NSW Dams Safety Committee (DSC) Submission to the Independent Expert Panel for Mining in the Catchment – Task 2

The Committee understands Task #2 to be:

> ***Undertake a review of current coal mining in the Greater Sydney Water Catchment Special Areas with a particular focus on risks to the quantity of water available, the environmental consequences for swamps and the issue of cumulative impacts.***

1. BACKGROUND

The Dams Safety Committee (DSC) is a NSW government body that was created under the *Dams Safety Act 1978*. The DSC's current role under the existing 1978 Act in regards to mining is to ensure the safety of any prescribed dam and to ensure there is no significant loss of stored waters which would threaten lives (other than underground miners) or whereby the risks to the community from uncontrolled loss of storage are tolerably low.

In regards to the matter of what is deemed a significant loss of water that could threaten the health of the population. The DSC in 2008/09 in consultation with the SCA (now WaterNSW) developed a Tolerable Storage Loss criterion (see more on this later) in relation to mining at Dendrobium near Cordeaux Reservoir. The DSC has subsequently, due to lack of other advice adopted the same criteria for other mines in the Catchment.

DSC delineates Notification Areas around certain prescribed dams and their storages under Section 369 of the *Mining Act*. These Notification Areas are small areas designed for administrative purposes and within which it is considered possible that the effects of mining may potentially directly impact either dams and/or their water storages. It is emphasised that the DSC has no jurisdiction outside of these Notification Areas. The DSC does not have a role in regulating the environmental impacts of mining on creeks, swamps, water quality etc.

Based on the role of the DSC described above it is able to provide information relating to the following parts of Task #2:

- Risks to the quantity of water available
- Issue of cumulative impacts.

2. QUANTITY OF WATER

The DSC requires the mine to carefully monitor the balance of water entering and leaving the mine throughout the mining process. The impact of mining on the local groundwater is also monitored using extensive piezometer networks, which surround the workings allowing the mine and the DSC to assess the impact of the mining on the local groundwater.

DSC's submission to the Department of Planning and Environment (DP&E) in April 2016 for Dendrobium's SMP application for extraction of LWs 14 to 18 contained an assessment of the correlation between rainfall and Total Water Balance (mine inflow).

Although rainfall interception is not part of the core issue for the DSC which focuses on losses from the Reservoir, it was raised in relation to the suitability of the Groundwater model to predict losses from the Reservoir. It may however be relevant to the IEPMC and is therefore repeated here.

'Water make' (Total Water Balance) in Dendrobium Mine has been closely monitored since 2003. 'Water make' is defined as the additional water pumped from the workings over and above that which has been pumped in for dust suppression etc. at the mine face.

Generating a Rainfall Cumulative Residual (RCR) curve from rainfall data collected by the mine since 2003 and comparing it to the total water balance curve produces Figure 1. This chart shows a strong relationship between RCR and total mine inflows.

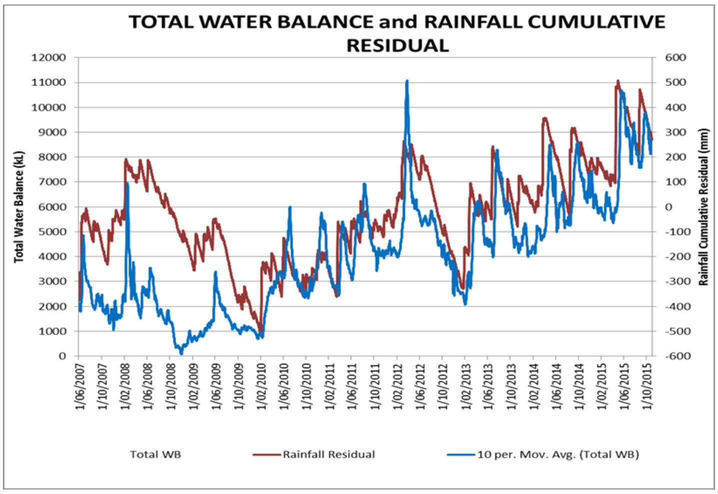

Figure 1

A strong relationship between RCR and inflows in Area 2 is easily demonstrated (Ziegler and Middleton 2011- Appendix A) and is readily acknowledged by South 32 to the extent where they allow for this rainfall input into Area 2 mine water make in their TARPS. However even when Area 2 inflows are excluded from consideration from total mine inflows there is still a very strong relationship between RCR and inflows(Total Water Balance) into the Mine since the development of Area 3A commenced, as shown by Figure 2.

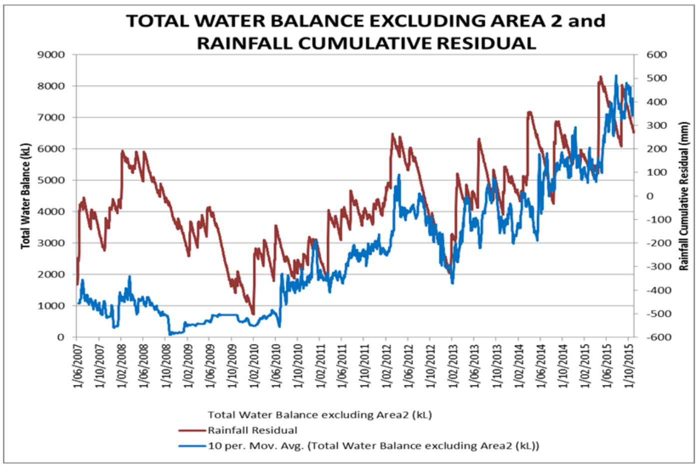

Figure 2

The correlation in the charts above is best from the end of 2009. Correlation for both cases since 2009 when extraction of Area 3A commenced is greater than 85%.

Total Water Balance (volume) is related to rainfall (linear). Therefore, a relationship between the volume of rainfall (linear x area) and the volume of mine inflows should exist. By calculating the total area extracted at any time and multiplying by the applicable daily rainfall value, a volume of daily rainfall was generated. The comparison of a 75-day moving average value for rainfall volume and a 14-day moving average total water balance is shown in Figure 3.

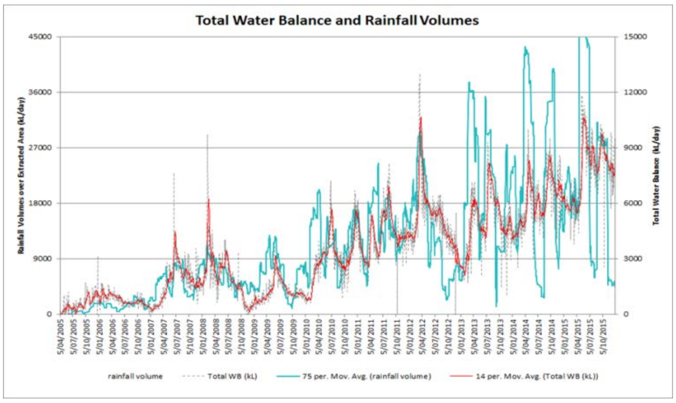

Figure 3

When cumulative totals (Figure 4) are compared it was noted that the cumulative mine inflow value is approximately 30% of the cumulative rainfall volume from 2010 onwards.

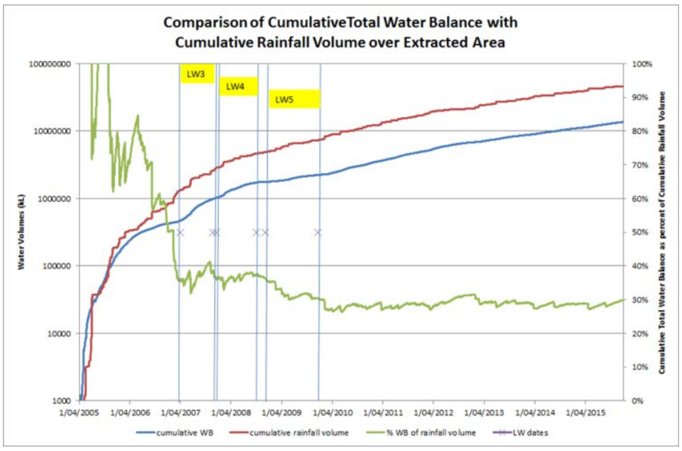

Figure 4

A rainfall infiltration rate of 30% is much higher than the 6% generally used in hydrological modelling So the quantity was checked, using publicly available data for Ulan Mine from the DP&E web site for mining applications. Ulan was identified as a longwall mine with a Width/Depth ratio equal to or greater than that at Dendrobium. Groundwater models supplied in support of mining applications provided mine plans (area extracted) and annual inflow quantity. Annual rainfall was obtained from the nearest BOM weather station. A similar relationship of 20% to 40% (volume inflow/volume rainfall) was calculated.

It should be stated that this does not mean that 100% of mine inflow at Dendrobium is young (surface) waters.

Analysis of the water entering Dendrobium has been undertaken since the mine commenced mining within the Cordeaux Notification Area. Area 2 was the only area to show a measurable percentage of young waters, as determined by Tritium Values.

It is also not the case that every rain event results in increased mine water make (Total Water Balance).

Following extended dry periods rainfall does not result in increased mine water make. During the extraction of Area 2, the DSC adopted a pulse model to explain that the strata needed to be saturated before the mine water balance would show a response to rainfall. This method used the Area 2 water make and a Rainfall Cumulative Residual (RCR) to determine the likelihood of increased inflow to Area 2 following a rain event. In Figure 5, there are four occasions when the mine water make (blue line) spikes above the zero RCR (red line – 0 on right axis). If rainfall occurred when the RCR was 0 or greater, than it was likely that mine inflow would increase rapidly.

From the DSC point-of-view, this is important because it means that the steady head of water, that is the Reservoir, is not the cause of the mine inflow.

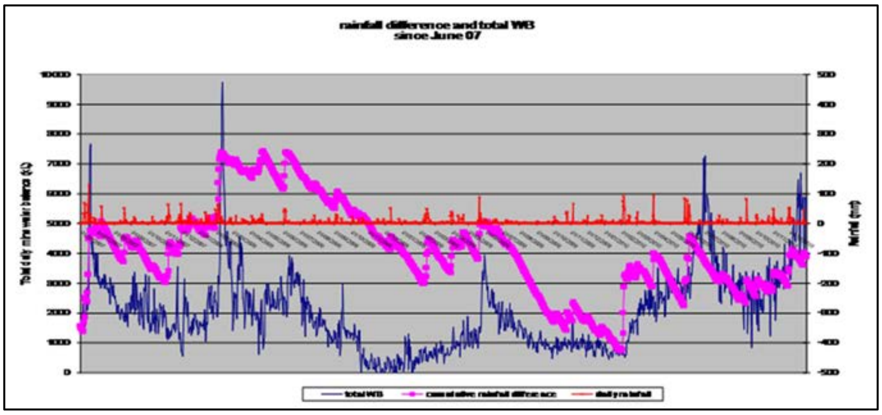

Figure 5

This means that a higher quantity of the rainfall is entering the groundwater system, than has been assumed in groundwater models.

Groundwater models for the Southern Coalfield use 6% of annual rainfall as an infiltration estimate. DSC's RCR model indicates that a value of 30% is more appropriate in mining areas where a high longwall extraction Width/Depth ratio exists.

Water chemistry does not support the premise that rainfall is entering the mine directly from the surface. The pulse model used by the DSC would therefore indicate that water is lost from the catchment into the groundwater system. A portion of this groundwater displaces deeper groundwater into the mine. Some of the groundwater may reappear on the surface in the future or it could also find its way to the mine.

A benefit of this increased recharge of the groundwater is that the time required for the groundwater system to return to equilibrium is a lot shorter than previously estimated.

3. CUMULATIVE IMPACTS

As mentioned in the introduction the DSC has developed a Tolerable Storage Loss criterion for use when assessing applications to mine within a Notification Area. The figure used is 1ML/day from a reservoir. So in the case of Dendrobium, which is operating between two catchments (Avon and Cordeaux) the figure is 2ML/day of reservoir water. As mentioned above the inflows into Area 2 are related to rainfall and therefore not from the reservoir.
The DSC's Tolerable loss is per reservoir and therefore is cumulative for each Reservoir.

3.1 TOLERABLE LOSS

The DSC's regulation of mining in the Notification Area at Cordeaux Dam in 2008 – 2009 considered the question of tolerable loss in detail. This was significant work, as the Committee had not previously investigated this topic in a rigorous, numerical manner before. In regulating mining by Dendrobium Mine, the Committee sought to determine what loss may be considered tolerable, and what is not.

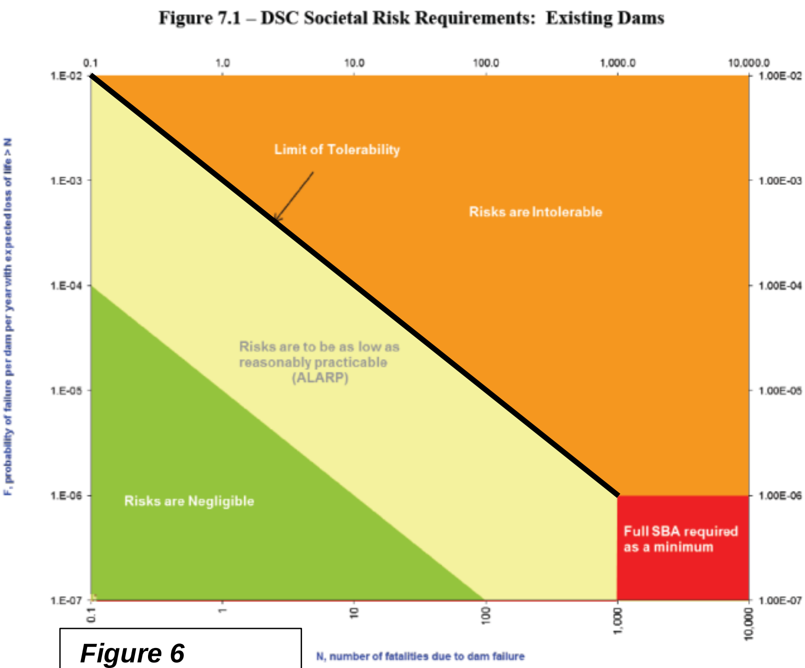

Figure 6

The following is an attempt to clarify what tolerable loss is, how it was derived at Dendrobium, and how applicable it is for future consideration of mining near reservoirs.

The Committee's approach to risk management was laid out in the 2006 Risk management Policy Framework for Dam Safety. The approach taken, consistent with general risk management procedures, is that higher consequences are only tolerable when they have lower likelihoods of occurrence. The Committee frequently regulates risks associated with dam failure in this manner. Figure 6 (***Figure 7.1*** from DSC 17/18 Annual report) shows the conventional risk matrix used by the Committee to consider whether dam safety is tolerable. The consequence of failure — in this case number of fatalities due to dam failure, is plotted on the x-axis, and the likelihood of failure is plotted on the y-axis. Note that the axes use logarithmic scales. The solid black line, the "limit of tolerability" is the boundary between what is tolerable and what is not tolerable. It has a negative slope in consequence – likelihood space, consistent with higher consequence requiring lower likelihoods to be tolerable.

Tolerable loss is the volume of water that can be lost from a reservoir without causing undue concern to the dam owner, the regulator, government, and the public. It is usually measured in ML/day. Using standard risk assessment practices, the level of tolerable loss can vary, depending on the predicted likelihood of the loss — i.e. higher water losses are required to have lower likelihood of occurring.

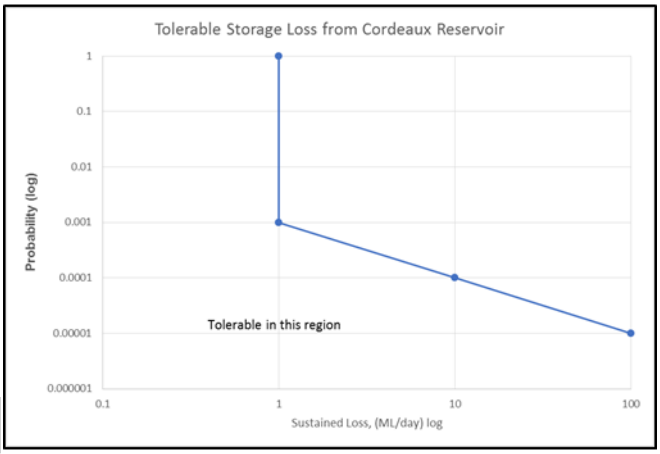

Figure 7

The tolerable loss can be drawn as a curve in Consequence – Probability space, that separates “tolerable” from “intolerable” flows. The tolerable loss curve eventually adopted by the Committee is shown in Figure 7. It is worth noting that:

- The curve separates a lower field, in which losses are tolerable, from an upper field, where they are not. Increasing the likelihood of a particular loss, or increasing the loss at a particular likelihood, moves an event closer to the intolerable field.
- It has a negative slope, with lower losses being more tolerable than higher losses:
  - A sustained loss of 1 ML/day is tolerable when the associated probability is less than 1:1,000.
  - A sustained loss of 100 ML/day is tolerable when the probability is less than 1:100,000.

Safe yield (now referred to as security yield by WaterNSW) is a separate measure of behaviour of a reservoir, which has sometime been confused with tolerable loss.

Safe yield is the rate at which water can be drawn from a reservoir over a period of years without causing eventual depletion or contamination of the supply. It is determined for each reservoir, considering hydrology of the catchment, infrastructure, and long-term climatic variations.

Note that safe yield is a measure of how much water the system can reliably supply; it is not related to how much water the system can tolerably lose. In the case of Cordeaux Reservoir, the safe yield is 18,000 ML/year, or approximately 50 ML/day (historically correct numbers, may have changed with new information).

The concept of Tolerable Loss was developed by DSC mining staff in 2008-2009 as a result of an application to mine within the Cordeaux Notification Area. Reviewing Dendrobium’s assignment of consequence categories, it was apparent that the suggested losses were about an order of magnitude higher than the Committee was likely to accept.

	Consequence			
Frequency	Dendrobium ML/day	Dendrobium %safe draft	MSC ML/day	MSC % safe draft
Almost Certain 10-1	0.1	0.2	0.01	0.002
Likely 10-2	1	2	0.1	0.2
Possible 10-3	10	20	1	2
Unlikely 10-4	100	200	10	20
Rare 10-5	>100		>10	

Possible losses and safe draft proposed by BHP and MSC.

So, for example — Dendrobium’s suggestion that 10 ML/day (20% of safe draft) was described as “possible”, and assigned a 1:1,000 chance of occurrence, was regarded as too high. The desired frequency for a “Catastrophic” loss of this magnitude was instead assigned a possibility of “unlikely”, with a 1:10,000 chance.

The reasoning behind this was:

- The government’s reaction to the Wongawilli Blue Panels 1982 inflow (2.5 ML/day) resulted in three approvals being rescinded.
- A comparison of the loss rates with the safe draft for Cordeaux Reservoir (50 ML/day). A 20% reduction of the safe draft would be a very serious situation in the Committee’s eyes.
- Consultation with the dam owner (SCA in 2008 now WaterNSW) whose modelling of the effect on the security of Sydney’s water supply from various rates of sustained loss from Cordeaux indicated a loss greater than 1ML/day would be significant.

In discussing the possibility of losses at Cordeaux, Dendrobium made a number of comments:

- Inflow in Wongawilli Blue Panel peaked at 2.5 ML/day, with a short-term average thereafter of 2 ML/day, and a longer term rate (after 2 years) of 1.15 ML/day. The peak flow rate was managed by the mine.
- Whilst this flow rate was of concern to Sydney Water, it is unlikely that is was observable or measurable on the reservoir.
- Average annual evaporation of Cordeaux Reservoir at FSL is about 1.7 m (± 0.05m). This represents 35 ML/day.”

The DSC makes the following comments in this regard:

- Regarding inflows at the Wongawilli Mine Blue Panels under Avon Reservoir, the government of the day responded to this incident by rescinding three approvals. Instead of this being an incident that was “managed by the mine”, the inflow resulted in cessation of mining in this area.
- Whether the Blue Panels loss was observable or not is irrelevant to managing water loss.
- Evaporation is an unavoidable natural phenomenon. It is included in the calculation of safe yield. It is irrelevant in considering losses due to mining impacts.

3.2 CUMULATIVE LOSS APPLIED TO AVON RESERVOIR

Applying the DSC’s Tolerable Limit of 1ML/day to Avon Reservoir will restrict future proposed longwall extraction around Avon Reservoir, which causes connective fracturing to extend to the Hawkesbury Sandstone (Avon Reservoir sits in the Hawkesbury Sandstone).

The DSC having identified a possible flow path from Avon Reservoir towards Dendrobium mine has been working with the mine to quantify the likely flow.

At the commencement of Dendrobium's application to mine within the Avon Notification Area in Area 3B, the position of the mine was that:

- losses from the Reservoir would be in the order of 0.03ML/day;
- no real hydraulic gradient would develop towards the mine;
- Groundwater models only need to model the change in permeability in strata directly above the longwall footprint.

To now:

- Acknowledging that losses from the Reservoir are likely to be 0.73ML/day up to the extraction of LW16;
- Acknowledging that an hydraulic gradient has been created from the Reservoir towards the mine in the Hawkesbury Sandstone;
- Having evidence of movement on basal shear plane resulting in increases in the permeability of the horizon of the shear plane of 2 to 3 orders of magnitude;
- Having evidence of increases in permeability of the Hawkesbury Sandstone for the strata between the shear plane and the FSL of Avon Reservoir of 1 to 2 orders of magnitude;
- Modelling increases in permeability for strata within and also surrounding the longwall footprint.

The work undertaken by the mine has quantified a new risk to the Avon storage. This risk (activation of shear planes) has not been quantified previously and the mechanism identified is a natural occurrence in valley formation. It should be assumed that it occurs elsewhere around the WaterNSW reservoirs and therefore needs to be considered when future mining applications around reservoirs are considered.

A flow path from Avon Reservoir exists at Dendrobium because the height of connected fracturing extends from over the goaf up to the Hawkesbury Sandstone. Longwall extraction has increased permeability of the Hawkesbury Sandstone between the mine footprint and the Full Supply Level (FSL) of Avon Reservoir.

This flow path does not exist at Metropolitan where the height of connective fracturing extends only as far as the Lower Bulgo Sandstone due to the narrow longwall panels.

The South Bulli Colliery extraction below Cataract Reservoir constrained the height of connective fracturing to the Lower Bulgo Sandstone and did not cause a connection between the mine and the reservoir by virtue of narrow longwall voids (Appendix A 1996 paper by Reid and Anderson).

RECOMMENDATION

Future longwall extraction around Avon Reservoir should be designed so that the height of connective fracturing does not enter the Upper Bulgo Sandstone.

Loss from the Reservoir as a result of longwall extraction can also be controlled by increasing the distance between Avon's FSL and the mine footprint. By increasing the distance, the hydraulic gradient driving the flow from the reservoir towards the mine will be reduced. Hence reducing losses from the reservoir. It is recommended that future longwalls at Dendrobium be set back at least 500m from Avon's FSL.

3.3 CUMULATIVE IMPACTS-CATARACT RESERVOIR

The DSC has been regulating mining within Notification Areas within the Sydney storage catchment for 40 years.

A small selection of papers published by the DSC on mining within Notification Areas is included in Appendix A.

A1987 paper published in IMWA proceedings addressed pillar extraction at Bulli Colliery below an arm of the Cataract Reservoir. This extraction occurred around dykes that aligned with an inlet of the Cataract Reservoir (Figure 8).

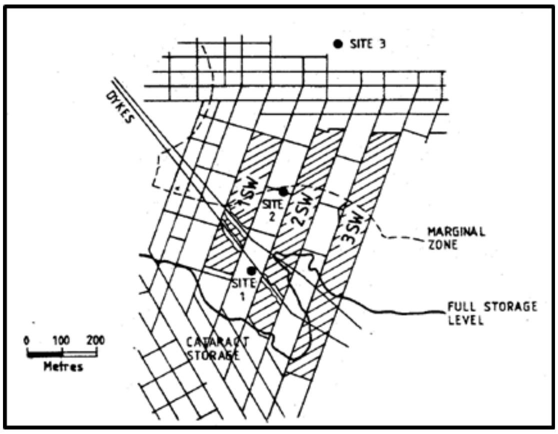

Figure 8

A 1996 paper by Reid and Anderson on "Underground coal mine design for the protection of large dams" reported on a case study of South Bulli Colliery mining under Cataract Reservoir. At that time, South Bulli Colliery had obtained approval for 14 longwalls beneath Cataract Reservoir. At the time of the paper the first seven had been extracted (Figure 9).

It was reported that

- There appears to be an upper zone where the piezometric head has not been affected by mining, underlain by a zone, which has effectively been drained into the workings (the fracture zone). The boundary between these two zones is not accurately defined, but is between about 80 and 180m above the seam.

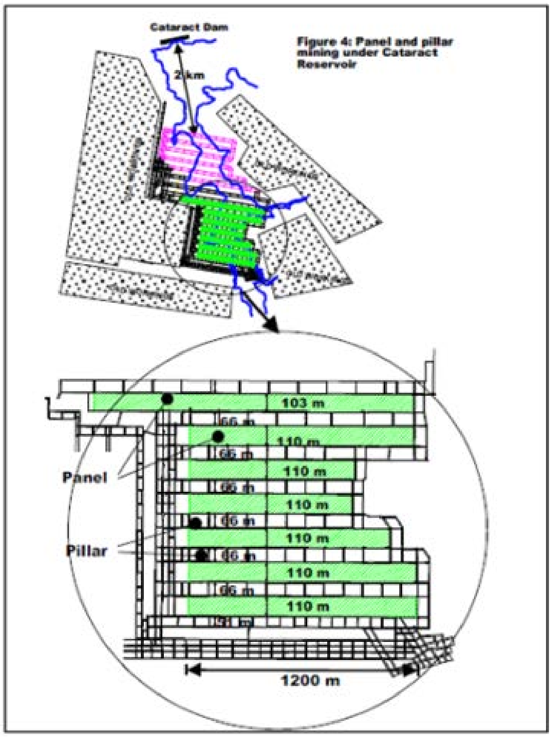

Figure 9

Another paper in 2007 by Reid documented far field horizontal movement around Cataract Reservoir, of up to 25mm at distances of 1.5km.

In 2014, a paper by Ziegler and Middleton documented on-going movement over longwall panels and a possible shear plane connection between a borehole over LW514 and Cataract Reservoir. The possibility of losses from the reservoir via a shear plan to Lizard Creek, outside the Cataract catchment, was postulated.

The knowledge gained from years of monitoring and reporting on mining within the Cataract Notification Area was included in a submission on the proposed Russell Vale Mine. The submission addressed the possible cumulative effects of multi seam mining:

- Mining below longwalls that had already caused movement at the Cataract dam wall put the dam at risk of further movement.
- Mining below previous longwalls may cause further movement on shear plans that would connect the reservoir to drainage lines outside the catchment.
- Mining through identified structure, including faults and dykes, which project below the reservoir. Possible connection of the mine to the reservoir.
- Presence of lineaments on either side of the reservoir which align with faults and dykes in underground workings- possible leakage path.

The DSC has showed the value of a body that monitors the mining around reservoirs over a long period. This level of on-going oversight should be extended to include the whole of the Metropolitan Catchment and Special Areas.

RECOMMENDATION

An independent expert body with authority to undertake investigations and monitoring of mining within the catchment should be established to replace the work of the DSC. In this way, information from the various mining operations would be contained in the one place and cumulative impacts would be more readily identified.

Brian Cooper
Chairman NSW Dams Safety Committee

APPENDIX A

UNDERGROUND COAL MINE DESIGN FOR THE PROTECTION OF LARGE DAMS

Peter Reid[1] and Ian Anderson[2]

ABSTRACT: *Underground mining for coal can have an impact on the overburden and at the surface. Where mining is underneath or adjacent to a dam this may damage the dam structure, or it could result in the loss of the stored water.*

Panel and pillar layouts can significantly mitigate the damaging effects of mining when the ratio of the width of the extracted panel of coal to the depth of cover is limited. Such layouts have been successfully used in N.S.W. to permit mining under the stored waters of major dams, and under the structures of some smaller, earth or rockfill dams. In all cases a monitoring programme has been included as a condition of the approval.

KEYWORDS: coal, mining, dams, strata control, pillar design, groundwater.

1. Introduction

An important water supply catchment south of Sydney, NSW overlies what is known as the Southern Coalfield. Within the catchment area there are five large dams which together store around 540 000 ML (i.e about 20% of Sydney's water supply) and six underground coal mines which produced in total over 6 million tonnes of coal per annum in total (latest figure). In other areas of NSW underground and open cut coal mines operate adjacent to power stations and the dams associated with these facilities.

The NSW Dams Safety Committee (the Committee) has functions under both the Mining Act and the Dams Safety Act in relation to coal mining near dams. These functions have resulted in the Committee regulating such mining in conjunction with the NSW Department of Mineral Resources. The aim of the Committee is to ensure that the safety of these dams and their storages is maintained. At the same time, the Committee does not wish to arbitrarily restrict mining.

Generally the effects of underground coal mining on dams can be conveniently subdivided into effects on the stored waters of the dam, and effects on the structure of the dams.

2. Effects of underground coal mining on stored waters

The concern when mining under stored waters is the risk that water will be lost into the mine. In order to understand this risk it is necessary to first review the typical effects of underground mining on the overlying strata, see Figure 1. When doing so it is best to keep in mind that, while data collection is relatively easy at the surface and in the coal seam itself, it is difficult and expensive to collect data on the strata in between. As a result the response of the strata is poorly understood.

Underground mining in NSW typically involves the removal of a relatively flat layer of coal (the seam) between 1.5 and 3 m thick at depths between 100 and 400 m. As much as 80% of the seam may be removed in what is known as "total" extraction. The remaining 20% is left in the form of pillars of coal which are not economic, or safe, to remove.

When the seam is mined the immediate roof fractures and falls into the void created. This movement creates another void where the immediate roof was, and the roof above that then fractures and falls into it. In this way the void propagates upwards through the rock. At some stage the void is either filled by broken rock, which has a greater volume than intact

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rock, or the roof of the void is spanned by a sufficiently strong “beam” of rock. This is the top of what might be called the “caved” zone.

Above the “caved” zone the strata will sag down towards the mining on top of the rubble in the caved zone, which is compacting under its own weight and the weight of the strata above it. Typically this leads to fracturing of the rock, but not complete failure. This then is the “fractured” zone. Above this the strata does not sag sufficiently to extensively occur. For example, cracking may occur which causes a creek to disappear over a short distance.

There is a risk with shallow mining under a water storage that the fracture zone may extend to the surface. In this situation it would be possible to lose enough water into the mine to fill it, possibly up to 50 000 ML for a large coal mine. Depending on the relative levels of the stored water and the access points to the mine, it may be possible to lose more.

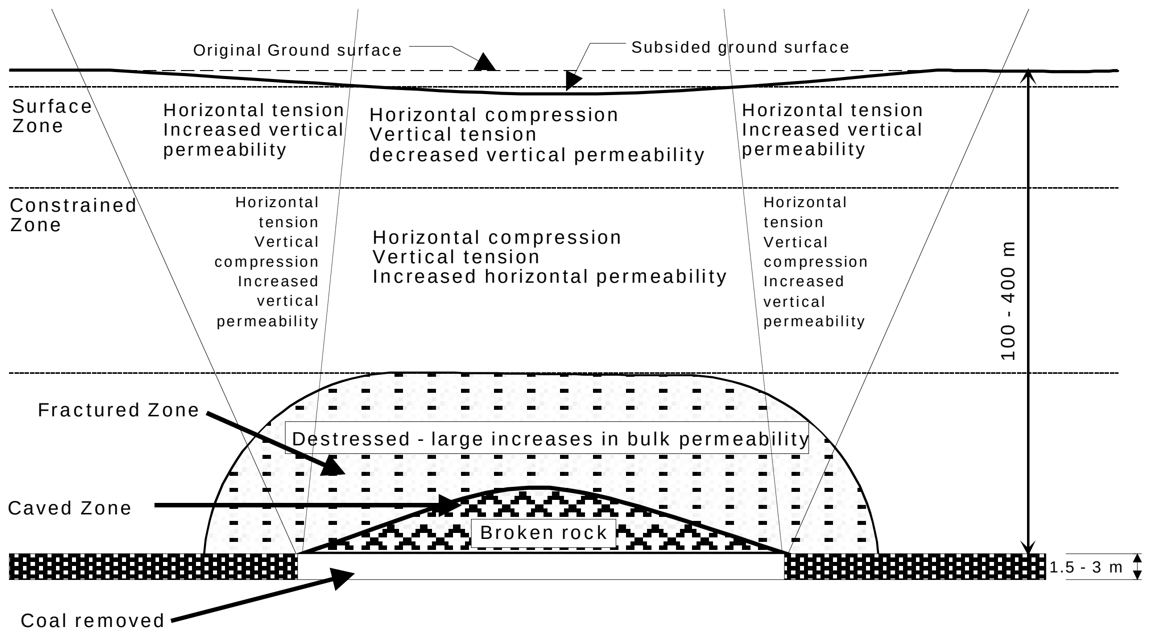


Figure 1:
Theoretical Stress Changes and Hydrogeological Model.
(After Forster, 1992)

fracture the rock, although some localised fracturing would be expected. Here, it is believed that most large movements occur along horizontal planes between rock layers. This has been called the “constrained” zone because it is in this zone that barriers to vertical drainage are most likely to be found. However, the extent to which vertical permeability develops depends on whether impermeable layers exist before mining.

Finally, the surface in its natural state contains some fractures, open joints, and the like. The result of these is that there is a greater potential for movement at the surface, and as such relatively large, but localised, effects may

If the constrained zone is naturally permeable (i.e before any mining) then high leakage rates are possible, regardless of the depth of cover or type of mining. It is also possible that the existing groundwater system could be modified in such a way that leakage paths either into the mine or to some other sink are created.

Successful mining under stored waters requires that the rocks be relatively impermeable before mining, and that they remain so after mining.

3. Effects of underground coal mining on dam structures

When the lateral extent of an underground excavation is small, surface impacts are limited. However, most mining layouts will induce differential vertical lowering of the surface and hence create surface strains. The level of these strains can be significantly magnified if the land surface is not flat. Even relatively gentle slopes of 1 in 10 may magnify surface strains. Valleys have quite dramatic effects on strain magnitude and concentration. As many dams are constructed in valleys, the impact of underground mining may be catastrophic. In New South Wales there are several examples of earth/rock fill dams being successfully undermined (Mattes 1988, Reid 1991), however predicting the behaviour of a dam influenced by mining induced ground movement is complex. Ultimately any decision to permit mining under a dam structure should be the result of a full risk assessment where social, economic and environmental consequences of dam failure would be the determining factors. Engineering analyses and prediction would play a subservient role.

4. "Panel and Pillar" mining - A solution

Prior to underground mining occurring, a state of equilibrium exists within the rock environment. An excavation within the rock mass disturbs this equilibrium and creates a redistribution of stresses. Zones of tension are created around the mining void as shown on Fig. 2 (after Galvin). If the excavated void is wide in relation to its depth from the surface (i.e. its width to height ratio) these zones of tension may extend close or even completely to the surface. This phenomena has serious implications for retention of storage integrity.

As well as re-distributing stress, excavation voids induce vertical ground movement which in turn creates surface strain. It is these strains that damage surface features, both natural and man made. The magnitude of surface strains are a function of vertical surface movement, which is in turn a function of void width to height ratio. Development of surface subsidence may be estimated as shown in Fig. 3 (after Holla). It can be seen that if void widths are carefully managed, for any given depth, it may be possible to minimise the impact of mining on surface features or structures. Such a system of mining is called the panel and pillar technique, where the voids are the panels and the coal left between the voids are the pillars. Such a layout is shown in Fig. 4.

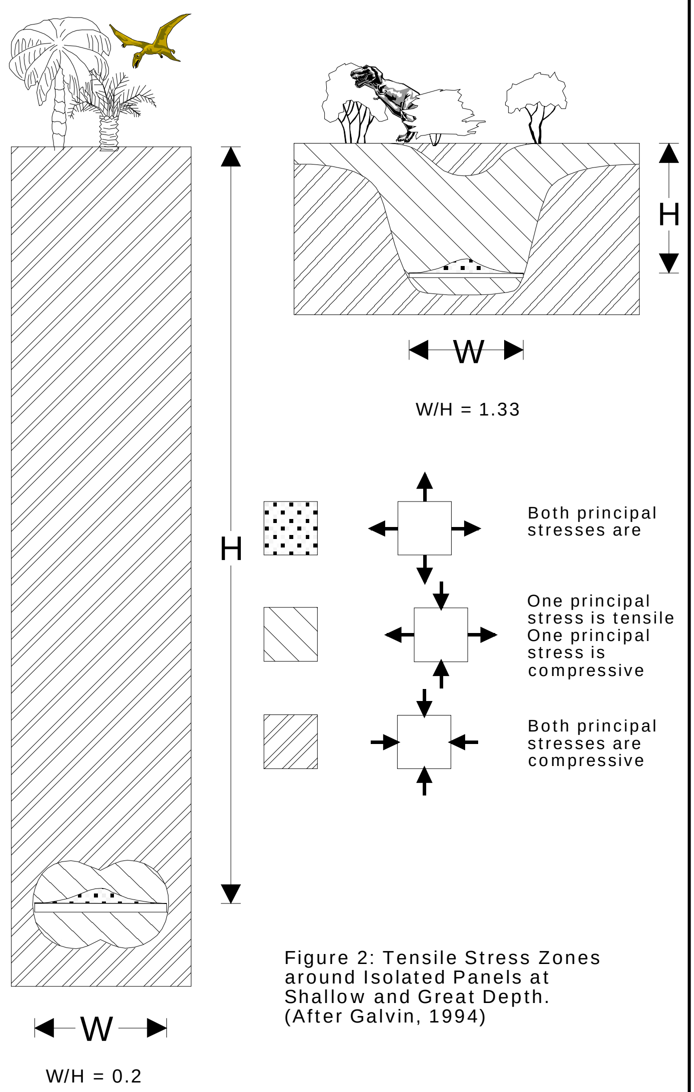
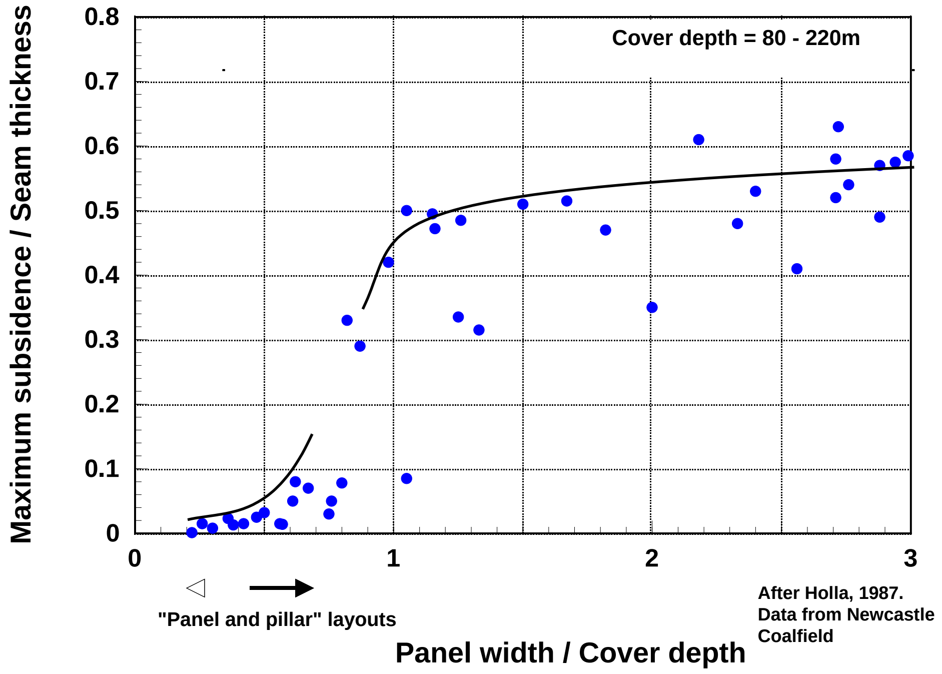


Figure 2: Tensile Stress Zones around Isolated Panels at Shallow and Great Depth. (After Galvin, 1994)

For this system to be successful the dimensions of coal pillars left must be sufficiently strong in order to accept the strata load previously carried by the mined coal from the void. In recent years the strength of pillars has been determined for Australian coals and can be expressed, for large pillars, by the form

Figure 3 - relationship of maximum subsidence to W/H ratio



$$Sp = \frac{19.24\,[0.2373[(W/5h)^{2.5}-1]+1]}{w^{0.1334}\,h^{0.0667}}$$

where: Sp = Pillar strength (Mpa)

w = minimum pillar width (m)

h = pillar height (m)

A high level of confidence can be placed on the structural performance of panel and pillar mining.

5. Regulation of Mining under Stored Waters

A “lease” is a form of title which is required before coal mining is permitted in NSW. The Committee has a role in making recommendations to the Minister administering the Mining Act in respect of certain leases to mine coal (those near prescribed dams). These recommendations generally require that the colliery obtain a special approval to mine any coal which is close to a dam or its stored water.

When the colliery applies for such special approval the Committee will review the application. At this stage the colliery will supply supporting information, as required by the Committee. Before coming to a conclusion, the Committee will consider:

- Dam construction materials. Concrete dams are relatively brittle and have less capacity to absorb tensile strains than earth or rockfill dams which may have some limited flexibility.
- Dam design. Conservative design will in general improve the capability of a dam to withstand ground movements, whereas less conservative design will lead to greater

concern for the safety of the structure should ground movement occur.

- The hazard rating of the structure.
- Applicability of the prediction techniques to the type of mining and location of the dam.
- The importance of the storage. An essential water supply will require a more conservative mine layout.
- Geological and hydrogeological factors, such as the depth of the coal seam and type of strata, and the presence of "defects" (faults, dykes, major joint zones). Generally, greater depth of cover; the presence of thick, relatively impermeable zones, and no major geological defects decrease the risk of significant loss of storage.
- The outcome of a major inrush. The layout of the workings; provision for permanent "plugs" in the workings to minimise loss of stored water in an emergency; the depth of the storage above the workings; and differences in elevation between the storage, the workings, and any mine portals will be considered. In some cases temporary dams or bed sealing techniques could be employed to halt or reduce an inrush.

Having determined the likely impact on the dam, the Committee will recommend to the Minister administering the Mining Act that the application be rejected, or that it be approved subject to conditions.

6. Typical Conditions for a Mining Approval

Conditions placed on the approval include both administrative conditions (such as conditions specifying the procedure to be followed when seeking minor changes to the approval) and monitoring conditions.

The purpose of monitoring conditions are:

- to confirm the predictions on which the approval has been made;
- to highlight any problems as they develop so that remedial action can be taken; and
- to add to the understanding of the effects of mining.

Monitoring can be undertaken in the seam, at the surface, or in the strata above the workings. The following is an indication of the sorts of monitoring which have been required by the Committee.

6.1 In-seam monitoring

6.1.1 Inspection of the workings

The colliery provides a report of mining undertaken each month. The report indicates the areas where coal has been extracted, and includes comments on any geological features which were encountered or events which occurred, as well as a report on the performance of the workings based on a visual inspection.

6.1.2 Water Monitoring

Where mining may affect a valuable water storage it is critical that the rate of water ingress into the mine be monitored. This provides information on the extent of the impact of mining on the overlying strata, as well as providing a convenient alert. Monitoring is typically done by measuring the water entering, or pumped out of, a sump.

6.1.3 Geological Mapping

The process of collapse which follows the removal of coal can be influenced by unusual geological features, such as the occurrence of unusually strong roof rock. As well, the presence of large scale geological defects (faults, dykes, and joint zones) which penetrate through a substantial proportion of the overburden are potential conduits for the ingress of water into the mine. These same features can also influence pillar stability. Geological mapping aims to identify these features so that they can be assessed prior to the final mining. Such mapping may include geophysical methods or longhole horizontal drilling to extend beyond the current mining.

6.1.4 Pillar Monitoring

Where a panel and pillar style of layout is employed the performance of the pillars is critical. Pillars are often monitored by installing an array of stress cells which measure the increase in vertical stress as a result of mining. This can then be compared with the predicted increase, or the profile of stress increase through the pillar can be analysed, to determine if there has been any deviation from the original prediction or if the pillar is behaving unusually.

6.2 Surface Monitoring

6.2.1 Subsidence and Strain Surveys

A set of measurements of vertical ground movements is known as a "subsidence" survey, while measurements of horizontal movements are usually expressed as the change in distance between survey markers over the original distance and are known as "strain" measurements.

Predictions of surface ground movements as a result of mining are usually the most important supporting evidence that a mining company will supply when it seeks to mine under or close to a dam. Therefore, some measurement of actual ground movements is usually incorporated into the monitoring programme so that these predictions are verified.

6.2.2 Geological Mapping

Surface geological mapping allows for the correlation of geological features determined by the seam level geological mapping with their surface expression, if any. This means that an assessment of the vertical extent of a geological feature may be estimated.

6.2.3 Vibration Monitoring

Where mining may result in significant ground vibrations, for example as a result of blasting, peak particle velocity limits may be set at critical structures. Typically, the Committee will specify a conservatively low limit initially, for example 10 mm/sec at a dam wall. This is because of the difficulty of accurately predicting vibration. As mining progresses, and more confidence is gained in the prediction, the limit may be lifted.

6.2.4 Subsurface Monitoring

While some of the surface or in-seam monitoring programmes are "standard", there are no "standard" subsurface monitoring conditions. Each is developed to suit the requirements of a particular mining application.

To date these subsurface programmes have included installing and monitoring piezometers, vertical subsidence tools, and horizontal strain gauges. In addition, borehole permeability tests, cross hole seismic tests, or other borehole and surface geophysical tests may be undertaken.

7. Case Study - South Bulli Colliery mining under Cataract Reservoir.

7.1 Layout and Background

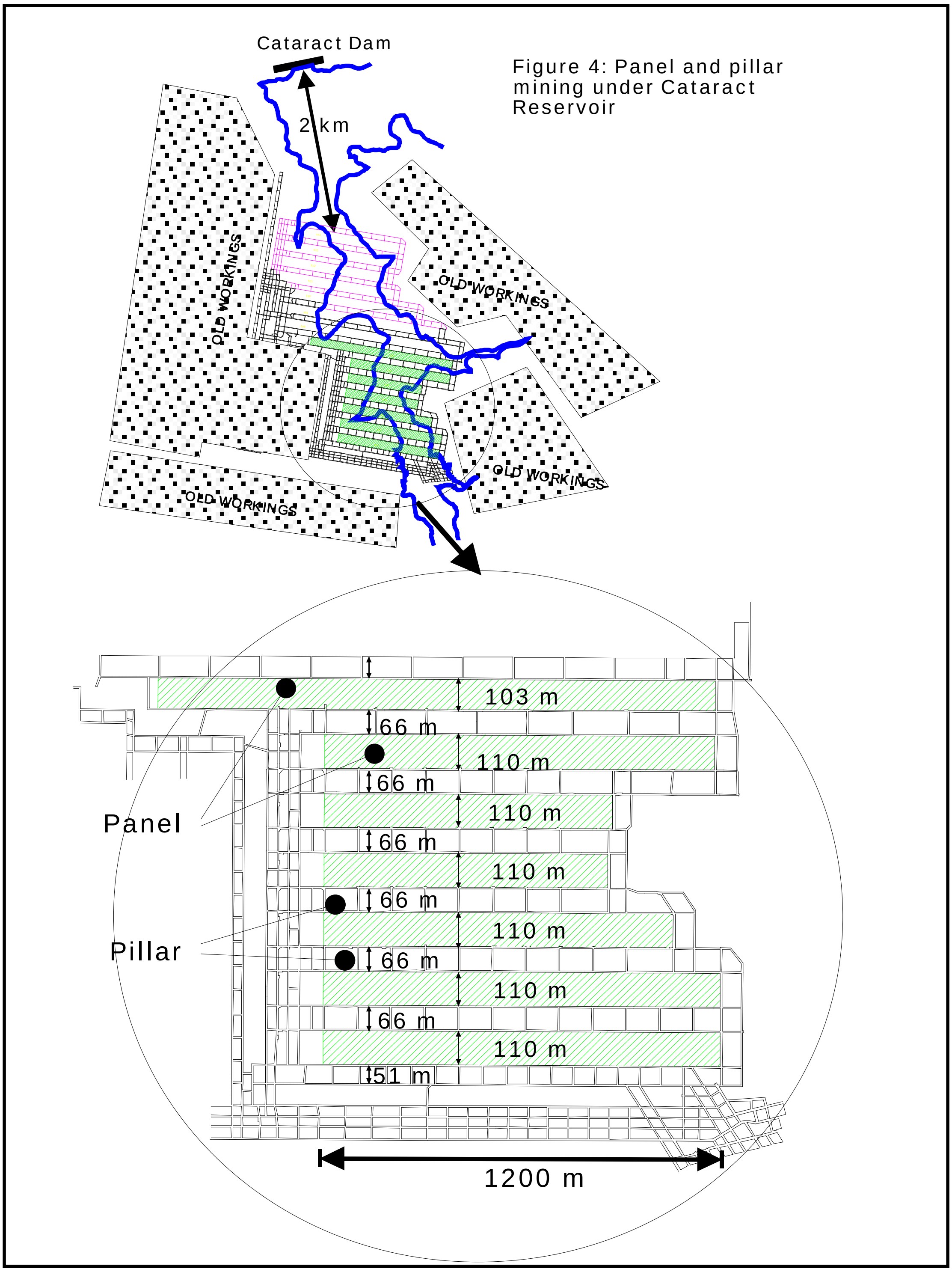
South Bulli Colliery has sought and obtained approval to extract 14 longwall panels beneath the stored water of Cataract Reservoir, 60 km south of Sydney (see Figure 4). As at August 1996 they had extracted the first seven of these. The layout is of the panel and pillar type, Table 1 summarises the physical dimensions.

Table 1 - Dimensions of the South Bulli Approval

	Minimum	Maximum
Pillar width (m)	55	66
Panel width (m)	110	121
Depth below surface (m)	295	445
% coal extracted	63%	69%

7.2 Considerations

The mining is located far enough from the dam structure (more than 2 km) to guarantee that there will be no mining impact at the dam wall. The objective in this situation is to ensure that mining does not cause a significant loss of stored water as a result of changes to the overburden.



The geology is favourable in this area as it is thick, poorly permeable, and with very few large defects. The colliery chose to limit surface ground movements, and hence the impact on the overburden, by adopting a "Panel and Pillar" style layout.

In addition, the colliery developed a contingency plan to be put into effect in the unlikely event of a major inrush. The plan essentially involves pumping and storing up to 1 000 ML of water underground in old workings to give the colliery time to reduce the inrush by grouting or other means. If this fails, the fall back is to install concrete plugs at strategic locations in the workings to seal off the area where the inrush is occurring, which would limit the volume of water lost.

In the future the colliery plans to mine closer to the dam wall. With this in mind, a number of sensitive borehole strain meters have been installed in conjunction with the dam owner, Sydney Water, to determine the far-field effects of mining. Early indications are that the influence of mining can extend for a considerable distance, perhaps as far as 1 km, although at these distances the magnitude is vary small.

7.3 Pillar design and Performance

Table 2 (from Galvin, 1996) summarises the design parameters for the least conservative portion of the workings. The values in the "Strength" column have been calculated using the formula given in this text. As can be seen, the minimum factor of safety is about 3. Given the variability of natural materials and the importance of the surface feature which is being protected, this is at the lower limit of acceptable design.

Pillar loads have been monitored at several sites to date, however, due to a number of equipment failures in the harsh mining environment, meaningful results are available from only one of these. In addition, regular visual inspections have been carried out as mining progressed. These results and inspections suggest that the actual loads imposed on the pillars are less than the predicted strength of the pillars, and that the pillars are behaving as expected.

7.4 Effect of the layout on the surface and the overburden

Figure 5 shows the effect on the surface of the "Panel and Pillar" layout used at South Bulli compared with an adjacent area of "Total Extraction", and the theoretical maximum subsidence if all the coal had been removed from the seam.

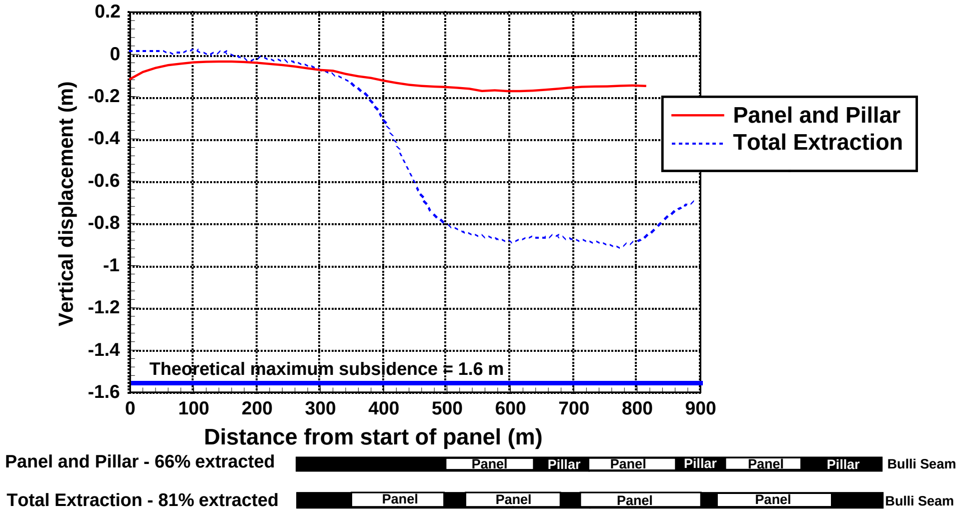
Clearly, the panel and pillar layout results in less subsidence (less than 200 mm versus about 900 mm for the total extraction and 1 600 mm for the theoretical maximum subsidence). Also, the profile of the subsidence trough is smoother and flatter, which means smaller differential settlements, and hence less horizontal strain.

Because subsidence and strain is only an indication of the impact on the strata, the colliery has installed piezometers at various levels in the overburden. The results to date have confirmed in general terms the hydrogeological model in Figure 1. There appears to be an upper zone where the piezometric head has not been affected by mining, or has been temporarily modified by mining but is recovering (the constrained zone), underlain by a zone which has effectively been drained into the workings (the fractured zone). The boundary between these two zones is not accurately defined, but is between about 80 and 180 m above the seam (Reid, 1995).

Table 2. Pillar Design Parameters for South Bulli Colliery

Pillar width (m)	Seam height (m)	Pillar width / Seam height	Panel width (m)	% extraction	Depth of Cover (m)	Pillar Load (Mpa)	Strength (Mpa)	Safety Factor
55	2.6	21.2	116	67.8	-	-	-	-
Under Water					340	24.4	100.5	4.12
Under Land					420	32.7	100.5	3.07

Figure 5: Effect of "Panel and Pillar" layout in Reducing Subsidence.



Subsidence Data from 500 and 300 series panels, South Bulli Colliery. Seam height about 2.6 m.

8. Conclusion

Panel and pillar mining is a type of underground coal mine where the widths of the extracted panels are controlled so as to limit the impact on the surface and the overburden. Where there is a sufficient thickness of impermeable rocks before mining, and an absence of significant geological defects, a panel and pillar layout can be designed to maintain this impermeability, and therefore allow for the extraction of coal underneath or adjacent to important water storages.

9. References

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10. Further Reading

The DSC information sheet DSC 32 “Notes on the Administrative Role of the DSC in the granting of Coal Leases and Approval of Mining Applications” contains more information, including flow charts, on the regulation of mining near dams.

Information sheet DSC 34 “Typical Monitoring Programme Requirements for Mining near Prescribed Dams” provides details on the type and extent of monitoring required when mining near dams.

Horizontal Movements around Cataract Dam, Southern Coalfield

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1. Summary

Sydney Water Corporation have been making precise measurements of distances near Cataract Dam in the Southern Coalfield since 1972. The results show horizontal movements of up to 25 mm occur even when underground coal mining is about 1.5 km from the survey monuments.

From an analysis of these and other survey results it is concluded that mining effects extend a long way from mining. The results also show that horizontal movements are typically at least as great as the vertical component, that the maximum horizontal movement occurs soon after undermining, and that movements are generally directed towards the goaf.

2. Introduction

It is well known that ground movements due to underground coal mining consist of both vertical and horizontal components. Typically, the horizontal component is measured between adjacent survey pegs and expressed in terms of strain rather than movement vectors. The pegs are close together, of the order of 20 m apart (a common rule of thumb is bay-length = depth of cover/20). Electronic Distance Measuring (EDM) equipment may be used to provide measurements in three dimensions over longer distances, although once again the distances tend to be relatively small for subsidence surveys.

Precise measurements over long distances between survey monuments have been recorded in the Cataract Dam region as part of the surveillance of the dam. There are a number of grids in the area. Of particular interest to the Dams Safety Committee is the Cataract Tectonic Grid which encompasses the dam wall and about 20 km^2 of the adjacent catchment. Measurements have been taken on this grid since 1972, partly with the aim of determining the effect of underground coal mining on the dam. The distances between survey monuments varies from about 1 to 3 kilometres.

The magnitude of the measured horizontal movements, and the fact that some of these movements have commenced when mining was as far as 1.5 km from the survey monuments, has surprised many observers and lead to questions about whether the movements have been due to mining, or to a tectonic mechanism, or to a combination of factors. When expressed in terms of an “angle of effect”, 1.5 km is equivalent to an angle in excess of 70°.

This paper discusses the measurements from the Cataract Tectonic Grid, together with “traditional” subsidence data from the same area, and postulates these movements are due to mining.

3. Horizontal displacements induced by underground coal mining

Kratzsch (1) discusses the expected horizontal movements where the terrain is flat. In this situation horizontal movements are all towards the centre of the subsidence basin, and reach a maximum just inside the goaf perimeter. When the extraction is critical in width, and half the critical length, the maximum horizontal movement occurs and is about

0.4 x Maximum Subsidence. As vertical subsidence decreases away from the goaf so do horizontal movements until eventually both vertical and horizontal movements are zero.

Peng (2) discusses mining induced horizontal movements in general, and includes some useful case histories. He notes that horizontal displacement vectors generally point towards the centre of the subsidence basin, but in steep terrain they may point in the down slope direction. His suggested mechanism for this down slope movement is sliding (presumably on pre-existing planes such as bedding planes, although this is not specified) triggered by mining. In flat terrain the maximum horizontal displacement is proportional to the maximum vertical subsidence such that:

Maximum horizontal displacement = *b* x Maximum vertical subsidence

where b = 0.12 to 0.3, depending on the inclination of the coal seam.

As the terrain steepens the down slope movements increase and eventually dominate the total movement. Peng reports a case where horizontal movements as large as 1 000 mm, although typically about 300 mm, occur in the opposite direction to that expected. The movement vectors point in the down slope direction on slopes generally less than 26° which have been directly undermined by 140 m wide panels. In another case horizontal movements up to about 500 mm in the down slope direction occurred on 11° slopes directly over the goaf. For this case, Peng states that on slopes greater than 11° all surface points moved down slope. That is, in these cases the down slope movement dominates. He separates the movements into two components. The first is that induced by underground mining and the second is that due to down slope sliding. The latter can be determined by taking the flat terrain horizontal movement predicted using the formula above away from the measured horizontal movement.

The conclusion from the published literature seems to be that in flat terrain the magnitude of maximum horizontal displacement is proportional to the maximum vertical subsidence, generally being 0.4 x the maximum vertical subsidence or less, and the direction is towards the centre of the panel. Magnitudes of horizontal displacement decrease away from the goaf. In steep terrain this may be modified as the direction of movement may be down slope rather than towards the panel, and there may be an additional component of movement which may be associated with a down slope sliding of strata.

Note that the depth of cover in at least one of the cases discussed by Peng was significantly less than the depth of cover in the Cataract area (230 m as opposed to 350 to 450 m at Cataract). It would be expected that, as with the vertical component, the horizontal movement would decrease with increasing depth of cover.

4. Previous Investigations around Cataract

Don Kay (then at the Department of Mineral Resources) gave a presentation entitled “Ongoing Horizontal Ground Movements Near Cataract Dam” at the November 1992 Mine Subsidence Technological Society Technical Session in Sydney. This presentation was based on an unpublished report prepared by the Department for Sydney Water (Kay (3)). The main conclusion from this report was that the inferred horizontal movements at monuments Y and KO3 (shown on Figure 1) did not fit expected subsidence patterns.

A number of other investigations were also undertaken in conjunction with Kay’s 1992 investigation. These included a structural geology reconnaissance of the area and an investigation of the available seismic data in the area.

This paper reviews all of the data from the Cataract Survey Grid since 1972, and in particular that from the additional survey points added following the 1992 review of the data.

There is additional data from medium distance EDM surveys, traditional surface strain surveys, other long baseline EDM surveys, dam deflection surveys, and bore hole strain surveys, all near Cataract, which are relevant to this study. These may be reviewed and reported at a later time. There are also published and unpublished reports on horizontal movements at Baal Bone Colliery, Appin Colliery, Coal Cliff Colliery, Newstan Colliery and others which, due to time and space constraints, have not been discussed in this report

5. Geology

The strata is generally sub-horizontal. All of the Cataract Survey Grid monuments are located on Hawkesbury Sandstone, which, except for some insignificant outcrops of the overlying Wianamatta Shale on higher hill tops, is to be found at the surface everywhere. It extends to about the level of the bottom of the Lake. Underneath this is the relatively thin Bald Hill Claystone, and then the thick Bulgo Sandstone.

The Hawkesbury Sandstone is relatively strong, and has at least two persistent joint sets. As a result it tends to have a "blocky" appearance when it is exposed in outcrop. Outcrops often occur as ledges up to about 4 m high. The soil in the vicinity of the monuments is generally thin and sandy.

6. Measurement Methods and Equipment

Sydney Water Corporation, the owner of Cataract Dam, regularly makes precise distance measurements between a number of survey grids in the Southern Catchment, south of Sydney. One of these grids, the "Cataract Tectonic Grid", currently covers an area of about 20 km^2 and includes the dam itself plus part of the adjacent catchment. It was originally established with four survey points in 1972. An additional point was included in 1980, and five more points were added in 1992. The points are typically between 1 and 3 kilometres apart and are shown on Figure 1.

Table I summarises the down slope directions at each monument. As the monuments are established on topographic high points the down slope direction may be ambiguous. These directions have been measured off the best available topographic plans for the area, generally the 1:2 000 or 1:4 000 topographic plans prepared by South Bulli Colliery. It can be seen that the area is not particularly steep, with most slopes being less than 15°.

Table I: Survey Monuments - Cataract Tectonic Grid

Point	Year added to grid	Down hill slope direction (° to GN)	Down hill slope (° from horizontal)
A	1972	218	13
B	1972	212	14
Y	1972	180	25
KO3	1972	054 or 075	15
E29	1980	020	7
X	1992	250	13
269	1992	310 or 030	9
Z29	1992	135, 266, or 355	13 - 7

Horizontal measurements are made by E.D.M. Accuracy up to 1986 was ± 5 mm +1 ppm (Martin (4)), which means an accuracy of 6 or 7 mm between typical points. After 1986 the accuracy was improved to ± 3 mm + 1 ppm (say, 4 or 5 mm between typical points).

7. Mining

Figure 1 shows the progression of mining in this area with time. First workings have been omitted from this figure. The irregular shaped panels indicate pillar extraction panels, and the rectangular panels correspond to longwall panels.

In the area of interest the workings are all in the Bulli Seam. Essentially, three areas within the Cataract Tectonic Grid have been mined.

Firstly, Bulli Colliery mined the headland between the North and South Arms of Lake Cataract in the vicinity of E29. The mining was completed in 1980, except for a very small area consisting of four pillars which were extracted in 1981. A pillar extraction method was used, resulting in maximum subsidence of about 900 mm.

Finally, South Bulli Colliery commenced mining directly under the stored waters of Cataract in about 1992. This mining has continued to the present and has been designated “Bellambi-6”. A panel-and-pillar type layout with panels up to 120 m wide separated by 60 m wide pillars has been employed to minimise surface subsidence, and it has resulted in about a maximum of 200 mm subsidence.

8. Measured Movements - Cataract Tectonic Grid

8.1 Data Presentation

Table II: Magnitude of movements during each period.

Period	Date	Y	KO3	E29	Z29	X	269	Panels Mined
0	Pre 1980		33D					Bulli Colliery
1	Mar 80 - Feb 81			62G				Bulli Colliery
2	Feb 81 - Jan 82							Bellambi-4 (301)
3	Jan 82 - Oct 84		53D					Bellambi-4 (301-303)
4	Oct 84 - Feb 86		26G					Bellambi-4 (303)
5	Feb 86 - Feb 92	48G	85G	16G				Bellambi-4 (304-307)
6	Feb 92 - Feb 93							Quiet
7	Feb 93 - Feb 94					26G	83G	Bellambi-6 (501-502)
8	Feb 94 - July 94				8D	16G	72G	Bellambi-6 (502-503)
9	July 94 - Feb 95				10?	6G	55G	Bellambi-6 (503-505)
10	Feb 95 - Feb 96				28G	13G	18G	Bellambi-6 (505-507)
11	Feb 96 - Aug 96				13G	12?	8?	Bellambi-6 (507)
12	Aug 96 - Mar 97				62G	11?	10?	Bellambi-6 (507-511)

“D” denotes a down slope movement, “G” a movement towards the mined area (goaf).

Secondly, South Bulli Colliery commenced mining near KO3 in 1981 and continued mining westwards until about 1992 in an area designated “Bellambi-4”. The layout consisted of longwalls up to 180 m wide, and resulted in maximum subsidence of about 1 m. There were some earlier workings to the west of monuments Z29 and 269, however these were completed long before either of these monuments were established. These earlier workings are not considered significant except that they may have been re-activated by the later Bellambi-6 mining.

Movements have been grouped into periods of unequal length designated 0 to 12. Mining during each period is indicated on Figure 1 and Table II. Within each period movements of each monument have been in the same direction, presumably because the same mechanism is operating throughout the period. Table II categorises these movements into down slope movements (marked “D”), or movements towards the goaf (marked “G”).

Figure 1 shows the magnitude and direction of the significant horizontal movements. A significant movement is one which is greater than the accuracy of the surveys or is part of a series of consecutive movements in the same direction the sum of which is greater then the accuracy of the equipment. Where consecutive movements are in approximately the same direction they have been added together using vector addition.

For example, the movement at Y during period 5 is marked on Figure 1 as 48 mm. In fact, this is the sum of 13 measurements from February 1986 to February 1992, several of which were less than the accuracy of the measurements. It has been judged by the author that each of these were in the same direction and so the combined movements represent a slow movement of point Y in a WSW direction.

Except for the pre-1980 period 0, the analysis depends on monuments A and B being fixed. The data since 1980 suggests that this is the case, with virtually no movement between these two points. Independent measurements using GPS equipment between 1992 and 1997 have confirmed that these points have not moved significantly during that period.

During period 0 the possibility of monument B moving was recognised, and two analyses were done, one with A and B fixed, and another with A and Y fixed. These are the only two possible fixed pairs. There is no corroborating evidence to suggest that A and Y were fixed other than the survey data itself which shows the A-Y distance to be stable during this period. In any event there was no significant difference between the two analyses.

In the tables below distances to mining are given as positive or negative depending on whether mining is moving towards or away from a monument, respectively. Negative subsidence measurements indicate a drop in the ground surface, positive measurements indicate a rise in the ground surface. The magnitude of the maximum horizontal movement was calculated using vector addition and so does not equal the sum of the magnitude of the incremental movements, whereas maximum subsidence is a straight sum of the positive and negative subsidence values.

8.2 Results from 1972 to 1980 - Period 0

During this period the closest mining to the grid was at Bulli Colliery in the area of monument E29 (Figure 1). Essentially the data records a progressive shortening of the distance between KO3 and B, see graph below. An analysis of the data has been done assuming that A and Y were stable. This suggests that most of the movement has occurred at KO3, and this is plotted on Figure 1. Movements appear to have occurred at B, but they are close to the level of accuracy of the measurements and do not follow any discernible pattern. As such they are not considered to be significant and have not been plotted.

Table III summarises the distances to active mining, the maximum measured subsidence over the workings, and the changes in the measured distance between monuments B to KO3. The

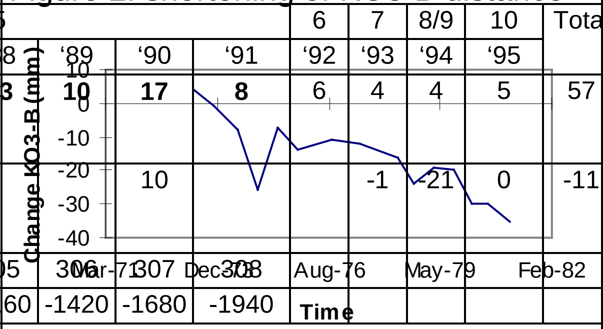
Table III: Incremental movements near B and KO3 up to 1981 - Period 0

	‘72	‘73	‘74	‘75	‘76	‘77	‘78	‘79	‘80	‘81	Total
km from B to active mining	1.2	1.4	1.4	1.5	1.6	1.8	1.8	1.7	1.9	-	
km from KO3 to active mining	2	1.3	1.6	1.8	0.75	0.9	1.7	0.9	1.1	-	
Maximum vertical subsidence (mm) over Bulli workings	-116	-345	-549				-830		-875		
Incremental change B to KO3 (mm)		-1	**-25**	**11**	3	-1	**-12**	4	**-10**	-5	-33

Table IV :Incremental movements near KO3

Period	3			4	5						6	7	8/9	10	Total
Date	‘82	‘83	‘84	‘85	‘86	‘87	‘88	‘89	‘90	‘91	‘92	‘93	‘94	‘95	
Horizontal Movement KO3 (mm)	**32**	**10**	**15**	**20**	**16**	**22**	**23**	**10**	**17**	**8**	6	4	4	5	57
Vertical Subsidence XL2/2 (mm)	-8	31	-14	5	3	-16			10			-1	-21	0	-11
Nearest Panel	301	302	303	303	304	305	305	306	307	308					
Metres to panel CL	-220	-470	-680	-680	-920	-1160	-1160	-1420	-1680	-1940					

Figure 2: shortening of KO3-B distance



base distance (1971) between B and KO3 is 2709.346 m, so the error is ±8 mm. There were no surface subsidence measurements near either B or KO3 during this period.

As the distances are to the nearest active mining there may still have been some residual ground movements occurring over one of the previously mined panels. For example, the active mining in 1978 was 1.7 km from KO3, however there may have been continuing movements over the 1976 mining which was 0.75 km from KO3.

Observations:

1. The movements coincide with a period of mining located mid-way between the two monuments.
2. Significant horizontal movements start when mining was 1.4 and 1.6 km from monuments B and KO3, respectively.
3. Completion of mining at Bulli was followed immediately by the commencement of mining in the Belambi-4 area near KO3, so that there is no way of determining if the end of mining coincided with the end of the movements.
4. The direction of movement at KO3 was broadly down slope, although there were numerous deviations from this. It is also towards the Bulli Colliery goaf.
5. There has been no discernible movement of monument B, all of the movement appears to have occurred at KO3.
6. A major fault was discovered in the workings. Most of the mining was done on the “KO3” side of the fault.

8.3 Results from 1981 to 1992 - Periods 1 to 5

This period starts with the completion of mining at Bulli Colliery near E29 and the commencement of mining near KO3, and ends with the completion of mining in the Bellambi-4 area. Three monuments were affected during this period: E29, KO3, and Y. None of them were directly undermined.

8.3.1 Monument KO3

Table IV and Figure 1 summarise the movements of KO3.

Observations:

1. Horizontal movements generally occur in conjunction with vertical subsidence which is known to be related to coal mining, and coincide with a period of mining.
2. Horizontal movements start when mining commences 220 m away.

1. As mining moved away the movements continued until the mining was nearly 2 km away.
2. Movement during period 3 was in the down slope direction. Subsequent movements were in the opposite direction, towards the Bellambi-4 goaf.

Table VI: Incremental Movements near E29

Period	1	2	3			4	5					
	‘80	‘81	‘82	‘83	‘84	‘85	‘86	‘87	‘88	‘89	‘90	‘91
Horizontal Movement E29 (mm)	**63**	**8**	**10**	4	3	**6**	**6**	**6**	**2**	**8**	**3**	4
Nearest active panel	Bulli	Bulli	301	302	303	303	304	304	305	306	307	308
Metres to active panel	50	100	1500	1700	1900	1900	2100	2100	2300	2500	2700	2900

1. Horizontal ground movements are usually greater than the corresponding vertical subsidence during the same period.
2. The total horizontal movement is greater than the total vertical movement
3. As mining has moved further away the magnitude of the movements have decreased.

8.3.2 Monument Y

Table V and Figure 1 summarise the movements of Y.

There are no subsidence records in the immediate vicinity of Y. 303/1 and 304/16 are 500 m and 300 m respectively from Y, one to the south and the other to the west. Taken together these points give an indication of movement or stability only in the vicinity of Y.

There is a major fault which runs between Y and the mining. It is known from surface subsidence measurements that ground movements are significantly reduced to the north of the fault, where Y is.

Observations

1. Horizontal movements correspond to a period of mining, and occur in an area believed to be affected by mine subsidence.
2. Over that period the distance to mining did not change significantly, varying between 700 and 1600 m.
3. The direction of the movements has been reasonably consistent to the West-South-West, towards the Bellambi-4 goaf.
4. Over the period 1985 to 1991 the magnitude of horizontal movements were approximately the same, being just above or below the level of accuracy of the surveys.

8.3.3 Monument E29

Table VI and Figure 1 summarise the movements of E29.

Observations

1. There have been two periods of activity, the first during 1980 - 81, and the second from 1986 - 1991. The initial movement coincides with a period of mining at Bulli Colliery, and the second with a period of mining in the Bellambi-4 area.
2. The initial movements occurred when

Table V: Incremental Movements near Y

Period	3			4	5						6	7	8/9	10	
	‘82	‘83	‘84	‘85	‘86	‘87	‘88	‘89	‘90	‘91	‘92	‘93	‘94	‘95	Total
Horizontal Movement Y (mm)	2	5	3	**8**	**8**	**6**	**7**	**10**	**15**	**8**	1	3	2	1	48
Vertical Subsidence 303/1			10	-8	11	-7	-7	0	-3						-4
Vertical Subsidence 304/16			15	-11	7	-4	2	-5	2			-3	-7	3	-1
Nearest active panel	301	302	303	303	304	304	305	306	307	308	309				
Metres to active panel	1500	1200	800	1500	700	1600	800	1100	1300	1400	1500				

mining was 50 m away. The subsequent period of movement occurred when mining was more than 2 km away.

3. The initial 63 mm movement was clearly due to nearby mining. Unfortunately the commencement of this mining movement was not measured, however the movement ceased with the cessation of mining at Bulli Colliery.
4. The large initial movement was in the down slope direction, which coincides with the direction to the Bulli goaf.
5. Over the period 1985 to 1989 there were a number of small movements at about the level of accuracy of the equipment. The direction of these movements was generally towards the West-South-West, in the direction of the Bellambi-4 goaf.
6. The direction of the period 5 movement is roughly parallel to both the KO3 period 5 and Y period 5 movements.

8.4 Results from 1992 to present - Periods 6 to 12

This period starts with the commencement of mining in the Bellambi-6 area, and continues to the present. Three monuments have recorded significant movements during this period: 269, Z29 and X. Of these, 269 and Z29 were directly undermined.

8.4.1 Monuments 269 and Z29

These two survey monuments were directly undermined by the “panel and pillar” Bellambi-6 workings. The area was also subsided just before the Bellambi-6 mining by nearby longwall mining in the Cordeaux-2 approval area. The monuments are located over previously unmined areas, and as such the impact of mining is clear.

Tables VII and VIII compare the horizontal movements measured on monuments 269 and Z29 respectively with vertical subsidence measurements taken on nearby survey pegs (Standard Deviation of the error is about 3mm for the vertical subsidence component). In the case of monument 269 the subsidence survey peg is immediately adjacent to the monument, so it is an accurate indication of the vertical movement at 269. Z29 is located 180 m away from the survey peg. However, this is along a line parallel to the long axis of the panel, so the monument is located at the same point with respect to the ribside as Peg 422. It is likely that there will not be a significant difference in the subsidence between Peg 422 and Z29, perhaps 20% less at Z29.

Table VIII: Incremental movements near 269

Period	7			8	9		10	11	12			
Survey Date	Feb-93	Aug-93	Feb-94	Jul-94	Feb-95	Aug-95	Feb-96	Aug-96	Mar-97	Sep-97	Mar-98	Max
Horizontal Movement - 269 (mm)	**9**	**26**	**58**	**69**	**54**	**9**	**20**	**9**	**11**	1	6	244
Vertical subsidence Peg 138 (mm)	2	1	-43	-55	-47	-3	-5	-6	0	-4		-160
Nearest panel	LW18	LW19	501	503	504	505	506	507	508	509		
Metres to panel CL	880	700	0	-360	-520	-700	-875	-1040	-1210	-1390		

Table XI: Incremental movements near X / Table VI: Incremental movements near Z29

Period	7			8	9	10		11		12		
Survey Date	**Feb-93**	**Aug-93**	Feb-94	Jul-94	Feb-95	Aug-95	**Feb-96**	Aug-96	Mar-97	Sep-97	Mar-98	Max
Horizontal Movement - Z29 (mm) / X (mm)	6 6	2 3	**24** 4	**15**	**9** 9	**10**	**6 14**	**7 15**	**15 13**	**6 8**	**4 3**	**10** 1	165 42
Nearest panel	LW18	LW19	501	503	504	505	506	507	508	509		
Metres to panel CL	1660	1500	420	380	520	740	800	800	-1600	800		
Vertical subsidence Peg 422 (mm)			-3	2	10	0	-12	-28	-125	-45		-201
Nearest panel	LW18	LW19	501	503	504	505	506	507	508	509		
Metres to panel CL	1940	1760	1060	720	540	360	180	0	-160	-330		

The following observations can be made about these movements:

1. Horizontal movements coincide with a period of mining, and occur together with vertical subsidence known to be caused by mining.
2. A clear mining influence has been measured 880 m (monument 269, Feb 93) and 720 m (monument Z29, July 94) ahead of mining.
3. When a point has been undermined movements continue even when the active face is 1200 m away (269 March 97).
4. Down slope movements appear to play a role at Z29. The coincidence of the down slope direction and the direction to mining at 269 masks any of this effect.
5. The maximum total horizontal movements are of the same order as the maximum vertical subsidence.
6. The incremental horizontal movements are usually greater than the incremental vertical subsidence movements.
7. Maximum horizontal movement occurs soon after mining, generally increasing as mining approaches and decreasing as mining moves away.

8.4.2 Monument X

This monument has not been undermined. It is located over old workings, so the re-activation of these workings may confuse the picture somewhat. The closest approach of the Bellambi-6 mining was about 380 m (45°) in May 1994. There are no subsidence records in the vicinity of the monument.

Observations:

1. Horizontal movements coincide with a period of mining nearby.
2. A mining influence was measured when the face was 420 m away (Feb 94).
3. The effect of mining continued until active mining was about 1600 m away.
4. The coincidence of the down slope direction and the direction to the goaf makes determining if there was a down slope movement difficult.
5. Horizontal movements are not as great as those measured at 269 and Z29 where the monuments were directly undermined.

9. Measured Movements - Other Subsidence Measurements

Table X summarises the extent of subsidence beyond the goaf edge in the Cataract area. These results are from “traditional” surface subsidence lines measured by levelling the tops of steel pegs driven into the ground. They are generally done to Class C precision (Manual of the New South Wales Integrated Grid) or better, and the standard deviation of the error is between about 2 and 6 mm.

10. Discussion and Conclusions

10.1 What caused the movements?

Table XI summarises the properties of the measured horizontal movements. It is clear that 269, Z29, X, E29 1980 - 1981, and KO3 1981 - 1992 are mining induced.

At 700 m or more Y is a long way from mining. However, the magnitude of the movements are similar to those measured at 269 and Z29 when mining was 700 to 900 m away. Surface subsidence measurements in this area record vertical subsidence effects as far as 860 m from mining, and we know from mining around 269 and Z29 that a mining effect can extend this far, Together with the coincidence of the movements with a period of extensive mining and the direction of the movement being towards the goaf, it is concluded that these movements were mining induced.

KO3 Pre-1980 is a little further from mining than Y at more than 750 m, although once again we know that a mining effect can extend further than this in this area. The movements coincide with mining activity and the direction generally is towards the goaf. If the mining effect was symmetrical either side of the goaf we would expect to see similar movements to those recorded at KO3 at B. It is postulated that the major fault encountered in the workings has shielded B from the effects of mining. Survey records across the fault record a significant decrease in subsidence on the “B” side of the fault.

E29 1987 - 1992 is located the furthest from mining at 1400 m. This movement was over previously mined workings, so some re-activation of these workings may be involved. The timing coincides with a period of extensive mining, and the direction is towards the goaf and roughly parallel to mining induced movements at KO3 and Y.

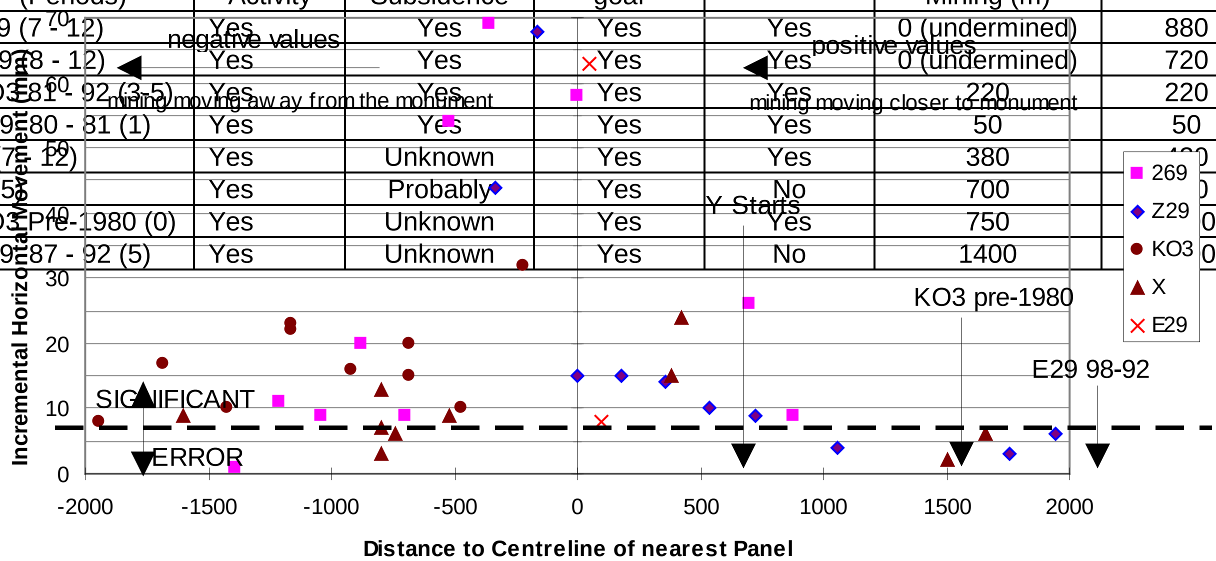
Table X: Subsidence measurements (vertical movement) over workings near Cataract Dam

DSC Approval	Line	Survey Date	Last panel extracted	Extent of Mining Influence		Depth of cover (m)	Comment
				measured ground movement (mm)	distance from workings (m)		
Bulli-1	B	2/86	3SW	6	460	280-340	
Bulli-1	D	7/87	3SW	9	600	280-340	
Bellambi-4	304	8/90	306?	30	430	430-460	truncated by fault
Bellambi-4	XL4	10/87	304	18	510	400-450	
Bellambi-4	XL4	9/85	303	14	730	400-450	
Bellambi-4	XL2	9/85	303	34	550	400-450	
Bellambi-4	XL2	10/83	302	4	480	400-450	
Bellambi-4	XL2	9/82	301	7	680	400-450	
Bellambi-6	D	5/94	502	5	800	380-420	
Bellambi-6	D	5/95	505	5	500	380-420	
Bellambi-7	F	2/97	508	8	860	380-400	
Bellambi-7	G	2/97	508	11	720	380-400	may be due to reactivation of old workings
Cordeaux-2	A	11/94	20	6	460	360-450	
Cordeaux-2	B	11/94	20	7	300	360-450	
Cordeaux-2	X	8/92	17	5	250	440-460	
Cordeaux-2	X	1/93	18	5	260	440-460	
Cordeaux-2	X	6/93	19	6	240	440-460	

Table X3: Properties of movements

Monument (Periods)	Correlates with… Mining Activity	Vertical Subsidence	Moves towards goaf	Moves down slope	Minimum Distance from Mining (m)	Influence starts (m)
269 (7 - 12)	Yes	Yes	Yes	Yes	0 (undermined)	880
Z29 (8 - 12)	Yes	Yes	Yes	Yes	0 (undermined)	720
KO3 81 - 92 (3-5)	Yes	Yes	Yes	Yes	220	220
E29 80 - 81 (1)	Yes	Yes	Yes	Yes	50	50
X (7 - 12)	Yes	Unknown	Yes	Yes	380	[illegible]
Y (5)	Yes	Probably	Yes	No	700	[illegible]
KO3 Pre-1980 (0)	Yes	Unknown	Yes	Yes	750	[illegible]
E29 87 - 92 (5)	Yes	Unknown	Yes	No	1400	[illegible]

Figure X3: Horizontal movements during 12 month periods compared to distance from mining



It is the author's opinion that all of the "significant movements" are mining induced. The last two, KO3 Pre-1980 and E29 87-92, depend on the timing of the movements in relation to mining, the direction being towards the goaf, and the knowledge that a mining effect has been shown to extend a long way from mining. However, there is no corroborating evidence, such as independent subsidence measurements, to confirm that these are due to mining.

10.2 Is there a down slope component to the movements?

All of the monuments except Y experienced movements which were in the down slope direction. However, in the case of 269, X, and E29 this direction coincided with the direction to the goaf. Only Z29 and KO3 1980 - 1992 experienced movements which were down slope and away from mining, that is they exhibited a clear down slope movement. Interestingly. the monument on the steepest slope (Y) did not experience any down slope movement.

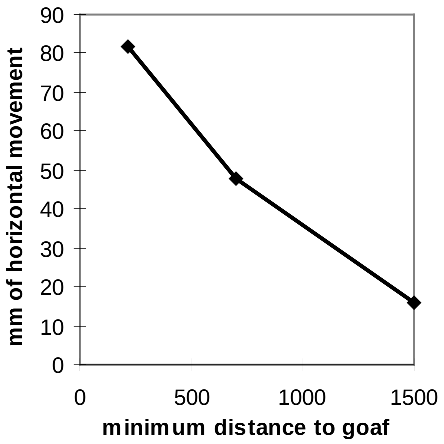
It is therefore difficult to conclude anything about down slope movements except to say that they may be occurring.

10.3 Are the magnitudes and directions of movement in keeping with the published literature?

Where both vertical and horizontal measurements have been made the general pattern is for the horizontal to be greater than the vertical, in absolute terms. This applies both to the incremental movements and the total movements. The difference is usually not great, generally the components are of the same order. The literature would suggest that the vertical component should be greater in flat terrain, but in steep terrain this may not be the case. Although the terrain around Cataract is not particularly steep, there may be a down slope mechanism operating, so it is difficult to determine if the magnitudes measured around Cataract are significantly at odds with the published literature.

There is a strong tendency for the movements to be directed either towards

Figure 4:magnitude of movement with distance from goaf



the goaf or down slope, which is in keeping with the published literature.

10.4 Is there a relationship between distance and the magnitude of the horizontal movements?

Intuitively we would expect that the magnitude of the horizontal movements to decrease further from the influence of mining. Distance to active mining and magnitude of incremental horizontal movements for 269, Z29, X, and KO3 1980 - 1992 have been plotted on Figure 3. The commencement of movement at the other sites is indicated by arrows because the individual movements are less than the error of the measurements; it is the combination of these “small” movements in a consistent direction which makes them significant.

The effect of mining extends out to about 900 m in front of the advancing face for single significant movements, and more than 2 000 m ahead of the face when the “small” movements are taken into account. This is similar to the distance an effect is measured after mining has passed a site, up to about 2 000 m.

The maximum incremental movement occurs soon after mining has passed the site, as would be expected.

10.5 How does topography influence the horizontal movements?

Period 5 movements at Y, KO3, and E29 are interesting in this regard. All three are in roughly the same direction (towards the goaf), with the magnitude decreasing almost linearly away from the goaf. This suggests that the flooded Cataract River valley is not having a significant influence on the movements.

11. Acknowledgments

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Analysis of mine water origins using geochemistry, Tritium isotopes and algae

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Abstract In 1979, the New South Wales Dams Safety Committee (DSC) was constituted under the Dams Safety Act 1978, to oversee the safety of the State's dams and to prevent significant uncontrolled loss of their storages. The DSC regulates mining within designated notification areas around the dams that supply drinking water for Sydney Australia. This paper examines one mine operating within a notification area of a major water supply dam and analyses the source of water entering the mine, using Tritium isotopes, water chemistry, algae and water balance. A relationship between rainfall, mine water balance and water chemistry is developed.

Key Words longwall mining, geochemistry, Tritium isotopes, algae, mine water

Introduction

The Dams Safety Committee (DSC) is a New South Wales government body created under the Dams Safety Act 1978, as a consequence of the Reynolds Enquiry (1977) which sought to establish guidelines for regulating the competing demands of mining and safety of water storages. Sydney, the capital of New South Wales, draws its drinking water from dams which are located to the south of the city (Figure 1A). These major water supply dams are underlain by extensive coal deposits, presenting a challenge to the dam safety and security of the water supplies. The DSC regulates mining around the water storages by designating areas around the dams and their storages within which mining cannot occur without prior application and demonstration of safety to the water storages. These regions are referred to as Notification Areas (Figure 1A).

Dendrobium Mine has been longwall mining around Lake Cordeaux since 2005 with extraction of Longwalls 1 to 5 (LW1-LW5) conducted sequentially in Areas 1 and 2 during the period 2005 to 2009 (Figure 1B). Extraction in Area 1 (LWs1—2) commenced in April 2005 with the initiation of LW1 and was completed in March 2007, while extraction in Area 2 (comprising LWs 3—5) commenced March 2007 and ceased in December 2009.

As part of the approval to mine within the Cordeaux Notification Area, the mine is required to monitor the quantity of water entering and leaving the mine, to determine a water balance, along with its chemistry, algae concentrations and

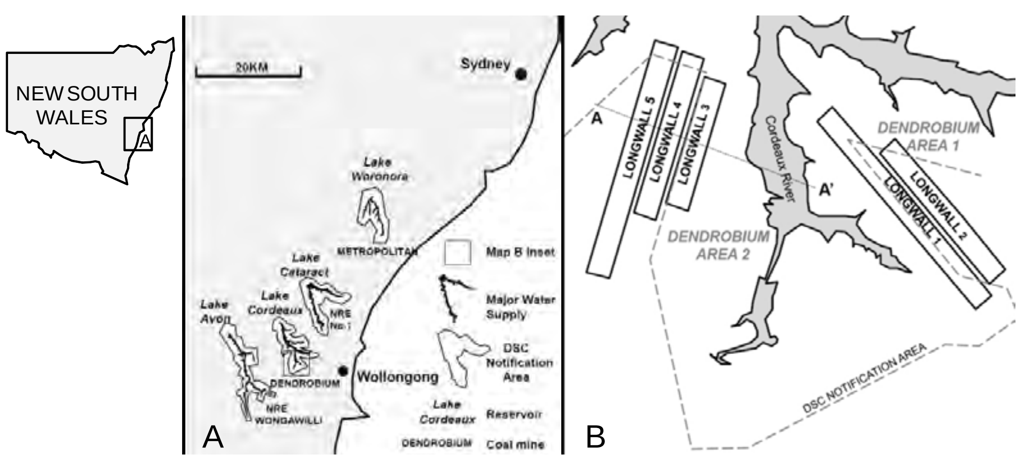

__Figure 1__ A - Location of major water supplies South of Sydney; B - Dendrobium Mine illustrating location of longwalls 1—5 (LW1—5) and cross section A-A' Figure 3.

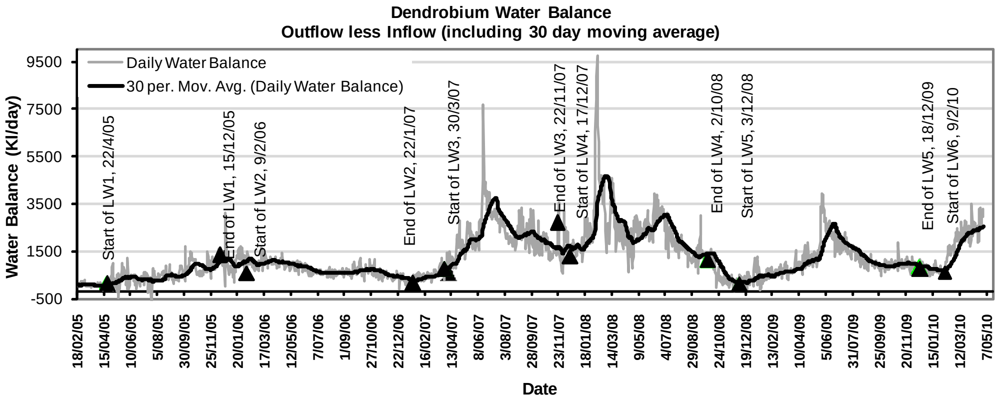

Figure 2 *Dendrobium Water Balance through time showing periods of water inflow to the mine.*

Tritium levels. The aim of this monitoring is to identify the origins of the water, as hydrogeological models for the mine predict that groundwater will drain to the mine workings and eventually reservoir water will make its way into the mine.

The Dams Safety Committee (DSC) has adopted a risk based approach to the safety of the stored waters which has determined that the total loss of water from the reservoir to the mine must not exceed 1ML/day. This limit of 1ML/day for Dendrobium is referred to by the DSC as the 'tolerable limit' for Dendrobium. The extent of conservatism in this limit is apparent when it is compared with the total loss from the reservoir by evaporation which is ≈ 35 ML/day).

Since longwall mining commenced there have been a number of inflow events at Dendrobium, where total water balance in the mine has exceeded 1 ML/day (Figure 2). Approval of future applications for mining within the Cordeaux Notification Area is dependent on the determination of what proportion of inflow waters are potentially from the reservoir.

Hydrogeology

Dendrobium Mine extracts the lower 3.5m of the Late Permian Wongawilli Coal Seam within the Illawarra Coal Measures. Overlying the Coal Measures are the Early Triassic Narabeen Group (which comprises the Coal Cliff Sandstone through to the Baldhill Claystone) and the Middle Triassic Hawkesbury Sandstone (Figure 3). Hydrogeological modelling has identified a potential flow path from the reservoir through the Scarborough Sandstone into the disturbed strata above mine workings in both Areas 1 and 2 with time (Leventhal, 2006), although estimates of loss to the reservoir over the long term are estimated to be in the order of less than 0.5 ML/day.

Water Chemistry

The mine has interpreted mine water chemistry data as consistent with water predominantly sourced from the target Wongawilli Coal Seam and adjacent shales with a contribution from the Scarborough Sandstone during times of inrush. Certainly the bulk of the chemical data does seem

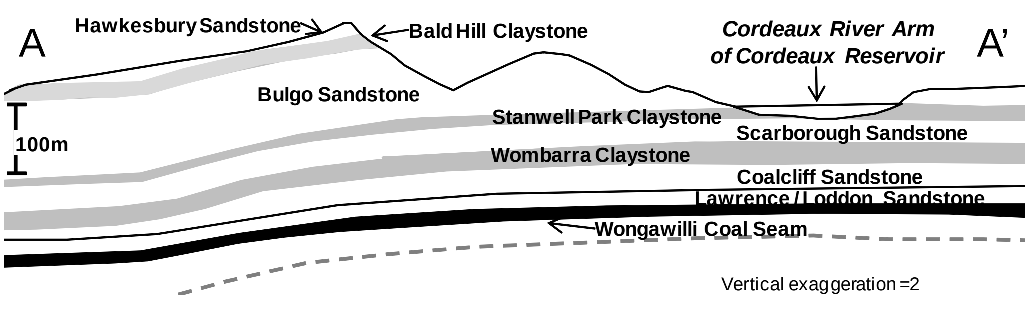

Figure 3 *Cross section through Area 2 and Cordeaux River Arm of Cordeaux Reservoir (see location of cross section on Figure 1B.*

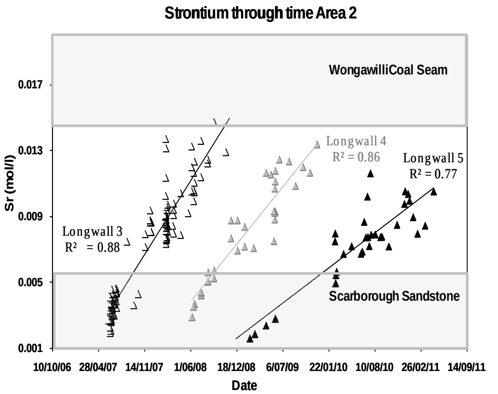

Figure 4 *Variation Sr in goaf waters with time, fields for Scarborough Sandstone and Wongawilli Coal seam are defined by average values ±1Standard deviation.*

consistent with the mine waters being of intermediate composition between these two formation water end members, for example (Figure 4). However not all of the water chemistry concurs with this interpretation.

Analysis of Area 2 mine water salinities indicates that rather than a simple continuous mixing trend between two fluids being observed that three discrete fluid populations seem to be present.

When the changes in the salinity of the mine waters are plotted versus progressive extraction of the longwalls (Figure 5), it becomes apparent that during longwall extraction a low salinity fluid is present. Once extraction has ceased salinity of the mine waters increases, suggestive of increased rock water interaction occurring with increased residence time in the goaf.

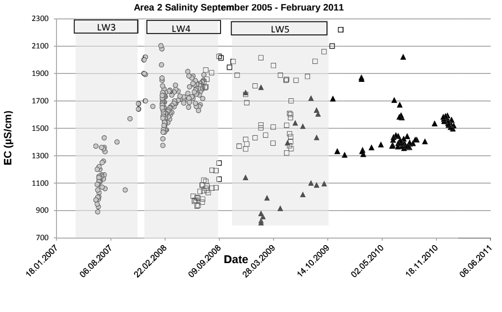

Figure 5 *Evolution of water salinities with extraction of progressive longwalls 3 to 5. Waters present after the cessation of extraction are more saline than those present during longwall extraction.*

Tritium is measured in mine water samples to determine the proportion of modern water present. During periods of increased mine water inflow it is apparent that not only do Tritium levels increase (Figure 6), but that they can increase beyond what is typical for either the Wongawilli Coal Seam (< ≈ 0.1 TU) or the Scarborough Sandstone (0.01—0.3 TU), to levels that are more typical of the overlying Bulgo Sandstone (≈ 0.6—1.2 TU). The overlying Bulgo Sandstone crops out at the surface and is influenced by meteoric recharge (TU ≈ 2.2), it is also known to be impacted by longwall mining in Area 2 (Madden, Merrick, 2009), consequently some input from the Bulgo Sandstone is not only possible but probable. However as the local meteoric tritium signature is ≈ 2.2 TU and Lake Cordeaux (which is predominantly charged by rainfall) has a Tritium signature of ≈ 2 TU, the Tritium water chemistry during times of inflow is also consistent with the mixing of older formation waters with a proportion of modern surface waters (ie reservoir, stream or meteoric waters).

The question for the DSC then becomes, what is the origin of the surface water that is presenting in the mine? This is a question that cannot be definitively addressed with water chemistry alone at this stage.

Significance of Algae

The report by Justice Reynolds on "Coal Mining under Stored Water" (Reynolds, 1977) discussed water inflow at Huntley Colliery. The mine had driven development roadways below an arm of the Avon Reservoir at a depth of 64m. Sections of the roadways experienced heavy dripping. Samples of the water were analysed for the presence of algae. On the study of algae Justice Reynolds states:

"Algae can develop and multiply only in the presence of a strong light source, normally sunlight, and die without it within a certain period. Therefore, any algae which are found in the lightless environment of a colliery must have been introduced from an external source and if they are characteristic of a certain body of standing water then the water must have come from that body."

Whitfield (1988), in discussing water inflow to Blue Panel at Wongawilli Mine, which extracted coal close to the storage of Avon Reservoir, concluded that a coal mining environment was not conducive to the longevity of algae hence *"... the commonality of the algae species between the mine water inflow and the Avon Reservoir ... suggest[ed] a surface to seam connection."*

Presence of Algae

Analysis of algal data from Area 1 and LW3 has indicated the presence of the same species of algae in mine and reservoir waters at the same time as

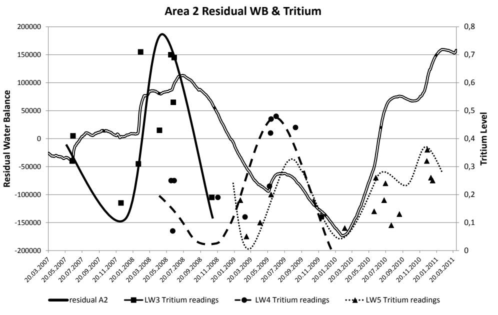

Figure 6 Residual water balance for Area 2 plotted with Tritium values for the various longwalls– lines have been drawn to elucidate the trends in Tritium levels.

the mine water balance shows inflows of water (Figure 7).

The Kembla Arm of the Cordeaux Reservoir lies between LW1 and LW3. While LW1 and LW3 goafs were sealed in 2008 (hence the short duration of results from these goafs) water samples from LW2 were able to be sampled through until early 2011. Water samples from LWs 4, 5 & 6 have been collected and analysed for algae. However the results have not yet been fully assessed.

Correlation of mine water balance with rainfall

The possible causes of the cyclic occurrence of inflows to the mine have been the subject of some discussion between the mine and the DSC. Possible causes are; periods of caving in the goafs intersecting discreet bodies of groundwater, or periods of high rainfall driving the increased pressure in the groundwater resulting in groundwater entering the mine, or rainwater entering the mine via a structure. (It is important to note that significant direct connection between the mine and the reservoir can be dismissed on the grounds that the observed inflows would occur continuously as opposed to sporadically).

At an early stage in the investigation of the inflows at Dendrobium it was noticed that they occurred soon after heavy rainfall events, if the water table had been recently recharged by rain. However, no inflows were observed if heavy rainfall followed a relatively dry period. The following two charts (Figures 8 & 9) show the residual values (a "cumulative difference" or "Residual Balance" is determined by plotting the cumulative value of a variable over time, adding a linear trendline and then calculating the difference between the cumulative value and the trendline, resulting in plus values(wet period) and negative values (dry period)). for rainfall and mine water from areas 1 & 2. The "residual balance" depicts the positive and negative values around a long term average. For rainfall, this depicts "wet" and "dry" periods. If mine water inflow is influenced by rainfall then it would be anticipated to relfect excess and deficit rainfall and this is indeed observed.

Correlation functions for rainfall versus mine water inrush were produced using the "correlation" function in Excel (Figures 10 and 11). The best statistically valid correlations were achieved by offsetting rainfall values by various periods. As can be seen Area 2 has a lower correlation than Area 1. However, the response time to inflow following rainfall in Area 2 is a lot shorter than in Area 1, possibly indicative of a different method of recharge. Using this method of correlation the best correlations of rainfall with mine water balance are 79% for a 3 month offset in Area 1, and 62% for a 3 week offset with Area 2. The quick response of Area 2 compared to Area 1 is thought to be indicative of the presence of a geological structure, through which the groundwater is recharged in Area 2, while Area 1 is thought to be more slowly recharged through the stratigraphy.

Discussion

As mine water is a mixture of formation waters,

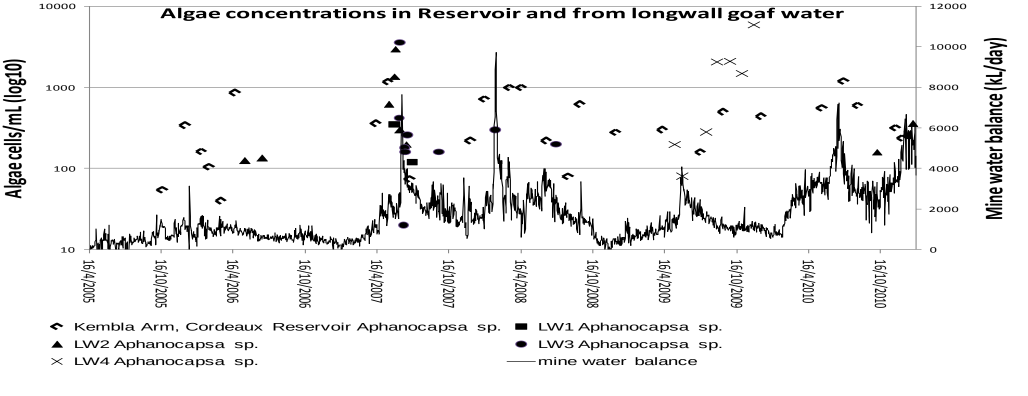

Figure 7 concentrations of the same species of algae in lake and mine waters.

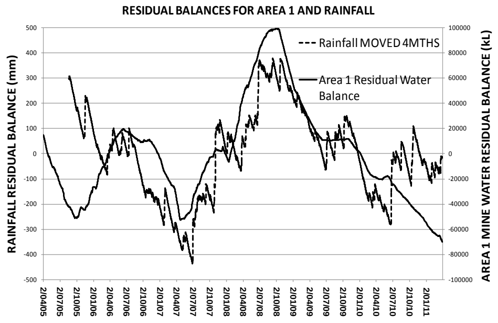

Figure 8 *Area 1 rainfall and mine water balance.*

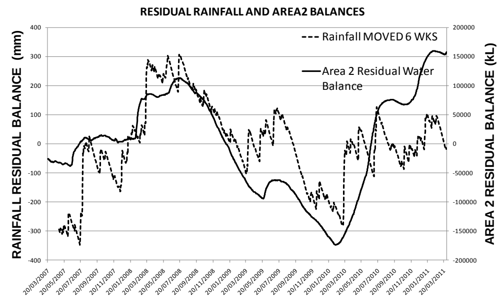

Figure 9 *Area 2 rainfall and mine water balance.*

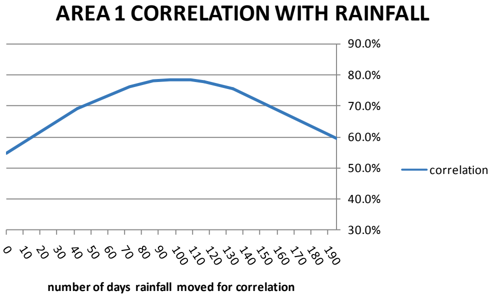

Figure 10 *Area 1 correlation of rainfall with mine water balance by moving rainfall forward in time incrementally.*

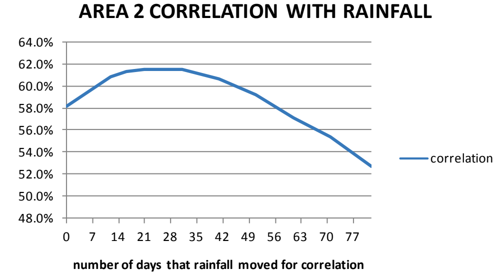

Figure 11 *Area 2 correlation of rainfall with mine water balance by moving rainfall forward in time incrementally.*

process waters and various contaminants such as lime, salt and hydraulic fluids used underground, it can be difficult to determine the provenance of any modern waters present using water chemistry alone. Tritium values are elevated for mine waters relative to the formations from which they are presumably sourced and are consistent with contributions of around 20% of modern water/surface water to the mine. The Tritium data cannot however distinguish between influxes of rainwater or reservoir water as these are sufficiently similar to each other that they cannot be successfully discriminated between. Furthermore even in conjunction with existing water chemistry data available it is not possible to determine the relative contribution from upper formation waters which have been meteorically recharged in recent times and the contribution from modern surface waters.

While available water chemistry is unable to discriminate between the various potential sources of modern water, the presence of the same algae species in both the reservoir waters and the mine waters does strongly suggest that a proportion of the water presenting in the mine is coming from a surface source (either the reservoir itself or a tributary water body) via fractures (which must be >50μm across to pass algae).

The presence of intact and viable algae in the mine workings has been interpreted in the past by the DSC and others to indicate a flow path of short time duration (less than 100 days) from the surface to mine workings. At this stage no argument can be mounted for a significant connection between the reservoir and the mine, as once such connection was established any inrush would be ongoing rather than rain related. It is however obvious that the presence of algae underground (especially freshwater species in high concentrations) needs to be thoroughly investigated, not only in its role as an indicator of lake water inflow as was undertaken by Whitfield (1988), but also for other potential applications (biofuels?).

The DSC is necessarily conservative and as it cannot be adequately demonstrated what specific component of the modern water presenting in the mine is from the reservoir, the DSC makes the assumption that all of the modern water entering the mine is from the reservoir. The question then becomes if all modern water presenting in the mine is assumed to be derived from the reservoir, how much reservoir water is entering the mine?

Estimates (based on average Tritium levels in mine waters in Area 2) indicate that ≈ 20% of the water presenting in the mine is of 'modern' (ie < 50years old) origin. Consequently once the total mine water imbalance for the three areas being mined at Dendrobium is 5ML/day, then the DSC tolerable level of 1ML/day has been reached.

Acknowledgements
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Is there a 4th Dimension to Subsidence Monitoring?

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Summary

This paper presents the collation of over 20 years of data on vertical and horizontal movements around Cataract Dam in the Southern Coalfield of New South Wales, reporting subsidence that continues 25 years after extraction in the area ceased. The occurrence of increased vertical movement over old goaf areas as the result of extraction in the same seam at greater than 1km distance has been observed, together with a change in the behaviour of measured head of water six years after extraction ceased in the area. These points raise the question 'How long should subsidence monitoring continue after extraction has ceased in areas of important infrastructure?'.

Keywords

Residual subsidence, dam reservoir, hydrological changes induced by mining, mining impacts on infrastructure

1. Introduction

It is well known that ground movements due to underground coal mining consist of both vertical and horizontal components. Typically, the horizontal and vertical components are measured between adjacent survey pegs or monuments, with horizontal movement expressed in terms of strain rather than movement vectors, and vertical movement expressed in terms of subsidence or upsidence. The period of time during which subsidence occurs, is generally relatively brief. Classically 90-95% of the total movement associated with longwall extraction occurs during the actual period of extraction, with the final 5-10% of movement (the residual subsidence) completed well within two years of cessation of extraction (Reddish & Whittaker, 1989, Al Heib M et al 2005).

Around areas of important infrastructure such as major dams and bridges, surveillance of mining induced subsidence is continued until it can be demonstrated that all mining induced movement has ceased. How long surveillance continues post extraction depends on how long 'residual movement' (ie post extraction movement) continues. On the basis of studies conducted elsewhere it might be assumed that two years of post extraction surveillance would capture >99% of total mining related movement, however longitudinal studies undertaken around the Cataract Dam, which has been monitored for over 40 years, indicate that this is not the case in this area. This raises the question'How long should movement monitoring continue after extraction has ceased within areas of important infrastructure?'.

Precise measurements over long distances between survey monuments have been recorded in the Cataract Dam region as part of the surveillance of the dam for over 40 years. There are a number of grids in the area. Of particular interest to the Dams Safety Committee is the Cataract Tectonic Grid which encompasses the dam wall and about 20km^2 of the adjacent catchment. Measurements have been undertaken on this grid since 1972, partly with the aim of determining the effect of underground coal mining on the dam. These measurements provide over 40 years of data. The distances between survey monuments vary from about 1-3km.

In addition to the Cataract Tectonic Grid an extensive amount of traditional surveillance data has been collected along survey lines crossing areas in which mining has occurred. The survey pegs are close together, of the order of 20m apart (a common rule of thumb is bay-length = depth of cover/20). Electronic Distance Measuring (EDM) equipment may be used to provide measurements in three dimensions over longer distances although once, again the distances tend to be relatively small for subsidence.

This paper discusses the measurements from the Cataract Tectonic Grid, together with 'traditional' subsidence data collected by mining companies from the same area over a period of years, and postulates that ongoing movements occurring years after extraction has ceased in the area are due to mining.

In previous papers on this subject, Reid (2001,1998) presented some long-baseline horizontal data collected by the Sydney Catchment Authority (SCA) around Cataract Dam. The conclusions drawn in those papers were:

(i) mining induced horizontal ground movements of up to 25mm were recorded at a distance of up to 1.5km from underground coal mining;

(ii) Far Field Horizontal movements were generally at least as great as the vertical component. This applied whether or not the survey peg had been directly undermined. It was noted that this was at odds with the published literature;

(iii) the rate of horizontal movement peaked soon after undermining;

(iv) horizontal movements were generally directed towards the goaf. A possible down-slope component was identified but the evidence of this was inconclusive;

(v) there was no apparent influence from the Cataract River valley.

Following on from this work, Reid (2000) presented some additional survey results collected by the dam owner and collieries near Cataract Dam. Among other things, the following matters were discussed:

(i) movements of Cataract Dam wall of the order of 20mm as a result of coal mining;

(ii) the predominance of compressive strain over panel and pillar mining in this area, where tensile strain dominates for total extraction workings;

(iii) the possibility that in-situ stress was influencing the horizontal movements.

This paper presents more recent results and further analyses of previously published results. Interested readers are referred to Reid (1998) for a brief review of published literature on horizontal ground movements, a summary of other investigations around Cataract Reservoir, and a detailed description of the recorded movements.

2. Background to the measurements

Cataract Dam is a 56m high mass gravity cyclopean masonry dam that was completed in 1907 as an essential component of Sydney's water supply. The consequences of failure of Cataract Dam would be extreme, not only in the probable loss of life, but in the loss of an extremely valuable component of Sydney's infrastructure. As the dam is situated in the Southern Coal Fields, Sydney Catchment Authority (SCA), the owner of Cataract Dam, regularly makes precise distance measurements between a number of survey grids in the Southern Catchment, south of Sydney. One of these grids, the 'Cataract Tectonic Grid', currently covers an area of about 20km^2 and includes the dam itself plus part of the adjacent catchment. It was originally established with four survey points in 1972. An additional point was included in 1980, and five more points were added in 1992. The points are typically between 1-3km apart and are shown on Figure 1.

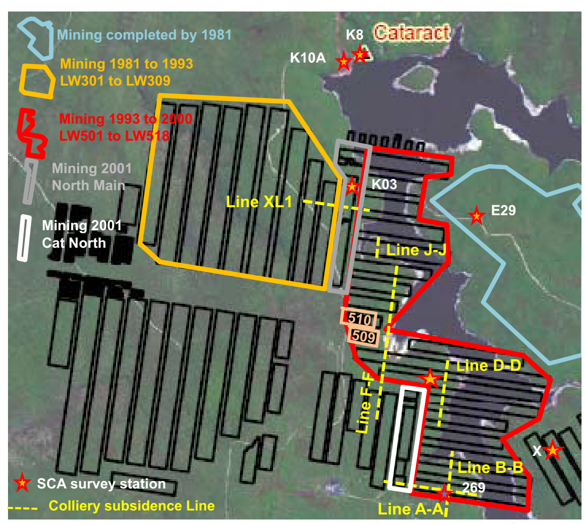


Figure 1 **Cataract Reservoir and Mine workings**
Stars (*) represent locations of SCA valley survey monuments
Dashed lines are conventional subsidence lines

Horizontal measurements are made by EDM. Accuracy up to 1986 was ± 5 mm +1 ppm (Martin 1998), which means an accuracy of 6 or 7mm between typical points. After 1986 the accuracy was improved to ± 3 mm + 1 ppm (say, 4 or 5 mm between typical points). This is an unusual grid compared to traditional subsidence grids because of:

(i) the very long distances between survey monuments (about 1-3 km);
(ii) the long history of measurements (> 40yrs from 1972 to 2013); and
(iii) the high precision of the measurements.

Mining in the Cataract area has been ongoing for over 100 years and predates the construction of the Cataract Dam by some decades. The Mine (under various owners) has carried out conventional subsidence surveys over a number of lines. Some of the survey points are close to those of the SCA and the results are therefore directly comparable.

Importantly the two different survey methods have given similar results, providing confidence that the subsidence being measured is real and not the result of survey error.

3. Geology

The strata in the vicinity of the dam are generally sub-horizontal. All of the Cataract Survey Grid monuments are located on Hawkesbury Sandstone, which outcrops throughout the area, except for some insignificant outcrops of the overlying Wianamatta Shale on higher hilltops. The Hawkesbury Sandstone extends below the level of the bottom of Lake Cataract (Figure 2).

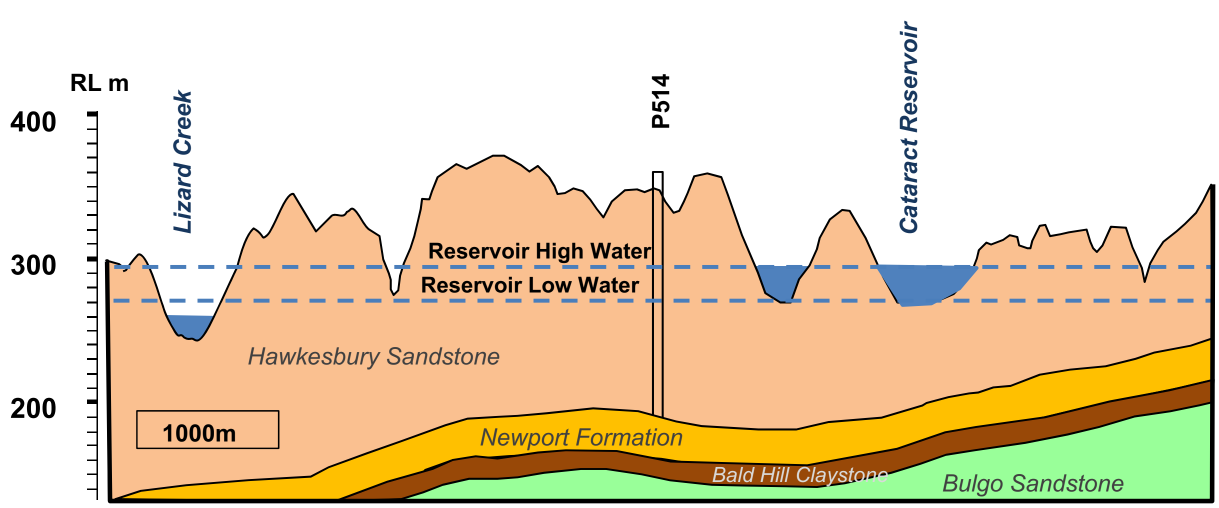
The Narrabeen Group, comprising a series of claystones and sandstones, directly underlies the Hawkesbury Sandstone and is itself directly underlain by the Illawarra Coal Measures which contain at least two economic coal seams, namely the Bulli and the Wongawilli Coal seams.

Traditionally the Bulli Seam has been the targeted seam in the study area and all subsidence results presented in this paper are recorded in response to mining development and extraction (to around 2.5m thickness) within the Bulli Seam. However, extensive extraction of the Wongawilli Seam (which underlies the Bulli Seam and will be extracted to a thickness of around 3.5m) is proposed in the future.

The Hawkesbury Sandstone is characterised by a system of pre-mining fractures which comprise steeply dipping joints, low angle bedding planes and local unconformities. However, regional scale surface structures have not been identified within the Bulli Seam and individual structural features located within the Bulli Seam are not identified at surface. Two major faults that have been intercepted between the northern extent of the Bulli Seam workings and Cataract Dam, but are not evident at the surface, are illustrated in Figure 3. The faults have throws of 30-50m, with the workings on the downthrown side.

A major dyke (see Figure 3), bisects the workings from NE to SW and caused the elimination of LW 510 and shortening of LWs509 and 511 to 514,

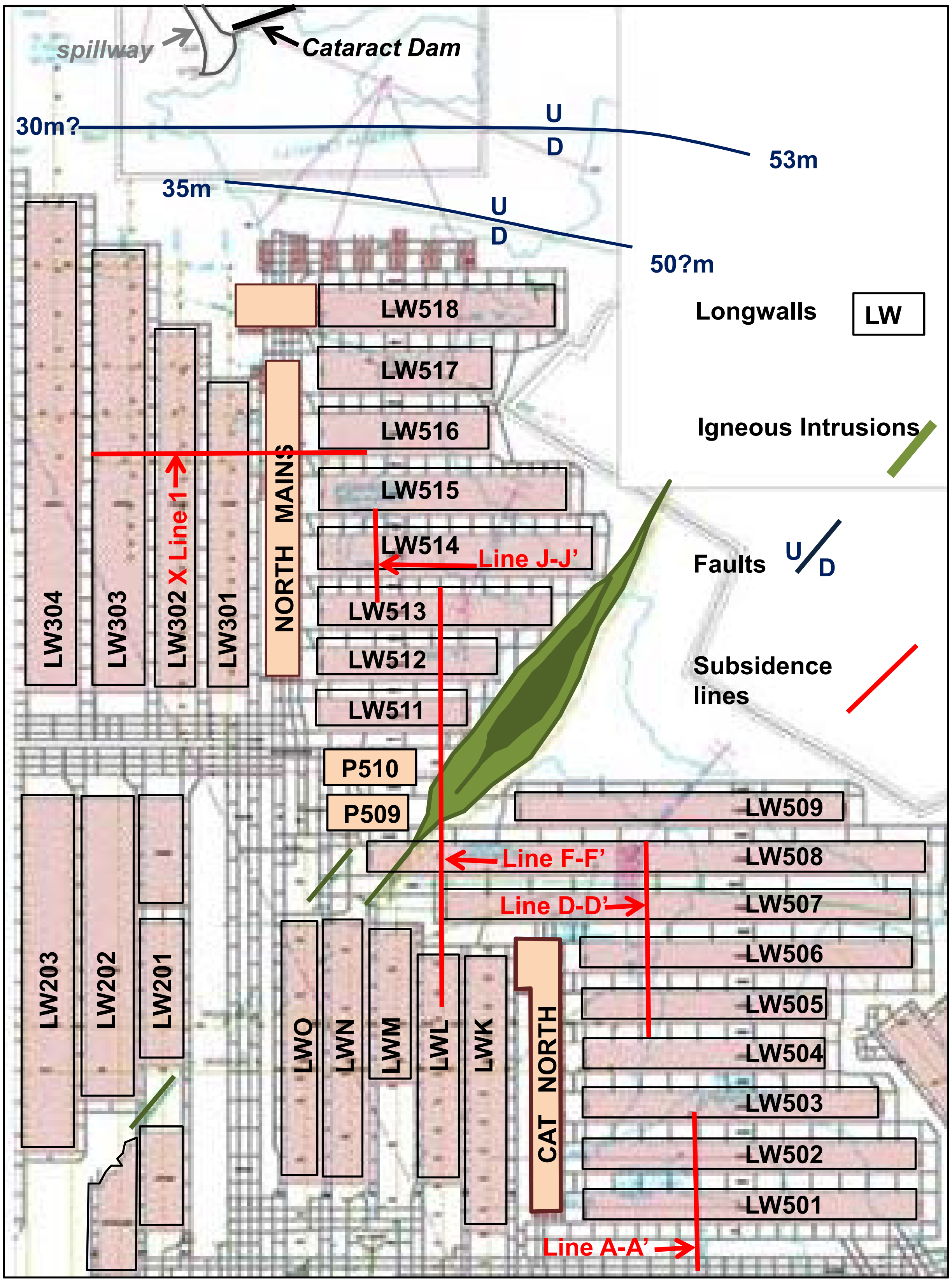
Figure 2 **Section through the reservoir and Lizard Creek (after Pells & Pells 2011) See Figure 5 for orientation of section line.**



dramatically changing the initial mine plan. While at a later stage (2006) shortened LW509 and 510 remnants were mined as pillar panels 509 & 510, the loss of coal due to the dyke was substantial.

Important formations within the Narrabeen Group which are mentioned in this paper include the

Figure 3 **Plan showing Bulli Seam workings and major structures in the area below the reservoir**



Newport and Garie Formations, which directly underly the Hawkesbury Sandstone, and the underlying Bald Hill Claystone which is considered a regional aquitard in hydrogeological models. The thickly bedded Bulgo Sandstone which underlies the Bald Hill Claystone (Figure 2) is the most voluminous member of the Narrabeen Group and has the potential to behave as a bridging formation during subsidence.

4. Mining

Figure 1 shows the progression of longwall or second workings in this area with time. First workings have been omitted. The irregular shaped panels indicate pillar extraction panels, and the rectangular panels correspond to longwall panels.

The workings are all in the Bulli Seam. Mining occurred during three distinct periods.

(i) 1972-1981 - initial extraction was conducted when Bulli Colliery mined the headland between the North and South Arms of Lake Cataract in the vicinity of E29. The mining was completed by 1981. Extraction resulted in maximum vertical subsidence of about 900 mm.

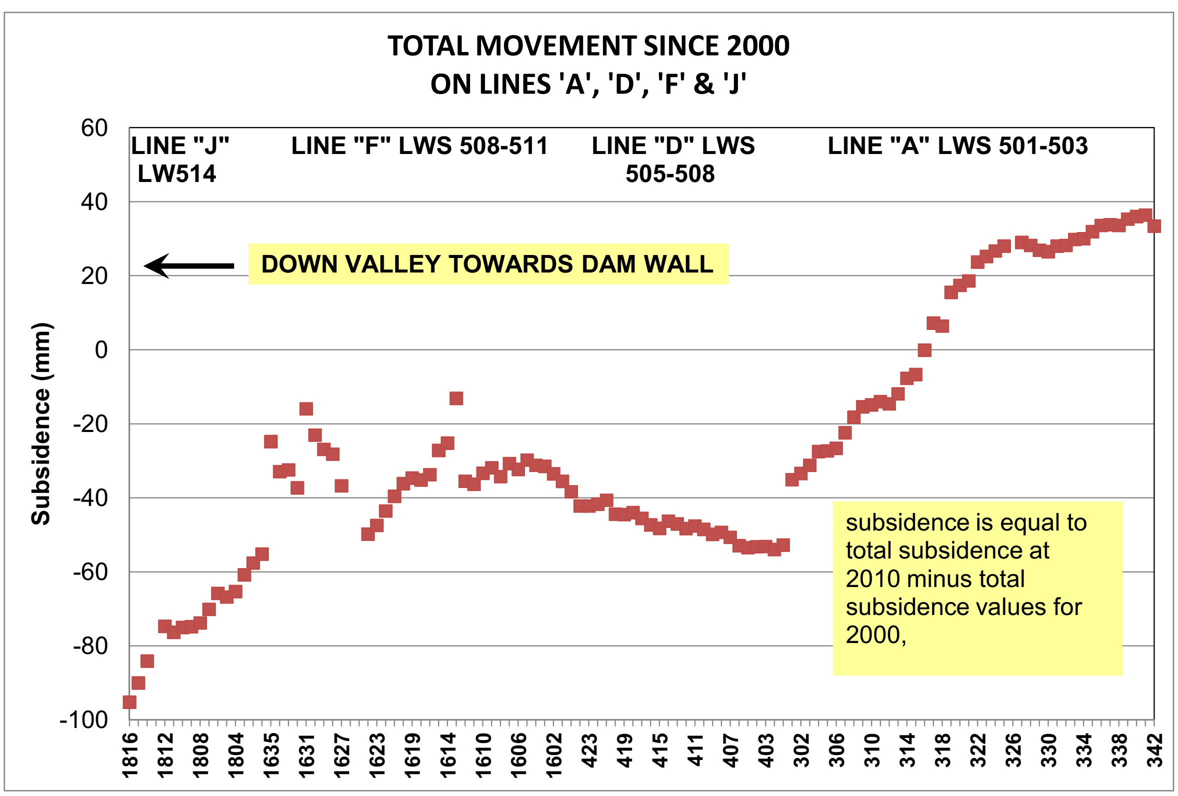
(ii) 1981-1993 - South Bulli Colliery mined a longwall area from 1981 to 1993 (Longwalls 301 to 309). Maximum vertical subsidence of about 1m resulted. These longwalls approached to within 650m of Cataract Dam.

(iii) 1993-2000 - South Bulli Colliery commenced mining directly under the stored waters of Cataract in 1993 with longwall LW501. Mining continued in a northerly direction towards the dam wall. The final longwall panel below the lake (LW518) was completed in 2000, approximately 850m from the dam wall.

Following the completion of longwall extraction, mainroad pillars were extracted. The Cat North mainroad pillars, which are to the west of LW501 to LW506, were extracted between January 2001 and August 2001. North Main pillars, which lie to the west of LW511 to LW518, were extracted between February 2001 and October 2001.

Further extraction in the area did not occur until the remnant blocks of coal at the western ends of panels 509 and 510 were extracted as pillar panels between August 2005 and June 2006. As discussed previously, these pillar panels (509 & 510) were formed by the presence of a large igneous dyke dividing the proposed longwalls 509 & 510 (Figure 3).

Figure 4 Movement along Catartact Valley since 2000



5. Measured movements

Movement on four survey lines which are orientated in a NNE direction and covering longwalls 501 to 514 (see Figure 4) have been combined to show movement over the ten years between 2000 and 2010. Since 2000 there has been up to 100mm of subsidence over LINE J-J (LW514) and 40mm of upsidence over LINE A-A.

Line A-A starts over a longwall panel in the adjoining Cordeaux Mine, then crosses the barrier pillar and mainroad pillars before reaching LW501goaf edge at peg 322. LW20 in the adjoining Cordeaux Colliery runs parallel to the Colliery Boundary and preceded extraction of LW501 by approximately one year. Monitoring of Line A-A commenced before the extraction of Cordeaux LW20. Hence monitoring stations over LW20 recorded initial subsidence. As longwall extraction in the 500 series in South Bulli Colliery developed, monitoring stations over Cordeaux LW20 experience a reversal of direction of subsidence and record upsidence.

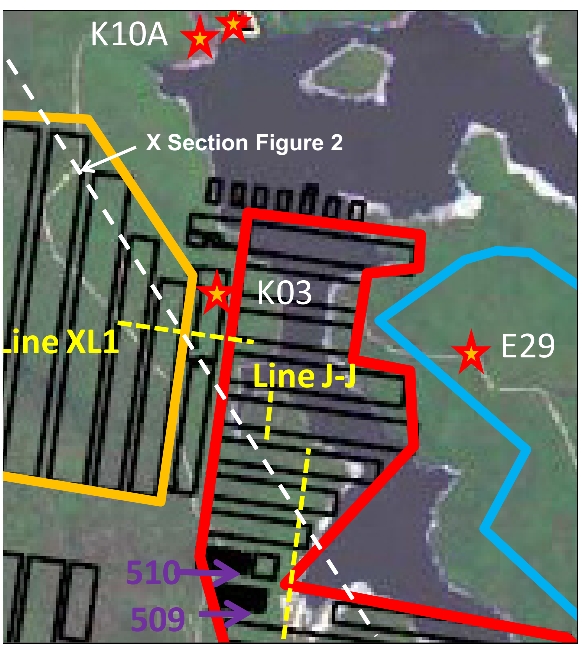


Figure 5 General location of survey station K03, Line J-J and Pillar Panels 509 & 510

5.1 Comparison of survey results

LW514 (see Figure 3 for location) was extracted in 1999, while the last longwall in the 500 series (LW518) was extracted in 2000. This was followed in 2001 by the extraction of the North Main pillars below K03. SCA monument K03 is 550m from LW514 and Line J-J as shown in Figure 5.

Movements at station K03 and peg 1814 on Line J-J since 2005 have been plotted on the same chart (Figure 6) for comparison. Two independent survey methods have produced the same result of on-going subsidence over an extensive area.

The step increase in subsidence shown by both survey stations in Figure 6 coincides with the extraction in pillar panels 509 and 510 (see Figure 5 for location). Extraction in these panels occurred between August 2005 and June 2006. Panel 510 is 750m from peg1814 and 1250m from K03. Peg 1814 indicates that subsidence is continuing some 4 years after the extraction of panel 510 and ten years after the extraction of LW514, with no sign of ceasing.

5.2 On-going movements

Cross Line 1 (Line XL1 in Figure 1) runs east-west across chain pillars between LW515 and LW516, main road pillars in North Main and then above LW301 to LW303. LW301 was extracted between November 1981 and August 1982. Peg20 on Line XL1 lies above LW301 goaf. Movement at Peg20 since October 1987, when LW304 was completed, is shown in Figure 7. The timing of extraction in the area of Line XL1 is also shown on Figure 7. Longwall extraction continued west until LW309 was extracted in 1993. This was followed by extraction of LW511 to LW518 to the east between 1997 and 2000 and the mainroad pillars of North Main in 2001.

Since October 1987 subsidence has increased by 19% above LW301 goaf, with most of the increase occurring following the extraction of the North Main pillars. However, it also is apparent that the extraction of LW511 to LW518 caused approximately 40mm of subsidence over LW301. That is, subsidence over LW301 occurred even though it was separated from the extraction in the 500 series longwalls by barrier pillars and North Main pillars, over a distance of 250m. Monitoring ceased on this line in 2007 with what appears to be a slight increase in subsidence following the extraction of pillar panels 509 and 510 some 1100m away.

When Line XL1 subsidence results are compared to Line 'J-J' and SCA station K03 a similar trend

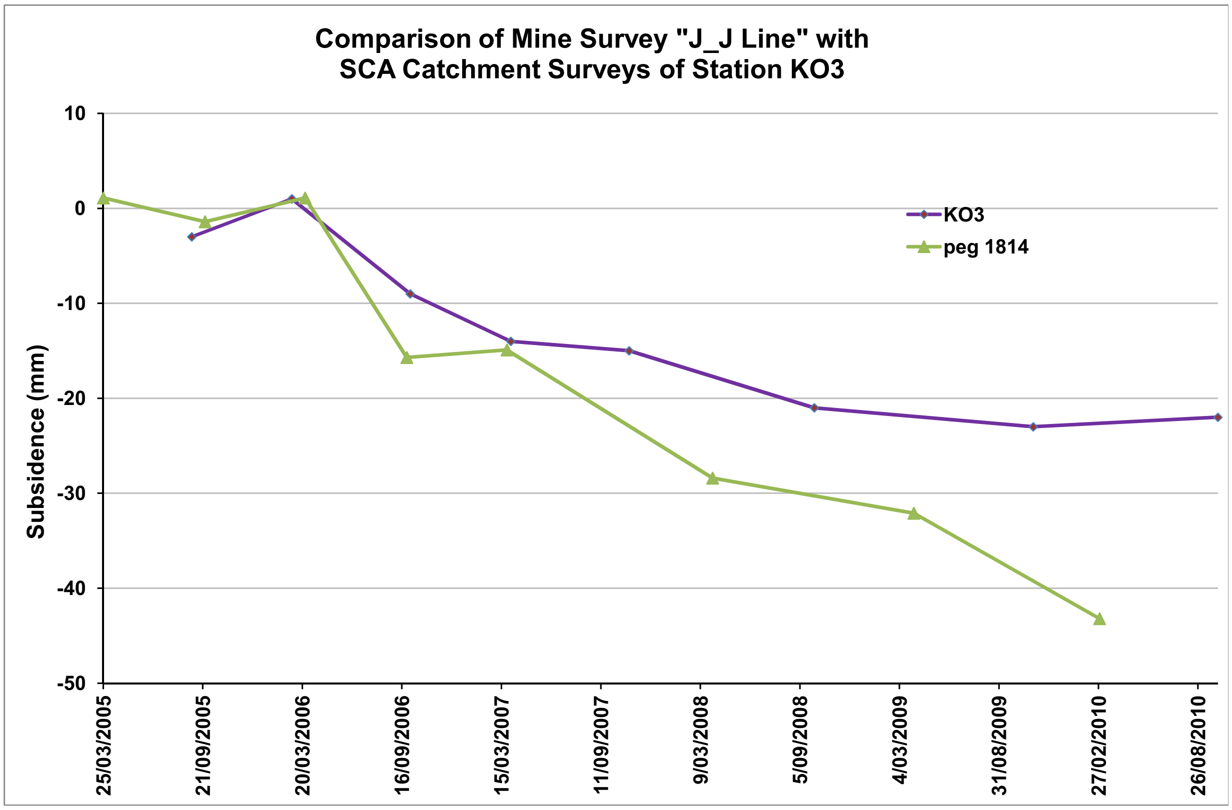


Figure 6 **Comparison of Mine Survey 'J_J Line' with SCA Catchment Surveys of Station KO3**

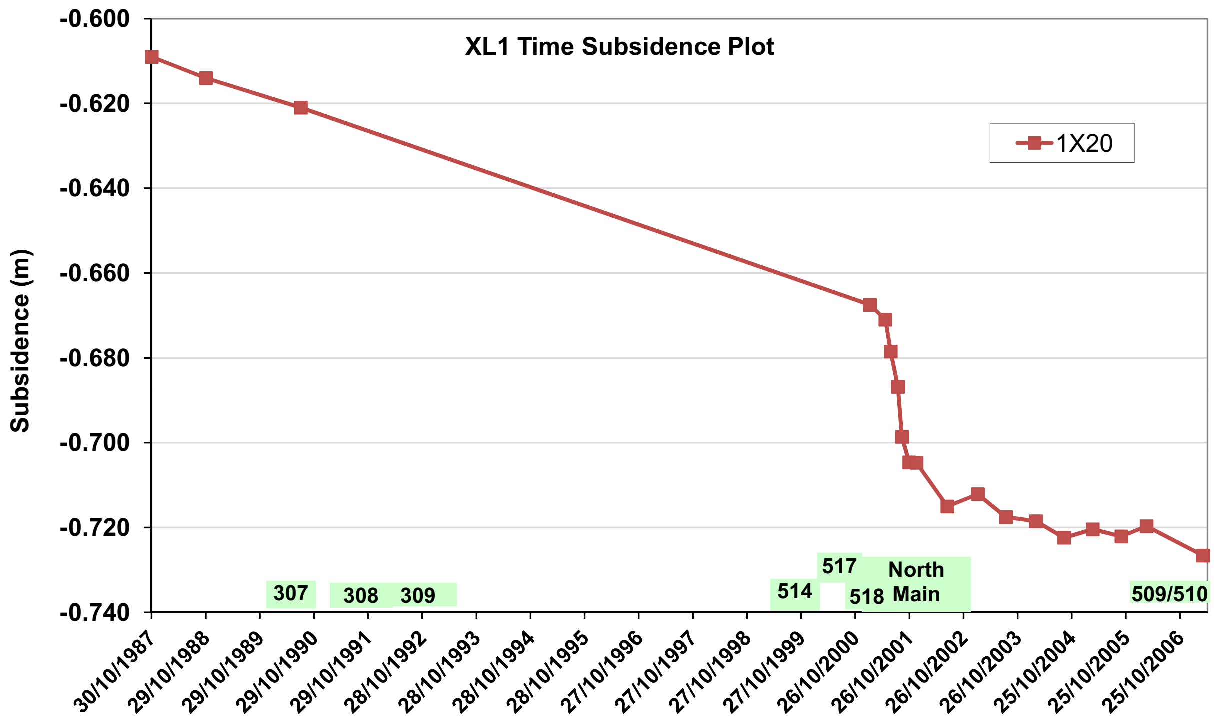


Figure 7 **Time series of subsidence at Peg20 on Line XL1**

is noted. As can be seen in Figure 8 the three different surveys all show an increase in subsidence after March 2006 which coincides with the extraction of pillars 509/510.

Therefore subsidence increased by approximately 1/5 over a 20 year period and has shown no signs of slowing and, in fact, the rate has increased since 2006.

Moving up the Cataract Valley away from the Dam shows similar results of increasing subsidence. Figure 9 is a time series of pegs along Line F-F (see Figure 1 for location).

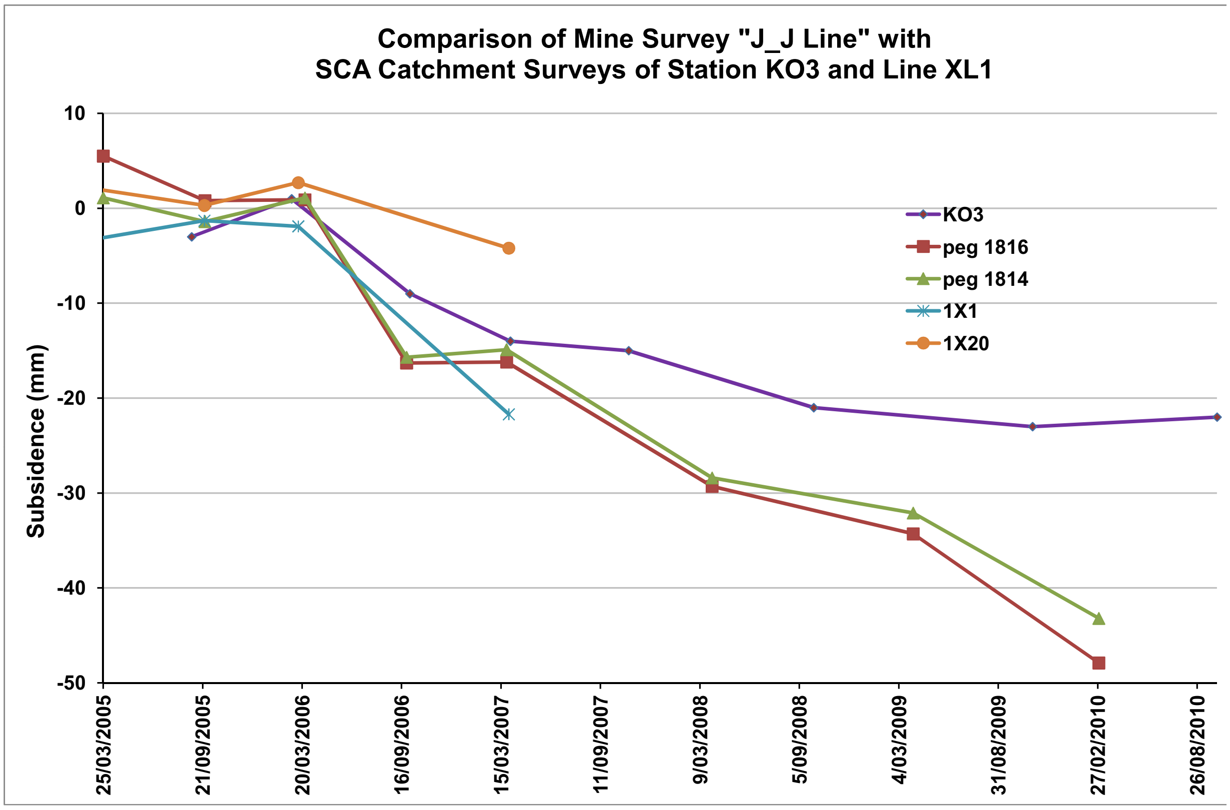


Figure 8 Comparison of Line XL1 subsidence results

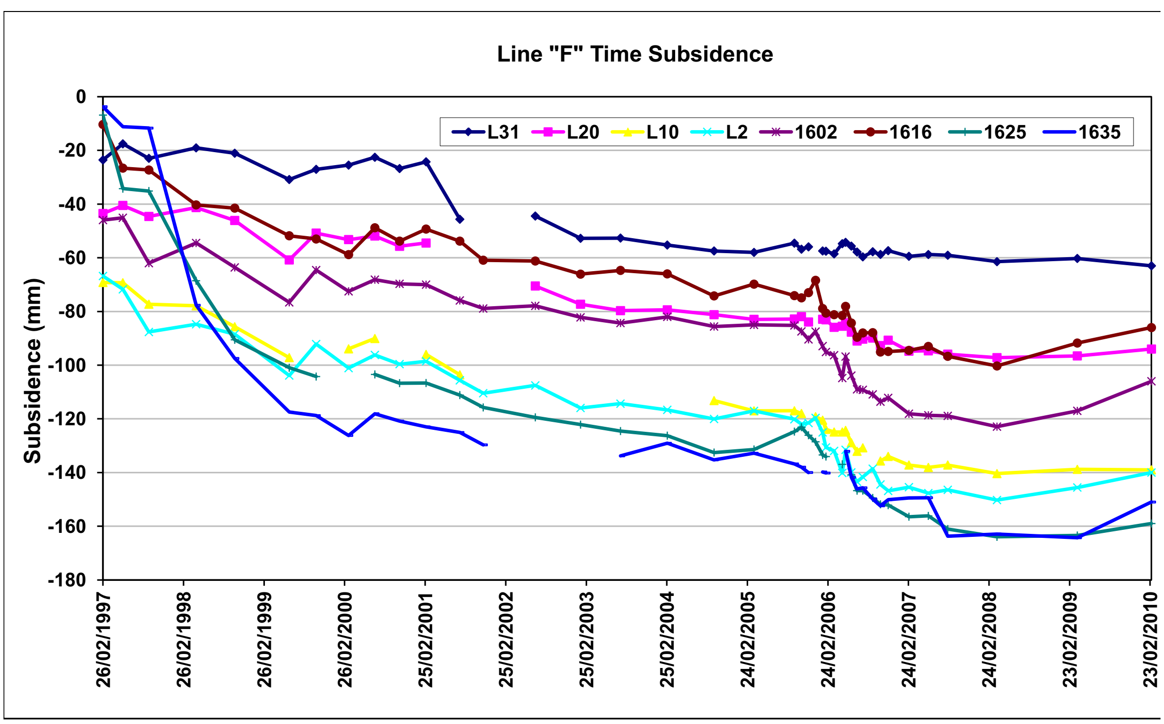


Figure 9 Time series of subsidence at various pegs along Line F-F

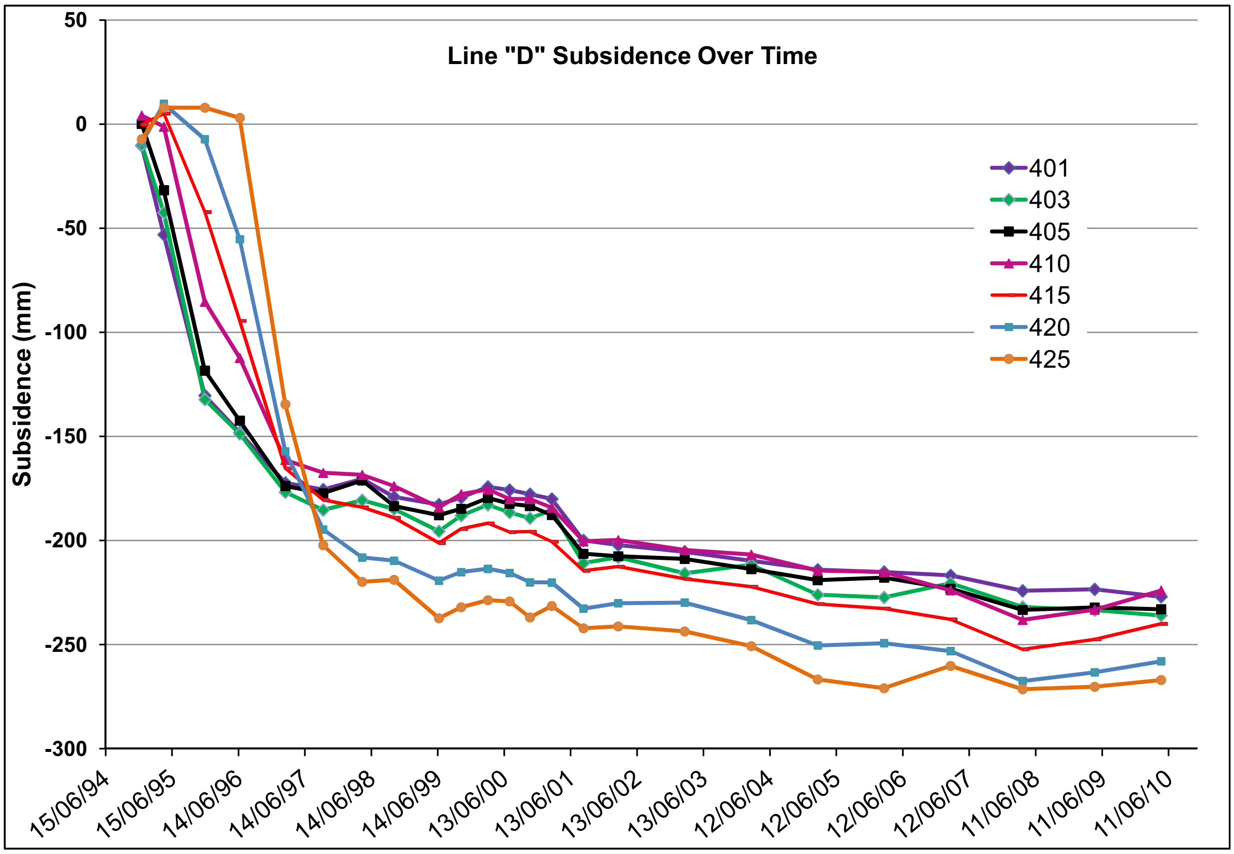


Figure 10 Time series of subsidence at various pegs along Line D-D

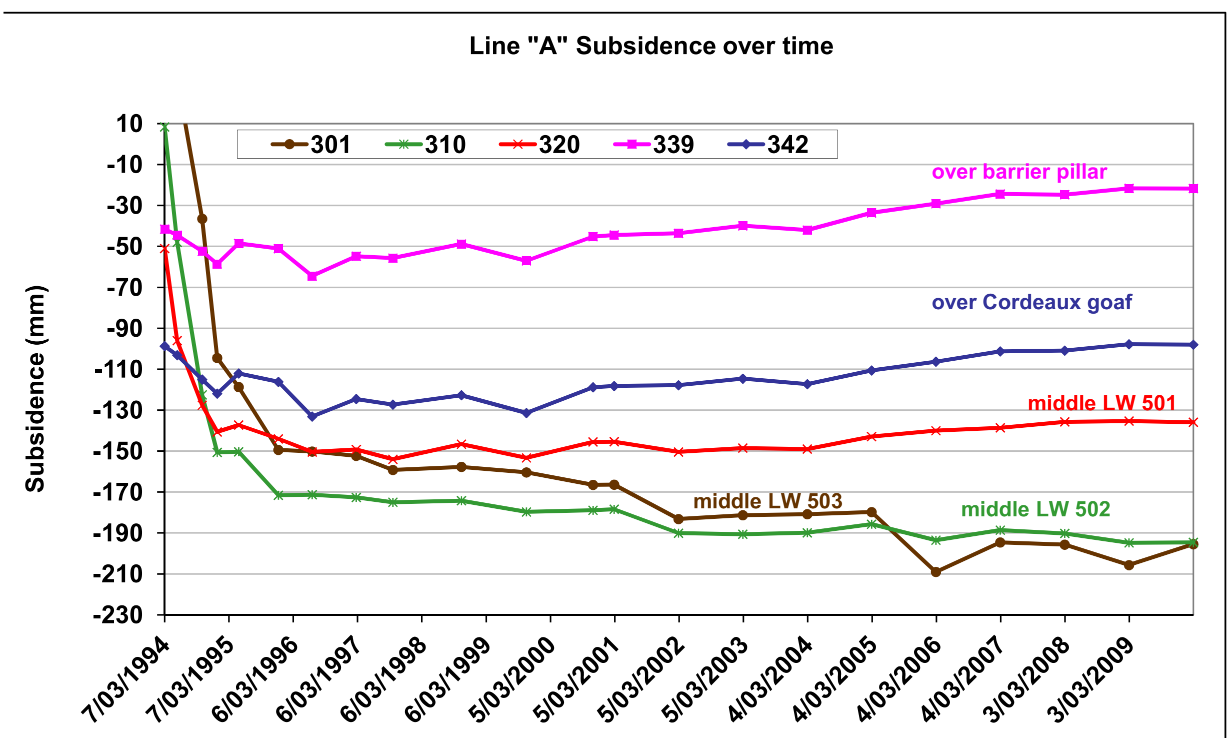


Figure 11 Time series of subsidence at various pegs along Line A-A

Part of Line F-F lies above longwall ‘L’. Peg L31 is above the goaf of longwall ‘L’, it shows an increase of 20mm of subsidence in 2001 at the time that Cat North mainroads were extracted.

Over the 10 years from 2000 to 2010 subsidence PegL31 increased by 40mm. Peg1635 is over LW511 and it also shows an increase in subsidence of 40mm over the 10year period. There is a reversal of this trend with the last two survey epochs.

Subsidence Line D shown in Figure 10 (location shown in Figure 1) lies over LW506 to LW508. This line shows a similar trend with an increase in subsidence of 40mm to 50mm (25% increase in subsidence) over 10 years before a slight reversal in the last two epochs. There is also a change in slope associated with increased subsidence associated with the extraction of Cat North in 2001 and panel 509/510 in 2006.

The final survey line in the series is Line A. This survey line starts over the adjoining Cordeaux Colliery’s longwall 20, crosses the barrier pillar and main road pillars before running above LW501 to LW503. A time series for various pegs on Line A is presented in Figure 11. Peg numbers start over LW503 and finish over Cordeaux goaf. Peg342 above the Cordeaux goaf and Peg339 above the barrier pillar both show an upsidence of

Longwall	Extraction Starts	Extraction Finishes
LW 511	12 March 1997	1 May 1997
LW 512	10 February 1998	26 April 1998
LW513	15 June 1998	16 October 1998
LW514	10 December 1998	1 June 1999
LW515	14 June 1999	15 October 1999
LW516	12 November 1999	3 March 2000
LW517	23 March 2000	16 June 2000
LW518	17 July 2000	3 December 2000
North Main	5 February 2001	13 October 2001

Table 1 Extraction schedule for Cataract North LW511-518 various pegs along Line A-A

approximately 30mm since 2000. While Peg301 and Peg310 above LW503 and LW502 goafs both show subsidence of 30mm since 2000.

Bellambi Line J-J is positioned over part of LW 513 and the complete width of LW514. This enables examination of the difference in subsidence through time between goaves and their intervening pillars, with successive extraction (Figure 12).

Data collection for line J-J relative to base line data began in October 98, coincident with the completion of LW 513 and predating the start of extraction in LW514 (Table 1). Extraction of LW514 began in mid December 1998 and was completed in Mid June 1999, with LWs515 to 518 completely extracted by the beginning of December 2000.

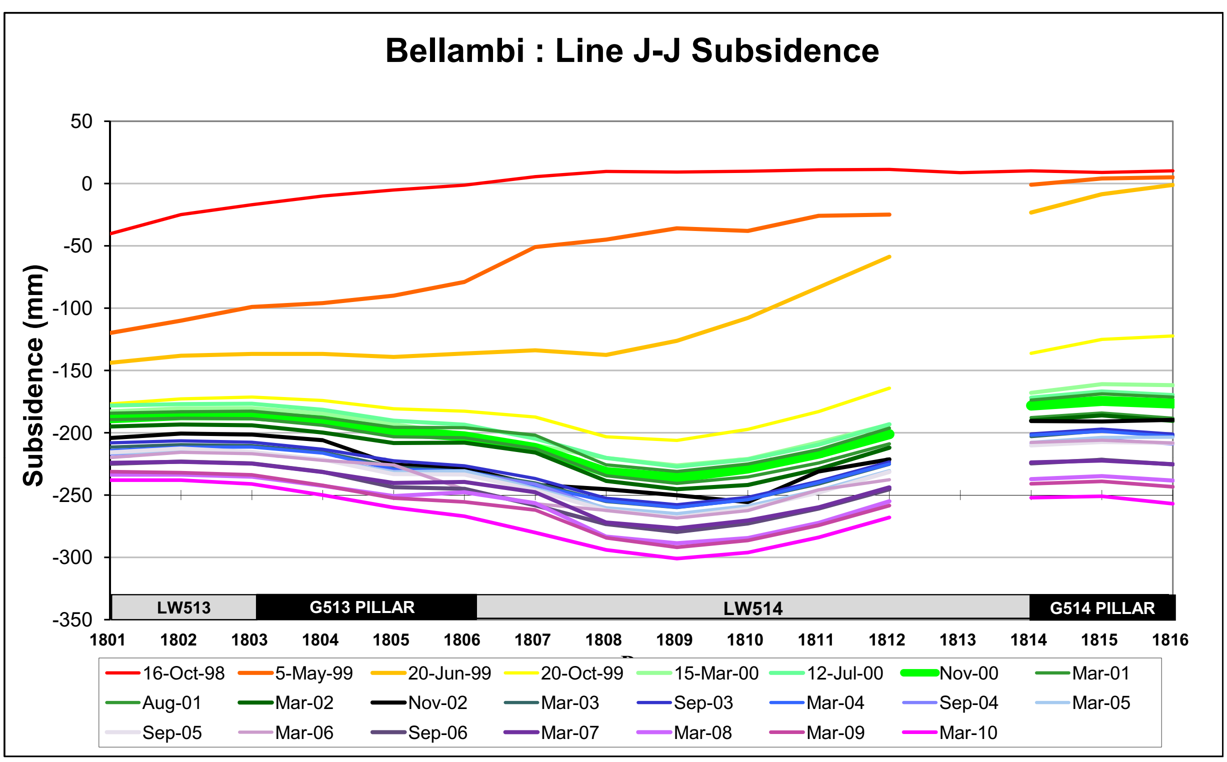


Figure 12 Subsidence on J-J line with time

Measurable subsidence of up to 25mm is evident on Pillar G513 adjacent to LW513 coincident with extraction on 16 October 1998. By the time LW514 was completely extracted in June 1999, Pillar G513, which separates the goaves of LW513 and LW 514, had subsided by 130-135 mm across its full width. By July 2000, at the start of extraction of LW518, the shape of the subsidence trough across G513 Pillar, LW514 Goaf and G514 Pillar had stabilised, although subsidence is still ongoing. Significantly, subsidence is still ongoing at the same rate as it was during the extraction of LWs 517 and 518, ie at >5mm/year ten years after LW extraction finished and five years after any form of mining in the area has ceased!

Rates of subsidence are similar over goaved areas and pillars for the final ten years of measurements (Figure 12), which is consistent with the rate of subsidence being controlled by the continued compression of the intervening pillars, rather than being driven by the ongoing subsidence of the goaves alone. If the pillars, which are designed to be long-term stable, are undergoing ongoing compression ten years after extraction with no reduction in the rate of movement obvious, then what are the implications for the cumulative impacts of successive mining ventures and proposed multiseam longwall extraction in the area through time?

6. Residual subsidence

Extraction ceased in the vicinity of Line J-J with the extraction of North Main in October 2001. Since this time there has been a fairly uniform sub-

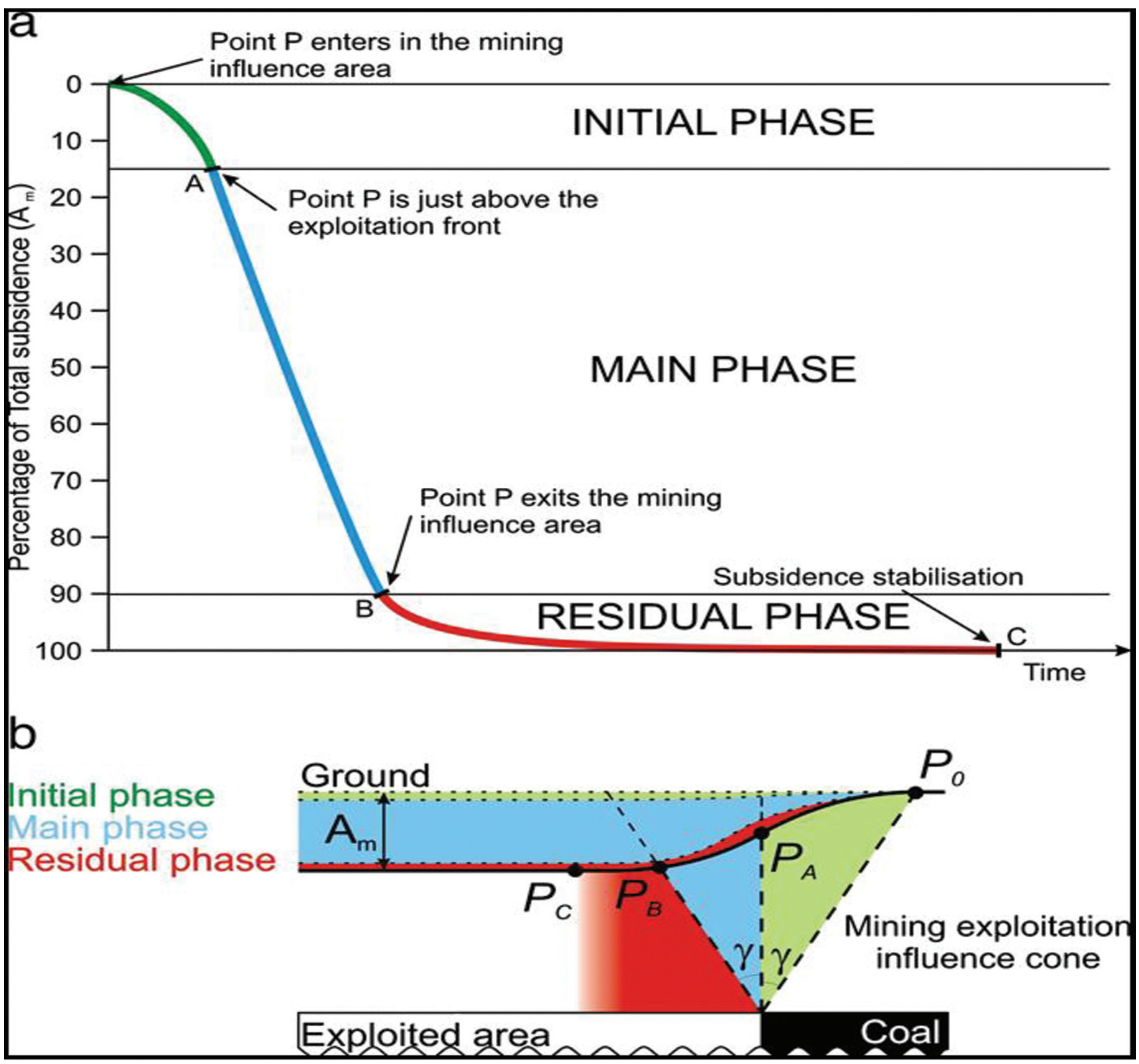


Figure 13 Residual subsidence (from Gueguen et al 2009)

sidence of 50mm along the length of Line J-J. This equates to a 25% increase in subsidence over the chain pillars of 513 and 514 and a 20% increase in subsidence over the LW514 goaf.

These figures for Residual Subsidence exceed accepted understanding of on-going subsidence. Al Heib et al 2005 concluded that the duration of residual subsidence does not exceed 24 months and adds about 5% of the total subsidence. Gueguen et al 2009 presents the residual subsidence phase graphically as shown in Figure 13 and describes the phase as varying between 5% and 10% of the maximum subsidence percentage, with a decreasing residual subsidence rate over time.

7. Hydrological changes in connectivity

A borehole was installed over LW514 goaf to measure the changes in the water table during and following extraction of LW514. The primary objective of this open hole was to determine if extraction of the longwall impacted the water table in the Hawkesbury Sandstone. The borehole yielded data from November 1998 just prior to the onset of extraction in LW 514 through until 2009 at which point it became blocked and unusable.

Up until 2005 the density of available data is low, as measurements were taken only around twice a year. However, from 2005 until 2009 measurements were taken much more regularly and often monthly. In Figure 14 borehole water levels have been compared to levels in the Reservoir.

Although data are variably dense, what is apparent is that from early 2005 the borehole water levels became closely aligned with those of the Dam Reservoir (see Figure 15), whereas this was not the case previously. That is, previously the two levels were more independent.

After 2005 the head difference between the piezometer reading and the reservoir level moves in a narrow band of 0.5m to 1.5m, suggestive of a very good connection between the piezometer and the reservoir. Significantly, from the perspective of regulating mining, the maintenance of a water table in the Hawkesbury Sandstone indicates that a connection to the mine workings has not been established. However, it does appear that a horizontal connection has opened between the borehole and the reservoir, possibly caused by opening along strata. Of concern is that Lizard Creek lies to the West of the reservoir (see Figure 2) and the RL of the creek is below the reservoir level. Therefore the possibility may exist for reservoir water to be lost to Lizard Creek via a pathway along bedding planes opened up by mining impacts.

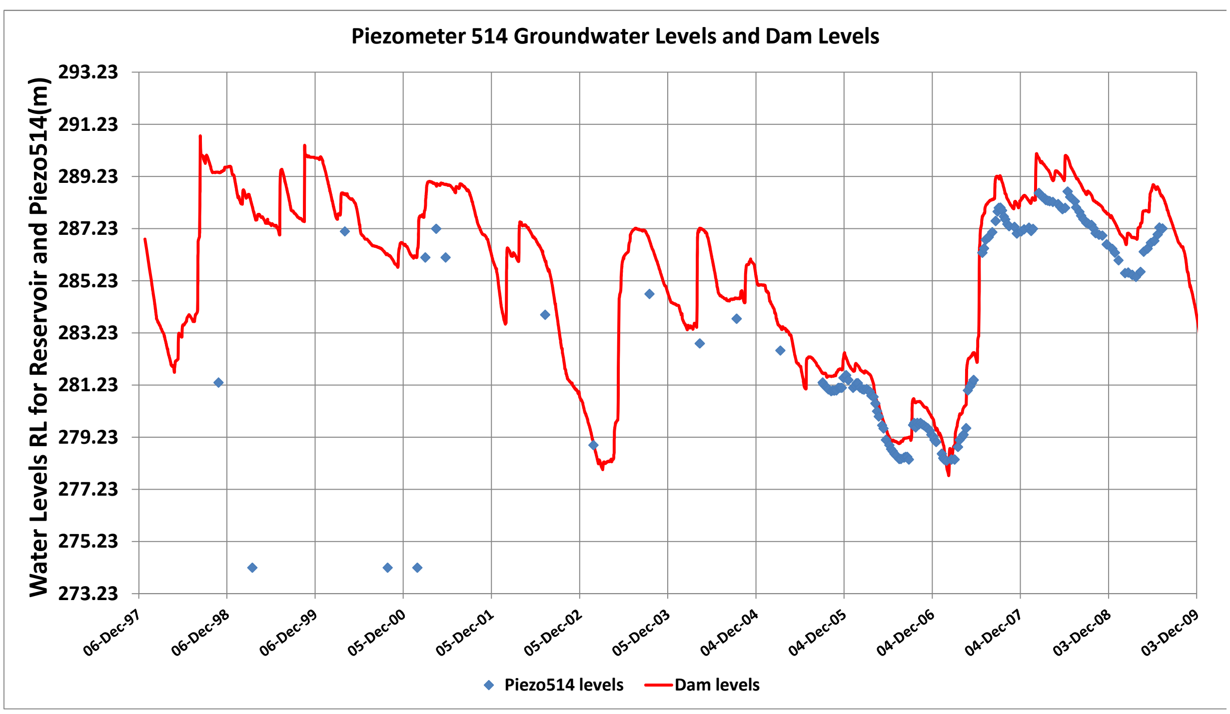


Figure 14 Comparison of groundwater and dam levels

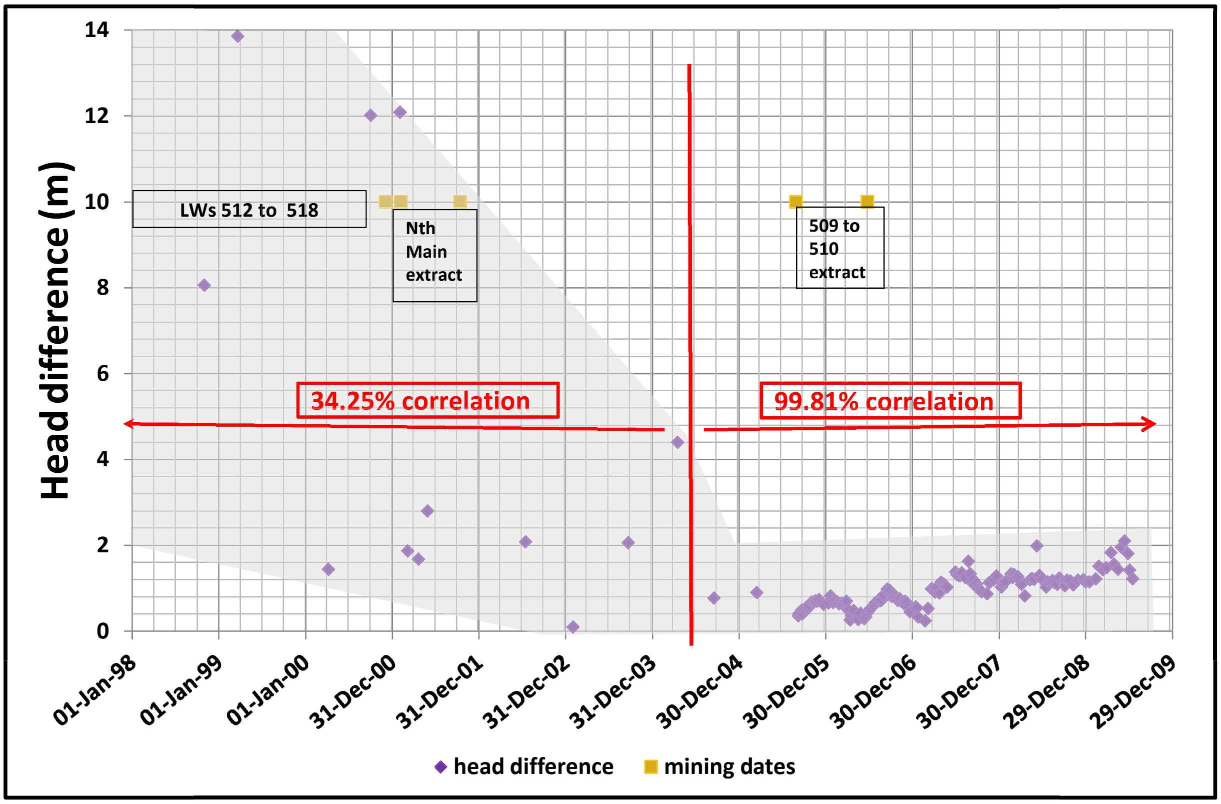


Figure 15 **Difference in water levels in Cataract Reservoir and Piezometer 514**

It is also clear that the reservoir level has been above that of the groundwater in the 514 borehole since measurements commenced in November 1998 (Figure 14), consistent with groundwater in the Hawkesbury Sandstone being charged by the reservoir. That is, the reservoir is losing water to the Hawkesbury Sandstone. With the limited data available, it is not known if the reservoir was charging the Hawkesbury Sandstone prior to longwall extraction in the area and the current situation reflects the pre-mining case. It is possible that prior to extraction, the Hawkesbury sandstone was charging the reservoir and that this reversed once longwall extraction had occurred. Hence the importance of the requirement set by the DSC and other departments that two years' baseline data should exist prior to mining so that the actual impacts of mining are unequivocal.

The close alignment of the water level in Piezometer 514 and the reservoir appears to be an impact caused by the residual subsidence. Piezometer 514 is located above LW514, which was extracted in 1999, whereas the change in the Head difference between the reservoir and the Piezometer did not occur until the end of 2004.

8. Conclusions

Analysis of subsidence data provided from two independent sources shows that subsidence is continuing over these longwalls some 25 years after they were extracted. This is cause for concern when considering the cumulative impacts of mining on the safety of a major water supply dam.

Data from an open hole shows that the water table in the Hawkesbury Sandstone has not drained into the mine workings as a result of longwall mining below the reservoir. However, the data also indicate that the level of the water in the borehole moves with the level of water in the reservoir, suggesting a greater degree of connection exists following the occurrence of mining in the area.

The data presented show that old goaf areas are not isolated from impacts (reactivation) by the presence of barrier pillars and main road pillars. Reactivation of goaf areas has occurred over 1100m from active extraction areas.

Subsidence is continuing 25 years after extraction of longwall areas.

Residual subsidence has added 25% to the initial subsidence in this area, a figure that is much higher than the typical 5% to 10%.

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