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Abstract A detailed study on the impact of longwall-mining induced subsidence in the Waratah Rivulet catchment, New South Wales, Australia has been carried out to assess changes in the hydrology and hydrochemistry of surface and subsurface waters. Comparison of hydrological data upstream and downstream of current longwall-mining activities has shown that a significant proportion of the surface flow during low flow conditions is diverted into subsurface routes. Surface water recharges the subsurface system and flows as groundwater in the heavily fractured aquifer over distances of hundreds of metres. This water re-appears at the ground surface where it discharges from fractures under artesian pressure. Changes in chemical composition of surface water along the rivulet are attributed to enhanced chemical reactions from water interacting with minerals exposed in fresh fractures in the subsurface. This water-rock interaction is characterised by accelerate hydrogeochemical reactions including dissolution of carbonates, reductive dissolution of oxides and hydroxides and oxidation of metal-sulfur minerals. Chemical processes mobilise Ca, HCO₃, Fe, Mn, Sr, Ba, Zn, Co and Ni from the rock mass into the aquatic system.

Keywords: Longwall mining, hydrology, hydrogeology, hydrochemistry

1. Introduction

Longwall mining, also known as the full extraction method, is the most common method of underground coal mining in Australia and in many other parts of the world. This method of coal mining is economic and efficient and provides reasonably reliable and predictable subsidence. Twenty-seven longwall mines are currently operating in Australia producing about 80 million tonnes of raw coal in 2005 (Kram, 2006). Longwall mining can however have a significant impact on surface hydrology, groundwater systems and water quality as a consequence of the subsidence with extensive fracturing and reactivation of existing joints along riverbeds and rockbars (Booth, 2003, 2006). In the vicinity of creeks and rivers, mine subsidence can reactivate existing fractures, joints, lineaments and faults, and cause new fractures and fracture zones. This impact is widespread in many catchments affected by longwall mining. The extent of mining-induced fracturing depends on factors such as depth of cover and proximity of the mining to a river, panel width and extracted thickness, topographic factors associated with the river valley such as valley depth and steepness, local, near-surface geological factors such as bedrock lithology, thickness and integrity of bed strata, orientation and dip of strata, degree of cross-bedding and existing jointing, and insitu horizontal stresses in the bedrock. The impact of subsidence on surface waterways is characterised by fracturing of riverbeds and rockbars, resulting in diversion of surface water to subsurface flow, creation of additional ponding and enhanced flooding, changes to stream alignment, increased interaction between surface water and groundwater and deterioration in water quality (Kay et al. 2006). Stream ponding associated with changes in flow rate and subsidence, and loss of water into subsurface routes are the most visible impacts on surface water (Peng et al. 1996; Kay et al. 2006). Surface flow can be lost either permanently or temporarily from longwall mining impacted waterways with the possibility of some water re-emerging downstream of mining related subsidence area (TEC, 2007).

A number of studies indicate that increase of fracture porosity and fracture permeability due to subsidence-induced fracturing lowers groundwater levels (Liu et al. 1997; Booth and Spande, 1992; Booth 1986). Groundwater flow systems are disrupted and the hydraulic gradient near a creek can be reversed, *Proceedings of the XXXV IAH Congress: Groundwater and Ecosystems, Lisbon, Portugal, 17-21 September* 1 2007, *Ribeiro, Chambel, Condesso de Melo (eds), Published by International Association of Hydrogeologists, ISBN 978-989-95297-3-1*

greatly increasing exchange of surface water and groundwater. Large and rapid decreases in head during the tensional phase of subsidence are compensated by a partial recovery during the compressional phase with a long-term trend towards pre-mining levels (Booth et al. 1999; Booth et al. 2000; Hill and Price 1983). Surface water-groundwater interaction develops a complex environment characterised by rapid changes in space and time particularly during mining of subsequent panels below the surface waterways.

Subsidence of up to 25 mm has been measured in the NSW Southern Coalfields at distances up to 1.5 km away from the edge of mining panels (Hebblewhite et al. 2000; Holla, 1997; Holla and Barclay, 2000). However, horizontal rock mass movements and displacements were observed at a distance up to 3 km away from the edge of longwall panels (ACARP, 2002, 2003; Holla and Barclay, 2000), and it is likely that the displacement are also associated with fracturing. The horizontal extent of these impacts depends on factors such as depth of mining, thickness of the coal seam, panel dimensions and environmental factors such as topography and geology of the area.

Water quality in the surface waterways upstream of areas impacted by subsidence is quite different to that in the impacted area, where surface water-groundwater interaction influences water chemistry. The fractured strata below the ground surface act as a conduit for surface flow into the subsurface and allow water to interact with newly exposed fresh rock in fractures. The changes in groundwater chemistry are much more pronounced in shallow aquifers above the mined area where changes to groundwater flow during the decline and recovery phases enhance chemical reactions resulting in deterioration of water quality and changes in water chemistry (Booth and Bertsch, 1999; Booth, 2002). The chemical reactions include dissolution of carbonate minerals, reductive dissolution of metal oxides/hydroxides and oxidation of metal-sulfur minerals, which mobilise cations, anions and metals from rock strata. Water discharging from subsurface routes is rich in metal content and causes rapid changes in water quality downstream. Metals such as iron and manganese are oxidised by atmospheric oxygen and precipitate as metaloxides/hydroxides in surface waters and promote blooms of oxidising bacteria during laminar flow conditions at low water stages. The grow of bacteria and precipitation of iron-manganese oxides/hydroxides produces thick bacterial mats which reduce the flux of oxygen into the aquatic system and impact adversely on the interstitial habitat, clogs the stream, reduces available food and causes development of toxicity through decreased oxygen content.

This paper presents preliminary hydrological and hydrochemical results from a small drinking water supply impacted by longwall mining catchment – Waratah Rivulet in the Southern Coalfields of New South Wales, Australia. Changes to surface flow and water quality upstream and downstream of mining-induced subsidence area are discussed.

2. Environmental setting

The Waratah Rivulet catchment is located approximately 45 km southwest from Sydney (Fig. 1). The elevation varies from around 360 m in the headwaters to 170 m at where the rivulet enters Woronora Lake. The catchment is located in the southern part of the Sydney Basin. 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 the Hawkesbury Sandstone. 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 and the Permian Illawarra Coal Measures. The total thickness of the Hawkesbury Sandstone is exceeding 100m with the Narrabeen Group having more than 430 m thickness. The mining occurs in the upper coal seam unit of the Illawarra Coal Measures known as the Bulli Seam, which has a thickness of 3.2 - 3.6 m across the catchment area.

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Fig. 1. Location of the Waratah Rivulet catchment.



Fig. 2. Sampling points and location of longwall panels.

The main surface waterway in the catchment is the Waratah Rivulet which flows north and discharges into the Woronora Lake, one of the Sydney's water supply system storages (Fig. 2). The longwall panels are located directly underneath the catchment on the southwest – northeast direction, 450 - 500 m below the ground surface (Fig. 2). Fourteen of the seventeen longwall panels have been mined as at the date of this paper, with a further three planned.

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Waratah Rivulet has been severely affected by longwall mining-induced subsidence as evidenced by extensive fracturing of riverbeds, cracking of rockbars, ponding, loss of surface water into subsurface routes, leakage of rockbars and decline in water quality. Monitoring of flow and water quality started in 2001 and a much more comprehensive and detailed water quality monitoring program was put in place in 2005.

3. Methodology

Flow data has been obtained from two gauging stations located upstream (above the edge of panel 10 mined between September 2003 and May 2004) and downstream (above the edge of panel 12 mined between April 2005 and December 2005) of the impacted area. The area around the downstream gauging station has been further impacted by subsequent panels – 13 and 14 mined between January 2005 and May 2007 (Fig. 2).

Surface water sampling locations for water chemistry determination were set-up along the rivulet and are representative of areas upstream of the present mining, impacted part of the rivulet and downstream of mining. A reference point located in a tributary creek represents pristine water quality. Groundwater samples were collected from recently drilled boreholes along the rivulet and along two main tributary creeks. These locations are set-up to cover pristine and impacted areas for groundwater chemistry (Fig. 2). General parameters and unstable elements were measured in the field, and major, minor and trace elements and metals were analysed in laboratory on acidified and filtered samples where required.

4. Results and discussion

Monitoring data of surface flow include two gauging stations FLOW1 and FLOW2 located in the Waratah Rivulet. Flow was monitored over 5 years, between 2002 and 2006. The flow data from both stations is shown in Figure 3.



Fig. 3. Daily flow rates in upstream and downstream gauging stations.

In pristine catchment conditions, downstream flow is higher than upstream flow due to discharge of baseflow. In contrast, in the mining-impacted areas cracking of the riverbed provides excellent hydraulic

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connectivity with subsurface due to enlarged existing and developed new fractures and fracture zones. This connectivity, together with a drop of groundwater level in the subsidence zone, causes surface water to divert flow into subsurface routes to fill open fracture and void spaces. Analysis of flow data from the rivulet indicate that during high flows, the flow in station downstream of longwall panels is larger than flow in the upstream station. However, during low and medium flows, flow in the downstream station is lower than to the upstream station. Prolonged periods of dry weather causes the surface flow to disappear from the channel when flow matches the storage capacity of the aquifer. The loss of water in the rivulet can be partial, during the time when downstream flow is lower than upstream flow, or complete when downstream flow ceases, resulting in approximately 1300 m of dry riverbed channel. Analysis of the flow data indicates that the downstream flow can be up to 100% higher than upstream flow during rainfall events, however, loss of surface flow downstream is much more pronounced with decreases in volume of up to 1600% (Fig. 4). This is an equivalent to approximately 400 L/sec loss between upstream and downstream stations during periods of low flows (Fig. 5). The flow volume in the downstream gauging station was lower than in upstream station during 29% of the monitoring time.



Fig. 4. Percentage flow differences between upstream and downstream gauging stations.

Detailed analysis of the flow data from the Waratah Rivulet indicates that the subsurface fracture network in the sandstones that has been modified due to subsidence has limited transmissivity and storativity This system is not capable of storing a large volume of water during high flow events. Thus during high flows, flow volume increase along the rivulet and the flow in the downstream station is higher than upstream. During low stages, when most of surface inflow would be re-directed into subsurface routes, the baseflow discharge is reduced or disappears due to a reverse of hydraulic gradient along the rivulet. The volume of water lost depends on the aperture of the new and existing fractures, and their vertical and horizontal extent and distribution. The capacity of the groundwater system to contain the surface flow is extremely variable and changes periodically during mining of subsequent longwall panels due to changes in fractures and fracture zones and subsequent connectivity of surface water and groundwater. The storage of the subsurface system is sufficient to contain water during low flows causing surface flow to disappear.

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Inflow into the subsurface occurs at many different places along the rivulet where fracture zones crosses the channel. Some of the water lost into the underground flow reappears downstream and discharges from horizontally-oriented fractures intersecting the ground surface. Because the monitoring period is relatively short and downstream gauging station is located in a slightly impacted area it is not possible to determine whether all lost water re-emerges downstream or whether there is permanent water loss from the catchment. If the fracture system has significant horizontal extension and intersects one or more bedding zones it is feasible that some water could join regional groundwater flow and water can be lost to a neighboring catchment. Alternatively, water could discharge several kilometers northeast on the cliff escarpment to the east where springs are known to occur. Detailed information on the volume of water that recharges the aquifer and discharges downstream to the rivulet is presently unquantified but is appeared to be substantial particularly, during low flows.



Fig. 5. Flow differences between upstream and downstream gauging stations.

Chemical data shows that concentration of major, minor elements and metals is much higher in groundwater than in surface water (Figs. 6-8). Also higher concentrations are present when fracture networks are well developed. Electrical conductivity (EC) of groundwater in impacted area varies between 400 - 700 μ S/cm, pH varies from acidic where metal-sulfur minerals are abundant to slightly alkaline where carbonate minerals are more abundant in the rock mass. Ca, Na, HCO₃ 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 dissolution of carbonates, reductive dissolution of oxides and hydroxides and oxidation of metal-sulfur minerals. These processes mobilises Ca, HCO₃, Fe, Mn, Ba, Sr and S (SO₄) from the rock mass.

Comparison of chemical composition of surface water along the rivulet shows significant changes in water chemistry and quality (Figs. 6-8). Surface water flowing through the impacted area and downstream of longwall panels have much higher EC, pH and content of major, minor and trace elements, and significantly lower Eh and dissolved oxygen content compared to surface water flowing in pristine environment (upstream of longwall panels, tributary creek, pre-mining data) (Figs. 6-8). The surface water chemistry in the rivulet shows significant changes in content and concentration over the 2 km length of the

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channel sampled. The salinity of surface water upstream of the subsidence area is low with EC values ranging between 200 and 280 μ S/cm. The salinity increases along the rivulet as more water re-emerges from subsurface and concentrations are between 260-340 μ S/cm. The pH upstream is slightly acidic with ranges of 6.5-7.1 increasing to pH 7.7 where subsurface water dominates surface flow. The chemical composition of surface water changes from Na-Ca-Cl-HCO₃ type upstream to Ca-Na-HCO₃-Cl type downstream of the mining area showing high rates of chemical reactions during water-rock interaction. 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.



Fig. 7 Variation of Fe and Mn along the rivulet.

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The increase in salinity, ion and metal concentration is related to subsidence-induced fracturing below and around the creek bed channel 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 content of metals and increased salinity, and aesthetic changes of the river channel through precipitation of reddish/brownish iron-oxides and hydroxides. The occurrence of metal precipitates and iron-oxidising bacteria is particularly evident where groundwater discharges through surface water.

Chemical reactions increase the concentration of Ca, Na, Mg, HCO₃, Cl and SO₄ in water discharging from subsurface routes to the surface. The pH and HCO₃ increase due to chemical reactions involve carbonate minerals calcite, siderite, rhodochrosite, strontianite and barite, which are the most abundant carbonates in the aquifer matrix. The presence of metal carbonates in the rock mass causes iron, manganese, strontium and barium to be mobilised, significantly increasing 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 pH of 3 - 6 and surface run-off infiltrate into 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 meters downstream dissolved metal concentrations decrease as Fe and, Mn oxides and hydroxides are precipitated, causing yellowish through orange/red to brownish stains in the creek channel (Fig. 7). Discharge of groundwater rich in iron and manganese into the creek 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 the interstitial habitat, clogs the stream, reduces available food and causes development of toxicity through decrease of oxygen content. Loss of native plants and animals occurs directly through iron toxicity or indirectly via smothering.



Fig.8. Variation of Ba and Sr along the rivulet.

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 creek channel (Fig. 8). Both elements are present only in the rock matrix, unless they are mobilised during subsurface flow. Oxidation of traces of pyrite (FeS₂) during subsurface flow increases the concentration of iron and sulfate. Calcium, magnesium and bicarbonate are

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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 HCO_3 into the aquatic system occurs significantly increasing concentration of these elements in groundwater and surface water. Only CaCO₃ was found to be slightly supersaturated in a few surface water samples and originate 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 remobilises iron and manganese oxides and hydroxides, eroding them from rocks and creek channels and returning these metals again into 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.

The highest correlation coefficient between TDS and HCO_3 indicates that the main influence on the TDS (and EC) content is from the dissolution of carbonates; and the second highest is between Ca and Sr indicating high availability and mobilisation rates of these elements. High correlation between Ba and Sr indicates similar availability for mobilisation rates of these ions from the rock mass.

Conclusions

Mining-induced subsidence alters the hydrological system of surface water and groundwater and intensifies surface water and groundwater connectivity. Increased water-rock interaction on the newly exposed rock in fractures and fracture zones mobilises chemical elements from the rock mass. This in turn increases salinity of water, brings more metals into the surface waterways and results in deterioration of water quality. A full understanding of the impact on surface waterways and groundwater system is needed before any remediation options to reduce loss of water into subsurface routes and minimise impact on water quality are considered.

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