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D. Kay
Mining Subsidence Engineering Consultants

J. Barbato
Mining Subsidence Engineering Consultants

G. Brassington
Illawarra Coal

B. de Somer
Centennial Coal

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IMPACTS OF LONGWALL MINING TO RIVERS AND CLIFFS IN THE SOUTHERN COALFIELD

Daryl Kay[1], James Barbato[1], Gary Brassington[2], and Ben de Somer[3],

ABSTRACT: Extraction of coal using longwall mining techniques causes subsidence which has potential to affect surface features, including environmentally sensitive areas such as rivers and cliffs.

There are currently a number of proposed extensions to coal mining operations in the Southern Coalfield of New South Wales that are seeking to mine close to rivers and cliffs. These proposals have attracted some community concern at a local and regional level. This concern is largely founded on impacts that have occurred as a result of previous mining activities, the majority of which occurred directly beneath the impacted sites. It was therefore considered a timely exercise to revisit the history of impacts that have occurred as a result of mining close to rivers, particularly where they have occurred in the Southern Coalfield. The rivers reviewed include the Cataract, Nepean, Georges and Bargo Rivers.

Potential effects of longwall mining on clifflines can include rock fracturing; rock falls from cliff lines, riverbed fracturing and water loss. Consideration will be given in this paper to the major mining, geometrical, geotechnical and environmental factors affecting the likelihood of rock falls from cliff lines and riverbed fracturing and water loss, and reference will be made to previous mining experience at collieries in the Southern Coalfield of New South Wales.

Where the mining has not occurred directly beneath rivers, rock fractures, water loss and rock falls from cliff lines have occurred to a much lesser extent when compared to rivers that have been mined directly beneath. The fractures have been observed in local, isolated areas only and were minor in nature. In addition, changes to flow conditions have not been observed in these areas.

A clear understanding of potential impacts from mining of longwalls beneath or near rivers and cliffs is essential for developing relevant baseline studies, assessing potential impacts and formation of appropriate remedial methods. Management plans can then be implemented to monitor and mitigate the identified risks without unduly restricting the extent of mining.

INTRODUCTION

Extraction of coal using longwall mining techniques causes subsidence which has the potential to affect surface features, including environmentally sensitive areas such as rivers and cliffs.

There is an extensive history, in Australia and overseas, of mining directly beneath or close to rivers and cliffs. A number of studies have been conducted that describe many of these past experiences (ACARP, 2002; Holla and Barclay, 2000; Kay D., 1991; and Pells et al, 1987). The majority of these studies have focussed upon mining activities that have occurred directly beneath rivers and cliffs.

There are currently a number of proposed extensions to coal mining operations in the Southern Coalfield of New South Wales that propose to mine close to rivers and cliffs. These proposals have attracted some community concern at a local and regional level. This concern is largely founded on impacts that have occurred as a result of previous mining activities, the majority of which occurred directly beneath the impacted sites. It was therefore considered a timely exercise to revisit the history of impacts that have occurred as a result of mining close to rivers, particularly where they have occurred in the Southern Coalfield. The rivers reviewed include the Cataract, Nepean, Georges and Bargo Rivers.

[1] *Mine Subsidence Engineering Consultants*
[2] *Illawarra Coal*
[3] *Centennial Coal*

CHARACTERISTICS OF MINING CONDITIONS AND SURFACE LITHOLOGY IN THE SOUTHERN COALFIELD

The collieries in the Southern Coalfield lie in the southern part of the Permo-Triassic Sydney Basin, within which the main coal bearing sequence is the Illawarra Coal Measures, of Late Permian age. The Illawarra Coal Measures contain numerous workable seams, the uppermost of which is the Bulli Seam, and it is generally this seam which has been extracted under rivers and cliffs.

The river beds and cliffs that subside from mining lie within the Hawkesbury Sandstone unit, although there are outcrops of the Wianamatta Shale Group within their catchment areas.

The depth of cover over the Bulli Seam is generally between 400 and 500 metres. The thickness of the seam is generally between 1.8 and 3.5 metres, which is usually fully extracted, using longwall mining techniques.

MINE SUBSIDENCE RELATED MOVEMENTS THAT OCCUR BEYOND THE EDGE OF LONGWALLS

The maximum observed subsidence movements occur above the extracted longwall panels. Typically, the amount of subsidence at the goaf edge is less than 50 % of the maximum. Where the surface is relatively flat, the observed movements reduce with increasing distance from the goaf edge. As a general guide, they typically extend to approximately half a depth of cover from the edge of longwalls, particularly in the Southern Coalfield. Given that the typical depths of cover are between 400 and 500 metres, the limit of subsidence (as defined by a limit of 20 mm) is generally observed to be between 200 and 250 metres from the edge of longwall panels.

Where the surface includes river valleys or gorges, additional movement patterns are associated with longwall mining. Valley closure and upsidence movements are consistently observed in river valleys and gorges in the Southern Coalfield. The sides of valleys are observed to close in response to mining, with concentrations of compressive strain generally observed near the bases of the valleys. The bases of the valley are generally observed to rise relative to the valley sides, and this is termed upsidence. Similar movements have been observed in valleys even where no mining has occurred, and these movements are referred to as valley bulging and it is a natural phenomenon (Patton and Hendren, 1972), although it is understood that the process is accelerated by mining. The upsidence and closure movements are thought to occur in response to a redistribution of in-situ stress as a result of mining. Further details regarding observations, mechanisms and methods of predicting valley closure and upsidence are provided in a report by Waddington Kay & Associates (2002), now named Mine Subsidence Engineering Consultants Pty Ltd.

Closure and upsidence effects can be detected some distance from the edges of longwalls, well beyond the limit of vertical subsidence. In deep valleys and gorges in the Southern Coalfield, closure and upsidence movements have been detected more than 500 metres from the edges of longwalls, which is approximately twice the distance to the limit of subsidence in plateau areas.

In relation to vertical movements in rivers, the net vertical movement is a combination of subsidence and upsidence. If subsidence is greater than upsidence, net subsidence is observed. Conversely, the base of the river may experience net uplift if the upsidence is greater than the subsidence.

The various modes of movement reduce the further away a point is from the edge of longwalls. Depending on the proximity of longwalls to a river, upsidence can exceed subsidence beyond the goaf edge, resulting in net uplift. In the Cataract Gorge, for example, monitoring indicated that upsidence of 700 mm occurred while the area generally subsided by 500 mm, resulting in a net uplift of 200 mm.

POTENTIAL IMPACTS THAT CAN OCCUR AS A RESULT OF MINING

Rivers can experience a number of potential impacts as a result of mining, many of which have been well documented (Holla and Barclay, 2000). A summary of potential impacts is listed below.

- Fracturing in the riverbed and rockbars
- Surface water flow diversion from the surface to the shallow sub-strata
- Additional ponding, flooding or desiccation
- Additional erosion

- Changes to stream alignment
- Changes to water quality
- Impacts on terrestrial and aquatic flora and fauna

Where mining is close to, but not directly under rivers, the changes in the gradient that occur as a result of subsidence are generally small and an order of magnitude less than the natural river gradients or cross-gradients. The potential for additional ponding, flooding, desiccation or changes to stream alignment are therefore very small. Scouring or increased erosion is of greater concern for alluvial beds or bedrock containing soft strata, but not for the relatively hard Hawkesbury Sandstone that is found in the beds of the major rivers in the Southern Coalfield.

Fracturing of rock and surface water flow diversion are the most visible and well known impacts associated with mining beneath rivers. The potential changes to water quality and, to a lesser extent impacts to flora and fauna are also largely dependent on the severity of these impacts.

Further details regarding fracturing and surface water flow diversion are discussed below.

OBSERVATIONS OF FRACTURING BEYOND THE EDGE OF LONGWALLS

Fractures and joints in bedrock and rockbars occur naturally during the formation of the strata, and from erosion and weathering processes, which include natural valley bulging movements. When longwall mining occurs in the vicinity of creeks and rivers, mine subsidence movements can result in additional fracturing or reactivation of existing joints. A number of factors are thought to contribute to the likelihood of mining-induced fracturing and these are listed below.

- Mining-related factors, which affect the level of ground movements that occur. These factors include among other things, the depth of cover and proximity of the mining to the river, panel width and extracted thickness.
- Topographic factors associated with the river valley, which include valley depth and steepness of the valley.
- Local, near-surface geological factors, which include bedrock lithology such as rock strength, thickness of bed strata, orientation and dip of strata, degree of cross-bedding and existing jointing.
- In-situ horizontal stresses in the bedrock.

A number of collieries in the Southern Coalfield have recorded the extent and location of fractures that have developed during and after longwall mining operations in the vicinity of rivers and gorges. The mining operations reviewed for this paper include Tower and Appin Colliery beneath or near the Cataract River, Tahmoor Colliery beneath or near the Bargo River, West Cliff Colliery beneath or near the Georges River, and Elouera Colliery beneath or near Wongawilli Creek. Other operations in the Southern Coalfield have also mined beneath or near rivers and creeks and these are the subjects of other research.

In comparison, where river beds have not been directly mined beneath, the effects of subsidence have occurred to a substantially lesser extent. Where the rivers have not been directly mined under, a smaller number of mining-induced fractures have been observed. The fractures have been observed in local, isolated areas. These fractures were noted as minor in monitoring reports, and there were no indication of changes to flow conditions in these areas. It was found that the majority of mining-induced fractures are observed where rivers are located directly above extracted longwalls.

Figure 1 shows a graphical representation of fracturing relative to distance from the nearest edge of longwall mining, which can be measured from fracture maps that have been provided by each colliery. The plot refers to the number of observed fracture sites and not the number of fractures. Substantially more mining-induced fractures have been found at each fracture site above extracted longwalls.

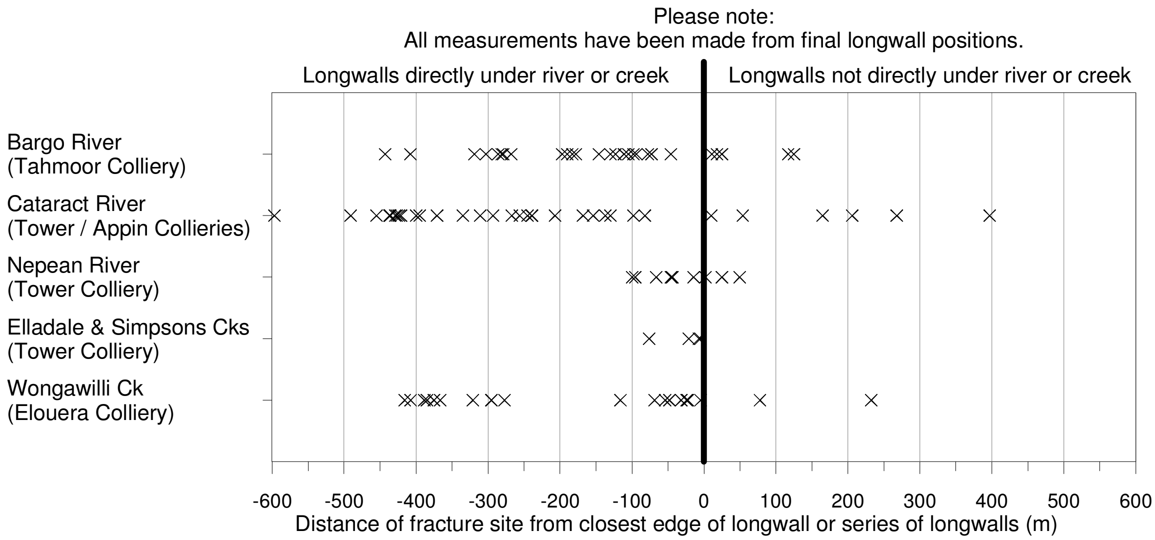

Fig. 1 - Distance of observed fractures to closest edge of longwall

In addition to the above information, extensive monitoring was undertaken as longwalls approached and passed beneath the Georges River at West Cliff Colliery. Fracturing was generally noticed in each section of river after it had been directly mined beneath, although some minor fracturing or movement of existing joints occurred in front of the extraction face. These minor subsidence movements did not impact water flows or quality in the river.

The above observations appear to generally correlate with established understanding of the behaviour of sandstone under strain. Fracturing is generally considered possible if systematic tensile strains are greater than 0.5 mm/m, or compressive strains are greater than 2 mm/m. A conservative analysis of observed ground movements suggests that compressive strains due to closure are generally greater than 2 mm/m in deep valleys (greater than 50 metres) only when they are within approximately 250 metres of the goaf edge, as shown in Figure 2. Only minor fracturing has been observed within rivers within this proximity to mining.

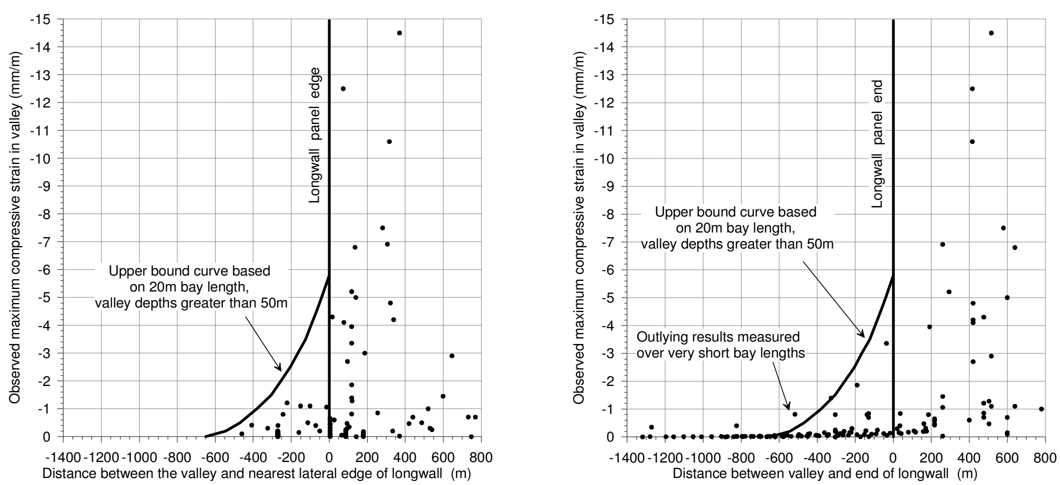

Fig. 2 - Observed compressive strains in valleys relative to side or end of longwall

The observation of small amounts of localised fracturing at more remote distances from extracted longwalls is understandable as the level of stress and bedrock strength varies along the length of a river. The level of existing stress in the bedrock varies depending on its position in the natural erosive cycle and the level of in-situ stress that has been imposed on it. The bedrock strength varies along the river depending on the type of rock, its layer thickness and extent of natural joints and fractures.

Fractures resulting from small subsidence movements, such as those that occur adjacent to longwall mining can occur where the bedrock is close to its elastic limit. A good example is the fracture in the bedrock beneath Broughtons Pass Weir on the Cataract River (identified in Fig 1), which occurred in rock that was already under stress as a result of the excavation and construction of the Weir, and its strength was relatively weak given that it was a thin layer of shale, rather than a layer of massive sandstone.

Given the above complexities, it is difficult to accurately predict precisely where fractures may develop in response to mine subsidence. However, monitoring of past mining experiences provides a good level of confidence for predicting the likelihood, style and extent of fracturing in rivers from longwall mining.

OBSERVATIONS OF SURFACE WATER DIVERSION BEYOND THE EDGE OF LONGWALLS

Mine subsidence related impacts on surface water are primarily concerned with diversion or loss of water in the following ways:

- Diversion of surface flows into subterranean flows, where water travels via fractures and joints in the bedrock into near-surface dilated strata beneath. This water generally resurfaces further downstream.
- Leakage through rockbars, where water held in ponds and pools may leak through fractures and joints in rockbars and resurface further downstream.
- Infiltration into the groundwater system, particularly where the groundwater table is lower than the surface water level of the river.
- Surface water into the mine.

In the Southern Coalfield, the main types of potential flow diversion are subterranean flows and rockbar leakages. Diversions of surface water through these mechanisms occur naturally due to erosion and weathering processes and natural valley bulging movements. Natural surface flow diversions are observed along the Cataract, Georges and Bargo Rivers in areas unaffected by mining.

Infiltration of surface water into deeper groundwater can not result unless a conduit is established for flow through to a deeper permeable horizon. Surface water loss is generally unlikely in the long term, especially where the groundwater table is higher than the surface water level of the river. Loss of surface water into the underground mine workings has not been observed in the Southern Coalfields where the depths of cover to the Bulli Seam operations is generally greater than 400 – 500 m, and the presence of the Bald Hill Claystone, which acts as an aquiclude.

Mining-induced surface flow diversion into subterranean flows occurs where there is an upwards thrust of bedrock, resulting in fracturing of the rock and redirection of surface water through the dilated strata beneath it. The water reappears downstream of the fractured zone as the water is only redirected below the river bed for the extent of the subsidence induced fracturing. This type of water loss has been observed previously in the Cataract, Georges, and Bargo Rivers and is illustrated by Figure 3.

Mining-induced surface flow diversion due to rockbar leakage occurs in a similar manner to the above mechanism, except that the rockbar is elevated above the rest of the river bed and the general water table. The rate of leakage is dependent, among other things, on the extent of horizontal fracturing within the depth of the rock bar and the water level. The rockbar leaks at a higher rate when the pool is full as there is access to all drainage paths and the water pressure is at its highest. However, as the pool level falls, the drainage rate reduces as the water pressure falls and access is restricted to drainage paths near the base of the rockbar. This type of flow diversion has been observed previously in the Cataract and Georges Rivers and is illustrated by Figure 4.

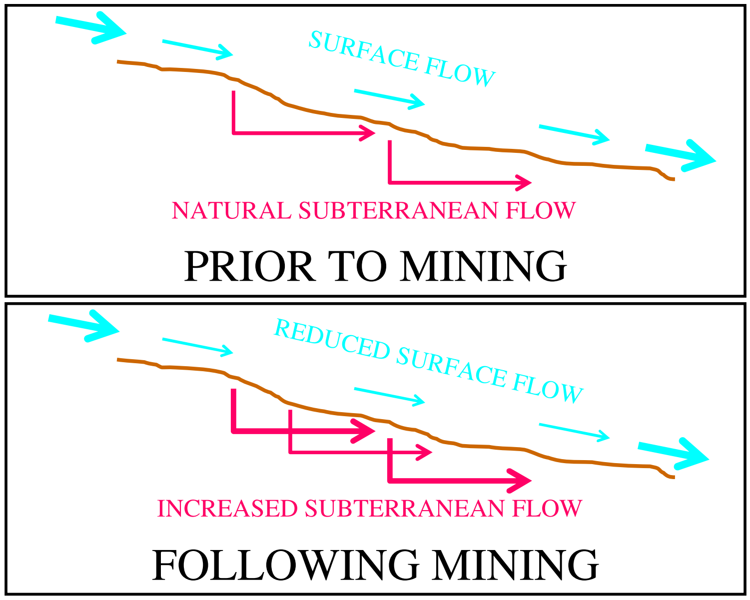

Fig 3 - Diagrammatic representation of subterranean flows

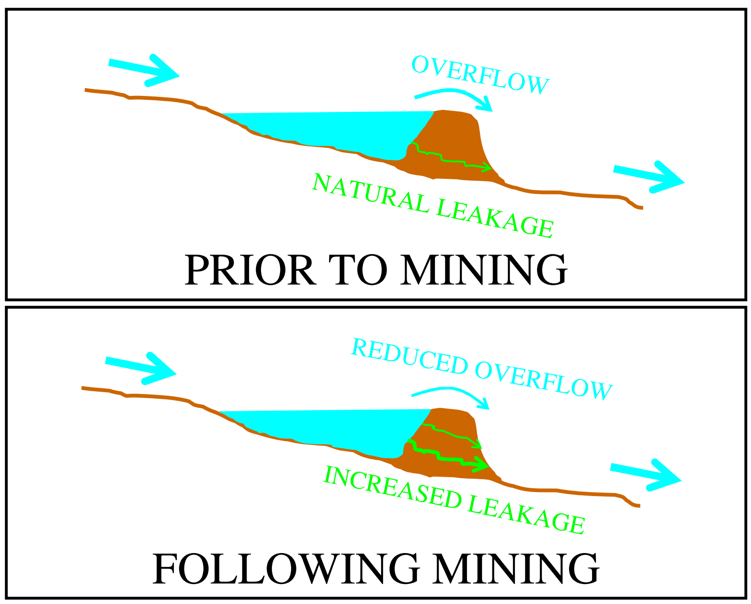

Fig. 4 - Diagrammatic Representation of Rockbar Leakage

As a key component to subsidence management, collieries in the Southern Coalfield routinely undertake investigations into the location and extent of surface flow diversions during and following longwall mining operations. Studies at Tower and Appin Colliery beneath or near the Cataract River, Tahmoor Colliery beneath or near the Bargo River, and West Cliff Colliery beneath or near the Georges River have been reviewed in the preparation of this paper.

The following comments are made from these reviews:

- There are no conclusive examples of surface water flow diversion beyond the edges of longwalls in the Cataract River. There is one site near the commencing end of Longwall 405 at Appin Colliery, where the surface flow diversions of approximately 2 ML/day have been observed but limited pre-mining investigations indicated that subterranean flows occurred prior to mining.
- Some sections of the Bargo River were observed to completely drain following a prolonged period of very low flows. The furthest distance of observed surface flow diversions from the edge of the extracted longwall was approximately 125 metres. Unfortunately, there were no pre-mining investigations to differentiate between natural and mining-related flow diversions.
- Periodic monitoring of surface flows in the Georges River indicate that surface flow diversions did not begin until the longwall passed directly beneath it. Water levels in pools were not observed to fall until the longwall had passed directly beneath them by 140 to 180 metres.

The potential for noticeable or complete surface water flow diversions are not only dependent on the amount of fracturing and bed dilation, but also the magnitude of flow in the stream. A simple formula can be used to illustrate the importance of water flow.

Upstream Flow	=	**AFFECTED RIVER SECTION** Diversionary Flow + Surface Flow	=	Downstream Flow

The formula simplifies an extremely complex system of flow conditions which vary from one section to another as a result of, for example, natural surface flow diversions and inflows from streams and other catchment areas within the affected river section. However, the formula is useful for demonstrating flow conditions of concern. If the maximum allowable diversionary flow is greater than the upstream flow, there will not be any surface flow within the impacted section of the river. If the rate of leakage through a rockbar is greater than the upstream flow, the pool will eventually drain.

Diversionary flow comprises two elements: natural diversionary flows and mining-induced diversionary flows. At present, there is relatively little information available to determine the amount of flow that is naturally diverted in streams. This is because until recently, detailed investigations of flow conditions in the river prior to mining had not been undertaken. However, post-mining investigations can estimate the total amount of natural plus mining-induced diversionary flows by observing the minimum level of upstream flow that is required to keep some surface water flowing along the river.

A good demonstration of this principle can be found by comparing the time that impacts were reported in a river with flow rates that were measured upstream. Figure 5 shows measured upstream flow rates over time in the Bargo River, as Longwalls 14 to 19 at Tahmoor Colliery were extracted. It can be seen from Figure 5 that flows were observed to remain continuous on the surface provided that flows were 2 ML/day or greater. The highest upstream flow that was recorded while discontinuous surface flows were observed downstream was 1.7 ML/day. Continuous surface flows were observed in 2004 and 2005, even during times of low flow, as the fractures had been naturally sealed by sediment.

Prior to the installation of a grout curtain in a section of the Cataract River affected by subsidence, the minimum flow required to keep the pools flowing in this section where longwalls have mined directly under the river was estimated to be 3.5 ML/day. Where rivers have not been directly mined beneath, surface flows have remained continuous during sustained environmental flows of 1.7 ML/day. Prior to rehabilitation of the area, pools in the Georges River retained water above Longwalls 5A2 to 5A4 with flows of 1.9 ML/day.

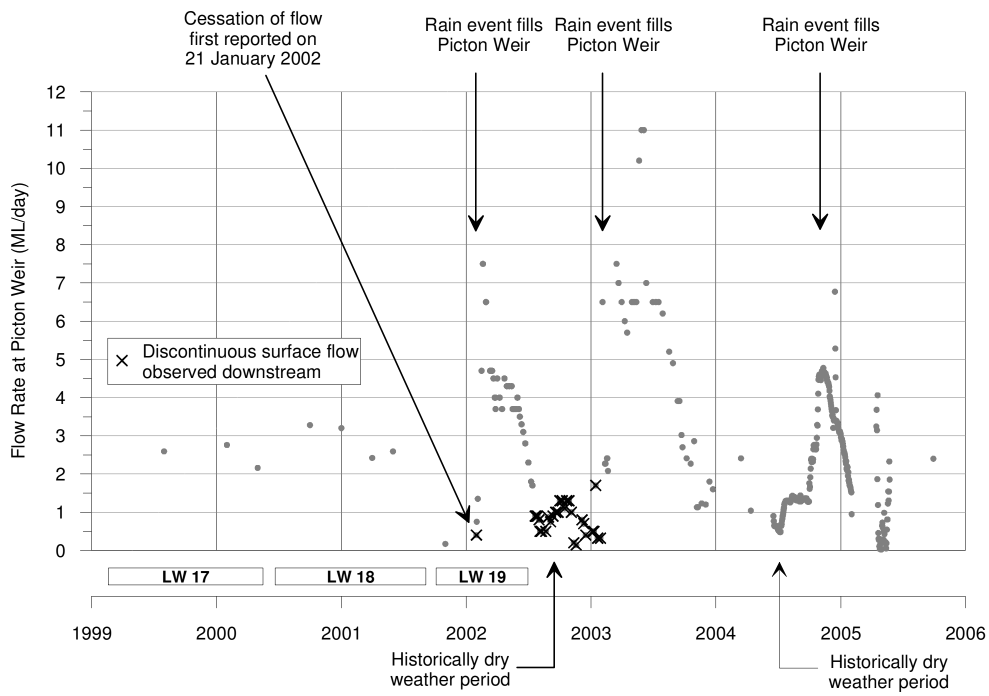

Fig. 5 - Observed Upstream Flow Rates in the Bargo River

These past experiences indicate that rivers will continue to flow even if they are impacted by direct mining, provided that flows in the river are greater than 3.5 ML/day. Collieries now routinely monitor baseline flow in rivers ahead of mining to understand flow conditions and identify sections along which flows are naturally diverting beneath the river bed. As these recently implemented studies mature, the collection of appropriate data and rigorous analysis is resulting in a far greater understanding of the impacts of subsidence on streams is becoming available. This in turn is allowing for much improved confidence in impact assessments and mine planning.

OBSERVATIONS OF IMPACTS TO CLIFFS BEYOND THE EDGE OF LONGWALLS

Instabilities occur naturally along clifflines due to a number of factors, including erosion and weathering, water seepage and water pressure, in-situ stresses in the bedrock, thermal expansion and contraction, changes in moisture content and the natural movement of the clifflines.

Mining can result in differential movements along cliffs which induce additional stresses in the rockmass, and as a result, can potentially reduce the stability of cliffs. The major factors which influence the stability of cliffs, both naturally and due to mining, are summarised below:

- Cliff geometry:
  - Height of the cliffs
  - Length of the cliffs
  - Shape, or horizontal curvature of the cliffs
  - Slope of the cliffs,
  - Size of the overhangs or undercuttings along the cliffs
  - Overall height of the valley
- Geotechnical factors:
  - Type of rock
  - Jointing, anomalies and inclusions in the rock which create weaknesses
  - Rock bedding
  - In-situ stresses in the rock

- Environmental factors:
  - Erosion and weathering which create unstable blocks
  - Seepage flow and water pressure
  - Heating and cooling from sun exposure
  - Changes in ground moisture content
  - Natural movement of the cliffs
- Mining factors:
  - Magnitude of subsidence, tilt, strain and curvature at the cliffs
  - Direction of tilt, strain and curvature relative to the cliffs
  - Proximity of mining to the cliffs
  - Direction of mining relative to the cliffs
  - Depth of cover at the cliffs

The complex interaction of the above factors makes it difficult to develop a model that can predict the likelihood of cliff or rockface instability based on predictions of ground movement. It is likely that in some cases, a rockface is close to a threshold point of instability prior to mining, and even the smallest additional movement may bring forward the timing of a rockfall.

There have been few instabilities in the Southern Coalfield as a result of mining under cliffs at depths of cover greater than 400 metres. Importantly, there have been no reported instabilities beyond the edges of longwalls. In the case of the Bargo River, there have been no reported cases of instabilities and only one small instability has been reported in the Georges River.

The most well known instances of instabilities have occurred in the Cataract River, where eight instabilities have been reported. Another two instabilities were reported in the Nepean River. These instabilities occurred during mining at Tower Colliery and their locations are shown in Figure 6, where it can be seen that no sites are located beyond the extent of the extracted longwalls. A check between the dates of each reported instability with actual longwall positions also confirmed that all instabilities occurred after they had been directly mined beneath.

The potential for cliff instability beyond the goaf edge remains even though no instabilities have been reported in the Southern Coalfield beyond the mining area. It is therefore prudent to examine the consequence of an instability occurring at each individual cliff, so that the risks associated with mining close to cliffs can be safely managed.

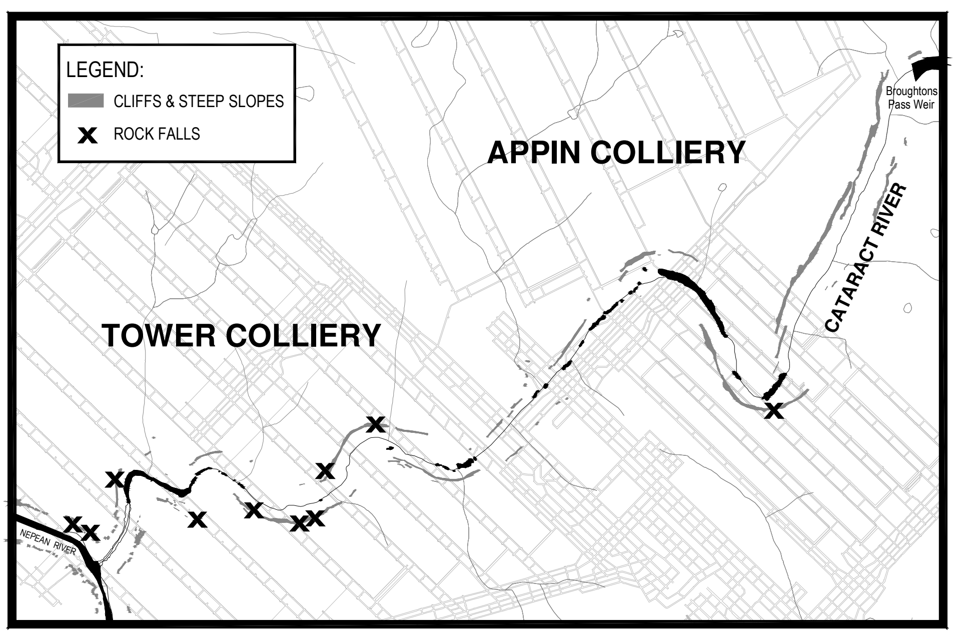

Fig. 6 – Observed rock falls over Tower Colliery

CONCLUSION

This paper illustrates the potential impacts of mining to rivers and clifflines in the Southern Coalfield. It is important to capture and consider the past when examining proposed mine plans and assessing the potential for impacts to occur. While some impacts might occur beyond the edges of longwall panels, the frequency and severity of impacts are substantially reduced when compared to those that have occurred where longwalls have been directly mined under these features.

A clear understanding of potential impacts of longwall mining is essential for developing relevant baseline studies, assessing potential impacts and formation of appropriate mitigation and remedial methods. This results in management plans being implemented to monitor and mitigate the identified risks without unduly sterilising coal resources.

ACKNOWLEDGEMENTS

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