

# Surface Water-Groundwater Connectivity in a Longwall Mining Impacted Catchment in the Southern Coalfield, NSW, Australia

J. Jankowski<sup>1</sup>, A. Madden<sup>1,2</sup>, W. McLean<sup>2</sup>

<sup>1</sup>Sydney Catchment Authority, 311 High Street, Penrith NSW 2750, AUSTRALIA

<sup>2</sup>Hydrogeology Unit, Parsons Brinckerhoff, Ernst & Young Centre  
Level 27, 680 George St, Sydney NSW 2000, AUSTRALIA

E-mail: [jerzy.jankowski@sca.nsw.gov.au](mailto:jerzy.jankowski@sca.nsw.gov.au)

## Abstract

*Mining-induced subsidence under surface waterways enhances surface water-groundwater interaction due to the enlargement of existing, and development of new, fractures and fracture zones. Fracturing of streambeds and rockbars causes surface flow to be diverted to subsurface routes. The vertical distribution of fracture zones and horizontal distribution of bedding planes limit surface water-groundwater interaction. The interaction in a pristine environment is dominated by baseflow discharge to streams. In mining impacted catchments interaction is much more complex, as new fracture zones develop sequentially with mining progress, acting as conduits for surface water influx to the subsurface. Interaction is constantly modified as composite impacts of sequentially mined panels cause changes to the size, distribution, extension and connectivity of horizontal bedding planes and vertical fracture networks. Surface water-groundwater interaction in the Waratah Rivulet, a small creek in the Southern Coalfield of New South Wales (NSW), Australia has been assessed by analysing hydrological, hydrogeological and hydrochemical data. Hydrological data includes flow measurements up-stream and down-stream of the longwall panels; hydrogeological data comprises groundwater level measurements in bores along the rivulet and is compared to the recently surveyed streambed; and the hydrochemical assessment is based on the changes in surface water and shallow groundwater chemistry along the rivulet. Leakage of surface water to subsurface flow through fractured streambeds and rockbars causes a reduction in flow down-stream during low flow conditions. Tensional and compressional stresses change surface water-groundwater connectivity and cause different segments of the rivulet to be connected-gaining or connected-losing. Changes in the chemical composition of the surface water along the rivulet are attributed to recharge of the aquifer by surface water and later discharge of subsurface flow and mixing with surface water. Chemical elements such as major ions, trace elements and metals occurring in the rock matrix are mobilised in new fractures and bedding planes of freshly exposed rock, adding to the chemical composition of surface water.*

## 1. INTRODUCTION

Vertical subsidence and horizontal rock movements change flow and interconnectivity in hydraulic systems causing changes in surface flow, groundwater level, and enhancing surface water-groundwater interaction. Surface water-groundwater interaction increases during mining due to enhanced fracture porosity and permeability (Booth, 2003). This can alter hydraulic gradients close to the surface water-groundwater interface, cause leakage between hydrogeological units, and can result in aquifers changing from confined to unconfined (Booth, 2007). Mining-induced development of joints and fractures can occur by vertical displacement of a single fracture or multiple fractures, horizontal displacement of a single horizontal shear or complex shear, vertical slips, compression and tension related upsidence, and complex deformations on bedding planes. Detailed field observations and analysis of geology, fracture distribution, and subsidence data indicates that in the Southern Coalfield of NSW, bedding planes produce horizontal pathways for groundwater flow, and reactivated or newly developed fractures and joints are major pathways for the vertical movement of water (Jankowski, 2007a).

An increase in rock permeability and aquifer storativity occurs along the vertical profile of the subsidised area, with some variations due to local rock characteristics and initial distribution and opening of fractures and joints (Booth *et al.*, 1998). Changes in aquifer hydrology can alter and create preferential pathways for groundwater flow, diverting surface water to subsurface flow, rerouting surface water and groundwater flows, and modifying their interactions (Sidle *et al.*, 2000). A total loss of surface water can occur if the flow in a stream is below the volume that can flow through fractures

and cracks to the subsurface (Dawkins, 2003) and over long periods of time when low rainfall prevails. The ability of a stream to recover downstream of the mining-impacted area depends on the width of fractures, their length, the surface gradient, the substrate composition and the presence of organic material (TEC, 2007). Underground mining beneath drinking water catchments, such as the catchments south of Sydney, are rare, however the impact can be considerable and more investigations should be undertaken to better understand this problem (Loveday *et al.*, 1983; Singh & Jakeman, 2001; Krogh, 2007; TEC, 2007).

## 2. KNOWN EFFECTS OF MINING-INDUCED SUBSIDENCE

The Southern Coalfield of NSW experiences subsidence of up to 1.8 m and the incremental maximum upsidence of up to 0.5 m, expanding and extending vertically and horizontally causing a well-developed network of fractures, joints and bedding planes. During subsidence the strata undergoes fracturing, opening of joints, separation of bedding planes, reactivation of faults, and creation of new fractures. Horizontal displacements have been observed over relatively great distances from the edge of longwall panels (Hebblewhite *et al.*, 2000; Holla & Barclay, 2000), with horizontal movements of up to 25 mm observed 1.5 km from the edge of a longwall panel (Reid, 1998). In areas of high relief, horizontal movements are approximately 40% of the maximum vertical movement (Holla, 1997).

The direction of dominant joints in the near surface Hawkesbury Sandstone of the Southern Coalfield follows faults and fault regions which generally have a northwesterly strike (Hebblewhite *et al.*, 2000), whereas sub-parallel fractures and joints possibly control drainage on the Illawarra Escarpment (Lee, 2000). Fractures are often reactivated along old joints partially cemented by the precipitation of carbonates or by weathering products of aluminosilicates. Large cavities develop during the dissolution of silica and siderite and the reductive dissolution of iron-oxides/hydroxides, providing a flow pathway from the ground surface to vertically and horizontally orientated fractured zones and bedding planes.

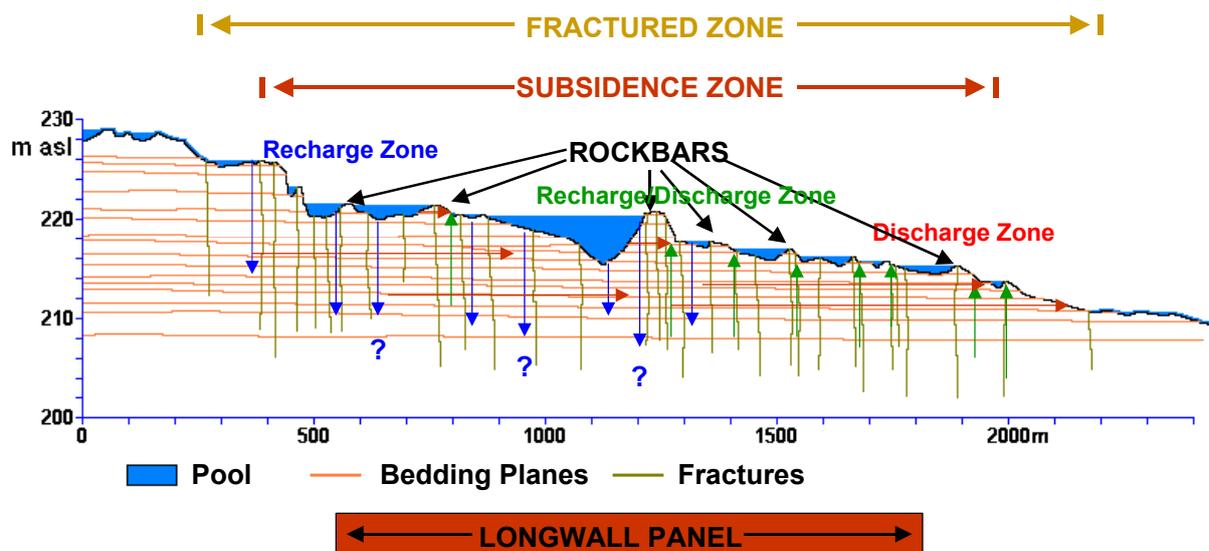
Changes to stream topography, morphology and drainage are closely related to mining-induced subsidence. Recharge and discharge zones are developed and/or reactivated due to subsidence-related enlargement of fractures, cavities, joints and bedding planes (Jankowski, 2007a), which are the main pathways for surface water to recharge an aquifer. Significant fracturing of streambeds and rockbars cause surface water to infiltrate subsurface flow and later discharge from the shallow groundwater system under artesian pressure, downstream of the mining impacted area (Jankowski, 2007a; Kay *et al.*, 2006). Fracturing of rockbars reduces pool water levels during low and no flow conditions, and during high flows when pools are full of water, significant leakage from the rockbars to the fractured subsurface can occur. After mining streams may recover, showing reduced high baseflow discharge and increased low baseflow discharge (Carver & Rauch, 1994).

In mining-induced subsidence areas with fractured and cracked streambeds above longwall panels, temporary or permanent surface water loss results. Permanent water loss can occur in areas where longwall mining produces a hydraulic connection between surface water and the mine, with a flow rate controlled by the hydraulic conductivity and storativity of the aquifer (Seedsman, 1996). Inflow to a mine typically occurs when there is an absence of a low permeability material (aquitard) that can limit or restrict inflow into mines, with inflow through a well-developed system of fractures, joints and voids. Temporary water loss occurs in areas where a longwall mine is separated from the ground surface by a low permeability seal that prevents inflow to the mine and to deeper aquifers (Booth, 2006; Dixon & Rauch, 1988; Forster, 1995). The Southern Coalfield mines are typically sealed by a low permeability material that underlies fractured sandstone aquifers, mostly preventing inflow of surface water to mines. However, the vertical downward movement of water from the ground surface to the base of the sandstone above the low permeability unit is possible as fractures, displacements, and deformations of the rock mass causes a relatively good hydraulic connection between different bedding planes and fractures. As a result of mining, there is generally an increase in fracture density and an increase in the vertical (Forster, 1995; Holla & Buizen, 1991; Holla & Barclay, 2000;) and horizontal permeability of the aquifer, over the total height of the overlying strata (Reid, 1996).

In the subsidence zone, declines in groundwater level is related to the maximum opening of fractures, joints and bedding planes during the tensional phase, causing a rapid increase in porosity and development of large open spaces draining groundwater downward to the new fracture void spaces.

Following, there is partial increase in groundwater level due to the partial re-closure of fractures, voids and joints during the compressional phase (Booth *et al.*, 2000; Booth, 2002).

A conceptual flow model (Jankowski, 2007a) of lateral and longitudinal surface water-groundwater interconnectivity in a mining-impacted stream flowing on fractured sandstone bedrock is shown in Figure 1. The connectivity creates an extended hyporheic zone in the fractured streambed, developed horizontally along bedding planes and vertically along fractures and joints. The flux of water to the subsurface occurs mainly along vertically outcropping fractures, joints, and veins that provide dominant pathways for surface water to infiltrate an aquifer. Flow can also occur along horizontal bedding planes. Depending on the opening, length, and position of fractures, the lateral and longitudinal extent of surface water-groundwater interaction can vary. Because some fractures and bedding planes are well connected and others are not, a complex flow pattern with flow in some part of the channel and a lack of flow in another part is created, particularly during low flows.



**Figure 1** Simplified conceptual model of surface water-groundwater interaction in a longwall mining impacted catchment.

Water quality studies of groundwater in coalfields around the world indicate that the high-extraction of coal through underground longwall mining affects the groundwater chemistry and quality of overlying aquifers (Booth, 2002; Booth & Bertsch, 1999; Booth *et al.*, 1998). Where subsurface cracks and new fracture networks allow surface water to infiltrate a shallow aquifer, exposed fresh rock reacts rapidly with flowing groundwater and chemical reactions are significantly enhanced during water-rock interactions. Deterioration of water quality occurs through elevated metal concentrations, increased salinity, and aesthetic changes to the stream through precipitation of red/orange/brown iron-oxides/hydroxides (Krogh, 2007). Chemical reactions increase the concentration of Ca, Na, Mg,  $\text{HCO}_3$ , Cl and  $\text{SO}_4$  in water discharging from subsurface routes to streams. The pH and  $\text{HCO}_3$  increase due to chemical reactions involving carbonate minerals calcite, siderite, rhodochrosite, strontianite and barite, which are the main carbonates in the Hawkesbury Sandstone aquifer matrix. The presence of metal carbonates allow iron, manganese, zinc, strontium and barium to mobilise, significantly increasing the concentration of these elements downstream, where subsurface flow re-emerges at the ground surface. The highest rates of chemical reactions occur during and after rainfall events, when acidic rainwater and surface run-off infiltrate the subsurface system and mobilise elements from carbonate minerals. Discharge of groundwater rich in iron and manganese to the stream causes the development of thick mats of iron/manganese-oxides/hydroxides together with large quantities of iron oxidising bacteria during laminar flow conditions at low stages. The bacteria grow thick mats of iron/manganese-oxides/hydroxides, which reduces the interstitial habitat, clogs the stream, reduces available food, and causes the development of toxicity through a decrease in oxygen content. Loss of native plants and animals may occur directly via iron toxicity, or indirectly via smothering when there are very high iron/manganese concentrations.

### 3. ENVIRONMENTAL SETTING

The Waratah Rivulet catchment is located approximately 45 km southwest of Sydney (Figure 2), in the southern part of the Sydney Basin. The elevation varies from around 380 m AHD in the headwaters to 170 m AHD where the rivulet enters Woronora Lake. The headwaters of the Waratah Rivulet are located in the Darkes Forest area and the rivulet flows in a northerly direction to the Woronora Dam, which is located within the Sydney Catchment Authority Woronora Special Area (WSA). The WSA is largely undeveloped, covered predominantly by native vegetation. The geology of this area comprises a gently deformed sequence of Triassic sandstone that forms the upper sequence of the Sydney Basin sediments. The surface geological unit exposed through much of the Waratah Rivulet catchment area is Hawkesbury Sandstone. The Hawkesbury Sandstone is also the major regional aquifer. This sandstone unit overlies other sandstones (Newport Formation, Bulgo and Scarborough Sandstones), claystones (Bald Hill and Stanwell Park Claystones) and shales (Wombarra Shale) of the Triassic Narrabeen Group. The total thickness of the Hawkesbury Sandstone exceeds 100 m, with the Narrabeen Group totalling more than 430 m in thickness and having an average total strata thickness above the mined area of around 460 m. The mining occurs in the upper coal seam unit of the Permian Illawarra Coal Measures known as the Bulli Seam, which has a thickness of 3.2 – 3.6 m across the catchment area, and which underlies the Narrabeen Group. The mining in the Waratah Rivulet catchment consists of longwall (LW) panels with a face width which has increased from 120 m for LW 1 to 158 m for LW 11-14. The length of the panels is around 1,550 m. Ground surface subsidence is up to 1.40 m above the mined longwall panels.

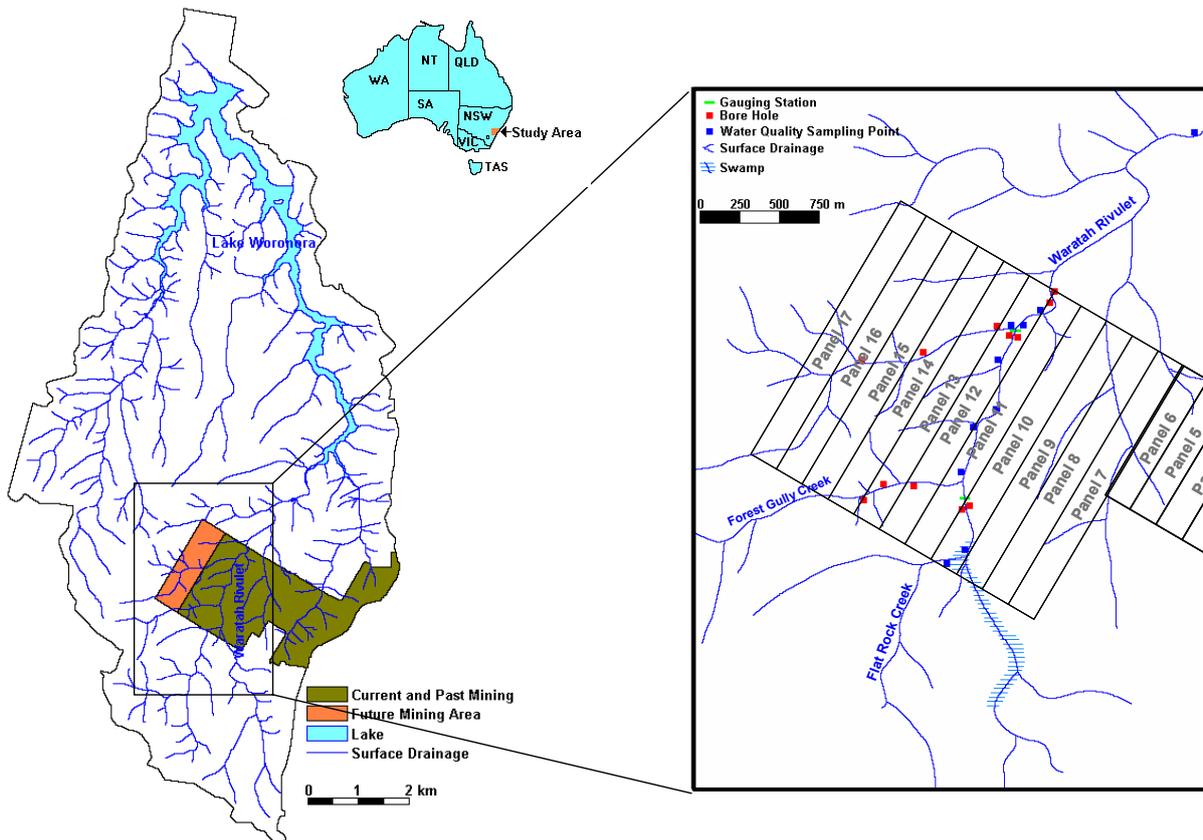


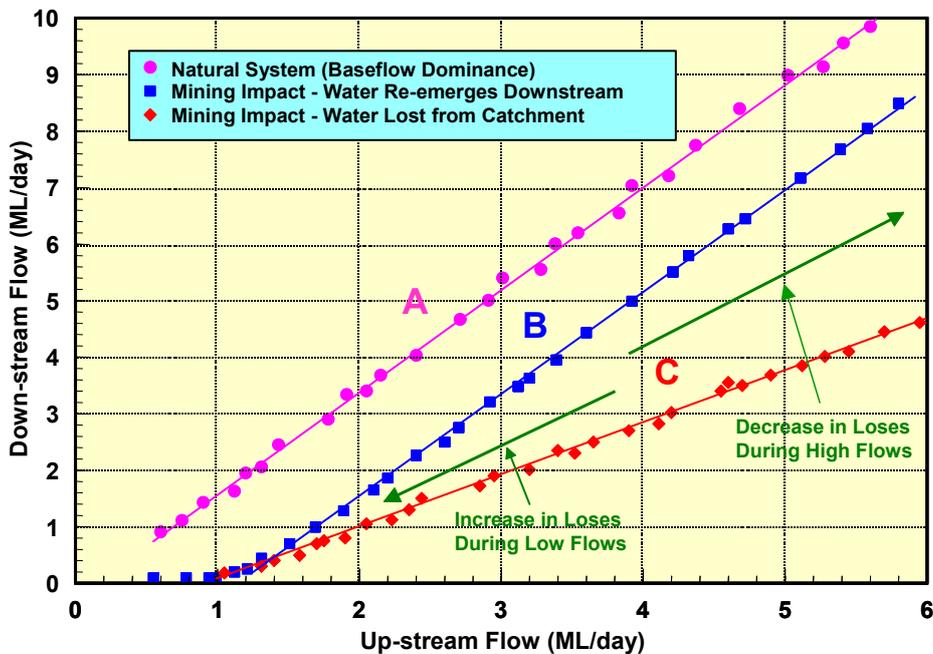
Figure 2 (A) Location of the Waratah Rivulet catchment and (B) location of sampling points and longwall panels.

### 4. RESULTS AND DISCUSSION

Analysis of flow data from the rivulet indicates that during high flows, the flow in a gauging station downstream of the longwall panels is greater than the flow in the upstream station. However, during low flows and in the majority of low-medium flows, flow in the downstream gauging station is lower

than the upstream gauging station. During periods of prolonged dry weather and low stages, when the surface flow volume equals or is less than the void storage capacity of the fractured aquifer, most of the surface water infiltrates the shallow aquifer. As a result, the surface flow will decrease and can cease altogether. There may be a partial loss of water in the rivulet when the downstream flow is lower than the upstream flow, or there may be complete loss when the downstream flow ceases, which has resulted in approximately 1,300 m of dry streambed. Some of the water lost to the underground flow reappears downstream and discharges from horizontally oriented bedding planes and vertical fractures intersecting the ground surface.

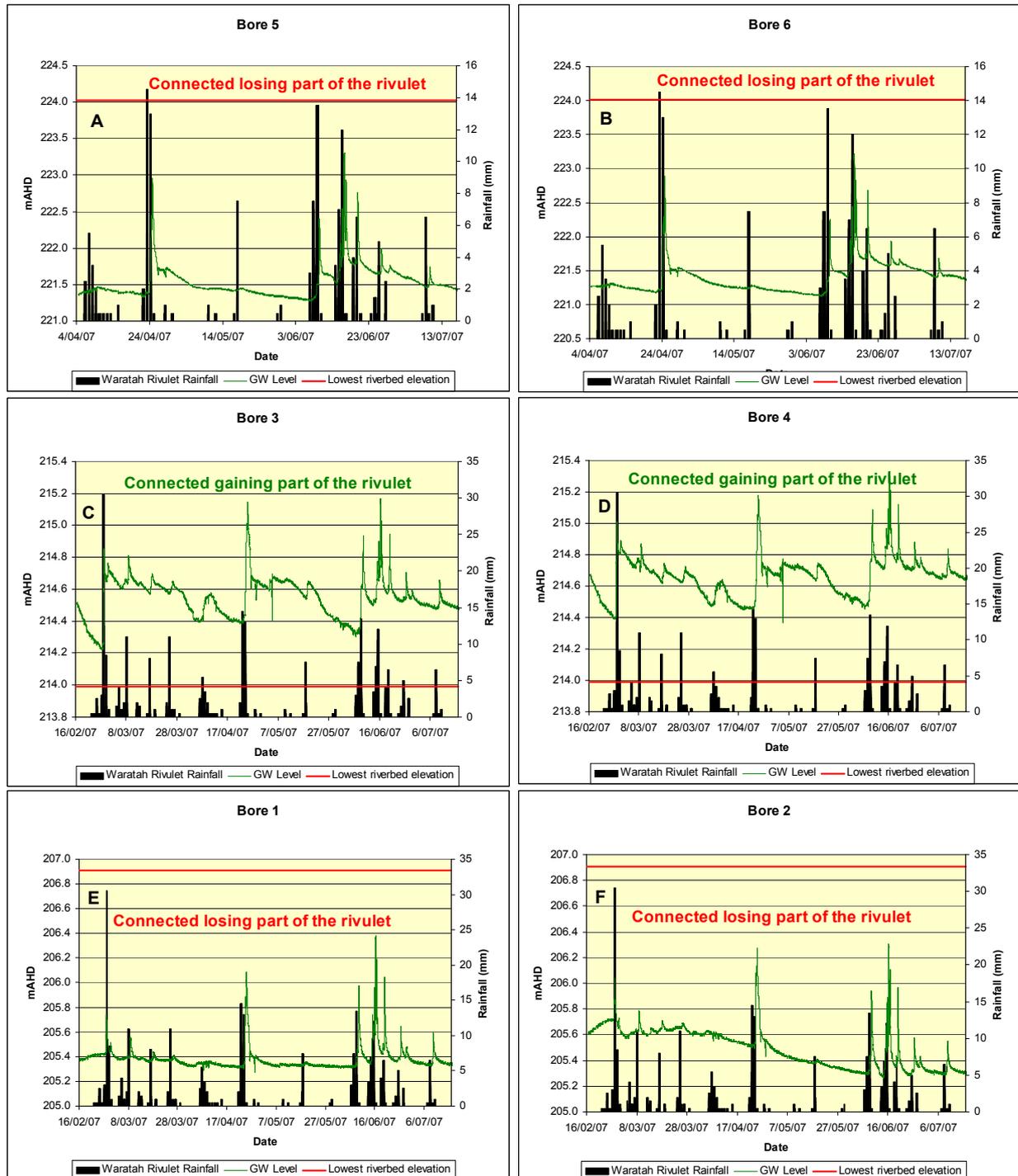
Flow data from the Waratah Rivulet indicates that due to subsidence, the subsurface sandstone fracture network has been modified and transmissivity and storativity have significantly increased. However, the shallow aquifer system is not capable of storing a large volume of water during high flow events. Thus during high flows, the flow volume increases along the rivulet and the flow in the downstream station is higher than in the upstream station, up to twice as high as the upstream flow during intense rainfall events (Jankowski & Spies, 2007). The volume of water that infiltrates the subsurface depends on the aperture of the new and existing fractures, and their vertical and horizontal extent, distribution and connectivity. The capacity of the groundwater system to contain surface flow is extremely variable in time and space and changes periodically during mining of subsequent longwall panels. The change with mining is due to the tensional and compressional phases of subsidence, modifying the horizontal and vertical extensions of fractures, joints, fracture zones and bedding planes, and the subsequent increase or decrease in connectivity between surface water and groundwater.



**Figure 3 Comparison of surface flow changes between a catchment in a natural environment and a catchment impacted by longwall mining; A – pristine catchment with baseflow dominance (Nattai River), B and C – longwall mining impacted catchment (Waratah Rivulet).**

Because the monitoring period is relatively short and the downstream gauging station is located in a slightly impacted area that was mined a few years ago, it is not possible to determine whether all water lost re-emerges downstream or whether some water is lost from the rivulet, joining the regional groundwater. If the fracture system has significant horizontal extension and intersects one or more bedding zones, it is feasible that some leakage could join the regional groundwater in a deeper part of the Hawkesbury Sandstone aquifer. Detailed information on the volume of water that recharges the aquifer and discharges downstream of the rivulet is presently unquantified, but appears to be substantial, particularly during low flows.

Based on the flow data (low flows) from a catchment not impacted by mining (Nattai River) and from the Waratah Rivulet catchment impacted by longwall mining, a comparison of surface flow changes has been made, as shown in Figure 3.



**Figure 4** Groundwater levels upstream (A, B), in impacted part (C, D) and downstream (E, F) of the longwall panels beneath the Waratah Rivulet (location of bores is shown in Figure 5).

Line A represents a non-mined situation, where flow increases downstream due to baseflow discharge and inflow from tributary streams. It is assumed that the hydrological system represents a connected gaining stream and flow does not recharge the aquifer. Line B represents a mining-impacted catchment, where water is lost upstream and re-emerges downstream. In this scenario, after a prolonged period of drought, lag-time occurs with no flow. During this time, surface flow developed upstream of the impacted area disappears to the subsurface, filling fractures in mining-induced fractured rock strata. Once the storage in the shallow aquifer, which is connected with the rivulet, reaches its capacity, surface flow commences. Even if flow increases downstream, water loss to the subsurface may still occur. The flow volume downstream can be compensated by inflow to the rivulet

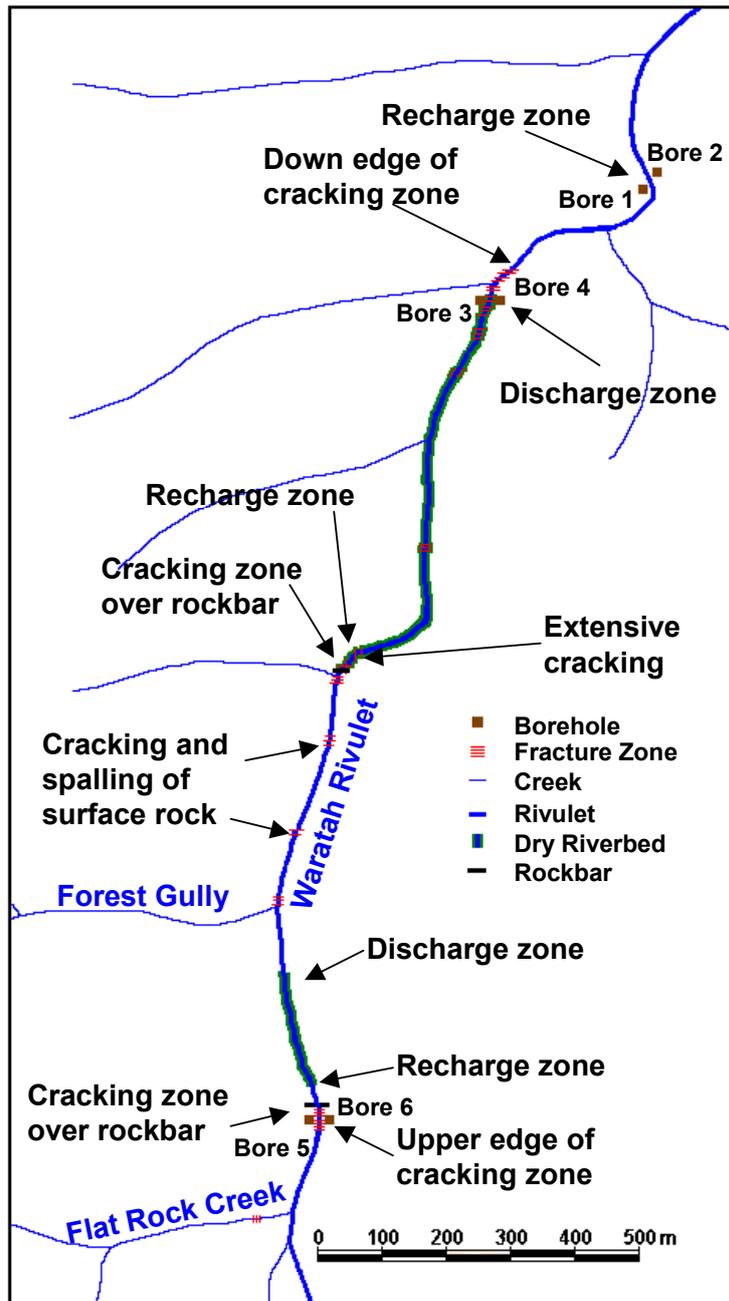
from tributary streams. Line C represents a mining-impacted catchment heavily recharging a fractured aquifer, where upstream flow is higher than downstream flow. In this scenario, three situations may occur: (1) flow can be lost for a long period of time to the subsurface with inflow into the mine; (2) flow can be lost temporarily, joining the regional groundwater flow system; or (3) flow may reappear further downstream. In the last situation, surface water loss downstream of the longwall panels increases during low and low-medium flow conditions, however during medium-high and high flow situations, surface water loss decreases.

Taking into consideration the rivulet channel morphology and groundwater levels at three locations representing upstream (A, B), in impacted part (C, D) and downstream (E, F) of the Waratah Rivulet catchment, current connectivity between surface water and groundwater has been depicted (Figure 4). Figure 4 A and B shows the connected losing part of the rivulet upstream of the current longwall mining, where groundwater is below the lowest streambed elevation across the channel between bores 5 and 6 (Figure 5). This area was mined between September 2003 and May 2004 and currently represents a nearly recovered part of the hydrological system. Fractures, joints and bedding planes still provide excellent pathways for subsurface flow, but openings are significantly smaller than they are above the active mining panel. Most of the time at this location, there is surface flow in the rivulet and surface flow recharges the subsurface system with relatively fast outflow, illustrating the high hydraulic conductivity of the aquifer. It is expected that the hydrological system is in partial recovery and lateral flow dominates recharge of the aquifer, whereas longitudinal flow dominates the subsurface flow. Figure 4 C and D represents the impacted part of the rivulet which is connected gaining, with the groundwater level above the lowest stream bed elevation across the channel between bores 3 and 4 (Figure 5). It is expected that this part is in the compressional phase of subsidence, where fractures have partially re-closed and there is limited vertical and horizontal extension of fractures and bedding planes. Compressional stress causes the groundwater level to partially recover and discharge through vertical fractures under artesian pressure. However, this area may also be undergoing some fracturing and incremental impact by subsequent longwall panels recently mined. Figure 4 E and F shows the downstream part of the rivulet. Groundwater is below the lowest streambed elevation across the channel between bores 1 and 2 (Figure 5). Mining has not occurred under this area, however it is close to the edge of a panel currently mined and is within the rib area covered by a 35° angle of draw, where subsidence still occurs. This part of the rivulet is connected losing, as subsidence developed significant openings with a high capacity to collect inflow of surface water.

Comparison of the groundwater level response to rainfall indicates the system is dynamic and groundwater levels in the shallow Hawkesbury Sandstone aquifer rise rapidly. The lag-time to the maximum groundwater level rise after a rainfall event is less than 24 hours. After a period of dry weather conditions, the response of the system is faster during intense short rainfall events than during moderate-long events. During wet weather conditions, the response of the system is similar for intense-short and moderate-long rainfall events, as less void spaces in fractures and joints are open to be filled by surface water.

Jankowski (2007b) and Jankowski & Spies (2007) reviewed the impact of subsidence on water quality and chemical composition of surface water and groundwater from the Waratah Rivulet. Surface water downstream of the mining-impacted area contains a much higher electrical conductivity (EC), pH and concentration of major, minor and trace elements, and significantly lower redox potential (Eh) values and content of dissolved oxygen.

Further assessment of chemical data shows that concentrations of major, minor and trace elements are higher in groundwater than in surface water (Figure 6). Also higher concentrations are present when fracture networks are well developed. The EC of groundwater in the impacted area varies between 400 and 700  $\mu\text{S}/\text{cm}$ , and the pH of groundwater varies from acidic where metal-sulfur minerals are abundant, to slightly alkaline where carbonate minerals are more abundant in the rock mass. Ca, Na,  $\text{HCO}_3$  and Cl are the dominant ions in the groundwater system. The higher concentrations are related to well developed fracture networks and exposure of more rock strata to water-rock interaction, which causes the dissolution of carbonates, reductive dissolution of oxides and hydroxides, and oxidation of metal-sulfur minerals. These processes mobilise Ca,  $\text{HCO}_3$ , Fe, Mn, Ba, Sr and S ( $\text{SO}_4$ ) from the rock mass.



**Figure 5** Location of bores, recharge and discharge zones, and main cracking zones along the Waratah Rivulet.

The chemical composition of surface water along the rivulet shows significant changes in water chemistry and quality (Figure 6). The water quality data from low flow conditions was used in Figure 6, as the data from high flows represents a mixture of rainfall, runoff, baseflow and stream water, which will mask the changes in baseflow water chemistry solely impacted by mining. Surface water flowing through the impacted area and downstream of longwall panels has a much higher EC, pH and concentration of major, minor and trace elements, and significantly lower Eh and dissolved oxygen content compared to surface water flowing in a pristine environment (upstream of longwall panels, tributary stream, pre-mining data) (Figure 6). The surface water chemistry in the rivulet shows significant changes in concentration over the 2 km length of the sampled channel. The salinity of surface water upstream of the subsidence area is low, with EC values ranging between 200 and 280  $\mu\text{S}/\text{cm}$  (Figure 6 A). The salinity increases along the rivulet as more water re-emerges from the subsurface, with concentrations between 260 and 340  $\mu\text{S}/\text{cm}$ .

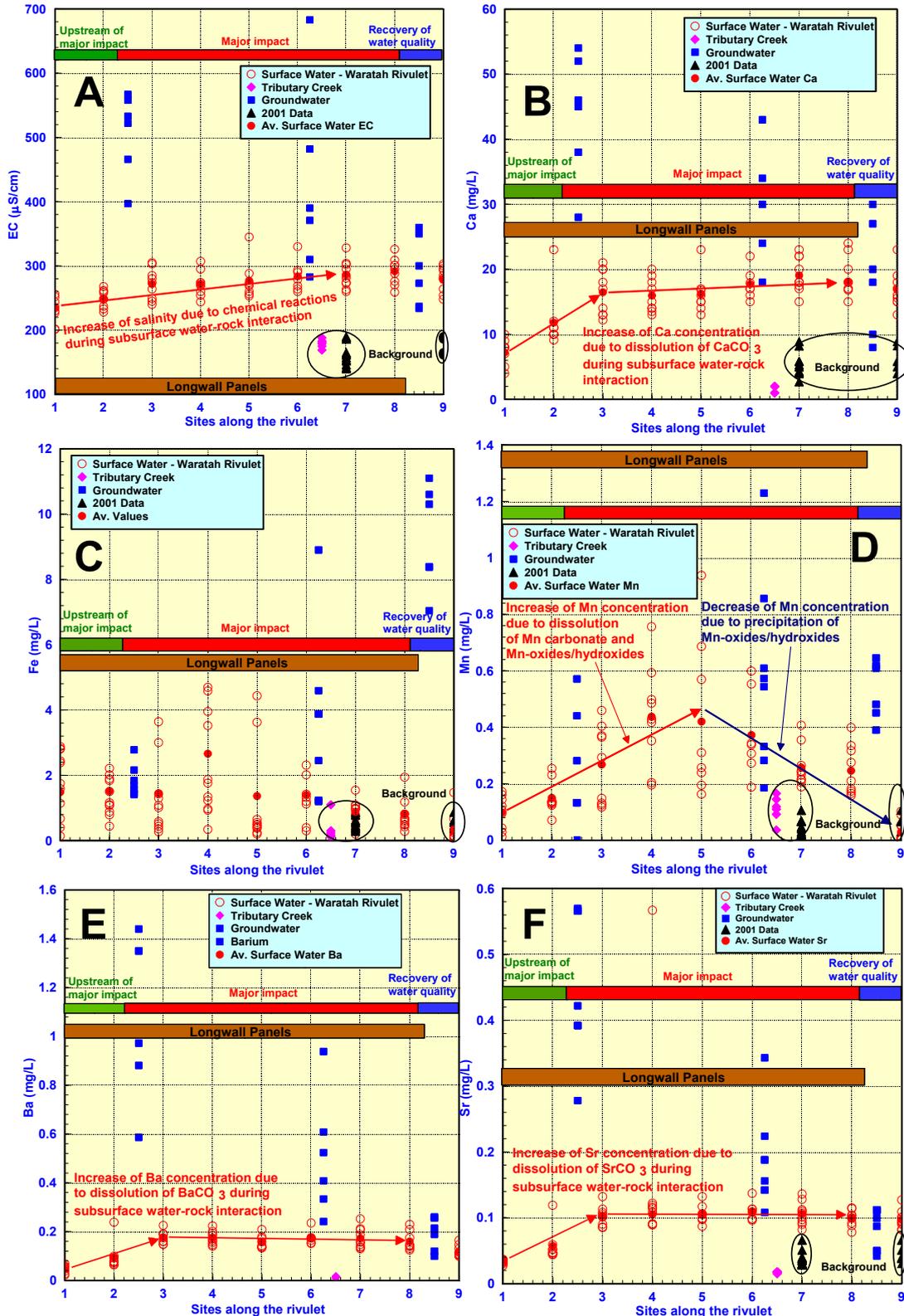


Figure 6 Variation of EC (A), Ca (B), Fe (C), Mn (D), Ba (E) and Sr (F) along the Waratah Rivulet.

The pH upstream is slightly acidic, with a range of 6.5 to 7.1, increasing to pH 7.7 where subsurface water dominates surface flow. The chemical composition of surface water changes from Na-Ca-Cl- $\text{HCO}_3$  type upstream to Ca-Na- $\text{HCO}_3$ -Cl type downstream of the mining area, indicating high rates of dissolution reactions of soluble minerals during water-rock interaction (Figure 6 B). Elevated concentrations of Fe and Mn in surface water flowing through areas not impacted by mining are

caused by baseflow discharge. Dominant minor elements in surface water that are mobilised during subsurface flow in the mining impacted area are Fe, Mn, Sr and Ba.

The increase in salinity, ion and metal concentrations are related to subsidence-induced fracturing below and around the streambed, which increases the exposure of fresh rock to inflowing surface water. Where subsurface cracks and new fracture networks allow surface water to mix with flowing groundwater, the resulting mixture may enhance chemical reactions between water and rock. Deterioration of water quality occurs through elevated concentration of metals and increased salinity, and aesthetic changes of the stream through precipitation of red/brown iron-oxides and hydroxides. The occurrence of metal precipitates and iron-oxidising bacteria is particularly evident where groundwater discharges through surface cracking to surface water.

Chemical reactions increase the concentration of Ca, Na, Mg,  $\text{HCO}_3$ , Cl and  $\text{SO}_4$  in water discharging from subsurface routes to the surface. The pH and  $\text{HCO}_3$  increase due to chemical reactions involving carbonate minerals calcite, siderite, rhodochrosite, strontianite and barite, which are the most abundant carbonates present in the Hawkesbury Sandstone aquifer matrix. The presence of metal carbonates in the rock mass causes iron, manganese, strontium and barium to be mobilised, significantly increasing the concentration of these elements downstream, where subsurface flow re-emerges at the ground surface. The highest rates of chemical reactions occur during and after rainfall events, when acidic rainwater with a pH of 3 to 6 and surface run-off infiltrate the subsurface system and mobilise metals from carbonate minerals.

Concentrations of iron and manganese initially rise in surface flow as groundwater discharges from the subsurface. However, a few hundred metres downstream dissolved metal concentrations decrease as Fe and Mn oxides and hydroxides are precipitated, causing yellowish through orange/red to brownish stains on the streambed (Figure 6 C and D). The discharge of groundwater rich in iron and manganese to the rivulet causes the development of thick mats of iron/manganese-oxides/hydroxides together with large quantities of iron oxidising bacteria during laminar flow conditions at low stages. Barium and strontium remain in solution and act as natural tracers that can be used to locate discharge points where groundwater re-emerges to the rivulet (Figure 6 E and F). Both elements are present only in the rock matrix, unless they are mobilised during subsurface flow. Oxidation of traces of pyrite ( $\text{FeS}_2$ ) during subsurface flow increases the concentration of iron and sulfate. Calcium, magnesium and bicarbonate are supplied from the dissolution of traces of the carbonate minerals calcite and dolomite, and water is generally undersaturated with respect to these minerals.

Hydrogeochemical modelling has shown that carbonate minerals magnesite, strontianite and siderite are strongly undersaturated. These minerals are dissolved from the rock mass and the addition of Mg, Sr, Fe and  $\text{HCO}_3$  into the aquatic system occurs, significantly increasing the concentration of these elements in groundwater and surface water. Only  $\text{CaCO}_3$  was slightly supersaturated in a few surface water samples that originates from high-pH water transported through subsurface routes. Carbonate minerals of trace metals such as smithsonite (Zn), rhodochrosite (Mn) and witherite (Ba) are also undersaturated, keeping these metals in solution as long as oxidation does not remove them from the aquatic system. All iron oxide/hydroxide-minerals are strongly supersaturated, including magnetite, hematite, maghemite, goethite, lepidocrocite, ferrihydrite and magnesioferrite, which quickly remove iron from the aquatic system. During rainfall events, acidic rain water and surface run-off with pH values ranging from 3 to 6 re-mobilises iron and manganese oxides and hydroxides, eroding them from the streambed and dissolving them from floating mats and returning these metals again to the aquatic system to cause further pollution downstream. During high water stages when turbulent flow prevails, iron mats are washed from pools and meanders where they have been immobile during low flow conditions, resulting in further contamination as they are dissolved in acidic conditions.

## 5. CONCLUSIONS

Conclusions from this study can be summarised as follow:

- Longwall mining-induced subsidence enhances surface water-groundwater interaction laterally and longitudinally;
- Vertical and horizontal extension and enlargement of fractures and bedding planes cause a more intensified surface water-groundwater interaction deeper in the aquifer system than would occur under pre-mining conditions;

- Several conceptual scenarios of surface water-groundwater interaction are possible depending on the groundwater level near the stream and the number of fractures and bedding planes present across the stream;
- The Waratah Rivulet system is both connected-gaining and connected-loosing over various segments of the rivulet, although the system could have been entirely connected-gaining before mining (URS, 2007);
- Chemical data indicates that deterioration of water quality in the mining impacted area occurs soon after subsidence, when surface water is re-routed into the subsurface;
- There are higher concentrations of metals and major ions, and increased salinity in mining-impacted surface water and groundwater;
- Iron and manganese are mobilised from the rock mass during and after rainfall events, as fresh runoff enters the subsurface environment and dissolve and/or oxidises metal carbonates, oxides and hydroxides;
- Discharging subsurface flow rich in iron and manganese is rapidly oxidised by atmospheric oxygen, removing metals from the surface aquatic system and precipitating as metal oxides/hydroxides, together with the development of thick mats in the rivulet;
- Precipitates of iron and manganese oxides/hydroxides, during wet weather conditions, are mobilised from the streambed when surface flow is dominated by acidic surface runoff;
- Barium and strontium appear to be excellent tracers in the system and can be used as indicators of the rates of chemical reactions as well as residence time in the subsurface. Their highest concentration is related to the maximum impact of mining-induced subsidence on water chemistry.

## 6. ACKNOWLEDGEMENTS

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