Subsidence Impacts on River Channels and Opportunities for Control

K.W. Mills, Strata Control Technology

Summary

Subsidence associated with longwall mining is recognised to cause ground movements that generate horizontal compression at topographic low points; a process referred to as valley closure. River channels in the Southern Coalfield of N.S.W. are typically located directly on rock strata that has the potential to be impacted by valley closure. This paper describes the nature of the subsidence impacts that have been observed in river channels in the Southern Coalfield, techniques for monitoring these impacts, and a range of strategies for prevention, and control of the impacts.

The Australian coal industry has supported ACARP research Project C12016 - Damage Criteria and Practical Solutions for Protecting Undermined River Channels. The results presented in this paper are based on the outcomes of this project.

Keywords : subsidence, valley closure, rivers, mining, remediation

1. Introduction

Mining in the vicinity of river channels in the Southern Coalfield and the impacts on surface flows within these river channels are recognised to be issues of significant community interest. This paper is intended to provide a summary of the nature of the subsidence impacts that have been observed through measurement and monitoring at several sites in the Southern Coalfield during the course of ACARP Project C12016. Specific results from several of these sites are detailed in Mills et al (2004), Mills and Huuskes (2004), and Brassington et al (2005).

The observations and results presented are intentionally non-specific in order to capture the nature of valley closure impacts and the opportunities for remediation that have so far been identified. The results and observations presented do not obviate the requirement for detailed site characterisation and monitoring at each site. Variations in behaviour are expected and it is expected that different sites will present different opportunities for remediation depending on local site conditions.

The paper is structured to provide a review of the types of river channels found in the Southern Coalfield, the rock strata in which they are formed, the impacts on this strata of valley closure associated with longwall mining, methods to measure the impacts, and approaches with potential to restore sub-surface flows to above ground flows.

2. River Channels

River channels in the Southern Coalfield typically comprise a series of rock pools retained behind sandstone rockbars with water flowing between pools in one or more channels over the face of each rockbar. The flow in these channels is strongly influenced by rainfall, but there is typically also a base flow from the groundwater system.

2.1. Types of River Channel

In the upper reaches, watercourses are often no more than low points in the topography that flow during heavy rain. Further downstream, there are defined stream channels that flow for a short period after rain, but may include pools that remain for extended periods.

As the catchment area increases base flow from the groundwater system increases until there is regular flow. River channels with catchment areas of greater than 5-10km^2 typically have minimum flows of greater than about one megalitre per day and peak flows after heavy rain of several tens to several hundreds of megalitres. These medium sized rivers flow into larger rivers with catchments measured in the hundreds of square kilometres.

There are numerous man-made dams, weirs and diversion structures built along watercourses in the Southern Coalfield. Many of these are associated with urban water supply infrastructure, but there are also many local farm dams, particularly in the west that divert and store water during heavy rainfall. The Menangle Weir retains a 12km section of the Nepean River. There are several other weirs.

Observations made in river channels in areas unaffected by mining indicate that, although the bulk of flow occurs as surface flow, sub-surface flow also commonly occurs through natural fracture networks. In some sections of river channels unaffected by mining, the entire flow has been observed to pass through the sub-surface fracture network so that most of the time there is no apparent surface flow.

The potential for natural no-surface-flow becomes less as the magnitude of the base flow in the river system increases. Natural no-surface-flow is commonly observed in the ephemeral sections of river channels and sections where the flows are less than about one megalitre per day. No-surface-flows are also occasionally observed in rivers with larger base flows, but it is uncommon in larger rivers except where flows have been artificially diverted.

2.2. Sandstone Rock Strata

The nature of the sandstone rich rock strata that forms the bedrock of river channels in the Southern Coalfield can be observed in road cuttings alongside some of the major freeways leading into Sydney. Figure 1 shows a photograph of the rock strata in a cutting on the F6 freeway south of Sydney.

Fig 1: Exposure of Hawkesbury Sandstone on F6 Freeway south of Sydney.

Bedding plane horizons comprising fine grained material typically occur at intervals up through the geological section. These bedding plane horizons are typically not flat or parallel. There are commonly local variations on bedding plane surfaces of several centimetres over a metre, as well as much larger variations on a larger scale. Cross-bedding is also commonly observed.

3. Monitoring Techniques

A range of monitoring techniques used to detect and measure the propagation of fracturing under rockbars has been investigated as part of ACARP Project C12016. These have included techniques to characterise the pre-mining fracture network as well as techniques to monitor the development of fracturing and the effectiveness of remediation activities.

A range of geophysical tools were evaluated for their potential to measure the pre-mining condition of rockbars. A fluid EC (salinity) and temperature sonde, a natural gamma sonde, an electromagnetic induction sonde (EM39), a magnetic susceptibility sonde, and a heat pulse flowmeter were used at several sites to investigate the pre-mining fracture networks. Fluid EC and temperature logs provided information on fracture flow, while the other logs provided information on variations in rock type. Frequency-domain electromagnetic (FEM) surveys were undertaken at two sites to investigate the potential of the technique to measure rock fracturing.

A caliper logging tool and straddle packer permeability testing system were developed during the ACARP Project to measure the location, nature and hydraulic conductivity of fractures both pre and post mining.

Overcore stress measurements were conducted to measure the in situ rock stresses prior to mining. Stress changes in the rock strata were also measured as mining progressed.

A borehole camera was used to give visual confirmation of the nature of fracturing and the effectiveness of remediation work.

The caliper tool, the straddle packer permeability testing system, and a borehole camera logged to a laptop computer were found to be most effective for determining the development of fractures during mining subsidence and the distribution of fracturing across rockbars impacted by mining subsidence.

Figure 2 shows the caliper logging system in use in the field. The locations of fractures are able to be identified with a high degree of confidence.

Short subsidence lines across the river channel surveyed in three dimensions allow the location of the main upsidence zone to be determined and the development of sub-surface fracture volume to be monitored.

Multi-point extensometers located in the centre of the upsidence zone have successfully measured the development of rock fracturing and dilation through the rock strata at each stage of mining. The extensometer results show where active fracturing is occurring. The total dilation can be correlated with subsidence monitoring results to confirm that all the dilation is being captured. Multi-point extensometers have been found to be more effective when installed after the location of the upsidence zone has been identified from initial subsidence monitoring.

In combination, these systems provide a basis to determine the nature and extent of natural fracturing prior to mining as well as the development of mining induced fracturing. Subsidence and extensometer monitoring, caliper logging, and packer testing systems have been found to be able to confirm the location, width, development and hydraulic conductivity of mining induced fractures with a high degree of confidence.

4. Subsidence Impacts

4.1. Valley Closure

Longwall mining causes subsidence movements that are predominantly vertical and, in the Southern Coalfield, typically in the range 0.8-1.3m. Horizontal ground movements are developed through a range of mechanisms as rock strata moves downward in response to longwall mining (Kay et al 2007).

Rockbars located in river channels are horizontally compressed by the opposing lateral movements associated with mining subsidence and valley closure.

Fig 2: Caliper logging system for fracture measurement.

The behaviour of bedrock in river channels subjected to the horizontal compression associated with mining subsidence is similar to the behaviour of sandstone rock strata subject to horizontal compression in other circumstances.

Figure 3 illustrates the key components of the fracturing that has been observed at various sites. The fracture network that develops in rockbars as a result of valley closure and upsidence can be broadly characterised by four main fracture zones. These are described in the following sections.

4.2. Surface Fracture Zone

The nature of fracturing in the surface fracture zone can be observed as the surface expression of valley closure effects.

Fractures in the surface fracture zone occur within 1-2m of the surface and tend to be influenced by the local topography of the rockbar. Joints open up, slabs of rock move into the free space of the river channel, and pieces of rock may become dislodged.

Tension cracks are commonly observed on the surface, often along pre-existing joints. Somewhat paradoxically these tension cracks are indicative of the location of the zone of maximum horizontal compression, because they typically occur as a result of upward buckling of the surface strata above the main upsidence zone.

4.3. Main Upsidence Zone

The main upsidence zone typically occurs within a 20-30m wide corridor where most of the differential horizontal movements and resulting vertical dilation is concentrated. The fractures in this zone develop progressively downward with increasing subsidence, usually to a final depth of about 6-12m below the surface. The actual depth

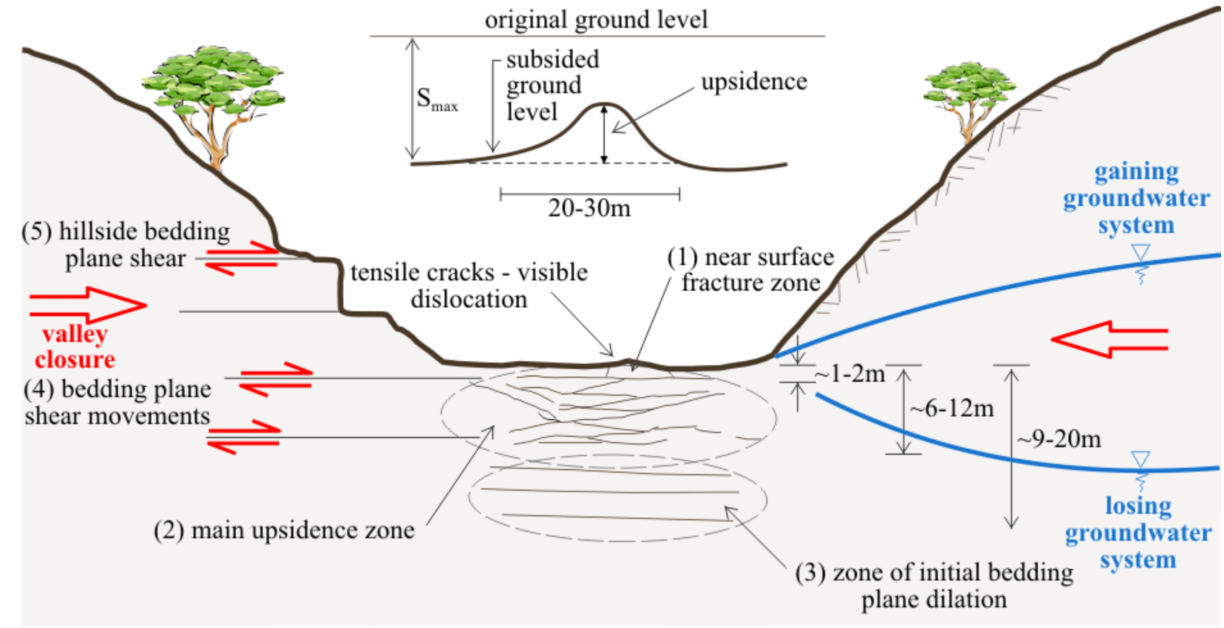
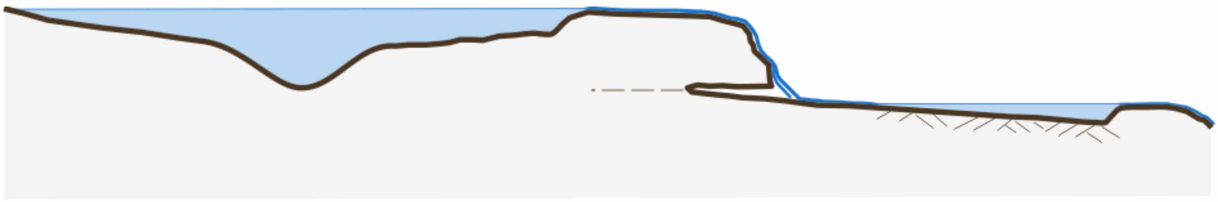
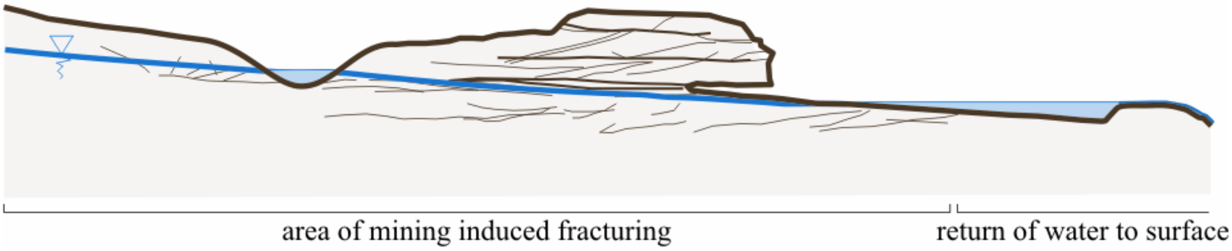


Fig 3: Cross section showing nature of rock fracturing observed due to valley closure in river channels in the Southern Coalfields.



PRIOR TO VALLEY CLOSURE IMPACTS



POST MINING FRACTURE NETWORK

Fig 4: Longitudinal section showing diversion of surface flow through the fracture network and return of flow to the surface.

is dependent on individual site characteristics and the magnitude of valley closure.

Most of the dilational volume created within the rockbar occurs within this main upsidence zone. Subsidence monitoring indicates that the dilational volume created in the main fracture zone is typically triangular in distribution with the greatest upsidence observed in the centre. Caliper logging of boreholes shows that the fracture network in this zone tends to be chaotic and comprise numerous inter-fingered fractures.

When horizontally bedded strata becomes overloaded in horizontal compression, low angle shear fractures develop in conjugate sets that dip in the direction of loading. These low angle shear fractures typically develop through fresh rock to form wedges, but the shear fracturing also takes advantage of low strength horizons such as bedding planes or joints wherever these exist.

Once a zone of conjugate shear fractures develops, further horizontal movements tend to concentrate at this same location because the fractured rock has much lower strength than the intact rock. As a result of this localisation of fracturing, the main upsidence zone tends to develop as a linear feature along the length of the river channel, although geological structures such as jointing are also observed to influence its orientation.

Due to the meandering of river channels, the main upsidence zone does not necessarily follow the centre of the river channel, especially at bends in the river, and may be located away from where the surface water flows.

The wedging action of the fractured rock strata along the low angle conjugate shear fractures causes rock strata above to buckle upward causing tension cracking on the surface and upward movement relative to the rest of the subsiding strata.

4.4. Dilated Bedding Planes

A zone of dilated bedding planes appears to develop in the interval 6-10m below the main fracture zone as a result of the early stages of horizontal compression. Caliper logging indicates the development of minor fractures at vertical spacings of several metres.

While this fracturing has increased hydraulic conductivity compared to the surrounding rock strata, the fractures appear to be less vertically connected and hydraulically conductive than the fractures in the main upsidence zone.

4.5. Basal Shear Fracturing

The basal shear fracturing zone extends laterally from the main fracture zone under the flanks of the valley. This zone tends to be better developed and more laterally extensive on the side of the valley closest to mining. The basal shear fracturing zone appears to comprise more than one bedding plane shear with shear movement progressively getting deeper with greater levels of subsidence and valley closure.

Horizontal shear on these bedding planes has the potential to cause dilation and an increase in hydraulic conductivity along the bedding plane. It is noted that the storage in such shear planes is very low and increased hydraulic conductivity along bedding planes under the flanks of valleys is likely to enhance flow from the surrounding country into the river channel in a gaining system.

Subsidence monitoring indicates a phenomenon described by Waddington and Kay (2004) as valley bulging. The dilation associated with bedding plane shear would be consistent with this valley bulging phenomenon.

4.6. Other Fracture Zones

Shear fracturing is observed to occur on bedding planes that daylight along the slopes above river channels. These fractures tend to daylight at the top and base of rock outcrops and cliff formations. They are typically not significant from the perspective of river flows, because they occur well above the river level, but they can interfere with remediation operations under the valley flanks.

Fracturing is also recognised to occur at depth above each individual longwall panel. In some geological environments, there is potential for flow through this zone into the mine. However, in the Southern Coalfield, this deeper zone of fracturing is typically remote from the near surface upsidence impacts that are the focus of this paper.

4.7. Sub-Surface Flow

In areas that have been impacted by valley closure there is potential for increased flow of surface water flow through the sub-surface fracture network. Sub-surface flow through the mining induced sub-surface fracture network only occurs along the section of the river channel that has been impacted by mining. Outside of this area, the fracture network is unchanged from its pre-mining condition and normal flow conditions exist.

When the water level in the river channel is perched above the general groundwater level, some water flows from the river into the groundwater. In this case, the stream system is referred to as a losing system.

If the water level in the river channel is below the general groundwater level, the converse is true and water flows from the groundwater into the river, and the stream system is referred to as an influent or gaining system.

Outside of the area affected by valley closure, the rate at which water returns to the surface from the sub-surface fracture network depends on the relative levels of the groundwater and river channel. If the system is a gaining system, then flow through the mining induced sub-surface fracture network returns to the surface as soon as the fracture network ceases to exist.

In a losing system, some flow in the sub-surface fracture network may continue in the groundwater system without returning to surface. The amount of flow diverted into the groundwater system depends on the hydraulic conductivity of the rock strata and the significance of this flow diversion to the groundwater system depends on the total flow in the river channel.

Before water in the river channel can enter the main upsidence zone, it has to enter the fracture network through the near surface fracture network. In some cases, the surface fracturing is remote from the watercourse so access for stream flow to the deeper fracture system is limited. In other cases, there may be direct access to the deeper fracture system.

Once surface water has entered the fractures of the main upsidence zone, water can flow downstream through this fracture network for as far as it extends. Downstream of the mining area where there is no disturbance caused by mining, the fracture network is no longer present so water has to either return to the surface or, when the water level in the river channel is above the groundwater level, some part of the flow may enter the groundwater system with the rest returning to the surface.

Figure 4 illustrates the process of water flow through the mining induced fracture network in the area affected by valley closure.

Water flowing in the mining induced fracture network follows a hydraulic gradient that is controlled by the hydraulic resistance of the fracture network. Depending on the thalweg of the watercourse (the longitudinal profile of the rock bottom) and the overall hydraulic gradient, the water level may rise above the surface at some locations within the zone affected by valley closure, so that some pools appear to hold water, while others dry up.

A characteristic of an enclosed fracture network such as the main upsidence zone is that the resistance to flow is strongly dependent on flow rate once the flow goes above a critical level. At low flow rates, flow can occur through the fracture network without much resistance. However, once the fracture network reaches its capacity, the hydraulic head required to drive additional flow through the fracture network increases significantly.

The effect of the increased resistance is to raise the water level within the fracture network. This phenomenon causes the surface flow to return when the flow in the river channel increases, for instance after rain or through controlled discharge from storage.

5. Opportunities for Control

Opportunities to control the effects of mining induced fracturing fall into three main categories:

1. Avoidance of longwall mining within the areas where intolerable valley closure effects would develop as a result of mining.

2. Reduction of the impacts on the river channel of the valley closure movements.

3. Control of the hydraulic gradient so that surface flow is maintained.

5.1. Mining Layouts

Empirical models for estimating valley closure have been developed and are being refined as understanding of the mechanics of valley closure improves (Kay et al 2007). It is currently possible to estimate, with a reasonable degree of conservatism, the level of disturbance that any given longwall layout might have on specific river channels.

Using these models, mining layouts can be designed to control subsidence impacts on specific river systems in the context of local flows and site conditions. However, while it is possible for longwall mining layouts to be designed to avoid major river systems, it becomes impractical and uneconomic for mining layouts to avoid all small to medium sized water courses.

The cost to the underground coal industry and to the community generally of avoiding all areas where valley closure effects may develop is considerable and unsustainable.

5.2. Impact Reduction

The horizontal compression movements that occur as a result of valley closure are the primary cause of mining induced impacts on river channels. If horizontal movements can be absorbed without causing rock fracturing the impacts of mining on river channels can be reduced.

Open slots are considered to provide the most effective means of reducing valley closure impacts. Slots can be designed to absorb valley closure movements so that disturbance to the near-surface rock strata is eliminated, but there needs to be a balance between the effectiveness of the slot and the practicality and impact of creating the slot itself.

Slots are likely to be most useful when the appearance of the surface rock formations is required to be preserved in specific locations but, if suitably designed, they can limit the development of the near-surface fractures, as well as prevent the development of low angle shear fractures in the main upsidence zone.

However, except in specific circumstances, the significant disturbance to the surface from the construction of slots tends to limit their widespread use. Mills et al (2004) describe the use of a slot to substantially protect Marhnyes Hole rockbar on the Georges River from the effects of valley closure.

Systems using diamond wire cutting techniques or mechanical cutter bars have potential to be more effective and less invasive than the overlapping boreholes used at Marhnyes Hole.

5.3. Control of Hydraulic Gradient

Artificial control of the hydraulic gradient provides a means of controlling the impacts of valley closure on river channels, in effect re-creating the circumstances where water flows over the surface. There are several different ways that the hydraulic gradient can be controlled:

1. Artificially maintaining the river channel flow at a level that is equivalent to flow through the sub-surface fracture network so that the flow across the surface can occur.

2. Increasing the hydraulic resistance of the sub-surface fracture network to a level that restores natural flow in the river channel back to the surface.

3. Providing an artificial barrier that forces the hydraulic gradient to the surface or above at the location of the barrier.

The opportunity to artificially maintain flow in the river channel exists in some river channels located below reservoirs or controlled discharge points. Such artificial flow has proven to be effective in keeping a base level of flow in the river channel sufficient to maintain surface flow at times when natural flow would not have been able to do so.

A significant advantage of artificial flows is that the natural remediation appears to be greatly accelerated when there is water in the rock pools. Artificial flows are therefore a very useful measure even on a temporary basis while other more permanent remediation activity is being undertaken.

Continuous pumping of natural flow from downstream of the sub-surface fracture network to upstream would also be effective, but this approach would be energy intensive and involve the installation of pumping facilities and an overland pipeline. The flow volumes required to maintain surface flow are typically in the few megalitres per day range, but may be more or less depending on circumstances.

The second strategy involves increasing the hydraulic resistance of the sub-surface fracture network. This strategy is essentially aimed at accelerating the remediation process that would occur naturally over time. Ideally the entire sub-surface fracture network created by mining as well as the fracture network that existed prior to mining would be substantially filled along the full length of the river channel with material of a hydraulic conductivity equivalent to the intact rock strata.

In practice, however, it is not necessary to fill the entire fracture network before flow is restored to the surface; only the fracture network in those areas that control the hydraulic gradient of the river channel and therefore force water to flow over the surface. The areas that require to be filled differ depending on the relative elevations of the river channel and the groundwater system generally.

In a groundwater system where the groundwater level is below the river level, there is always some leakage of water from the river into the groundwater. Any increase in fracturing in the near-surface rock strata, therefore, has potential to increase water loss from the river into the groundwater. Any fracturing that occurs deeper in the main upsidence zone below the groundwater level is not so critical in terms of impact on the hydraulic gradient within the river channel.

In a gaining system, the hydraulic conductivity of the entire fracture network cross-section at specific locations such as rockbars controls the hydraulic gradient within the river channel. The fracture network in ponded sections of the river channel does not affect the hydraulic gradient of the river system at all. Therefore, in a gaining system, there is potential to greatly reduce the length of the fracture network that needs to be filled.

Thus the approach that is used to fill fractures depends on whether the river system is a losing or gaining system.

Brassington et al (2005) report the results of work undertaken by BHPB Illawarra Coal to restore surface flow in sections of the Georges River subject to mining induced valley closure effects. A combination of short term artificial flows and cementitious grouting of the near-surface fracture network along extended lengths of the river channel was used. The requirement for artificial flows is reported to have ceased as a result of the grouting work.

To fill the entire cross-sectional fracture network at a specific location such as a rockbar requires a range of different approaches because of the different types of fracturing that have been observed to occur. In the near-surface fracture network, some fractures may be open ended, so some level of cohesion may be required depending on the fracture geometries. Cosmetic repairs to the surface and fracture network can be undertaken in keeping with the natural character of the rock strata.

In the main upsidence zone, the fracture volume is typically large so a bulk material is likely to be most suitable to fill the fractures in this zone. Access to the main upsidence zone through the surface zone is necessary to place the large volumes of material that are typically required. Multiple boreholes and open slots are both effective.

In the deeper shear fractures, the fracture aperture is small so a fine-grained material is required, but because the weight of rock above the fracture is low, low injection pressures must be maintained in order to prevent fracture propagation through hydraulic fracturing.

In the lateral shear fractures, the fracture aperture is also small, but the depth of cover over the fracture increases away from the river channel so there is potential to apply greater injection pressures.

Some filling materials are suitable for use in more than one of the fracture systems, but a combination of several different materials may be more effective in particular circumstances.

The third strategy for controlling hydraulic gradient involves creating, or taking advantage of, an artificial barrier that forces flow to the surface at some point along the river channel. The fracturing associated with valley closure becomes inconsequential when it occurs below a ponded section of river channel, so this strategy is most effective when the river is relatively flat and a long section of the river channel is, or can be, ponded behind an artificial barrier. Wood (2002) reports sub-surface flows were reduced at a rockbar in the Cataract River by 80% using this approach.

A thin flexible impermeable barrier installed in a narrow slot across a rockbar would also have potential to be effective as a barrier to sub-surface flow. This barrier could be installed prior to mining and would be expected to remain effective throughout the mining process. Barriers formed on the surface such as weirs or dams would be most effective if they are located outside of the mining area so as to avoid underflow through the mining induced fracture network.

6. Conclusions

Subsidence associated with longwall mining is recognised to cause ground movements that generate horizontal compression at topographic low points; a process referred to as valley closure.

River channels in the Southern Coalfield of NSW are typically located directly on rock strata that has the potential to be impacted by valley closure.

Empirical techniques are available to provide a generally conservative estimate of the level of valley closure and therefore the likely extent of mining impacts.

The impacts of valley closure on specific rockbars are able to monitored using a combination of tools that allow the location, depth and nature of fracturing to be monitored.

The nature of the mining induced fracturing in river channels has been observed at several sites in the Southern Coalfield to fall into four broad categories: a near-surface fracture network (1-2m deep), a main upsidence zone (6-12m deep), a zone of initial bedding plane dilation (9-20m), and a basal shear zone that extends laterally from the main upsidence zone.

There are considered to be opportunities to control the effects of mining induced fracturing using a combination of different strategies depending on the characteristics of each site.

Site characterisation and monitoring of ground movements provide valuable insights for characterising individual sites and for developing effective strategies to control surface subsidence effects.

7. Acknowledgements

The support of the Australian coal industry for ACARP Research Project C12016 - Damage Criteria and Practical Solutions for Protecting Undermined River Channels is gratefully acknowledged especially the direct support provided to the project by BHP Billiton Illawarra Coal.

All views and comments expressed in this paper are those of the author and not necessarily those of ACARP or BHP Billiton Illawarra Coal.

8. References

Brassington G, Wood J, Walsh, R, Tyrell W, and Jamieson M. 2005 “Georges River Report – Assessment of Georges River Remediation – West Cliff Longwalls 5A1-4” BHP Billiton Illawarra Coal Annual Environmental Management Report for West Cliff Colliery to DPI (2007) dated 23 November 2005.

Kay D, Barbato J, & Mills K. 2007 “Review of mechanisms resulting in observed upsidence and closure movements”. These proceedings.

Mills K., Brassington G, Poole G, Walsh R, Wood J, Riley P & Fredericks L. 2004 “Mitigation of subsidence impacts at Marhnyes Hole rockbar” Proceedings of Mine Subsidence Technological Society 6th Triennial Conference on Subsidence Management Issues, 31 October-2 November 2004, Maitland, NSW, pp. 47-63.

Mills K. & Huuskes W. 2004 “The effects of mining subsidence on rockbars in the Waratah Rivulet at Metropolitan Colliery” Proceedings of Mine Subsidence Technological Society 6th Triennial Conference on Subsidence Management Issues, 31 October-2 November 2004, Maitland, NSW, pp. 47-63.

Waddington A, & Kay D. 2004 “Management Information Handbook on the Undermining of Cliffs, Gorges and River Systems”. ACARP Research Projects Nos. C8005 and C9067, February 2004.

Wood J. 2002 “Cataract River Report” BHP Billiton Illawarra Coal Report dated November 2002.