td>
<td>24.5</td>
<td>3.2E-04</td>
<td>0.5</td>
<td>6.0E-06</td>
<td>0.88</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>WM0329</td>
<td>4</td>
<td>pg.783</td>
<td>Dougherty-Babu</td>
<td>53</td>
<td>11.0</td>
<td>3.7E-05</td>
<td>0.2</td>
<td>7.0E-07</td>
<td>3.43</td>
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<td></td>
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<td></td>
<td>WM0329</td>
<td>4</td>
<td>pg.784</td>
<td>Moench</td>
<td>53</td>
<td>11.2</td>
<td>3.5E-05</td>
<td>0.2</td>
<td>6.5E-07</td>
<td>3.77</td>
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<tr>
<td>Benelabri Formation below CLR sandstone</td>
<td>WM0363</td>
<td>17.8-32.8</td>
<td>0.04 - 0.1</td>
<td>WM0363A</td>
<td>7</td>
<td>pg.800</td>
<td>Cooper-Jacob</td>
<td>35</td>
<td>0.13</td>
<td>3.2E-04</td>
<td>0.004</td>
<td>9.2E-06</td>
<td>0.005</td>
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<tr>
<td>Hoskisson Coal Seam</td>
<td>WM0157L</td>
<td>40-52</td>
<td>0.2</td>
<td>WM0157_V03</td>
<td>8</td>
<td>pg.798</td>
<td>Hantush</td>
<td>26</td>
<td>3.0</td>
<td>4.3E-05</td>
<td>0.1</td>
<td>1.7E-06</td>
<td>0.80</td>
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<td></td>
<td></td>
<td></td>
<td>WM0157_V03</td>
<td>8</td>
<td>pg.799</td>
<td>Neuman-Witthespoon</td>
<td>26</td>
<td>2.8</td>
<td>3.6E-05</td>
<td>0.1</td>
<td>1.4E-06</td>
<td>0.90</td>
</tr>
</tbody>
</table>

### Table 4: Comparison of hydraulic conductivity, specific storage and hydraulic diffusivity values between field data analysis by GHD (2012) and numerical modelling by AGE (2013)

<table>
<thead>
<tr>
<th>Geological Description</th>
<th>EIS Model Layer</th>
<th>EIS Component</th>
<th>N</th>
<th>Hydraulic Conductivity, K (m²/s)</th>
<th>Specific Storage, Ss (m³)</th>
<th>Hydraulic Diffusivity, D (m²/s)</th>
<th>Mismatch in Log10(D) (i.e. orders of magnitude)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Namoi Alluvium</td>
<td>2</td>
<td>Field Data Analysis (GHD, 2012)</td>
<td>2</td>
<td>5.9</td>
<td>2.6E-07</td>
<td>1.7E-06</td>
<td>178.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EIS Model (AGE, 2013)</td>
<td>2</td>
<td>0.01</td>
<td>1.0E-05</td>
<td>1.0E-06</td>
<td>0.0001</td>
</tr>
<tr>
<td>Fractured Permian(?) Interburden</td>
<td>5?</td>
<td>Field Data Analysis (GHD, 2012)</td>
<td>2</td>
<td>0.2</td>
<td>6.5E-05</td>
<td>6.0E-06</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EIS Model (AGE, 2013)</td>
<td>2</td>
<td>0.01</td>
<td>5.0E-05</td>
<td>5.0E-05</td>
<td>2.3E-04</td>
</tr>
<tr>
<td>Permian Interburden</td>
<td>7</td>
<td>Field Data Analysis (GHD, 2012)</td>
<td>1</td>
<td>0.004</td>
<td>9.2E-06</td>
<td>0.005</td>
<td>Uncertain</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EIS Model (AGE, 2013)</td>
<td>1</td>
<td>0.0001</td>
<td>1.7E-05</td>
<td>1.7E-05</td>
<td>0.0001</td>
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<tr>
<td>Hoskisson Coal Seam</td>
<td>8</td>
<td>Field Data Analysis (GHD, 2012)</td>
<td>2</td>
<td>0.1</td>
<td>1.4E-06</td>
<td>1.7E-06</td>
<td>0.80</td>
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<td></td>
<td></td>
<td>EIS Model (AGE, 2013)</td>
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<td>0.0001</td>
<td>1.7E-05</td>
<td>1.7E-05</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

Values printed in red are substantially inconsistent with poroelastic theory.

*Note that the EIS model does not honour the high hydraulic conductivity interpretations within fractured Permian Interburden or the Hoskissons Coal Seam.

*Note also that the EIS model appears to compensate for hydraulic conductivity values being one order of magnitude too low by assigning specific storage values at least one order of magnitude too high.
3.3.3 Caroona Coal and Watermark Coal Project leases

For the purposes of this study CCAG requested from BHP and the NSW Government the aquifer pumping test data collected by BHP within the BHP Caroona exploration leases and adjacent to southern boundary of the then proposed Watermark Coal Project. This data formed the basis of modelling reports submitted to the NSW Government. WRL had planned to analyse these datasets for transmissivity, storage, hydraulic conductivity and specific storage to estimate vertical hydraulic conductivity and rates of leakage between bedrock and alluvium. This data was not released to CCAG by BHP. Enquiries made by CCAG and WRL over the course of 2017 and 2018 suggested that this data was not held by NSW Government. In relation to the BHP data (relating to monitoring wells located on Crown land) BHP indicated to CCAG that NSW Government now owns the monitoring assets and the data.

3.4 Comparison to other models

Of the groundwater flow models of the NSW Liverpool Plains considered in this audit, only one model, the Lower Namoi Alluvium Subsidence Model by Ali et al. (2004) was found to reasonably simulate specific storage as defined by Rau et al. (2018) in all model layers. The models that were considered in this audit included the Lower Namoi Alluvium Subsidence Model (refer Section 3.4.1), the BHP Caroona Coal Project Model (refer Section 3.4.2), the Upper Namoi Groundwater Flow Model (refer Rau et al., 2018) and the Namoi Catchment Water Study (refer Rau et al., 2018).

3.4.1 Lower Namoi Alluvium Subsidence Model

During 1974, in response to concerns about sustainability of groundwater abstraction between Narrabri and Wee Waa (north of Breeza), a series of survey benchmarks were established across the Lower Namoi Alluvium and supplemented further during the 1980s. Based on survey, subsidence was subsequently recorded. For the ten (10) year period between 1981 and 1990 land subsidence was recorded to be between 0.08 and 0.21 m (Ross and Jeffery, 1991).

Ali et al. (2004) reported calibrating a 3-layer computer model to predict the subsidence in the Lower Namoi Alluvium. The modelling was undertaken in the groundwater flow model, MODFLOW (McDonald and Harbaugh, 1988) using the Inter-Bed Storage (IBS) Package (Leake and Prudic, 1991). While not deforming the model grid to reflect the subsidence or altering the hydraulic properties through time, the IBS plugin did allow for a prediction of subsidence. These subsidence predictions are considered by some authors to be accurate to about 10%.
The output of the Ali et al. (2004) calibrated model for the lower Namoi Alluvium was a best fit specific storage value of $2.1 \times 10^{-6}$ m$^{-1}$ and an inelastic specific storage value (to represent water released by consolidation) of $1.6 \times 10^{-4}$ m$^{-1}$. Note that both of these values are very similar to the specific storage values estimated by Rau et al. (2018) for the Upper Namoi Alluvium when considering free water (mobile porosity) and total porosity (see Section 3.3.1).

### 3.4.2 BHP Caroona Coal Project

Table 5 compares the values of specific storage simulated within Watermark Coal Project EIS model by AGE (2013) to the values simulated within the Caroona Coal Project preliminary model by Nicol et al. (2014). Both models attempt to simulate groundwater flow processes beneath the upper parts of the NSW Liverpool Plains (Figure 5). Values in Table 5 that are substantially inconsistent with the limits of poroelastic theory ($-2 \times 10^{-7}$ to $1.3 \times 10^{-5}$ m$^{-1}$) are highlighted in italicised red text.

The following comments are provided with reference to the Ss values of the EIS model:

- **Namoi Alluvium**: Both models simulate specific storage orders of magnitude higher than the limits imposed by poroelastic theory and the available field measurements determined by Ali et al. (2004), GHD (2012) and Rau et al. (2018);
- **Tertiary Volcanics** are assigned a Ss value of $5.6 \times 10^{-5}$ m$^{-1}$. This is three times larger than the value in the Caroona Coal Project model and 4.3 times too large compared to theory;
- **Pilliga Sandstones** are assigned a Ss value of $5 \times 10^{-4}$ m$^{-1}$. This is 38 times too large compared to poroelastic theory and 42 times too large compared to the value used within the Caroona Coal Project model;
- **Late-Permian age Nea Subgroup and Jurassic / Early Triassic rocks** are assigned a Ss value of $5 \times 10^{-5}$ m$^{-1}$. This is 38 times too large compared to poroelastic theory and 60 times too large compared to the value used within the Caroona Coal Project model;
- **Clare Sandstones** are assigned a Ss value of $5 \times 10^{-5}$ m$^{-1}$. This is 38 times too large compared to poroelastic theory and 65 times too large compared to the value used within the Caroona Coal Project model;
- **Late-Permian Age Coogal Subgroup Benelabri Formation** are assigned a Ss value of $1.7 \times 10^{-5}$ m$^{-1}$. While this is similar to the values determined from the GHD (2012) aquifer test data from shallow observation wells about the proposed mine site, it is 187 times too large compared to the value used within the Caroona Coal Project model.
- **Hoskissons Coal Seam** is assigned a Ss value of $1.7 \times 10^{-5}$ m$^{-1}$. This is 10 - 11 times too large compared to the values determined from the GHD (2012) aquifer test data and 19 times too large compared to the value used within the Caroona Coal Project model.
Table 5: Comparison of modelled specific storage values on the NSW Liverpool Plains

<table>
<thead>
<tr>
<th>Model Layer</th>
<th>Geology</th>
<th>Watermark Coal Project (EIS Appendix T; AGE, 2013)</th>
<th>Caroona Coal Project (Nicol et al., 2014)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>EIS Model</td>
<td>Uncertainty Analysis</td>
</tr>
<tr>
<td>1</td>
<td>Namoi Alluvium (Narrabri Formation)*</td>
<td>Min: $1 \times 10^{-5}$&lt;br&gt;Max: $1 \times 10^{-3}$</td>
<td>Min: $4.0 \times 10^{-7}$&lt;br&gt;Max: $2.6 \times 10^{-6}$</td>
</tr>
<tr>
<td>2</td>
<td>Namoi Alluvium: (Gunnedah Formation)*</td>
<td>Min: $1 \times 10^{-5}$&lt;br&gt;Max: $1 \times 10^{-3}$</td>
<td>Min: $4 \times 10^{-7}$&lt;br&gt;Max: $2.6 \times 10^{-6}$</td>
</tr>
<tr>
<td>1&amp;2</td>
<td>Regolith</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Tertiary: Undifferentiated Volcanics (Tertiary Basalts)</td>
<td>$5.6 \times 10^{-5}$</td>
<td>Min: $5.6 \times 10^{-6}$&lt;br&gt;Max: $5.6 \times 10^{-4}$</td>
</tr>
<tr>
<td>4</td>
<td>Jurassic and Triassic: Pilliga Sandstone, Purlawaugh Fm, Glenrowan Intrusives, Garrawilla Volcanics, Napperby and Digby Fm (Jurassic / Early Triassic rocks)</td>
<td>$5.0 \times 10^{-4}$</td>
<td>Min: $5.0 \times 10^{-5}$&lt;br&gt;Max: $5.0 \times 10^{-3}$</td>
</tr>
<tr>
<td>5</td>
<td>Late-Permian - Nea Subgroup: Wallala and Trinkey Fm (Jurassic / Triassic Interburden)</td>
<td>$5.0 \times 10^{-5}$</td>
<td>Min: $5.0 \times 10^{-6}$&lt;br&gt;Max: $5.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>6</td>
<td>Late-Permian - Black Jack Group, Coogal Subgroup: Clare Sandstone</td>
<td>$5.0 \times 10^{-5}$</td>
<td>Min: $5.0 \times 10^{-6}$&lt;br&gt;Max: $5.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>7</td>
<td>Late-Permian, Black Jack Group, Coogal Subgroup, Benelabri Formation (Permian Interburden)</td>
<td>$1.0 \times 10^{-5}$</td>
<td>Min: $5.0 \times 10^{-6}$&lt;br&gt;Max: $5.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>8</td>
<td>Late-Permian - Black Jack Group, Coogal Subgroup: Hoskissons Member (Coal Seam)</td>
<td>$1.7 \times 10^{-5}$</td>
<td>Min: $1.7 \times 10^{-6}$&lt;br&gt;Max: $1.7 \times 10^{-4}$</td>
</tr>
<tr>
<td>9</td>
<td>Late-Permian - Black Jack Group, Coogal Subgroup: Arkarula/Brigalow Fm (Permian Interburden)</td>
<td>$1.0 \times 10^{-5}$</td>
<td>Min: $1.0 \times 10^{-7}$&lt;br&gt;Max: $1.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>10</td>
<td>Late-Permian - Brothers Subgroup: Pamboola Fm, Melvilles Coal Seam</td>
<td>$1.5 \times 10^{-5}$</td>
<td>Min: $1.5 \times 10^{-6}$&lt;br&gt;Max: $1.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>11</td>
<td>Early to Late Permian - Millie and Bellata Group: Watermark, Porcupine, Maules Creek and Leard Fm</td>
<td>$1.0 \times 10^{-5}$</td>
<td>Min: $1.0 \times 10^{-7}$&lt;br&gt;Max: $1.0 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

1 Parameters as reported in Table 9.2 of AGE (2013).
2 Parameters as reported in Table 22 of Nicol et al (2014).
*The spatial distribution of Ss in Namoi Alluvium for the Watermark Coal Project groundwater model is shown in Figure 1.
Only average Ss values are reported for the Caroona Coal Project model.
Values italicised in red are inconsistent with poroelastic theory.
3.5 Discussion

Figure 8 and Figure 9 highlight that the specific storage values represented within the Watermark Coal Project EIS Groundwater Model compare poorly with poroelastic theory, field data and typical values of rock modulus reported in the geotechnical literature. The specific storage values also compare poorly with some or all of the values utilised in other groundwater flow models.

Work by Ali et al. (2004), GHD (2012), Acworth et al. (2017), Rau et al. (2018) provides a consistent picture that the Namoi Alluvium has specific storage in the range of $1 \times 10^{-6}$ to $1 \times 10^{-3}$ m$^{-1}$. Between 30 m and 38 m depth at Cattle Lane the gravelly and sandy sediments that are embedded in a clay matrix have specific storage values on the order of $5 \times 10^{-6}$ m$^{-1}$. In contrast, the EIS model adopts values in excess of the limits of poroelastic theory that range between $1 \times 10^{-5}$ to $1 \times 10^{-3}$ m$^{-1}$.

In some layers of the EIS model, Tertiary, Jurassic, Triassic and Late Permian age rocks are represented with unrealistic values of specific storage values that are equivalent to the inelastic values of specific storage for under-consolidated clays that should be entered into a subsidence model, i.e. $5 \times 10^{-4}$ m$^{-1}$, $5 \times 10^{-5}$ m$^{-1}$ and $1.7 \times 10^{-5}$ m$^{-1}$. Given that the much younger clays of the Upper Namoi Alluvium (17 to 150 ka) are described as generally consolidated to over-consolidated (Timms et al. 2018, Bouzalakas, 2016), it is difficult to accept that much deeper and older (2.58+ Ma) rocks could be less consolidated than shallow clays. This would imply that the sands and clays are stronger and less compressible than the underlying rocks.

While some practitioners may suggest that the groundwater modellers were required to utilise unrealistic values of specific storage to calibrate their groundwater models to account for land subsidence processes, the following is noted:

- Land subsidence irreversibly decreases specific storage. It does not increase it.

- The observations of Timms and Acworth (2002, 2005), Acworth and Timms (2009), Crane et al. (2015) and Timms et al. (2018) that irrigation water and fluids are observed to move preferentially and very quickly down through the upper thirty metres of the Upper Namoi Alluvium at Breeza Farm and Cattle Lane, provides a plausible explanation for the unaccounted water created by the modellers, i.e. it originates from preferential, focussed (non-diffuse) recharge and not storage.

- The highly variable tritium and radiocarbon activities of water in the Upper Namoi Alluvium reported in Appendix T of the EIS support the notion of focussed recharge mixing with old groundwater (consider the origin and age of water bound to the clays when they were deposited and that clays absorb and desorb water).
• The observations of Acworth et al. (2015) that a clear distinction between the hypothesised Narrabri and Gunnedah formations was not encountered at Quirindi to the maximum investigation depth of 31.5m.

• The observations of Bouzalakas (2016) that the clayey sediments within thirty metres (30 m) of ground surface at Cattle Lane in Quirindi are generally consolidated to over-consolidated does not support a regionally extensive subsidence assumption.

• There are no reported observations of land subsidence for the Upper Namoi Alluvium in the EIS and neither AGE (2013) or Nicol et al. (2014) designed their MODFLOW models to simulate land subsidence.

• In locations where clay content may be high and land subsidence can occur in response to groundwater abstraction, analysis of the literature suggests that groundwater modellers utilising subsidence modelling packages should:
  o adopt specific storage values of approximately 1.5 x 10^{-6} m^{-1} (Rau et al., 2018, Ali et al., 2004) for sediments in the top thirty (30m) and possibly as low as 5 x 10^{-7} m^{-1} at depth (GHD, 2012).
  o ‘inelastic specific storage’ values (Ali et al., 2004; Rau et al., 2018) of no more than:
    ▪ 1 x 10^{-4} m^{-1} for very shallow sediments in the top 10m;
    ▪ 5 x 10^{-5} m^{-1} for sediments between 20 m and 30 m depth.

• Groundwater modelers of the Upper Namoi Alluvium should:
  o carefully catalogue historical groundwater pumping throughout the valley;
  o estimate irrigation returns to the water table by location, land and water use; and
  o vary these recharge rates during model calibration taking care to keep values of specific storage consistent with poroelastic theory and values of hydraulic conductivity consistent with values determined from pumping test interpretations.

• The conceptual, numerical modelling predictions of Anderson et al. (2018) that demonstrate the significance of the specific storage value adopted for modelling and the potentially significant impacts of adjustment of Ss values on drawdown predictions.

3.6 Audit of groundwater assessment

During the course of the specific storage audit, the authors identified a number of additional numerical modelling deficiencies and inconsistencies that may also significantly influence the predictions of the long-term groundwater impacts from the Watermark Coal Project. The following additional issues were identified:
1. When assessing groundwater drawdown impacts post-mining after coal extraction ceases, the numerical model boundary conditions that allow groundwater to enter the mined-out and back-filled voids should not automatically be switched off. In reality, groundwater will continue to flow into final voids in perpetuity (if the void is classified as a terminal sink) and into backfilled voids for many decades.

2. The modelled rainfall and focussed groundwater recharge rates (e.g. irrigation, creeks, rivers etc.) need to be updated from calibration to prediction because surface water and groundwater capture and surface water management practices by the mine will change these recharge rates to influence groundwater levels about the mine.

3. The water budget for the Upper Namoi Alluvium has 50% less rainfall recharge than the BHP Caroona Model (Nicol et al., 2014) and 10.5 GL/yr less groundwater – surface water interaction than the Watermark Coal Project EIS Surface Water model.

4. The water budget for the basalt outcrops have 500% less recharge than the BHP Caroona Model (Nicol et al., 2014) and 550% less recharge than Terranus Earth Sciences who undertook the salt impact assessment for the Watermark Coal Project EIS.

5. The water budget for the Jurassic, Triassic and Permian Outcrops has 2,000% less recharge than the BHP Caroona Model (Nicol et al., 2014).

6. Salt impact assessment:
   a. No off-site salt mass balance for post-mining conditions.
   b. Salt loads from seepage downgradient of the proposed overburden emplacement areas. The values estimated in the EIS appear to be 100 to 1,600 times larger than the natural atmospheric salt deposition rate.
   c. The site management practices that will prevent salt from overburden emplacement areas from being mobilised by rainfall and transported in subsequent runoff and groundwater recharge into surrounding agricultural land.
   d. No assessment of salinity in the final void beyond 470 years.
   e. No consideration of the time-scales of density dependent groundwater flow and diffusion impacts from evapo-concentrated salts in the proposed final void.

With increased groundwater recharge rates and higher hydraulic conductivity in shallow bedrock and in alluvium closer to the mine, it is anticipated that the mine may capture more groundwater and produce larger groundwater drawdown than currently predicted. However, this is difficult to confirm without first updating the model to utilise appropriate values of specific storage. Since salt impacts tend to be irreversible, a comprehensive salt impact assessment must be provided prior to designing the project and the water management plans.
4 Recommendation for re-assessment

Based on the work of the authors referenced above, it is recommended that the Watermark Coal Project impacts be re-assessed with revised data analysis, modelling and calibration constrained uncertainty analysis to include, at a minimum:

1. A geological model of the Upper Namoi Alluvium which has been subdivided into a greater number of model layers to better reflect the available geological and geophysical logs, geophysical maps, water chemistry and hydraulic head observations. The model should better represent the Upper Namoi Alluvium within 5 km to 10 km of the project.

2. A review to verify that there is consistency between observation and prediction in relation to the confinement of aquifers at key groundwater usage locations near the proposed mine.

3. A numerical model that has been re-calibrated with:
   a. appropriate specific storage values based on theory, re-analysis of field data and stress time-dependency (e.g. David et al., 2017; Domenico and Mifflin, 1965).
   b. revised hydraulic conductivity, specific yield and recharge values from rainfall and irrigation to ensure:
      i. that groundwater recharge signals from irrigation returns do quickly reach depths of approximately 30 m below ground level.
      ii. consistency with the results of available aquifer test analysis.
      iii. consistency with the results of recharge estimates by other tracer methods including General Chloride Mass Balance method.
      iv. hydraulic conductivity (K) values are larger than the values determined from small pieces of competent drill core which are not representative of the bulk average K of the formation (typically lab results are much smaller).
   c. an objective function that places greater weight on adjusting recharge and K to:
      i. generate baseflow predictions that are consistent with analyses of streamflow observation data and regional surface water modelling.
      ii. reproduce short-lived head changes in response to groundwater recharge and abstraction, including aquifer testing. MacMillan and Schumacher (2015) describe an efficient method that can be utilised to calibrate large regional models to aquifer test data without altering the size of the numerical model grid (and by extension the model time-step).

4. A salt mass balance that demonstrates long term protection of soil and water resources.
5 Conclusion

The predictions of groundwater impact provided for the Watermark Coal Project EIS are based on specific storage values that are orders of magnitude too high compared to in-situ field measurement data, poroelastic theory and other models of groundwater flow. Consequently, the EIS model misrepresents the amount of groundwater recharge and/or vertical leakage that is occurring.

Nearly two-thirds of the EIS model layers were modelled with unrealistic specific storage values that are larger than the limits allowed by poroelastic theory. The values that are utilised for modelling specific storage appear more consistent with the values of 'inelastic specific storage' that might be utilised within a subsidence model, however, these values are not utilised in subsidence modelling software. Furthermore, these values are utilised without any consideration of groundwater levels, the direction of groundwater level movement (up or down) or the pre-consolidation stress history of the sediments and rocks.

Preliminary review of the modelled hydraulic conductivity distributions also identified that some values chosen for modelling were inconsistent with actual ground conditions as determined during interpretation of aquifer test data. Similarly, it was identified that groundwater recharge and surface water – groundwater interaction rates were too low. Therefore, the EIS model must misrepresent the timing and potential magnitude of impacts to surrounding groundwater receptors.

With specific storage values set too high and vertical leakage too low, too much water will be captured from the bedrock units around the proposed mine, impacts during drought may be underestimated, and too little water may be captured from connected water sources, including the Upper Namoi Alluvium, the Mooki River and its tributaries. Anderson et al. (2018) demonstrate the significance of the specific storage value adopted for modelling and the potentially significant impacts of adjustment of Ss values on drawdown predictions.

In conclusion, the EIS hydrogeological conceptual model, its calibration methodology and its numerical model predictions are fundamentally flawed and do not provide a basis for reliable prediction. To promote good groundwater management practice on the NSW Liverpool Plains, which is one of the most productive agricultural regions in NSW, it is recommended that the project be re-assessed and managed with an improved modelling tool and an appropriate salt impact assessment. The revised work should addresses the issues and recommendations provided in Sections 3 and 4 of this report. Further work should be undertaken to demonstrate the
representativeness of the modelled agricultural water use, irrigation return, diffuse recharge, focussed recharge, hydraulic conductivity (horizontal and vertical) and specific storage values.
6 References


Price, G. and Bellis, L. (2012) "Namoi catchment water study – independent expert final study report", Tech. Rep. 50371/P4-R2 FINAL, Schlumberger Water Services (Australia) Pty Ltd, Department of Trade and Investment, Regional Infrastructure and Services, New South Wales (DTIRIS NSW), Locked Bag 21, Orange, NSW, 2800, Australia


