Underground coal mining and subsidence, channel fracturing and water pollution: a five-year investigation

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Key Points

- Underground coal mining triggered subsidence and severe fracturing of bedrock stream channels.
- Flow was lost in some fractured sections and was gained from upwelling groundwater in others.
- Subsidence fracturing was clearly linked to major changes in stream water quality.
- Salinity increased in fractured sections from c. 250 µS/cm (upstream) to 400 – 1800 µS/cm.
- Metal concentrations (iron, manganese, zinc, nickel, strontium, barium and lithium) in the fractured zone increased sharply.
- Zinc and nickel were often at concentrations hazardous to aquatic ecosystems.
- Very low dissolved oxygen was often associated with upwelling groundwater that emerged through stream channel fractures.
- Mosquitos were the most abundant macroinvertebrate at two subsidence-affected sites.
- Future rehabilitation of the fractured waterway channel will be very challenging.

Abstract

Subsidence from underground coal mining can be a problematic issue. Our study investigated a waterway that had been disturbed by a coal longwall that made multiple passes directly under it. The most obvious impact was loss of stream flow through sections of fractured bedrock channel. Water quality of the stream was monitored over a 5-year period, where the creek had flow. Ochre-coloured water appeared in some sections of the creek. Salinity increased by four times from <250 (upstream) to 1195 µS/cm in subsidence affected zones. The concentration of metals such as zinc and nickel increased by many times to levels in exceedance of the ANZECC water quality guidelines for aquatic ecosystems. The macroinvertebrate composition of sections of the creek was strongly impaired and mosquitos were abundant. One sampling site was conducted where upwelling groundwater entered the creek through recent subsidence fractures, and below that point the creek flowed continuously during the most recent six months of the study. Mean electrical conductivity increased due to that upwelling, rising 6.8 times from (230 µS/cm) at upstream/reference sites to 1806 µS/cm below the upwelling. Dissolved oxygen of the upwelling groundwater was extremely low (2.7 %) and was also acidic (5.8 pH).

Keywords

Channel fracturing, heavy metal pollution, salinity, flow modification, anoxia, macroinvertebrates

Introduction

Coal mining is well-known to contaminate ground and surface waters (Brake et al. 2001; Johnson 2003; Younger 2004). A poorly understood form of water pollution occasionally linked to coal mining is from subsidence triggered by underground coal mining activity. Longwall mining can cause surface subsidence due to removal of the coal seam (OEH, 2005; Krogh 2007). Changes to water chemistry have been associated with fresh rock fractures and chemical reactions involving anions, cations and metals (OEH, 2005; Jankowski 2007; Wright et al. 2015).

Degradation of waterways by longwall coal mining in Sydney's drinking water catchments has caused major concerns (OEH, 2005; Krogh 2007). Several waterways have been affected with cracking of bedrock sections of stream channels (OEH, 2005; Krogh 2007; Jankowski 2007). In places, the lost streamflow in fractured sections has flowed into near-surface aquifers and has re-emerged to the surface channel further downstream with higher Electrical Conductivity (EC) and elevated metal (including manganese, iron, barium and strontium) concentrations (Jankowski 2007).

One of the most detailed previous studies was by Jankowski (2007) who examined water quality in Waratah Rivulet, a catchment stream for the Woronora drinking water reservoir in southern Sydney. Along with increased EC levels, Jankowski (2007) also reported higher calcium and bicarbonate concentrations in the subsidence affected section of Woronora Rivulet. He also found higher concentrations of metals in the most damaged section of stream. They included manganese, iron, barium and strontium (Jankowski 2007).

Building on an earlier study on the same waterway (Redbank Creek) by Wright et al. (2015) this current study sought to determine what were the key water quality changes in a stream affected by channel fracturing caused by coal mine subsidence. This current study summarises results collected over a five-year period.

Methodology

Study sites

Samples were collected from Redbank Creek which is a small upland stream in the Hawkesbury-Nepean River catchment in the Picton area, on the south-western outskirts of the Sydney metropolitan area in south-eastern Australia (34° 11' S, 150° 35' E; Wright et al. 2015). The study area comprised of part bushland, peri-urban land and urban townships.

The Tahmoor Colliery has operated since 1979 (Tahmoor Coal 2014). It is an underground coal mine that extracts steel-making coal and was given approval to begin longwall mining in 1986 (Tahmoor Coal 2014). Tahmoor Coal provide detailed information on the multitude of environmental impacts associated with subsidence caused by their underground mining operations in a series of reports (Glencore Tahmoor Coal, 2018).

Five sampling sites were selected in the study (Figure 1) on Redbank Creek. The first three sites (RB1, RB2 and RB3) were initially sampled from June 2012 to December 2014 (Wright et al. 2015). Two more sites (RB4 and RB5) were added during the second phase of this study (November 2016 to October 2017). We were unable to collect more samples from RB2 and RB3 in the second phase (2016-7) as they were generally dry.

Site RB1 was sampled from 2012 to 2017 and was an upstream (urban) reference site within the township of Thirlmere, about 1 km upstream of the longwall mine and subsidence area (Figure 1). Three sites were located on Redbank Creek within a 770m section of creek that was affected by upwelling water associated with fracturing (RB2, RB3 and RB4). The site RB4 was located at the most recent subsidence fracturing in November 2016. The fracturing occurred progressively between 2011 and 2017. Site RB5 was located 1.4 km downstream of RB4. Site RB5 was located in the industrial outskirts of the Picton township.

**2.2 Water quality sampling**

Water sampling was conducted on multiple occasions over a 5-year period (June 2012 to October 2017). At each site, on each sampling occasion, physiochemical water quality attributes of pH, EC, Dissolved Oxygen saturation (DO) and water temperature were measured in-situ using a TPS AQUA-Cond-pH meter (for pH and EC) and a YSI ProODO meter (DO and water temperature). Grab samples were collected from the field, chilled and delivered to the laboratory for analysis (ALS, Smithfield, and Envirolab, Chatswood). All grab samples were analysed using methods endorsed by the National Associations of Testing Authorities (NATA) through their accredited laboratory methods for determination of total metals (aluminium, barium, lithium, strontium, zinc, nickel, aluminium, manganese, and iron).

Results

Water quality results show that subsidence-induced channel fracturing has caused a complex series of changes to Redbank Creek (Table 1; Figure 2). The salinity of Redbank Creek, from a background level of 230 µS/cm (RB1, upstream), before steadily increasing at the three sites within the fractured zones (406 - 1806 µS/cm) (Table 1). A further 1.4 km downstream of the lowest fracturing the mean salinity remained about six times higher than upstream (1530 µS/cm).

Figure 1. Photographs of Redbank Creek. a). Upstream of all fracturing (RB1); b). Top right. Dry section with extensive bedrock fracturing; c). Upwelling groundwater entering Redbank Creek through channel fractures; d). Site (RB5) 1.4 km below most downstream channel fractures.

a. **b.**

c. **d.**

DO levels in Redbank Creek displayed a very large variation, ranging from 0.1 to 111 % saturation (Table 1). All sampling sites had very low DO levels under low flow condition, always less than the ANZECC (2000) lower trigger value of 85% saturation. The lowest DO mean levels of 2.7% were recorded at RB4, the site where upwelling groundwater entered the stream through subsidence fractures (Figure 2). DO at this site was consistently depleted ranging from 0.1 to 4.6 % (Table 1). The pH of Redbank Creek varied from 5.07 to 7.85 (Table 1). The lowest mean pH was recorded at one of the fractured sites (RB3) where it was 5.97.

The concentration of metals in Redbank Creek was strongly modified in the subsidence fracture zones, and at the site 1.4 km downstream of all fracturing (RB5). The metal that had the largest increase was iron. It increased from a mean of 3933 µg/L (RB1, upstream) to 9700 µg/L and 52818 µg/L at RB3 and RB4, in the fractured zones (Figure 2). At the lowest site (RB5), 1.4 km below the fracturing, the mean iron concentration was considerable lower than the upstream site (1381 µg/L). The mean manganese concentration also increased in the fractured zone from 290 µg/L upstream to 4954 µg/L at RB3 (Table 1; Figure 2). Aluminium showed the opposite trend. The mean aluminium concentration was most elevated at the upstream site (RB1: 389 µg/L) and declined at all sites in the fractured zone (RB2: 191.4 µg/L; RB3: 99.2 µg/L; RB4: 9.54 µg/L).

Nickel and zinc concentrations in Redbank Creek were often at concentrations exceeding recommended toxicants for protection of aquatic species (ANZECC, 2000). The mean nickel concentration was <1 µg/L upstream of the fracturing. It increased at all sites in the fractured zone (RB2: 4.5 µg/L; RB3: 30.5 µg/L; RB4: 41.2 µg/L; Figure 2). The concentration of nickel was still more than 15 times higher than the upstream reference site, at the lowest site (RB5: 15.3 µg/L). The mean zinc concentration was 10.4 µg/L upstream of the fracturing. It increased at all sites in the fractured zone (RB2: 15.6 µg/L; RB3: 86.3 µg/L; RB4: 91.5 µg/L; Figure 2). The concentration of zinc was about 3 times higher than the upstream reference site, at the lowest site (RB5: 35.5 µg/L).

Barium and strontium concentrations in Redbank Creek were higher at sites in the fractured zone (Table 1; Figure 2). The mean concentration upstream of the fracturing were 26.9 µg/L. (Barium) and 53 µg/L (Strontium). Both metals had increased concentrations in the fractured zone. They were highest at RB4 (Barium 336.4µg/L; Strontium 115.5 µg/L). The concentration of barium was highest in Redbank Creek 1.4 km below the fracturing (RB5: 157 µg/L) which was more than 15 times higher than the upstream reference site, at the lowest site (RB5: 15.3 µg/L). The mean zinc concentration was 10.4 µg/L upstream of the fracturing. It increased at all sites in the fractured zone (RB2: 15.6 µg/L; RB3: 86.3 µg/L; RB4: 91.5 µg/L). The concentration of zinc was approximately 3 times higher than the upstream reference site, at the lowest site (RB5: 35.5 µg/L).

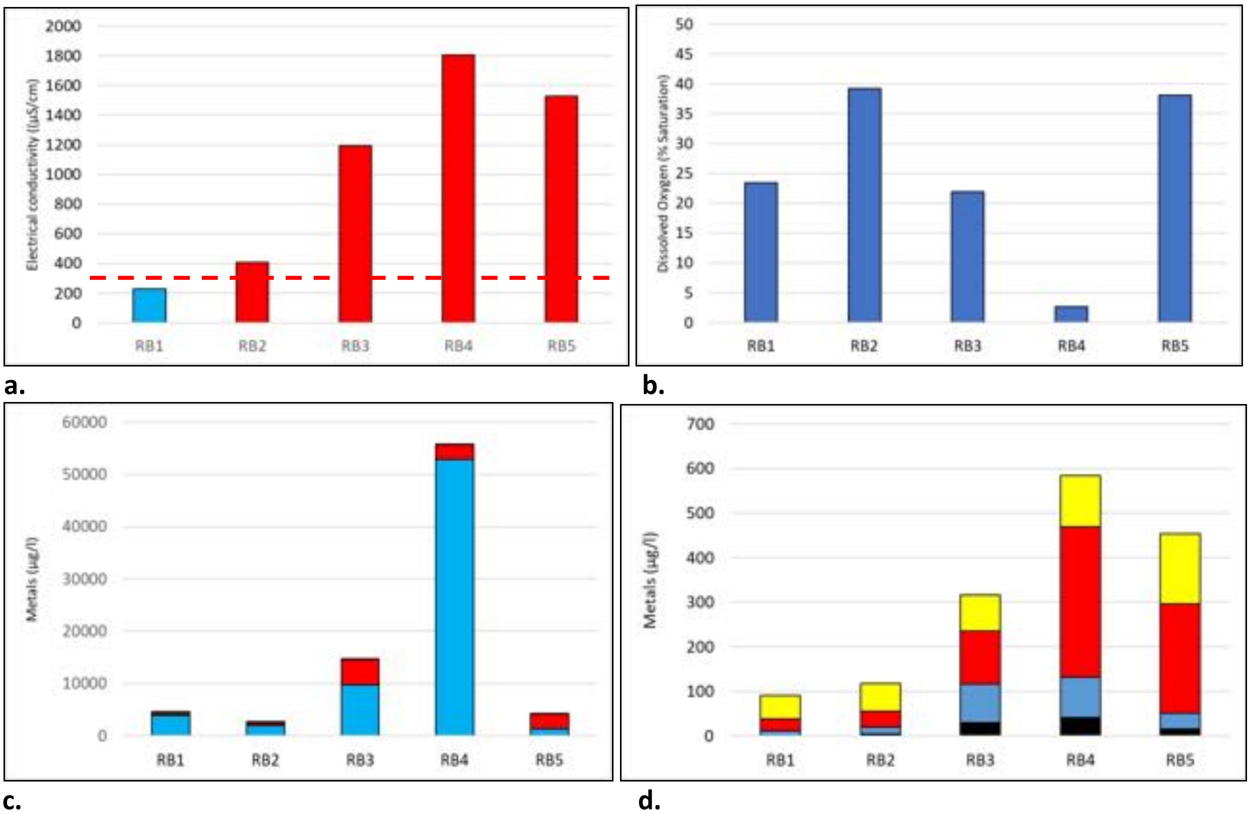
Lithium was only sampled at three sites (RB1, RB4 and RB5) in the latest round of sampling in 2016/7. It was always below laboratory detection limits at RB1 (upstream) and mean Lithium concentrations were 46.6 µg/L (RB4) and 37 µg/L (RB5).

Macroinvertebrates were also collected from three sites along Redbank Creek (RB1, RB2 and RB3) in 2014 (Wright et al. 2015). The proportion of the macroinvertebrates that were in the family Culicidae (Mosquitos) was calculated as a percentage. Mosquito larvae and pupae were very rare upstream (RB1: mean 0.64%) but they dominated the samples at the two sites in the fractured zone (RB2: mean 67% and RB3: mean 60.4 %). The lower sampling sites (RB4 and RB5) had flowing water and no mosquito larvae or pupae were observed (2016/7).

Table 1. Summary statistics (range, mean) of water quality results collected from five sites on Redbank from 2012-2017. Bd.=below detection. Ns.=not sampled.

	Upstream	Fracture Zone 1	Fracture Zone 2	Fracture Zone 3	Below Fracture
	RB1	RB2	RB3	RB4	RB5
Variables (units)	Range (Mean)	Range (Mean)	Range (Mean)	Range (Mean)	Range (Mean)
DO (% Saturation)	1.8 – 47.4 (23.4)	5.8 – 75 (39.2)	2 – 111 (21.9)	0.1 – 4.6 (2.7)	4.1 – 70 (38.1)
pH (pH units)	5.95-6.67 (6.37)	5.19 - 7.85 (6.63)	5.07-7.39 (5.07)	5.54 - 6.28 (5.80)	5.99-6.63 (6.37)
EC (µS/cm)	195 – 277 (230)	140 – 1013 (406)	156 - 2381 (1196)	1723 - 1921 (1806)	1099 - 1859 (1530)
Iron (µg/l)	1900 - 12000 (3933)	120 - 14800 (2013)	380 - 82000 (20163)	31000 - 70000 (52818)	1000 - 2200 (1381)
Manganese (µg/l)	78 – 870 (290)	2 – 2370 (424)	28 – 17000 (4954)	2700 – 2900 (2782)	1300 – 4900 (2818)
Aluminium (µg/l)	110 – 1500 (389)	40 – 540 (191.4)	5 – 440 (99.2)	5 – 20 (9.5)	30 – 70 (46.4)
Nickel (µg/l)	Bd. – 1.0 (0.63)	Bd. – 31 (4.5)	2 – 110 (30.5)	39 - 44 (41.2)	6 – 20 (15.3)
Zinc (µg/l)	5.0 – 14.0 (10.4)	Bd. – 77 (15.6)	13 – 300 (86.3)	82 – 100 (91.5)	11 - 56 (35.5)
Strontium (µg/l)	34 – 88 (53)	36 – 110 (62)	36 – 130 (81)	110 – 120 (115.5)	120 - 190 (157)
Barium (µg/l)	19 – 48 (26.9)	21 – 64 (35.7)	26 – 200 (118.7)	300 – 400 (336.4)	160 – 300 (246)
Lithium (µg/l)	Bd.	Ns.	Ns.	44-50 (46.6)	23 – 44 (37)

Figure 2. Summary of mean water physical and chemical properties from five sites on Redbank Creek (2012-2017). a). Top left. Electrical conductivity (µS/cm) with ANZECC guideline (red=exceedance and blue=compliant); b). Top right. Dissolved Oxygen (% saturation); c). Bottom left. Total metals (Iron=blue, Manganese=red, Aluminium=green); d). Bottom right. Total metals (Nickel=black, Zinc=blue, Barium=red, Strontium=yellow).



Discussion

This study found that stream channel fracturing from subsidence caused by the Tahmoor Colliery caused major changes to flow and water quality of Redbank Creek.

These results provide further evidence that underground coal mining can cause major disturbance and pollution to streams and rivers flowing on landscapes above the mines underground workings. This study found that the upwelling groundwater that entered Redbank Creek (RB4) caused the most substantial degradation to the water quality of the stream. This is directly associated with recent fracturing of the sandstone creek channel by an underground coal mine that used longwall mining practices. It is also likely that some of the contaminants relate to natural groundwater as well as to chemical processes triggered by the fracturing and interaction with groundwater.

There were numerous water quality changes in Redbank Creek which were hazardous for stream biota. Salinity increased from a mean level of 230 µS/cm (upstream/reference) to mean levels ranging from 400 to 1806 µS/cm, in the fractured zone. These levels range up to four times higher than the Australian water quality guidelines for ecosystem protection (ANZECC, 2000) which recommends <350 µS/cm for upland streams in south eastern Australia. Such levels of elevated salinity are associated with damage to aquatic plants and animals. Horrigan et al. (2005) reported that aquatic macroinvertebrate communities declined sharply at salinity levels above the 800 to 1000 µS/cm. The previous phase of this study at Redbank Creek (2012-4) detected mean EC as high as 1193 at RB3 (Wright et al. 2015). The magnitude of such a large increase in salinity, triggered by coal mine subsidence and channel fracturing, has not been reported by any published study before. One of the most detailed previous water quality studies was conducted on Waratah Rivulet by Jankowski (2007) who reported a comparatively modest increase in salinity from 200 – 280 µS/cm (upstream of mining) to 260-340 µS/cm, in the subsidence-fractured zone.

A novel finding in this study was such depleted dissolved oxygen of the upwelling water in the lower fracture zone in this study (RB4) was consistently very low (mean DO 2.7 % saturation) and was consistently lower than all other sampling sites. Such levels of DO are extremely hazardous to aquatic species, with Australian guidelines recommending 85-110% DO saturation (ANZECC, 2000). This differs from most studies on the impact of coal mines, which generally show that surface waterways affected by coal mining generally have minimal impact on dissolved oxygen. Similarly, the subsidence affected abandoned Majestic Mine in Ohio (USA) released mine drainage with very low dissolved oxygen levels, particularly in seasonal high flow conditions (Pigati & Lopez 1999).

The interaction of groundwater through longwall subsidence fractures increased the concentration of several metals in Redbank Creek surface waters. Of most ecological concern were the metals nickel and zinc. The mean zinc concentration increased from a mean of 10.4 µg/L (upstream/reference) to 91.5 µg/L at RB4. The nickel concentrations in Redbank increased from 0.9 µg/L (upstream/reference) to 41.2 µg/L at RB4. There is very little comparative data on changes in zinc and nickel concentrations linked to rock fracturing from mine subsidence.

The metals (iron and manganese) increased sharply at the subsidence-affected sites on Redbank Creek. They were highest at RB4, which had mean concentrations of 52.8 mg/l (iron) and 2.8 mg (manganese) compared to upstream/reference sites 3.9 mg/L (iron) and 0.29 mg/L (manganese). The Waratah Rivulet investigation by Jankowski (2007) reported considerable lower concentrations of iron (max. 12 mg/L) and manganese (about 1 mg/L) The earlier phase of research on Redbank previous detected a maximum mean iron concentration of 20.1 mg/L (Wright et al. 2015).

A group of trace metals (lithium, barium and strontium) also increased steeply in Redbank Creek. They had highest concentration in the upwelling of groundwater in the subsidence fracture zone (RB4). Comparative data was available from Jankowski (2007) who regarded barium and strontium as 'tracers' of groundwater re-emergence in his study of subsidence impacts on Waratah Rivulet. He detected barium at just over 200 µg/L in the subsidence impact zone. A larger increase in mean barium concentrations was found in the current study where it increased from 26.9 µg/L upstream/reference sites compared to 336.4 µg/L at the upwelling vent (RB 4). Strontium concentrations were very similar in this current study, compared to the Waratah Rivulet study (Jankowski, 2007). Lithium appeared to be a candidate for a tracer metal, for groundwater re-emergence, as it was undetected in reference/upstream samples, but was detected at all sites below the subsidence fracturing and creek re-emergence.

In terms of future management, this case study serves as a reminder of the long-term damage to stream channels, hydrology and water quality that can be triggered by subsidence from underground long-wall mining. Internationally our results appeared to have detected the most highly impaired water quality caused by coal mine subsidence. However, there is very little published literature available on this topic. The Tahmoor Colliery and its government regulators will address rehabilitation of the Redbank Creek channel fracturing in future (Glencore Tahmoor Coal, 2018). Previous attempts of such repair in the Sydney basin have had mixed results (OEH, 2005). We anticipate future research investigating the effectiveness of rehabilitation.

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References

ANZECC (Australian and New Zealand Environment and Conservation Council) and ARMCANZ (Agriculture and Resource Management Council of Australia and New Zealand). (2000). *Australian and New Zealand guidelines for fresh and marine waters. National Water Quality Management Strategy Paper No. 4.* Australian and New Zealand Environment and Conservation Council/ Agriculture and Resource Management Council of Australia and New Zealand, Canberra.

Brake, S.S., Connors, K.A., Romberger, S.B. (2001). *A river runs through it: impact of acid mine drainage on the geochemistry of West Little Sugar Creek pre- and post-reclamation at the Green Valley coal mine, Indiana, USA*. Environmental Geology, 40*,* 1471-1481.

Horrigan, N., Choy, S., Marshall, J., Recknagel, F. (2005). *Response of stream macroinvertebrates to changes in salinity and the development of a salinity index.* Marine and Freshwater Research 56(6), 825-833.

Jankowski, J. (2007). *Changes of water quality in a stream impacted by longwall mining subsidence* In: *Mine Subsidence 2007*: Proceedings of the Seventh Triennial Conference on Mine Subsidence, Sydney, N.S.W. Mine Subsidence Technological Society, 2007, 241-251.

Johnson, D. B. (2003). *Chemical and microbiological characteristics of mineral spoils and drainage waters at abandoned coal and metal mines.* Water, Air, and Soil Pollution 3*,* 47-66.

Krogh M. (2007). *Management of longwall coal mining impacts in Sydney's southern drinking water catchments*. Australian Journal of Environmental Management 14, 155-165.

OEH (2005) NSW Office of Environment and Heritage. Alteration of habitat following subsidence due to longwall mining - key threatening process listing. NSW Scientific Committee - final determination http://www.environment.nsw.gov.au/determinations/LongwallMiningKtp.htm

Pigati, E., López, D.L. (1999). Effect of subsidence on recharge at abandoned coal mines generating acidic drainage: The Majestic Mine, Athens County, Ohio. Mine Water and the Environment 18, 45-66.

Tahmoor Coal (2014). *Tahmoor Underground Management System & Framework Document*. Glencore. Tahmoor Coal, PO Box 100, Tahmoor, NSW.

Glencore Tahmoor Coal (2018) Annual Environmental Management Reports http://www.tahmoorcoal.com.au/en/publications/Pages/aemr.aspx

Wright, I.A., McCarthy, B., Belmer, N., Price P. (2015) *Subsidence from an underground coal mine and mine wastewater discharge causing water pollution and degradation of aquatic ecosystems*, Water, Air, and Soil Pollution, 226.

Younger, P. L. (2004). *Environmental impacts of coal mining and associated wastes: a geochemical perspective.* Geological Society, London, Special Publication 236, 169-209.