IMPACTS OF LONGWALL MINING AND COAL SEAM GAS EXTRACTION ON GROUNDWATER REGIMES IN THE SYDNEY BASIN PART 2 – PRACTICAL APPLICATIONS

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Australian Geomechanics Journal Vol 47 No. 3, p.51, September 2012

ABSTRACT

Part 1 of this paper presented simple equations for transient and steady state downwards flow, in saturated and unsaturated ground, that are considered to be useful in understanding flow and pressure regimes above extensive areas of longwall mining and coal seam gas extraction. This Part 2 paper presents field data from longwall mines in the Sydney Basin and relates the data to findings from Part 1. This Part 2 also analyses how different views have been expressed in relation to impacts of longwall mining on groundwater regimes, and proposes that these differences have largely arisen out of poor differentiation between seepage flows and pressures.

The field data presented in this part support a finding of Part 1, namely that the question that should be asked in respect to groundwater impacts from longwall mining, and CSG extraction, is not "if" impacts will occur, but "how long" will they take to occur.

1 INTRODUCTION

Impacts of underground coal mining on near-surface groundwater, and surface waters, in the Sydney Basin have elicited strong opposing views for about fifty years. Now those opposing views extend to coal seam gas (**CSG**) extraction. A link between these two activities is that both require substantial depressurisation and removal of groundwater from the coal seam. The strongly opposing views were encapsulated in the 1974-1975 Reynolds Inquiry into "Coal Mining Under or in the Vicinity of the Stored Waters of the Nepean, Avon, Cordeaux, Cataract and Woronora Reservoirs". For that Inquiry Messrs Orchard, Wardell, Williamson and Morton, working as consultants to the mining industry, expressed strong views that there was no downward flow through the Bald Hill Claystone and underlying Narrabeen rocks to the workings in the Bulli and Wongawilli seams. Equally, Professor John Knill and Messrs Williamson and Winchup, working on behalf of the Metropolitan Water Sewerage and Drainage Board concluded that downward seepage from the reservoirs was occurring and constituted a significant risk.

Not much has changed since 1975 and we must ask ourselves, why is this so given that all parties have access to the same facts. We think there are two reasons, one psychological and one technical.

The first reason is explained succinctly by psychologist Daniel Kahneman, 2002 Nobel Prize Laureate for Economics. He explains that we humans have two systems of thinking. System 1 operates automatically, quickly and with little effort. It is the originator of impressions and feelings that are the main sources for our explicit beliefs and deliberate choices of our second system of thinking. System 2 involves effortful mental activity, including complex computations; making choices, and decides what to do. However, a key point Kahneman makes is that "*System 2 is more of an apologist for the emotions of System 1 than a critic of those emotions – an endorser rather than an enforcer. Its search for information and arguments is mostly constrained to information that is consistent with existing beliefs.....*" This, we believe, explains our observation that publications on the issues of groundwater impacts show an almost one to one correlation between assessment of probable impacts and the authors' relationships to the mining and gas industries, or to environmentalist groups, or to their emotions about the environment, or their personal piece of countryside.

The second reason relates to differences of opinion regarding technical facets of groundwater impacts. These technical facets are the topic of this paper.

In Part 1 of this paper, analytical solutions to a range of idealised examples of vertical groundwater flow were presented with the purpose of providing a framework for explaining the observed effects on groundwater systems from large-scale depressurisation of underground regions, such as from longwall mining or CSG. In this paper, which is Part 2, the findings from theoretical analysis in Part 1 are applied with reference to factual data from the field, specifically within the Sydney geological basin.

The following technical matters are discussed.

- The differences between impacts of longwall mines, or CSG, on groundwater pressure and on groundwater flow.
- The impacts of heterogeneity and the nature of perched water tables, and 'disconnected' groundwater systems.

- The influence of lower permeability stratum on groundwater impacts, with specific reference to the Bald Hill Claystone found in the Sydney basin.
- Changes in hydraulic conductivity above longwalls due to fracturing.
- Transient effects and timing of impacts to groundwater systems.
- The effects of unsaturated groundwater flow, and important implications for groundwater impacts.

It is our aspiration that the material presented herein will assist with clarifying these issues from a scientific basis, and will assist with improving the quality of debate that is ongoing.

2 COAL MINING AND CSG IN THE SYDNEY BASIN

The reader may find descriptions of the stratigraphy of the Sydney Basin and underground coal mining operations in many publications (Herbert and Helby, 1980; Holla and Barclay, 2000)

In the Southern Coalfields, from which much of the field data are taken that are presented herein, mining is typically at depths of 200 to 500m. Very substantial areas have been extracted by both bord-and-pillar workings and longwall mines. For example in a 55km^2 area around Appin, the combined footprints of longwall extractions occupies 26km^2, and much of the remainder contains first workings.

While the only operating GSC extraction facility at the time of writing is at Camden (86 wells), huge areas are being explored covering thousands of square kilometres. There is the potential for thousands of wells, and in all cases the groundwater at seam levels has to be depressurised and extracted before the gas starts to flow in commercial quantities.

3 PIEZOMETRIC LEVEL DATA ABOVE COAL MINING IN THE SYDNEY BASIN

3.1 General Effects on Groundwater

Figure 1 presents the first 7 years of a 18 year record of multi-level piezometers data above a longwall mine near Cataract dam in the Southern coalfields. The timing of the passing longwalls 501 and 502, directly below the piezometers is also shown (Singh and Jakeman, 2001). Responses to the longwalls are observed, but the effects appear to be temporary for the shallower piezometers.

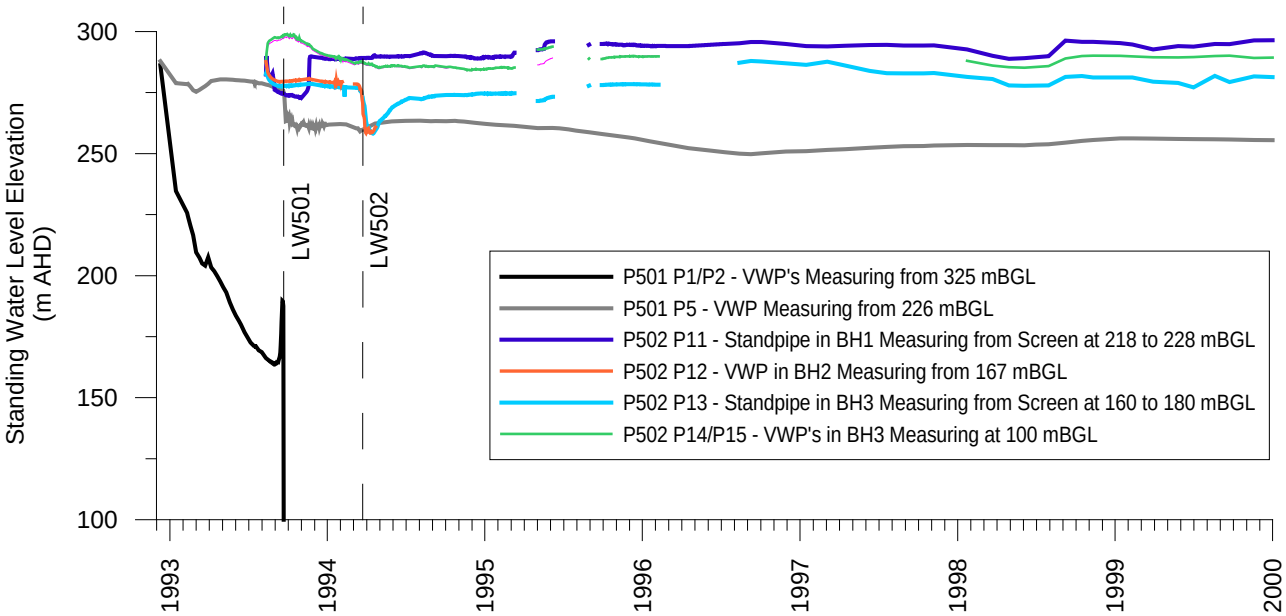

Figure 1 – Example of a Time-series of Piezometric Data from the Southern Coalfields During Passing of Longwalls

Such sudden decline and subsequent recovery has been observed at many mines (Matetic and Trevits, 1991; Booth et al, 1998; Booth, 2000). The rapid decline has been attributed to a temporary increase in secondary porosity during tilting and fracturing, and the subsequent recovery has been stated to be due to settlement of the overburden, reducing the secondary porosity again (ibid).

An expectation of continuing ground water recovery is reflected in many publications. Madden, et al (2009), citing Booth (2002), state that response of shallow confined groundwater systems to longwall mining includes a "long term groundwater level recovery due to settlement and recharge". Booth and Spande (1992) and Booth (1999, 2006) document the recovery of groundwater levels over a 7 year period in a shallow, 25m thick, bed of sandstone overlying 170m of shale, following longwall mining in Jefferson County, Illinois. However, there is no record of recovery of the precipitous drop in piezometric level in the shale at 100m depth. As acknowledged in the above-cited papers, recovery does not always occur.

Clearly, once mining has completed, and the mine and shafts fill with water, groundwater levels will return toward pre-mining conditions, although the time and nature of recovery will vary from site to site. However, it is the 30 year to >100 year period between depressurisation at seam level and mine refilling that is of key interest in this paper.

In Part 1 of this paper, it is shown that in the Sydney Basin, even if no fracturing takes place, the capacity for saturated vertical seepage into lower, depressurised, strata is typically higher that the available recharge. It follows, then, that depressurisation will continue to propagate outwards from the depressurised strata throughout the period of dewatering. Where fracturing occurs, the capacity for saturated vertical seepage will be increased. Hence, while an initial response and recovery may be observed, an ongoing growth in impacts is expected during the operation of mines in the Sydney basin.

Many of the dramatic effects on groundwater from longwall mining are related to fracturing. As such, interpretations for whether recovery will or will not be observed are commonly also given in terms of fracturing (e.g. Jankowski, et al 2008). The corollary, tacitly assumed in many publications - that groundwater impacts from longwall mining (or CSG) are not expected where fracturing is not present - is not supported by the analyses in Part 1 of this paper.

3.2 Perched Water Systems and Downward Flow.

Selected case examples of multilevel piezometer data taken during longwall mine operations in the Sydney Basin are presented in Figures 2 to 5.

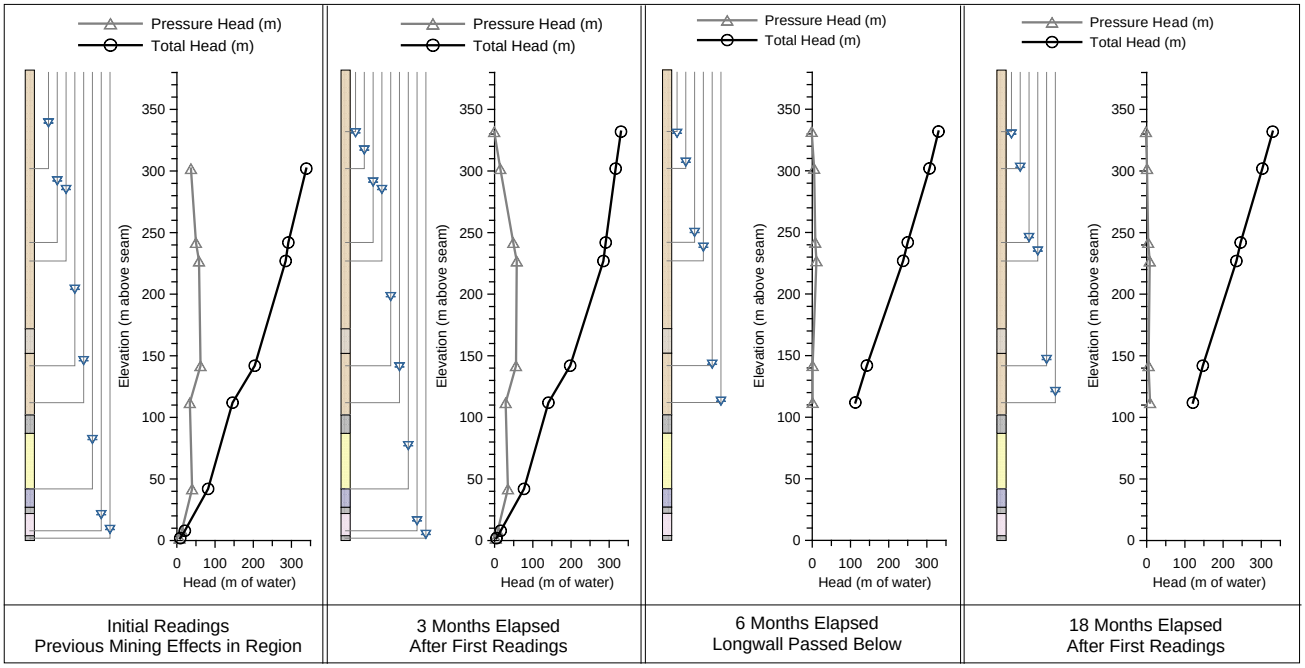

Figure 2 – Piezometric Profiles, Western Coalfields (using data from ACARP, 2007).

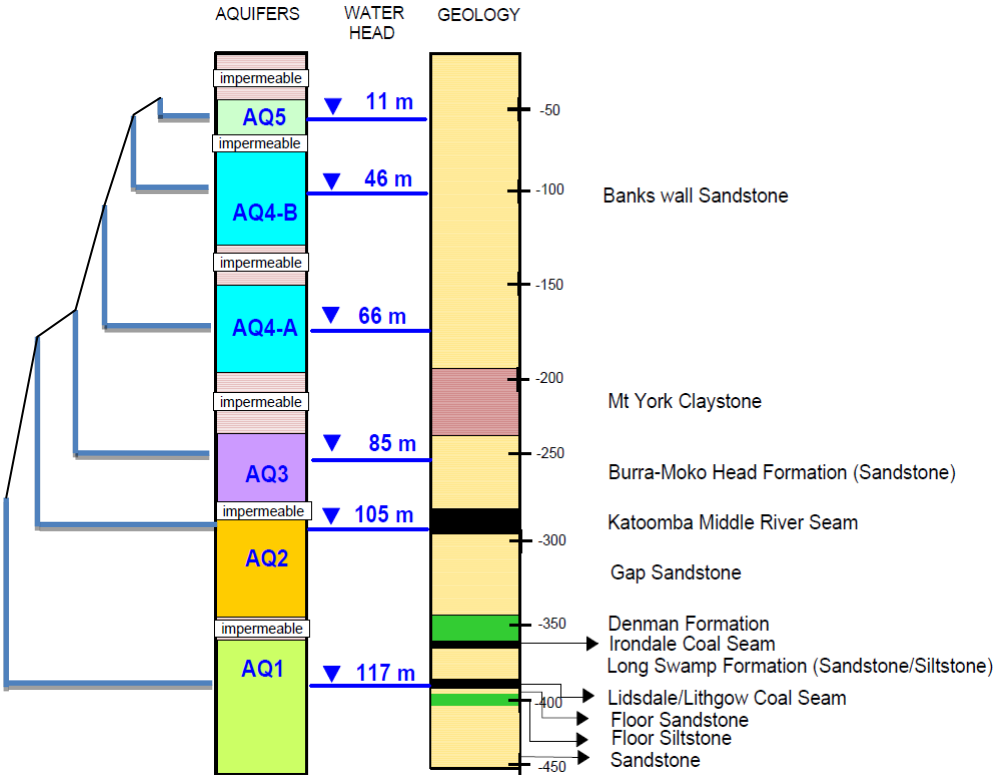

Figure 3 – Summary of Recorded Piezometric Levels, Western Coalfields (ACARP, 2007). Note their interpretive annotation of a series of 'aquifers' and 'impermeable' layers The piezometer lines on left are from authors of this paper

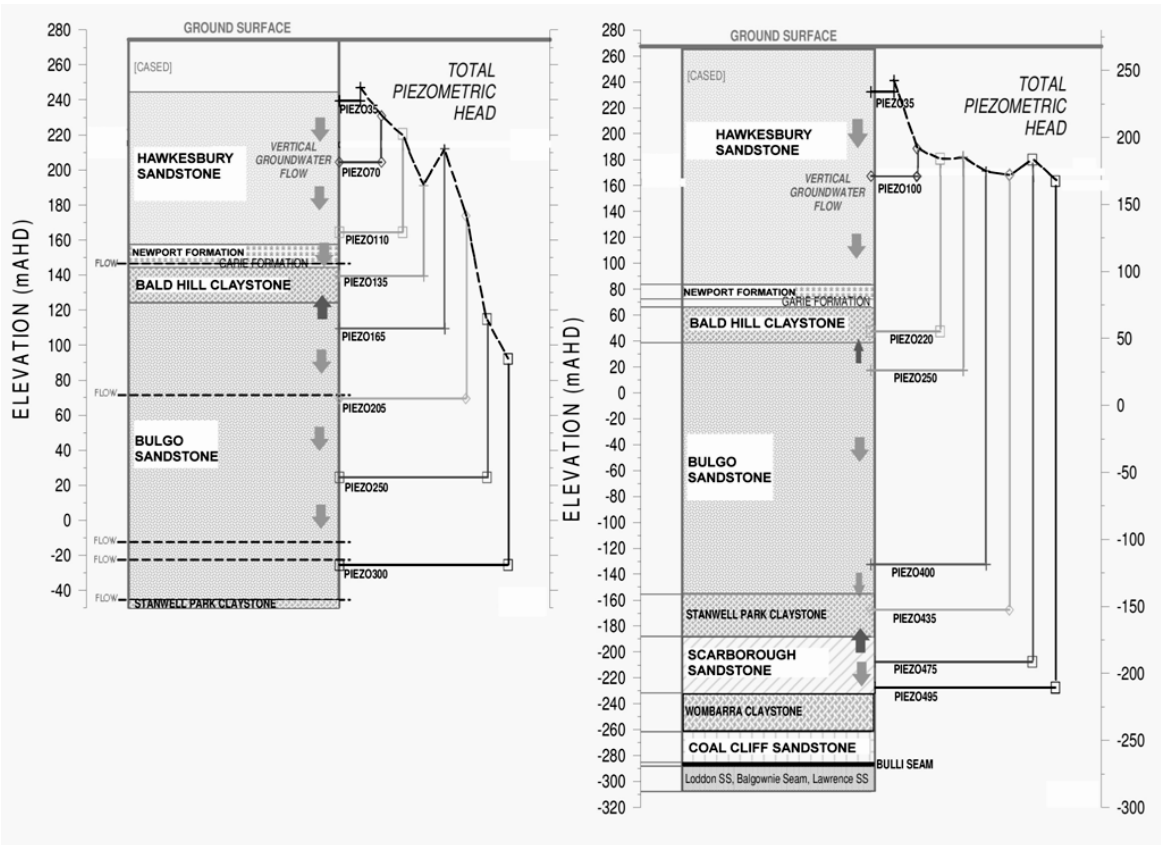

Figure 4 – Measured Piezometric Heads, Southern Coalfield Mined (Left) and in Unmined (Right) Regions Reproduced from Merrick 2009

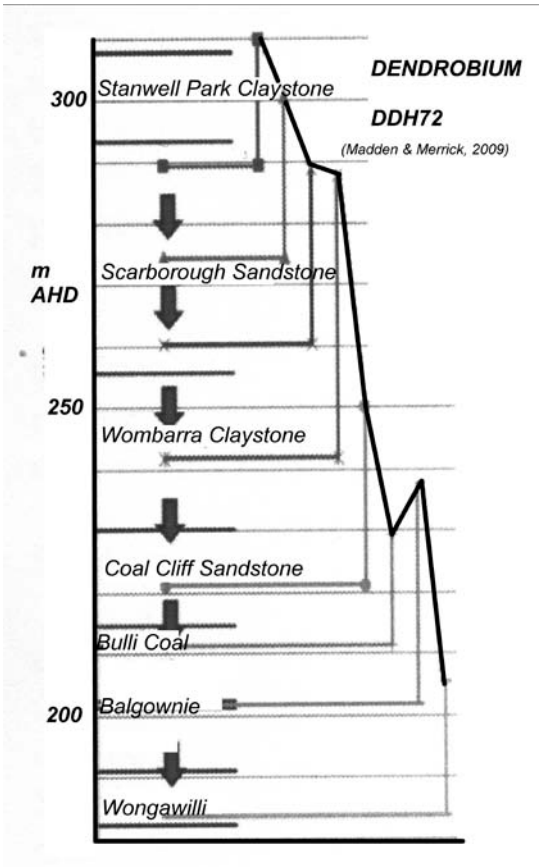

Figure 5 – Piezometric Profile, Southern Coalfields.
(from Madden and Merrick, 2009)

It is clear from these figures, and similar data not in the public domain, that piezometric data above a longwall mining region are commonly indicative of downwards hydraulic gradients.

This observation has historically been interpreted in two ways. Some see the vertical profile as a series of perched aquifers, exhibiting primarily lateral flow and disconnected from one another by horizontal 'aquitards' or 'aquicludes' (e.g. as interpreted by the authors of Figure 3). Others see the observed vertical gradient as indicative of a vertical flow profile. Those in this second camp, like the present authors are cognisant of the physics of groundwater flow whereby, as shown in the trivial example in Figure 6, piezometers at different levels in the same borehole in homogenous strata will show different heads, which have nothing to do with perched water tables, depending only on flow direction.

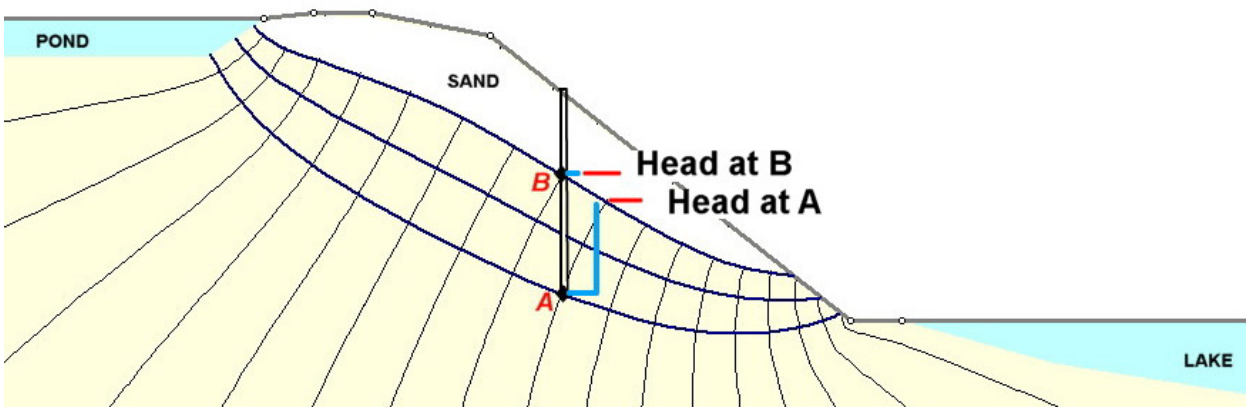

Figure 6 Different piezometric levels in vertical borehole in homogenous material

A debate between these two views polarised advisers to the Reynolds Enquiry (Reynolds, 1976). Those subscribing to the former viewpoint cited the many cases of mines or underground works for which the visible inflow rate was small. They also presented arguments based on provenance – the heritage of the terms 'aquifer', 'aquiclude' and 'aquitard', which had served the hydrogeological profession for many decades. This 'heritage' facet is discussed below, because it is one of the largest matters of contention between many hydrogeologists and geotechnical engineers.

3.3 Aquifers and Aquicludes, or a Continuum

The July 2008 report titled "Impacts of Underground Coal Mining on Natural Features in the Southern Coalfields" (**SCI)** (Hebblewhite, 2009) provides a typical exposition of the hydrogeology of the Southern Coalfields. The Hawkesbury Sandstone and Narrabeen Group rocks are described as either aquifers or aquicludes, with aquicludes defined as impermeable layers such as shale, clay or some claystones. The report takes on the view that there is no evidence of "any change in the hydraulic connectivity of water from reservoirs to mine workings". The report uses Everett et al (1998), Barclay and Holla (2000), Waddington & Kay (2002) and Galvin (2005) to support this view, and concludes that the reason for this absence of connectivity is either because of "the significant depth of mining (~ 500m), or the presence of the Bald Hill Claystone acting as an undisturbed aquiclude". The specifics of the Bald Hill Claystone formation are discussed in Section 7 below.

Clearly, horizontal layers of low conductivity material in the geological strata will introduce impedance to vertical flow. However, as demonstrated in Part 1 of this paper, the development of perched water tables will occur under purely vertical flow and do not have to represent lateral seepage along 'aquifers'. Furthermore, the presence of a perched water table does not indicate the cessation of vertical seepage. Rather, the water table represents a stored potential, which gathers to support ongoing vertical seepage at a rate of in accordance with the hydraulic properties of the material.

The present authors subscribe to the second viewpoint of the two discussed in the Reynolds enquiry – that these observed vertical profiles are indicative of vertical flow systems, not separate 'disconnected aquifers'. This is not a belief system; it is the direct result of the mathematics of Darcian groundwater flow as presented in Part 1.

It is considered that the 'provenance' of hydrogeological language has hindered understanding, as explained below.

It is postulated that many of the terms adopted in the hydrogeology field were done for conceptualisation of the earth into regions that could be solved with analytical mathematical solutions. Prior to the advent of computer and powerful numerical methods it was not possible to solve problems of heterogeneous permeability with complex boundary conditions. Aquifers and aquicludes were necessary to allow development of useful closed form solutions (e.g. Thiem's formula; Dupuit's formula etc); just as elasticity theory was useful in structural engineering. Thus a boundary through which water cannot flow became termed an aquiclude.

A fundamental component behind this characterisation is an assumption of horizontal flow systems. The equations, which could be developed on the back of the mathematical conceptualisations typically apply for situations where the vertical flow component is assumed to be negligible. This assumption of horizontal flow is also embodied in the widespread use of the term 'transmissivity' amongst hydrogeologists.

A further demarcation used is to designate whether aquifers are 'confined' or 'unconfined'. This demarcation makes reference to the position of an aquifer relative to adjacent 'aquicludes' or 'aquitards'. Lastly, hydrogeologists expend considerable effort in defining whether these regions are 'connected' or 'disconnected', with respect to the spatial distribution of these 'aquifers' and 'aquitards'

In the real world, the differentiation between aquicludes, aquitards and aquifers is unclear. There is no accepted standard of measurement which differentiates or defines them. In reality, geological formations represent a continuum of materials with wide ranging properties in regard to how water is stored and transmitted. Because the reality is a continuum, there is no accepted standard of measurement which differentiates or defines whether a portion of ground is 'confined' or 'unconfined'. For example, an aquifer that may be traditionally referred to as 'confined' will in fact still have 'unconfined' characteristics due to the 'leakiness' from adjacent formations. Similarly, an aquifer that has a free water table with an identifiably separate geological formation may be called 'unconfined', but it will still display characteristics of a 'confined' aquifer in that a change is head released water not just through the draining of pores but also due to changing in stresses in the matrix.

It is accepted that these terms adopted in the hydrogeological fraternity are descriptors, not absolutes. The terms are useful tools to describe geology in some environments and, by differentiating different regions, have supported the conceptualisation and development of various equations of groundwater flow. However, in many situations, the terms are neither helpful nor accurate, particularly in the assessment of vertical flow. The arguments made in the Reynolds Inquiry asserting negligible vertical flow based on provenance are thus without scientific basis.

It was therefore with some satisfaction that we note, and fully adopt, the following statement in the draft NSW Government Aquifer Interference Policy of March 2012:

> *"A groundwater system is any type of saturated geological formation that can yield anywhere from low to high volumes of water. For the purpose of this Policy the term aquifer has the same meaning as groundwater system---"*

4. FLOWS AND DEPRESSURISATION

It is evident that many underground mine workings exhibit very little inflow. The mines of the Southern Coalfields are mostly remarkably dry. The authors have inspected mine workings directly under the piezometers string from which the readings in Figure 1 (and 9 below) are produced – the workings were visibly dry, with clouds of dust kicked up as one walked. This is despite being located directly underneath Cataract reservoir.

The relatively small quantities of groundwater removed for some CSG activities has also been presented as evidence of 'lack of connectivity' between the depressurisation of the seam and upper aquifer systems (Ross, 2011).

However, low flows are not necessarily indicative of small pressure changes, but can occur under large pressure changes with low hydraulic conductivity. Flow quantities are a function of hydraulic conductivity, pressure head changes are a function of changed boundary conditions causing changed flow directions.

As shown in Part 1 of this paper, small inflows are explained by the hydraulic conductivity and storage characteristics of the groundwater system. They may also be explained, by significantly decreased hydraulic conductivities associated with unsaturated flow conditions following depressurisation (this latter point is discussed in Section 9, below).

As an example, undisturbed rock units typical in the study area represented by Figure 2 may be expected to have vertical saturated hydraulic conductivities in the order of $1x10^{-8}$ to $1x10^{-11}$ m/s. Under a hydraulic gradient of unity (as discussed in Part 1), this is equivalent to flow velocities of 0.3 to 300mm per annum, or discharges of $1x10^{-8}$ to $1x10^{-6}$ litres per second per square metre of mine. Such seepage rates would be imperceptible to the observer. Nonetheless, over time and a large mining area, this amounts to accumulation of 0.025 to 2.5 ML/month per square kilometre of mine, which is why such 'dry mines' still require ongoing dewatering. This is consistent with calculations by Williamson, for the Reynolds Inquiry, using flows into the mines of the Southern Coalfields. These gave a computed average gross hydraulic conductivity of $5.2x10^{-9}$m/sec to $0.7x10^{-10}$m/sec for the rocks overlying the Bulli Seam. As discussed in Section 7, these are reasonable values. In contrast to arguments made in the Reynolds Inquiry, low inflows are therefore not a good indicate of no vertical flow. They are simply a function of the hydraulic conductivity.

5. IMPACTS ON WATER BORES

As shown in Part 1 of this paper, where depressurisation at the base of a column propagates through the column, the resulting vertical flow system has a pressure distribution less than hydrostatic. This has a direct impact on the water level in bores situation and screened within the column.

Consider a homogeneous column such as Figure 7 taken from Part 1 of this paper.

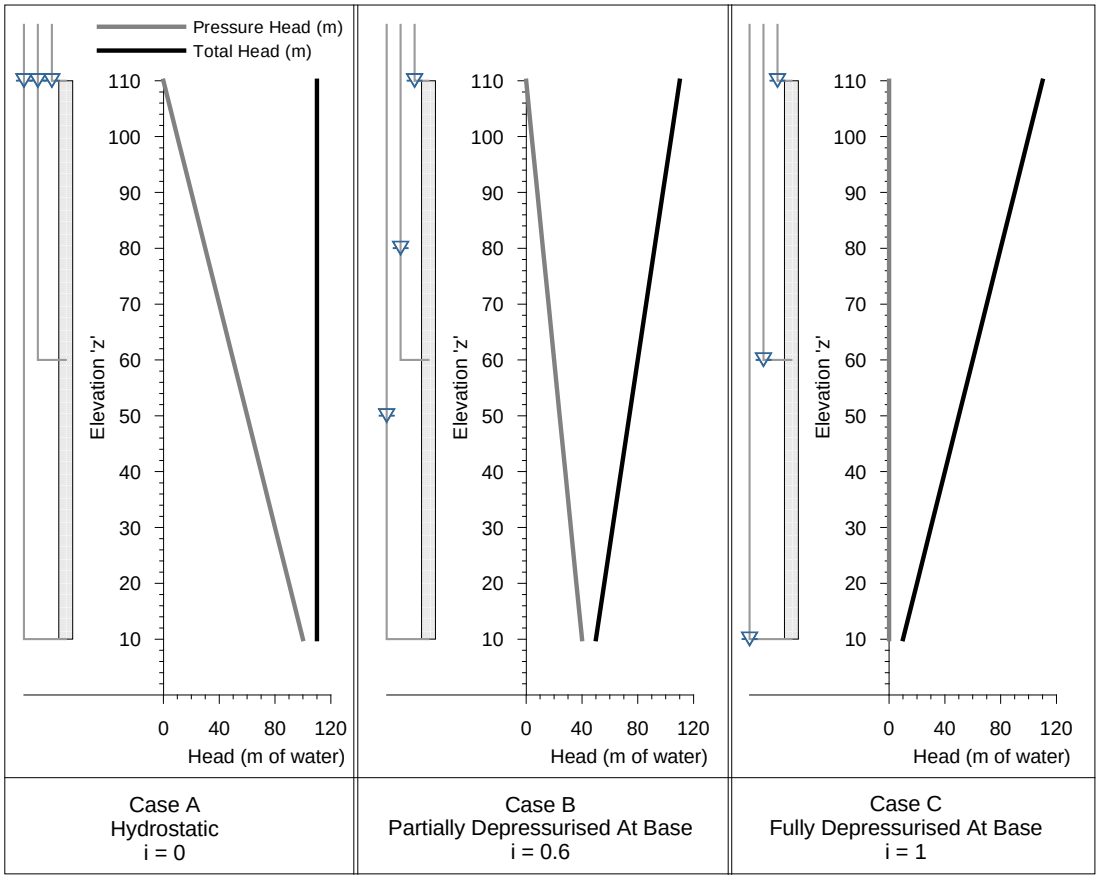

Figure 7

If the saturated vertical hydraulic conductivity of the formation is $1x10^{-9}$ ms^{-1}, under steady state conditions flow downwards into a depressurised cavern would occur at a maximum rate equivalent to the hydraulic conductivity – a rate of only 0.03 litres per square meter of formation per year. This remarkably low flow rate would nonetheless ultimately support the complete depressurisation of the column, and disappearance of all water from any bores situated in the column. Depending on the hydraulic diffusivity, this effect can also propagate through the formation in a short period of time (i.e. much less than the period of mining).

This is not simply a theoretical postulation. The authors have been personally involved in reviewing bores situated above longwall mining activities in the Sydney Basin. There are numerous instances where the standing water level in their bores dropped considerably following undermining, and the yield was, and remains, significantly reduced or completely removed. These effects have been noted in both inside and outside of regions of subsidence and fracturing.

6. PROPAGATION OF DEPRESSURISATION, AND 'DISCONNECTION'

In Part 1 of this paper, it was shown that the velocity of a wave of depressurisation is proportional to the hydraulic diffusivity of the formation. The hydraulic diffusivity varies by orders of magnitude, hence the velocity of depressurisation also varies considerably. It was also shown that the velocity of the depressurisation wave is typically orders of magnitude faster than the velocity of groundwater flow.

Ross (2011) presents evidence of 'disconnectivity' of various identified aquifers at a proposed CSG site, based on the results of a 150 day duration pumping tests and chemical and isotopic indicators. During this pumping test period, no effects of depressurisation were observed in bores placed in shallow aquifers or in the formation approximately 100 m above the well intake location.

A 150 day test period is long in terms of pumping test practice, although it is not long in terms of groundwater processes, or the life of a mine, or CSG project. Such a test could indicate that proposed CSG works will not impact largely on shallower aquifers, but also could simply indicate that the depressurisation wave had not yet arrived in accordance with the hydraulic diffusivity characteristics of the site. An estimation of this can be made with application of Equation (15) in Part 1 of this paper, or more accurately with a simple numerical model study.

Similarly, the application of chemical tracers study should consider the fact that the flow velocity is appreciably slower than the depressurisation wave velocity.

Certainly, identifiably distinct regions of groundwater chemistry and flow systems do exist. However, with respect to the discussion in Section 3.3 of this paper, it is questioned whether the designation of 'connected' or 'disconnected' is a helpful or accurate one. In most situations, the question of 'whether' a disturbance will arrive is less appropriate that the questions of 'when' it will arrive, and what its extent will be.

7 THE BALD HILL CLAYSTONE – AN AQUICLUDE?

Kay et al (2006) state explicitly that the Bald Hill Claystone (BHC) "acts as an aquiclude". Jankowski, Madden and McLean, (2008) state:

> *"The Southern Coalfield mines are typically sealed by a low permeability material that underlies fractured sandstone aquifers, mostly preventing inflow of surface water to mines"*

The NSW Planning Assessment Commission report for Bulli Seam Operations (2010) adopts the view of the SCI, explicitly stating:

> *"The deeper matrix type flows are apparently constrained in some areas to near horizontal flows by the presence of aquitards and aquicludes like the Bald Hill Claystone"*

In reviewing reports for various mines in the Sydney Basin, it is the authors' observation that this is the commonly accepted nature of the Bald Hill Claystone.

The authors compiled the available packer test data following review of a mine in the Southern coalfields, as summarised in Figure 8.

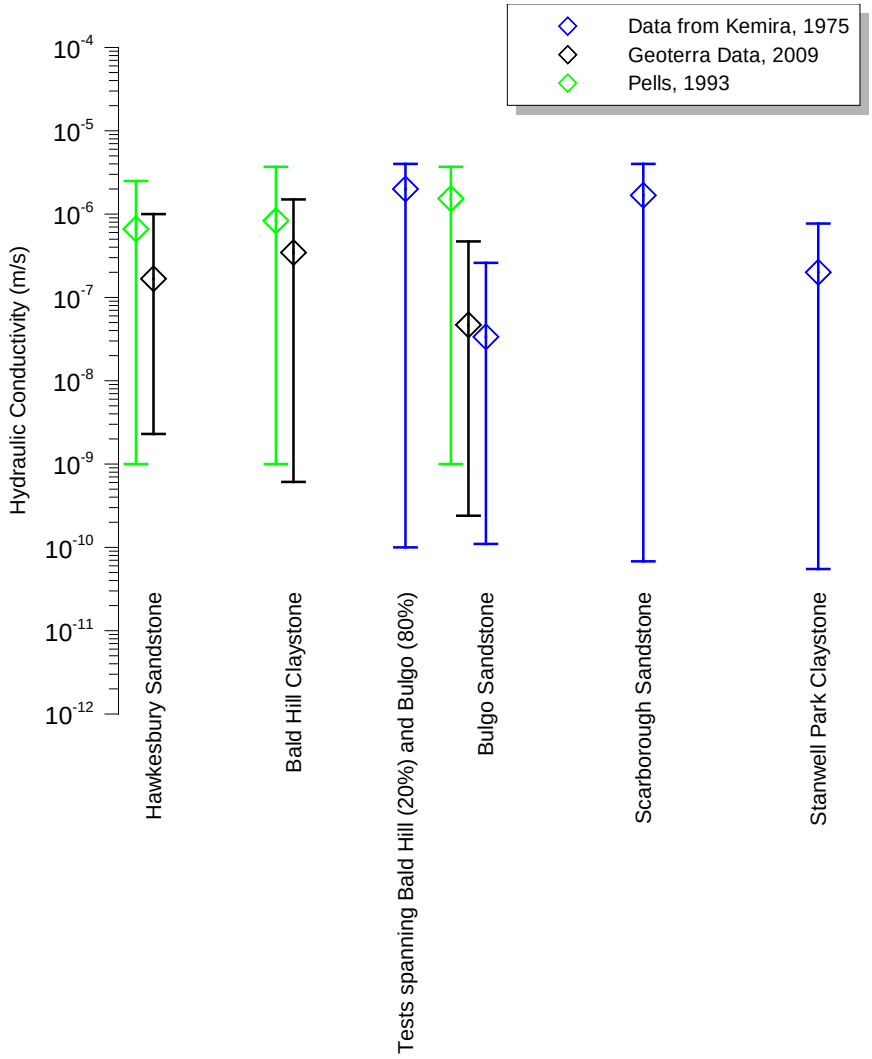

Fig 8 Hydraulic conductivity data for Triassic rocks of the Sydney Basin

The data in Figure 8 do not support the BHC having distinguishing features of an ‘aquiclude’ or ‘aquitard’. The Packer test results for the BHC span the same range for the Hawkesbury and Narrabeen Formations, and the log mean values are very similar.

Permeability data, additional to that given above, is presented in Reid (1996). The following points made by Reid are consistent with our evaluation:

> *“The Bald Hill Claystone has a narrower range of both joint spacing and laboratory permeabilities, however the laboratory permeabilities are significantly less than the Lugeon values. This suggests that the permeability of the Bald Hill Claystone is dominated (as one would expect) by secondary permeability.*
>
> *The typical Lugeon permeabilities of the Bald Hill Claystone and the Hawkesbury Sandstone are of a similar order, despite their marked lithological differences. The similarity between the laboratory and Lugeon permeabilities for the Hawkesbury Sandstone suggests that intergranular permeability makes a significant contribution to the overall permeability, in contrast to the Bald Hill Claystone.”*

In assessing these results cognisance must be taken of the fact that, where boreholes do not intercept joints, permeability is largely controlled by near horizontal bedding planes. To make an assessment of the vertical permeability of the BHC consideration must be given to the evidence regarding defects.

The BHC contains as many as eight soil profiles (i.e. eight superimposed palaeosols), is fissured and jointed, and is transgressed (in places) by faults and igneous intrusions (see Figures 9a and 9b).

Figure 9a: Through going joints in road cutting at Bald Hill, just north of Stanwell Park.

Figure 9b: Joints and Shears in Bald Hill Claystone at the Type Location (Anne Young photo)

Given the detailed sedimentary and structural data, of the kind summarised above, the authors consider that the vertical hydraulic conductivity of the BHC may be lower than the horizontal but, possibly, by only about one order of magnitude. This would suggest a log mean value of about 10^{-8} m/sec (~0.1 Lugeon). It is not an aquiclude; it is a low permeability horizon.

8 CHANGES IN HYDRAULIC CONDUCTIVITY ABOVE LONGWALLS

It is widely accepted that changes occur to the ground above longwalls in the Sydney coalfields similar to those shown in Figure 10. Many publications give versions of this figure that suggest clearly demarcated zones, commonly termed:

- "Caved/fractured" zone immediately above areas of full extraction, with major increase in permeability,
- "Constrained" zone, above 150m, or thereabouts, above the seam, with some increase in horizontal permeability, but little or no increase in vertical permeability , and
- "Surface "zone, with increased vertical permeability.

In fact, there is no information to justify demarcation of specific zones. That which is available publically is from work done by Holla (1989) at four collieries, Forster (1995) in the Central Coast, and south of Wollongong (Thomas, 1974). In our view the data only justify the postulation of gradational changes in hydraulic conductivity through the profile, as indicated in Figure 10.

The self-fulfilling nature of the concept of a "Constrained" zone is illustrated by the following quote from the Planning Assessment Commission report on Bulli Seam Operations (2010):

> "However, the SCI also noted that *'more commonly, mining is conducted at a sufficient depth to support the long term presence of a constrained zone'* which is a zone where vertical conductivity is negligible and downwards flow is governed by the natural (vertical) permeability of the strata."

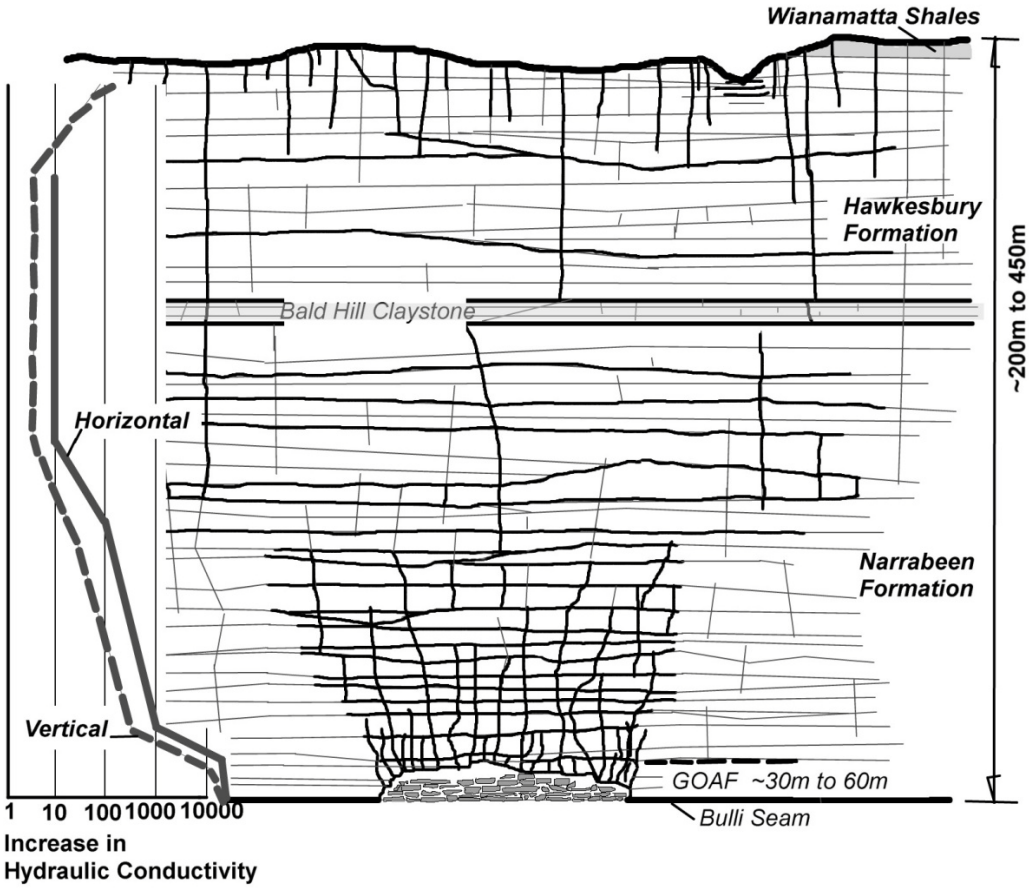

Figure 10 - Cartoon of postulated impact of longwall mining

Holla's data from Tahmoor is particularly interesting because measurements were made of strata dilation and permeability increases from the surface to below the Bald Hill Claystone at a depth of 155m (mining of Bulli Seam at 424m). The extensometer measurements showed that 35mm bedding opening occurred across the Bald Hill Claystone, giving an average tensile strain of 3.5mm/m.

Holla's measured permeabilities, expressed as log mean values, are summarised in Table 1

Table 1 Pre- and Post-longwall extraction Packer Test data from Tahmoor (Holla, 1989)

Unit	Packer test data (Lugeon) 1 Lugeon ~ 10^{-7} m/sec	
	Pre-longwall extraction	Post-longwall extraction
Hawkesbury Sandstone	1.4 (10 tests)	10.3 (9 tests)
Bald Hill Claystone	1.2 (1 test)	10 (1 test)
Narrabeen Formation	0.18 (6 tests)	12.1 (9 tests)

We acknowledge, as did Holla, the statistical limitations of the Tahmoor data. We also acknowledge that Packer tests in vertical holes will tend to be dominated by horizontal hydraulic conductivity.

The data in Table 1 are consistent with Holla's other measurements at sites with lesser cover at Invincible Colliery (110m cover) and Wyee State Colliery (206m). They are also consistent with Foster's data from the Wyong-Wyee area. We have used all this data to hypothesize that permeability increases above areas of longwall extraction are approximately as indicated in Figure 10. The thicknesses of the gradational zones depend on the extracted thickness, the depth of cover and particulars of the geology of the Triassic strata that overlie the Permian coal seams.

For example, at Ulan, where the Triassic strata are dominantly sandstones, and where there are Jurassic sandstones, the experience is that cracking propagates from the seam to the surface, albeit in a complex pattern of non-continuous cracks.

In the situation of CSG extraction there is no cracking induced in the overlying strata due to subsidence, although hydrofracturing may induce fractures propagated from the directionally drilled boreholes. For this situation we assume no changes to the rock mass permeability regime, only depressurisation of the groundwater at the levels of coal seams.

In Part 1 of this paper we discuss the role of fractures (bedding planes, joints and subsidence induced fractures) on rock mass hydraulic conductivity.

Analyses of many borehole camera measurements are given by De Castro, Rotter and Tammetta (2009). They note that the RAAX test equipment could not resolve openings of <0.3mm.

As would be expected in the real world of geology, there is much scatter in their data, but an overall summary is possible as given below.

1. Sub –horizontal bedding spacings average at about 0.9m down to 100m and appear wider below this depth
2. Near vertical joints average at about 1m down to 160m
3. The average measured opening of bedding planes was between about 1mm and 3mm down to 100m, and <0.3mm below that.
4. The average measured opening of near vertical joints was between , nominally 0.3mm and 1mm down to 160m

Intuitively, we think that bedding openings of 1mm to 3mm are too wide, and we suspect that erosion during drilling may have influenced the data. We also note that it is clearly impossible for any of the bedding planes or joints to be continuously open. The average proportion of wall-wall contact is unknowable. If we guess an average 80 % contact area, then by Equation 11, given in Part 1, we calculate an average mass horizontal conductivity of Hawkesbury Sandstone of about 10^{-5} m/sec (~100 Lugeon) for 1mm bedding opening and 2 x 10^{-7} m/sec (~2 Lugeon) for 0.2mm opening. Whilst of some interest when it comes to considering grouting of Hawkesbury Sandstone, these theoretical calculations have the main value of illustrating how a small increase in defect opening due to mine subsidence can lead to substantial increase in hydraulic conductivity.

9 THE SIGNIFICANCE OF UNSATURATED FLOW

Two further examples showing multilevel piezometric data from above longwall mines in the Sydney basin are shown in Figure 11 to 13.

Figure 11 covers the full set of data from the site described in reference to Figure 1, only plotted as pressure head and total head profiles. The first measurements were made prior to longwall mining impacts in the region. It can be seen that a hydrostatic profile prevailed. Following the passing of the longwalls, the levels in the lowest piezometers declined significantly. Unfortunately, several piezometers failed, but the data suggests that, some 17 years since mining, a wave of depressurisation may still be slowly progressing upwards.

The data in Figures 12 and 13 are from sets of piezometers in two holes just adjacent to the first two longwalls in Area 3A of Dendrobium Colliery in the Southern Coalfields (Merrick and Akhter, 2011). Being neither above an extensive area of longwall extraction, nor directly above even a single longwall, these piezometers are not in the areas where boundary conditions are valid for the 1D flow analysed in Part 1, and discussed above. However, the data provide some interesting insights that support the thrust of this paper.

The data in Figure 12 are from borehole DDH92. This indicates depressurisation to about 50m above longwall level in the Wongawilli seam, but no depressurisation in the upper 300m of Hawkesbury Sandstone and Bulgo sandstone. However, Figure 13 is data from borehole DDH97, a similar distance from the edge of the longwalls. This shows a significant, and upward expanding depressurisation through the whole profile

Full analysis of the Dendrobium Area 3A data would require 3D analyses because it is clear from the geometry that flow must be sideways and downwards. However, as a minimum, the data show progressive growth of depressurisation, and the fact that rock masses are complex, as the differences between DDH92 and DDH97 cannot be explained by stratigraphy or geometry – they must be due to geological structures.

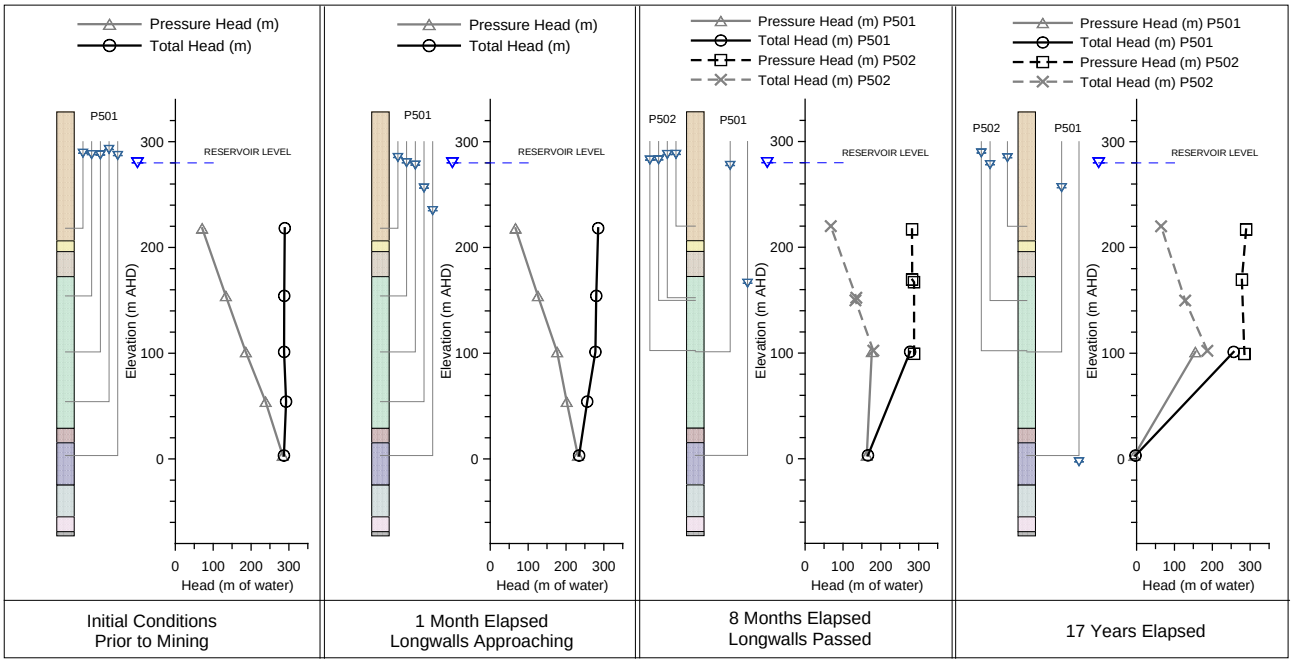

Figure 11 – Piezometric Profiles, Southern Coalfields
Using data from Coffey 1992, 1993a, 1993b; Singh and Jakeman, 2001, and data from mine owners

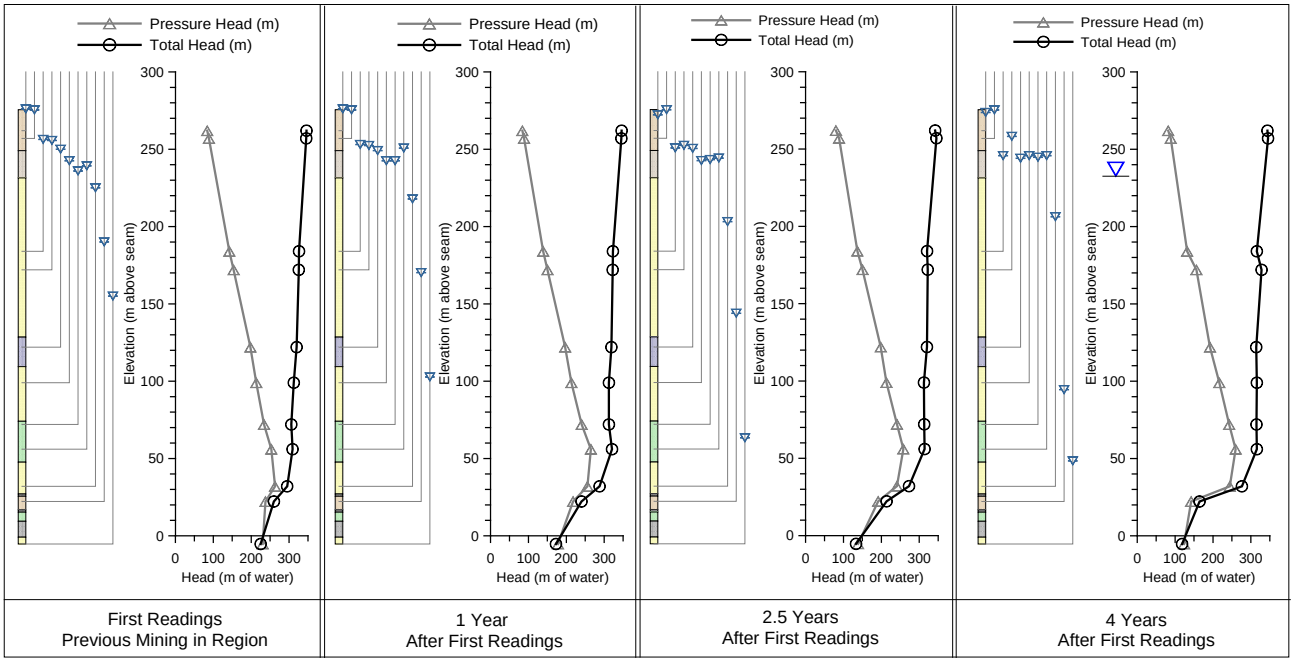

Figure 12 – Piezometric Profiles, Southern Coalfields. Dendrobium Area 3 DDH92

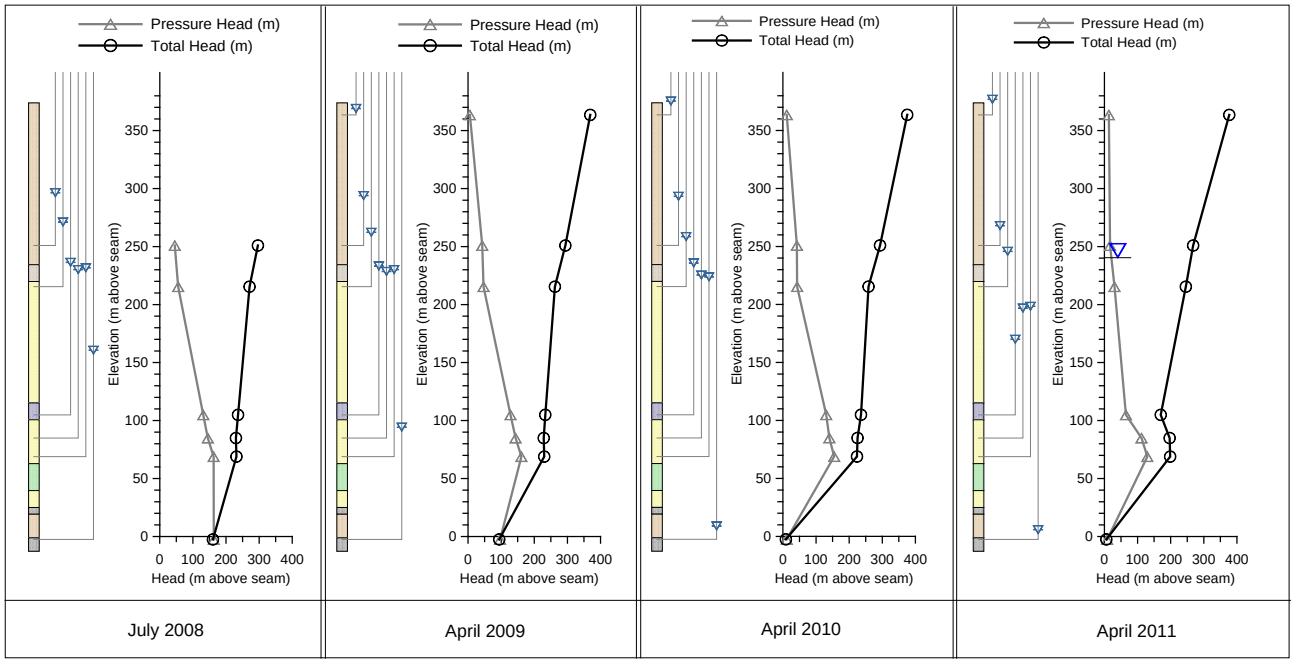

Figure 13 – Piezometric Profiles, Southern Coalfields. Dendrobium Area 3 DDH97

4 SUMMARY

As shown in Part 1 of this paper, aquifer characteristics do not alter the ultimate (steady-state) pattern and extent of depressurisation that occurs, they alter only the discharge under which is occurs. The quantity of water drawn by underground works is therefore not, alone, a good indicator of 'connectivity' or of impacts. Clearly, the removal of a small quantity of water does limit the volume of water lost from adjacent groundwater systems or surface water features. However, removal of small quantities of water can have profound impacts on the pressure distribution and hence the water available for bore users and recharge of swamps and streams.

The matter of changes in the directions of groundwater flows and the associated changes in equipotentials and pore (or joint) pressures must be distinguished from estimates of the quantity of groundwater flow. It is the view of the authors that this facet has not been properly recognised by those with a mining, or CSG extraction, predisposition. Professor Knill, was correct when he submitted to the Reynolds Inquiry:

> *Undermining of a body of water by mining or tunnelling will result in a downward movement of ground water towards the excavation and thus a radical change in the ground water flow pattern.*

As a final point it is noted that there is evidence to support the findings of Part 1 that reduction in hydraulic conductivity due to desaturation of jointed rock masses probably has a major impact on the time it takes for pressure changes to transmit from the level of depressurisation to near surface groundwater systems. This is a poorly understood area of the science that warrants detailed research. It may be the missing link in reconciling field measurements and theory.

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