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The regulation and impact of eight Australian coal mine waste water discharges on downstream river water quality: a regional comparison of active versus closed mines

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Keywords
bicarbonate; closed mines; environmental regulation; pH; pollution; salinity; underground mining; zinc and nickel.

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Abstract

Water quality of rivers that received coal mine wastes from four active and three closed mines were investigated, focusing on ecologically hazardous pollutants. Zinc and nickel concentrations were highest downstream of two closed mines, particularly from the Canyon mine that closed 20 years earlier. Coal mine wastes increased nickel concentrations in waterways by an average of 25 times. The average concentration of zinc increased below mines waste discharges from 8.6 µg/L (upstream) to 83.4 µg/L (downstream). All coal mine discharges increased river salinity. Salinity increased by more than 6 times (upstream mean 101.4–741.7 µS/cm downstream). This study provides a reminder that water pollution from coal mines is a major environmental issue for both active and closed mines. The study highlights the need for more stringent and consistent environmental regulation for all mines, including key hazardous pollutants from wastes emerging from both active and closed mines.

Introduction

Water pollution arising from coal mining activities is a major source of water pollution worldwide (Tiwary, 2000; Younger, 2004). A broad range of water quality issues has been reported internationally from the release of coal mines wastes into waterways. Commonly reported water quality issues associated with coal mines include increased metal concentrations, elevated salinity and modified stream pH (Banks *et al.*, 1997; García-Criado *et al.*, 1999; Verb and Vis, 2000; Brake *et al.*, 2001; Younger, 2001; Pond *et al.*, 2008). A frequently reported impact of coal mine waste discharges into rivers and streams is the degradation of aquatic ecosystems (Jarvis and Younger, 1997; Pond *et al.*, 2008; Belmer *et al.*, 2014; Wright *et al.*, 2017).

A growing environmental water pollution legacy is the continued release of contaminated waste water from coal mines after they have ceased commercial operation (Robb and Robinson, 1995; Banks *et al.*, 1997). Pumping of accumulated groundwater from closed mines generally stops and, in many cases, this triggers a gradual flooding of its underground voids with groundwater (Younger, 1993). The accumulating groundwater is often contaminated with pollutants associated with oxidisation of sulphur and increased mobilisation of minerals and metals (Robb, 1994; Banks *et al.*, 1997). This process termed ‘rebounding’ can occur rapidly as reported by Wright *et al.* (2018) or become a slow protracted process taking up to a decade to become surface water (Jackson, 1981, as reported in Younger, 2001).

Many of the world’s coal mines have ceased mining with environmental problems such as water pollution often becoming a damaging ongoing legacy (Jarvis and Younger, 1997; Johnson, 2003). There is a rich literature on water pollution problems caused by the closure of coal mines in the United Kingdom (e.g. Robb, 1994; Robb and Robinson, 1995; Younger, 1993, 2001). There are also many publications on this topic from the United States, including a regional comparison of water pollution caused by active and inactive coal mines (Brake *et al.*, 2001; Pond *et al.*, 2008; Petty *et al.*, 2010). The environmental problems associated with the closure of coal mines is likely to be a large and growing problem in Australia. This may be a surprise considering the increased production of coal from Australian mines in recent decades (Mudd, 2009) with the export of coal being one of Australia’s highest value exports (Minerals Council of Australia, 2015).

Investigations have reported water pollution from wastes discharged from active Australian coal mines (Belmer *et al.*, 2014; Wright *et al.*, 2015, 2017). However, fewer studies have examined water pollution from

Australian coal mines that have ceased operation yet continue to cause water pollution (Battaglia *et al.*, 2005; Wright and Burgin, 2009; Wright *et al.*, 2018). One study compared water pollution from an active coal mine (West Cliff Colliery) to that from a closed mine (Canyon Colliery) and showed that waste water from both caused surface water pollution issues (Price and Wright, 2016). Several studies investigated contaminated seepage from the closed Canyon Colliery and the resulting polluting of a high-conservation stream and river within a National Park reserve in the Blue Mountains area (Wright and Burgin, 2009; Wright *et al.*, 2011; Price and Wright, 2016). Closed mines (coal and other mines) in Australia is a growing environmental problem with estimates of 52,543 abandoned mines with few receiving rehabilitation (Unger *et al.*, 2012). The Australian Government recognises the growing problem associated with closed mines and is particularly concerned about how to rehabilitate the growing number of closed and abandoned mines (Noetic, 2016).

Coal mine waste water discharges in New South Wales (NSW) are regulated by the NSW Environmental Protection Authority (NSW EPA). The EPA issues an individual 'Environmental Protection License' (EPL) agreement to each colliery under the *Protection of the Environment Operations* Act 1997 (POEO Act; EPA, 2018). Each EPL sets discharge limits for water quality (physical and chemical) properties (usually concentrations) and volumes of the liquid colliery wastes which must be achieved to authorise their discharge to local waterways (Graham and Wright, 2012). There is considerable variation in EPL conditions that apply to collieries across the Sydney Basin (Table 1). The licences include a few standard pollutants, such as 'oil & grease', 'pH' and 'total suspended solids (TSS)' across the EPLs for most mines. The identification of a specific EPL pollutant concentration limit implies that pollutant is recognised by the EPA as being potentially problematic in that mine waste or in the waste-receiving waterway. However, the absence of identifying a pollutant in an EPL does not mean that it is permitted by the EPA to be discharged. Each EPL has a clause that makes this explicit (EPA, 2018), they state:

> *To avoid any doubt, this condition does not authorise the pollution of waters by any pollutant other than those specified in the table\s*

There have been few water quality studies (none in Australia) comparing water quality impacts from a regional group of coal mines that discharge wastes from active and inactive mines. The key question posed for this investigation: does surface water quality change due to the discharge of coal mine waste water from a regional group of active compared to inactive coal mines? The second question was: how well do the EPA discharge licences ('EPLs') match with the ecologically hazardous pollutants in each mine discharge, or in the waste-receiving river/stream downstream of the mine discharge point?

Materials and methods

This study investigated the impact of coal mine waste discharges on water quality of waterways that received colliery wastes from seven underground coal mines in the Sydney Basin that released wastes from eight discharge points into eight different waterways (Table 1: Fig. 1). The Springvale and Angus Place mines discharged wastes into three tributaries of the Coxs River (Springvale Creek, Kangaroo Creek and Sawyers Swamp Creek; Table 1, Fig. 1). The mine wastewater discharges included effluent from actively operating coal mines as well as drainage emerging from closed underground mines. A large component of the mine discharges was from accumulated groundwater that had seeped into each of the underground mines. The geology of all mine locations shared many similarities as they all extracted coal from various seams within the Illawarra coal measures spanning the southern and western coalfields within the larger Sydney Basin (Branagan *et al.*, 1979).

The collieries and waterways in this study were in two broad groups (Fig. 1). The other three mines in the southern coalfields of the Sydney Basin, south-west of Sydney (numbered 1–3 in Fig. 1). They are the Berrima (also called Medway) Colliery which is 57 km from the coast. This closed mine discharges drainage into the Wingecarribee River (530 m ASL). The other two mines are the Tahmoor Colliery (247 m ASL) in the Bargo area 33 km from the coast, and West Cliff Colliery (227 m ASL) near Appin, 16 km from the coast (Fig. 1). The other group of mines (numbered 4–7 in Fig. 1) were in the western coalfields, north-west of the Sydney Metropolitan area. They were situated in the Lithgow / Bell area of the Blue Mountains. This group of mines are located about 100–120 km from the coast in mountainous landscapes at elevations ranging from 790 metres (ASL), Canyon Colliery, to 988 m (Clarence Colliery) (Table 1; Fig. 1). The other two mines in this group are the Angus Place and Springvale Collieries.

Water samples were collected from rivers or streams upstream of the point where the mine wastes entered. The upstream sampling sites are reference sites and were compared with the water quality results with those collected downstream of the mine waste discharge. The distance upstream ranged from 75 m (Dalpura Creek) to 3.28 km (Sawyers Swamp Creek). For one

Table 1 Study sampling site details

Name of waterway/Colliery	Description relative to waste discharge	Location coordinates	Elevation (m ASL)	Dates of sampling (month/year)	Number of sampling visits
Sampling sites used as reference site upstream (US) of coal mine discharges					
Wingecarribee River (US Berrima)	120 m US drainage adit	34° 29′ 15.97″ S, 150° 15′ 39.61″ E	535	8/2016–9/2017	8
Dalpura Creek (US Canyon)	75 m US drainage adit	33° 32′ 32.69″ S, 150° 18′ 25.97″ E	820	12/2016–5/2017	3
Coxs River (reference for Angus Place)	4850 m US Kangaroo Ck / Coxs River confluence	33° 18′ 19.07″ S, 150° 5′ 49.83″ E	965	9/2015–5/2017	6
Georges River (US West Cliff)	150 m US Brennans Creek (waste) discharge	34° 12′ 21.24″ S, 150° 47′ 57.45″ E	229	12/2016–3/2017	4
Bargo River (US Tahmoor)	1480 m US Teatree Hollow (waste) discharge	34° 14′ 11.78″ S, 150° 34′ 46.75″ E	255	12/2016–3/2017	4
Wollangambe River (US Clarence)	200 m US waste inflow	33° 27′ 22.35″ S, 150° 14′ 57.27″ E	992	12/2016–5/2017	5
Springvale Creek (US Springvale)	1050 m US waste discharge	33° 24′ 37.1″ S, 150° 6′ 38.24″ E	905	9/2015–5/2017	6
Sawyers Swamp (US Springvale and Angus Place)	3280 m US waste discharges	33° 18′ 19.07″ S, 150° 5′ 49.83″ E	995	9/2015–5/2017	6
Sampling sites downstream of coal mine discharges					
Wingecarribee River (DS Berrima)	140 m DS drainage adit	34° 29′ 16.16″ S, 150° 15′ 40.23″ E	530	8/2016–9/2017	8
Dalpura Creek (DS Canyon)	50 m DS drainage adit	33° 32′ 35.04″ S, 150° 18′ 25.38″ E	770	12/2016–5/2017	3
Kangaroo Creek (DS Angus Place)	75 m DS Angus Place Colliery	33° 20′ 58.45″ S, 150° 5′ 56.1″ E	905	9/2015–5/2017	6
Georges River (DS West Cliff)	90 m DS Brennans Creek (waste) inflow	34° 12′ 14.72″ S, 150° 47′ 53.08″ E	227	12/2016–3/2017	4
Bargo River (DS Tahmoor)	80 m DS Teatree Hollow (waste) inflow	34° 14′ 37.06″ S, 150° 35′ 20.66″ E	247	12/2016–3/2017	4
Wollangambe River (DS Clarence)	1250 m DS waste inflow	33° 27′ 21.38″ S, 150° 15′ 26.09″ E	979	12/2016–5/2017	5
Springvale Creek (DS Springvale)	810 m DS waste discharge	33° 24′ 6.8″ S, 150° 5′ 40.57″ E	880	9/2015–5/2017	6
Sawyers Swamp Creek (DS Springvale and Angus Place)	900 m DS waste discharge	33° 22′ 50.61″ S, 150° 5′ 10.95″ E	890	9/2015–5/2017	6

The waterway or colliery name, the description, location (latitude and longitude coordinates) and elevation of sampling sites (above sea level; m ASL). The description includes the distance (in metres) upstream (US) or downstream (DS) of the mine waste discharge point. The month and year of the first and last sampling are provided, as well as the number of sampling visits.

waterway and mine (Kangaroo Creek / Angus Place Colliery), we were unable to access a sampling site upstream of the mine. In that case, we used a nearby (4.3 km upstream) undisturbed waterway (Coxs River) of similar physical characteristics (Table 1). The distance of sampling sites downstream of the mine waste discharge ranged from 30 m (Dalpura Creek) to 1.25 km (Wollangambe River). At all sites, the distance downstream was considered adequate to represent complete mixing of the mine drainage with the stream or river

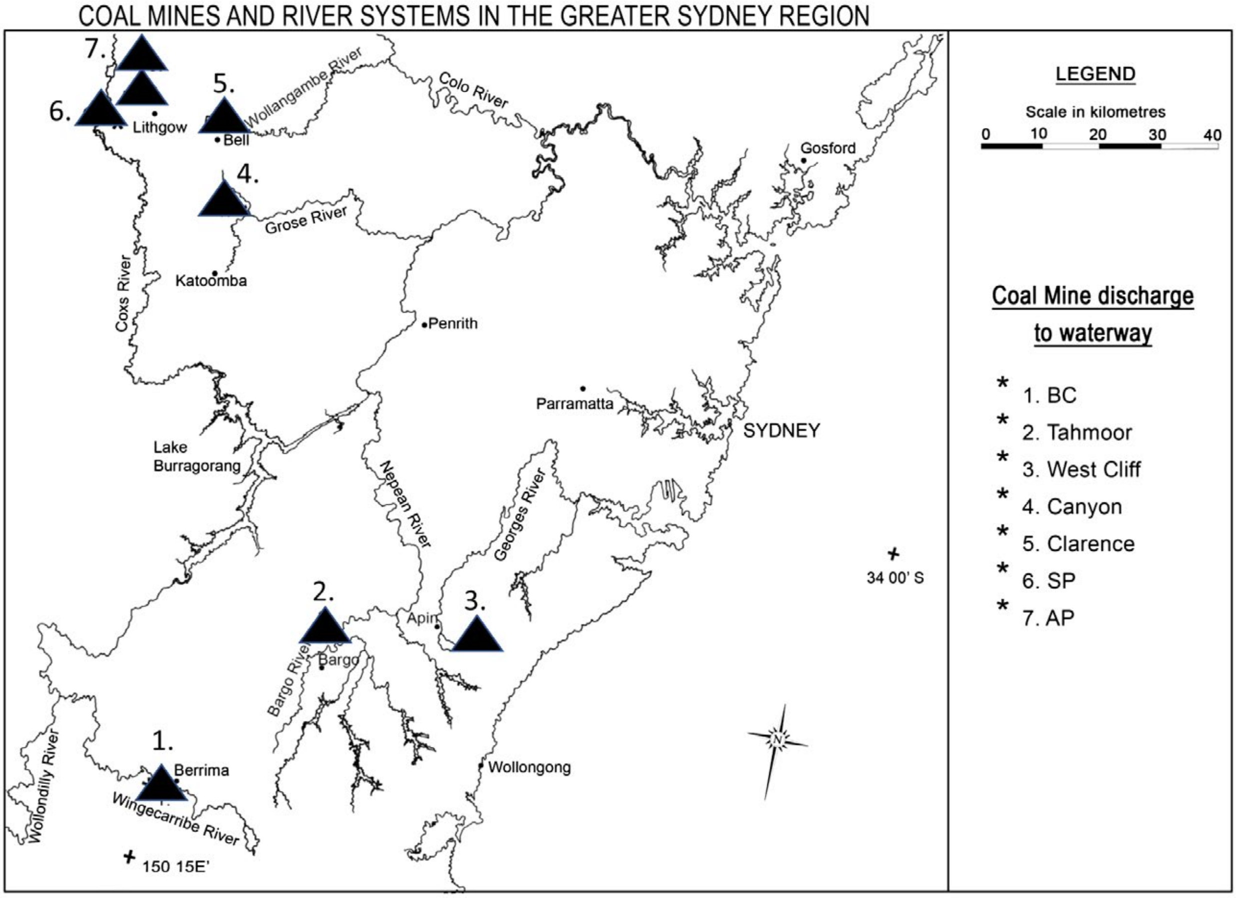

Fig. 1. Map of lower Sydney Basin, major waterways, settlements and location of the eight coal mine waste discharges (marked by black triangles). Seven mines are numbered (1 'BC' Berrima Colliery, 2. Tahmoor Colliery, 3. West Cliff Colliery, 4. Canyon Colliery, 5. Clarence Colliery, 6. 'Sp' Springvale Colliery, 7. 'AP' Angus Place Colliery). Springvale and Angus Place Colliery also discharge waste to Sawyers Swamp Creek (triangle between 6 and 7).

that was recipient of the wastes. This study allocated equal sampling effort to sampling the waterways receiving mine wastes upstream of (or at a reference waterway) the mine waste outfall to sampling downstream of the mine. In all cases, the sampling of a waterway upstream and downstream of the mine inflow was completed on the same day, under the same dry weather conditions.

Two adjoining mines (Angus Place and Springvale) each had two mine discharges included in this study. The waterway 'Sawyers Swamp Creek' received waste discharges from the two mines (Fig. 1).

Four of the coal mines in this study were actively mining coal and three were not. For this study, we termed 'closed' coal mine as a mine that was not engaged in coal mining during this study. The longest inactive mine closed in 1997 (Canyon Colliery). One closed mine (Angus Place) had not extracted coal for more than 2 years. It was in a state of 'care and maintenance' where the mine remained ventilated and groundwater in the mine was pumped out, with future mining activity still possible. The third closed mine was Berrima Colliery, that permanently ceased mining 2 years before this study, after which 15% of the underground workings were flooded (Wright *et al.*, 2018).

The mine waste that was released into waterways was untreated at two closed mines (Canyon, Berrima) where it emerged directly from a mine drainage adit. Mine wastes varied from mine to mine. It included mine drainage that resulted from seepage of groundwater into the underground mine workings. It also included coal washing wastes, and run-off from coal stockpiles and from the mine surface workings. The wastes from the other five mines were subject to onsite treatment. The mine waste treatment generally increased the pH and added flocculants to the wastewater to promote precipitation of dissolved metals. The treatment also used sedimentation and filtration to remove metal precipitants.

This study is based on water quality data collected from between 3 and 8 times, from September 2015 to May 2017 (Table 1). It includes data from a previous published study on the Berrima Colliery (Wright *et al.*, 2018). On each occasion at each site, duplicate water samples were collected, with a minimum of six individual samples collected from each sampling site. Three of the mines were sampled less intensively than other mines (Canyon mine, West Cliff mine and Tahmoor mine) but this was considered acceptable as they had previously been investigated, and the results collected in this study were compared and found to be consistent with previous published research (Wright *et al.*, 2015; Price and Wright, 2016; Wright and Ryan, 2016).

The coal mines in this study are regulated by the NSW Environment Protection Authority (EPA). The EPA regulate the disposal of mine wastes from each mine using an individual ‘environment protection licence’ (EPL) for each mine (Wright *et al.*, 2011). The permitted level of pollutants in the liquid wastes from each mine is specified in each EPL, generally as concentrations (µg/L or mg/L) for water quality (physical and chemical) attributes (Table 2). Table 2 summarises the individual EPL discharge limits (often as concentrations) for permitted pollutant levels in each colliery waste water.

Field meters were tested and calibrated, if required, on each sampling occasion to measure stream pH, salinity (measured as electrical conductivity ‘EC’) and water temperature from all study sites. The meters used were a TPS AQUA-Cond-pH meter and TPS WP-81 Conductivity, pH and Temperature meter with TPS Conductivity and Temperature probe and a TPS submersible k407 pH sensor.

The field meter probes were immersed in the main channel of the river or stream for several minutes to allow for the meter to equilibrate. Five replicate readings were collected from each site on each sampling occasion. After the field meter readings had been completed, water samples were collected from the same location. Duplicate grab samples were collected using unused bottles and were analysed using standard methods (e.g. USEPA, 1998) by Envirolab (Chatswood, NSW) a National Associations of Testing Authorities (NATA) accredited laboratory for eight metals (aluminium, copper, iron, lead, manganese, nickel, uranium and zinc) and for major anions (chloride, carbonate, sulphate and bicarbonate). The water samples were refrigerated and were conveyed to the laboratory for analysis. Analytical QA/QC procedures within the testing laboratory included the use of sample blanks and spiked samples to ensure the reliability of analytical procedures.

Student’s *t*-test was used to test for differences in water quality at reference sampling sites (upstream of mine waste discharge) compared to sampling sites downstream of mine waste inflows.

Results and discussion

The physiochemical properties of all waterways changed substantially because of the influence of coal mine waste water inflows from seven mines (Tables 3 and 4; Figs 2–4). Despite only four of the mines being actively mined during the study, all active and inactive mines continued to release coal mine drainage, or other mine wastes, that caused substantial modification of water quality downstream of their point of entry into one or more local waterways. Of the 15 water quality attributes examined in this study, 12 of them were significantly higher downstream, compared to upstream of the mine discharges (Tables 3 and 4).

The coal mine discharges increased the concentration of most metals, with zinc and nickel being of most concern as they were regularly found at hazardous levels for river and stream ecosystems. Nickel was frequently detected in waterways below mines at ecologically dangerous levels that were an average of 25 times higher than upstream (upstream mean 1.55 µg/L; downstream mean 41.4 µg/L; Table 4). Similarly, zinc concentrations also increased, rising by nearly 9 times (upstream mean 8.56 µg/L; downstream mean 83.4 µg/L). The downstream nickel and zinc concentrations were generally higher than the Australian guidelines for protection of 99% of freshwater species (nickel: 8 µg/L; zinc: 2.4 µg/L, ANZECC, 2000). The highest nickel and zinc concentrations in waterways receiving mine drainage in this study were detected in Dalpura Creek below the inflow of continuous mine drainage from the drainage adit from the closed Canyon Colliery (mean nickel:186.3 µg/L; mean zinc: 315.6 µg/L). This colliery ceased mining in 1997 and it continues to cause long-term pollution of high conservation value waterways within the Blue Mountains World Heritage Area (Wright *et al.*, 2011; Price and Wright, 2016).

International studies show that waterways receiving coal mine waste water often have highly elevated concentrations of nickel and zinc (Brake *et al.*, 2001; Pond *et al.*, 2008; Petty *et al.*, 2010). Similar to the current study, closed coal mines commonly produce mine drainage that is contaminated by elevated zinc and nickel for decades after mining ceases. For example, elevated levels of nickel and zinc were detected below the abandoned Green Valley coal mine (Indiana USA) more than 30 years after its closure, with nickel levels above 500 µg/L, and as high as 3780 µg/L and zinc often above 5000 µg/L (Brake *et al.*, 2001).

Although zinc and nickel were detected in waterways downstream of mine discharges at ecologically hazardous

Table 2 The NSW EPA Environment Protection Licence (EPL) pollutant limits for discharge of colliery wastes to streams/river (EPA, 2018)

Pollutant attribute (units of measurement)	Angus Place Colliery EPL 467 (*)	Berrima (Medway) Colliery EPL 608 (*)	Canyon Colliery EPL 558 (*) #	Clarence Colliery EPL 726 (*)	Springvale Colliery EPL 3607 Main (*)	Springvale Colliery EPL 3607 Minor (*)	Tahmoor Colliery EPL 1389 (*)	West Cliff Colliery EPL 2504 (**)
pH (pH units)	6.5–9.0	6.5–8.5	–	6.0–8.5	6.5–9.0	6.5–9.0	6.5–9.0	6.5–9.3 (*)
Oil and Grease (mg/L)	10	10	10	10	10	10	10	10 (*)
EC (µS/cm)	–	–	–	–	1200	–	2600	–
TSS (mg/L)	30	50	–	30	50	30	30	50 (*)
Turbidity (NTU)	–	–	–	–	50	–	150	–
Nitrogen (µg/L)	–	–	–	250	–	–	–	–
Aluminium (mg/L)	–	–	–	–	450 (d)	–	–	800 (d)
Arsenic (µg/L)	–	–	–	23 (d)	24 (d)	–	200	19 (d)
Boron (µg/L)	–	–	–	100	370	–	–	–
Cadmium (µg/L)	–	–	–	0.2 (d)	–	–	–	0.5 (d)
Chloride (mg/L)	–	–	–	25	–	–	–	–
Chromium (µg/L)	–	–	–	1 (d)	–	–	–	–
Cobalt (mg/L)	–	–	–	2.5 (d)	–	–	–	20 (d)
Copper (mg/L)	–	–	–	1.4 (d)	7 (d)	–	–	18 (d)
Iron (µg/L)	–	–	1000	300 (d)	400 (d)	–	–	–
Manganese (mg/L)	–	–	–	500 (d)	1700 (d)	–	–	40 (d)
Fluoride (µg/L)	–	–	–	1000	1800	–	–	–
Lead (µg/L)	–	–	–	3.4 (d)	–	–	–	6 (d)
Mercury (µg/L)	–	–	–	0.06 (d)	–	–	–	–
Nickel (µg/L)	–	–	–	11 (d)	47	–	200	200 (d)
Selenium (µg/L)	–	–	–	5	–	–	–	–
Silver (µg/L)	–	–	–	0.05	–	–	–	–
Sulfate (mg/L)	–	–	–	250	–	–	–	–
Zinc (µg/L)	–	–	5000	8	50 (d)	–	300	84 (d)

Each colliery has an individual EPL licence and with a unique licence number. The letter (d) after the EPL pollutant limit refer to the samples requiring filtering, and the pollutant concentration represents the dissolved (d) fraction. The EPL concentration limits apply for different proportions of times, expressed as percentiles: *100 percentile of the time; **90 percentile of the time. Two waterways receiving waste from Springvale Colliery were investigated, the 'main' discharge and 'minor' discharge. # Note EPL 558 has been surrendered.

concentrations (ANZECC, 2000), the NSW EPA regulation of these metals in the colliery discharges show a wide variation (Table 2). Two collieries (Angus Place and Berrima) currently have no limit on the permitted concentration of either nickel or zinc that can be discharged from each mine. Four of the seven EPA licences do specify a discharge limit for nickel concentrations in wastes. The specified concentration varies, ranging from a low of 11 µg/L (Clarence), then 47 µg/L (Springvale discharge to Sawyers Swamp) to the highest permitted concentration of 200 µg/L at both Tahmoor and West Cliff Collieries (Table 2; EPA, 2018). The highest concentrations of nickel, in this study, was detected in Dalpura Creek (ranging from 180 to 200 µg/L) below the closed Canyon mine, which did not have any EPA concentration limit for nickel. Zinc concentration limits were specified in six of the eight EPA licences with a range of discharge limits for zinc concentrations. Again, there were major differences in the permitted zinc concentrations ranging from a high of 5000 µg/L (Canyon), then 300 µg/L (Tahmoor), 84 µg/L (West Cliff), 50 µg/L (Springvale) and 8 µg/L (Clarence) (Table 2; EPA, 2018).

The salinity of waterways upstream of mines ranged from 10 to 357 µS/cm (mean 101.4 µS/cm; Table 3, Fig. 5). The salinity of waterways downstream ranged from 113.6 to 2093 µS/cm (mean 741.7 µS/cm), an increase of 631.5%

Table 3 Summary statistics (mean and range) for water chemical attributes and major anions (mg/L) collected from waterways upstream (US) and downstream (DS) active and closed coal mines

US all mines	pH (pH units)	EC (µS/cm)	Water Temp. (°C)	Chloride	Sulphate	Carbonate	Bicarbonate
Clarence	5.33	19.0	17.5	4.1	0.8	BD	BD
	5.18–5.52	17.3–21.7	15.1–19.1	4–5	BD–1	BD	BD
Canyon	4.72	26.1	12.7	4.8	1.8	BD	BD
	4.11–5.21	24.0–27.1	11.5–14.5	4–5	1–2	BD	BD
Sawyers	4.69	35.7	10.6	5.2	3.4	BD	4.2
	4.47–4.95	29.2–45.3	6.8–14.1	4–6	2–6	BD	BD–9
Springvale	5.30	53.6	11.6	8.0	5.2	BD	12.4
	4.12–6.48	38.3–84.8	9.3–19.0	5–12	4–9	BD	BD–21
Angus Place	5.13	42.8	12.5	4.3	0.5	BD	11.6
	4.31–6.07	19.5–88.3	8.6–19.8	3–6	BD–1	BD	BD–24
West Cliff	6.30	148.2	20.3	28.8	5.8	BD	18.0
	6.22–6.39	100–254	20–20.5	17–52	5–8	BD	9–35
Tahmoor	6.80	206.1	23.2	46.0	4.4	BD	12.6
	6.39–7.21	159–241	20.5–26.8	25–60	3–7	BD	11–15
Berrima	7.48	258.4	15.5	44.0	13.0	BD	60.8
	7.30–7.68	87.7–357	10.3–21.3	40–47	7–27	BD	47–69
All upstream sites							
Mean	5.74	101.4	14.02	15.2	4.12	BD	15
Range	4.11–7.69	10–357	6.8–26.8	3–60	BD–27	–	BD–69
DS active							
Clarence	7.35	289.5	19.6	3.8	104.0	BD	25.0
	7.24–7.46	286–293	18.3–21.0	3–5	88–110	BD	21–31
Sawyers	8.52	1162.4	20.8	5.9	26.9	51.2	597.7
	8.23–8.81	1113–1226	18.1–24.8	5–7	15–35	27–68	540–660
Springvale	7.99	840.2	12.9	13.4	85.2	8.7	374.0
	7.53–8.17	471–985	7.8–19.1	9–22	63–150	BD–23	110–540
West Cliff	8.92	1256.0	22.0	99.8	18.2	95.9	526.0
	8.50–9.17	368–2093	21.4–22.7	34–150	11–26	BD–160	170–830
Tahmoor	8.47	1011.3	21.8	57.2	9.0	52.0	488.3
	8.12–8.68	261–1498	20.2–23.0	28–72	8–10	BD–87	160–710
DS closed							
Canyon	5.95	129.0	15.9	3.8	26.0	BD	22.0
	5.58–6.22	113.6–149.8	15.8–16.0	3–4	26–26	BD	20–23
Angus Place	8.07	730.2	13.3	6.0	15.2	24.1	440.0
	7.61–8.51	344–994	9.5–20.0	4–8	9–33	BD–51	150–580
Berrima	7.25	397.6	15.1	45.4	74.7	BD	59.0
	6.98–7.49	258.4–539	10.4–20.4	41–50	19–110	BD	47–64
All downstream sites							
Mean	7.85	741.7	16.5	22.7	46.9	28.4	342
Range	5.58–9.17	113.6–2093	7.8–24.8	3–150	8–150	BD–160	20–830
Mean % increase							
(US vs. DS)	36.8	631.5	17.7	50	1037.6	–	2176.5
t-statistic; df	22.6; 361	20.4; 225	5.3; 408	1.7; 107	9.23; 71	–	10.4; 69
P-value	(***)	(***)	(***)	(ns)	(***)	–	(***)

Summary statistics (mean and range) are given for all upstream sites and for all downstream sites. Downstream sites are listed according to whether mine is 'active' or is 'closed'. The upstream versus downstream % increase is given. The *t*-static, degrees of freedom (df), *P*-values are given for upstream versus downstream. (ns = not significant; $*P < 0.05$; $**P < 0.001$; $***P < 0.0001$) are given for comparison of means US versus DS. BD = below detection.

(Table 3). The elevated salinity below several mines was at ecologically hazardous levels. The mean salinity level (741.7 µS/cm) downstream of the mine discharges was more than twice the level recommended Australian water quality ecosystem guidelines for upland streams in south-eastern Australia (<350 µS/cm; ANZECC, 2000). The increase in salinity appeared modest (mean 129 µS/cm) downstream of one closed mine (Canyon Colliery, Dalpura Creek), yet that was about 4 times higher than Dalpura Creek upstream of the mine (mean 26.1 µS/cm). At the

Table 4 Summary statistics (mean and range) for eight metals (µg/L) collected from waterways upstream (US) and downstream (DS) active and closed coal mines

US all mines	Aluminium	Copper	Iron	Lead	Manganese	Nickel	Uranium	Zinc
Clarence	93.8	7.6	497.8	BD	25.3	BD	BD	3.1
	70–130	BD–3	290–770	BD	21–29	BD	BD	2–6
Canyon	102.9	3.6	20.4	BD	15.3	BD	BD	2.6
	90–110	BD–22	13–27	BD	13–17	BD	BD	2–3
Sawyers	277.9	0.5	1613.4	BD	46.6	2.6	BD	20.4
	90–720	BD–1	17–5800	BD	32–62	2–4	BD	11–33
Springvale	341.8	1.7	1713.1	0.7	124.1	1.7	BD	11.5
	50–740	BD–3	BD–7400	BD–2	13–370	1–4	BD	3–24
Angus Place	270.0	0.7	16214.1	BD	434.6	1.3	BD	7.2
	40–840	BD–2	410–45000	BD	20–1500	BD–3	BD	3–20
West Cliff	214.3	2.3	497.1	BD	44.6	1.7	BD	7.6
	70–280	BD–9	360–790	BD	20–110	BD–6	BD	9–12
Tahmoor	231.7	1.0	1003.3	BD	119.5	1.5	BD	4.0
	10–500	BD–2	840–1200	BD	71–180	BD–2	BD	3–5
Berrima	184.4	1.1	461.1	BD	31.0	0.8	BD	2.4
	30–490	BD–2	210–830	BD	19–50	BD–2	BD	1–4
All upstream sites								
Mean	231.1	2.05	4239.7	0.53	141.1	1.55	BD	8.56
Range	10–840	BD–22	BD–45000	BD–2	13–1500	BD–6	BD	1–33
DS active								
Clarence	22.0	1.5	61.2	BD	103.3	31.3	BD	36.5
	11232.0	BD–10	42–86	BD	80–150	23–41	BD	19–56
Sawyers	484.7	0.8	558.3	0.8	69.8	4.8	0.8	12.4
	60–1210	BD–2	47–1500	BD–2	10–220	2–8	0.6–0.9	3–30
Springvale	515.0	2.9	2210.0	2.5	2308.8	10.3	0.7	46.4
	30–2800	BD–15	150–13000	BD–10	35–14000	2–42	0.5–0.9	9–240
West Cliff	1420.0	3.2	456.4	1.3	12.0	64.8	3.8	13.8
	110–3400	3–4	84–1000	1–2	6–20	14–120	1.7–5.7	10–18
Tahmoor	391.7	1.6	611.7	0.9	105.5	28.8	3.6	23.3
	110–740	1–2	170–1300	BD–2	22–380	6–47	1.8–5.8	11–44
DS closed								
Canyon	13.3	9.1	1074.4	BD	457.8	186.3	BD	315.6
	5–30	BD–52	670–1900	BD	420–510	180–200	BD	290–340
Angus Place	502.4	0.7	1306.5	0.9	178.9	3.8	1.6	38.2
	30–2000	BD–2	140–5800	BD–3	16–990	1–10	1.1–1.8	4–190
Berrima	128.9	0.8	1593.3	BD	1988.9	72.4	BD	228.3
	20–470	BD–2	950–2900	BD	340–3300	14–110	BD	76–290
All downstream sites								
Mean	396.9	2.1	1059.3	1.02	676.4	41.4	1.18	83.4
Range	5–3400	BD–52	42–13000	BD–10	6–14000	1–200	BD–5.80	3–340
Mean % increase (US vs. DS)	71.8	2.4	–75	93.5	379.6	2576	–	874.5
t-statistic; df	2.1; 95	0.5; 141	2.93; 83	2.84; 71	2.53; 78	6.12; 82	–	6.01; 82
P-value	(*)	(NS)	(*)	(*)	(*)	(***)	–	(***)

Summary statistics (mean and range) are given for all upstream sites and for all downstream sites. Downstream sites are listed according to whether mine is ‘active’ or is ‘closed’. The upstream versus downstream % increase is given. The *t*-static, degrees of freedom (df), *P*-values are given for upstream versus downstream. (ns = not significant; $*P < 0.05$; $**P < 0.001$; $***P < 0.0001$) are given for comparison of means US versus DS. BD = below detection.

other end of the scale, the highest salinity (mean 1256 µS/cm) was detected below the West Cliff mine. It was nearly 7.5 times higher than upstream (mean 148.2 µS/cm). It is perhaps surprising that only two of the seven waste discharge licences (EPLs) stipulated any salinity discharge limits. One was 1200 µS/cm from Springvale Colliery and the other was 2600 µS/cm from Tahmoor Colliery (Table 2; EPA, 2018). In both cases, the salinity level of the streams / river downstream exceeded the recommended salinity guideline.

In comparison to international studies, the increase in salinity of Sydney Basin waterways due to disposal of

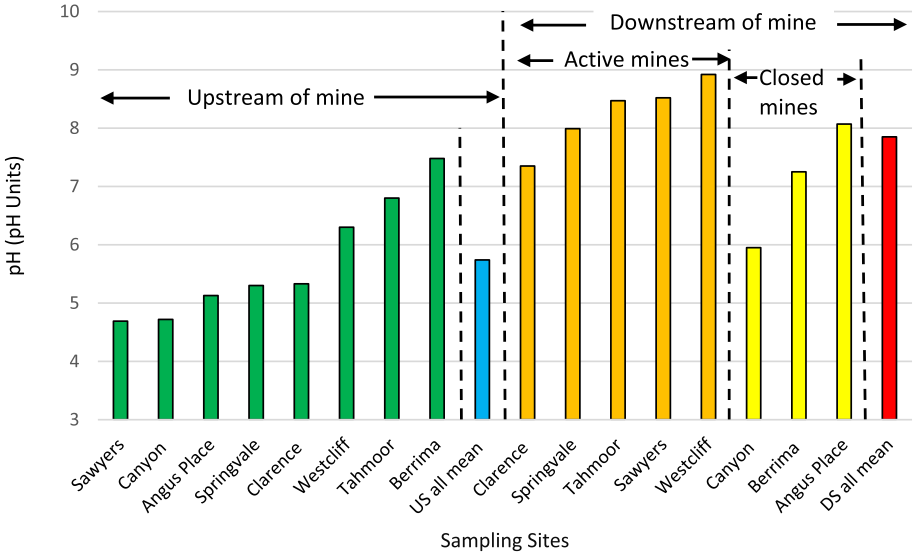

Fig. 2. Mean pH (pH units) results for sampling sites over this study. Sites upstream are at left (green bars) of mines. The overall mean upstream pH value is represented by the blue bar. Results for sampling sites downstream of waste discharges are on the right. Orange bars are sites below active mine and yellow bars are sites below closed mines. The mean downstream pH value is represented by the red bar. US = upstream and DS = downstream.

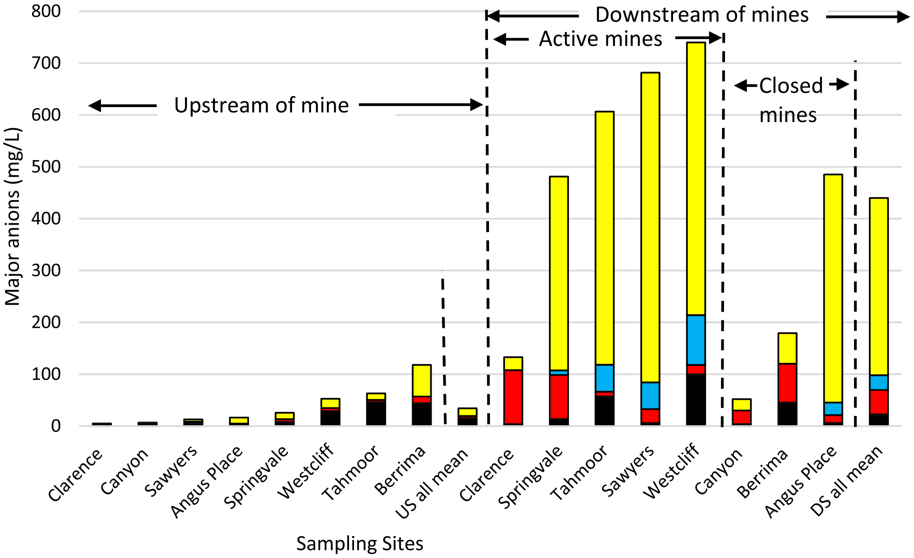

Fig. 3. Mean concentration of major anions (mg/L) results for sampling sites over this study. The stacked bars represent the mean concentration of chloride (bottom, black) then sulfate (second, red), then carbonate (third, blue) and bicarbonate (top, yellow). Sites upstream of mines are at the left. The overall mean concentrations are represented by 'US all mean'. Results for sampling sites downstream of waste discharges are on the right, grouped 'active mines' and 'closed mines'. The overall mean concentrations downstream are represented by 'DS all mean'.

mine waste water in this study was comparatively moderate. For example, slightly lesser increases in river salinity, due to coal mine discharges, were detected in the Boeza and Tremor Rivers in north-west Spain where García-Criado *et al.* (1999) reported very low salinity above coal mines (18–58 µS/cm) compared to downstream (144–449 µS/cm). Many waterways in this study had increased salinity comparable to that reported below West Virginian coal mines (Pond *et al.*, 2008) where salinity increased from 62 µS/cm in unmined streams to 1023 µS/cm downstream

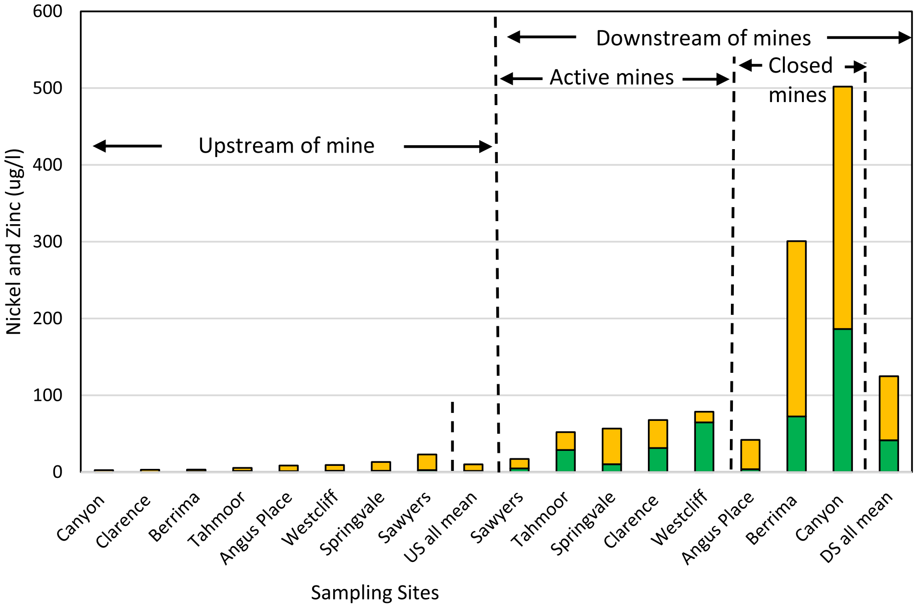

Fig. 4. Mean concentration of nickel (bottom, green) and zinc (top, orange) (µg/L) results for sampling sites over this study. Sites upstream of mines are at the left. The overall mean concentrations are represented by 'US all mean'. Results for sampling sites downstream of waste discharges are on the right, grouped 'active mines' and 'closed mines'. The overall mean concentrations downstream are represented by 'DS all mean'.

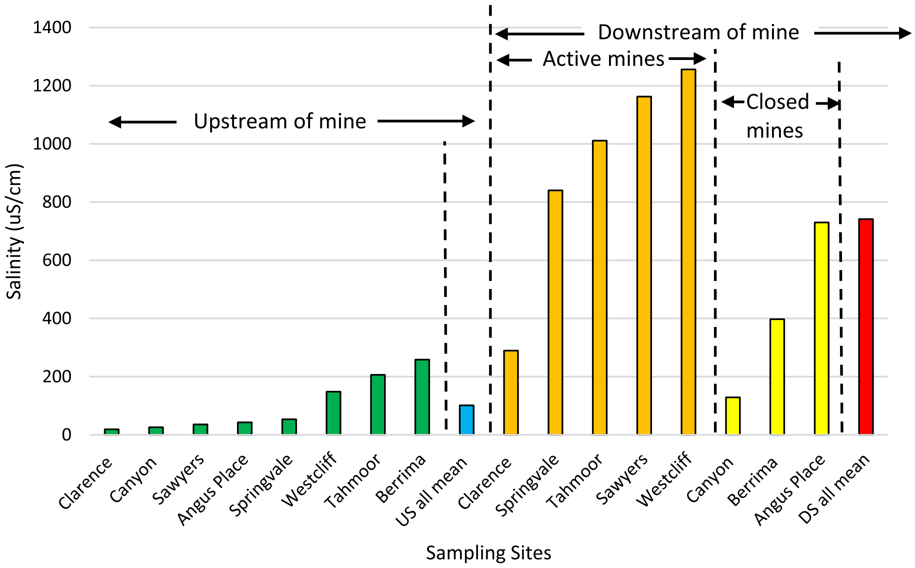

Fig. 5. Mean salinity (µS/cm) results for sampling sites over this study. Sites upstream are at left (green bars) of mines. The overall mean upstream salinity value is represented by the blue bar. Results for sampling sites downstream of waste discharges are on the right. Orange bars are sites below active mine and yellow bars are sites below closed mines. The mean downstream salinity value is represented by the red bar. US = upstream and DS = downstream.

of mine discharges. Similar increases in salinity were also reported for the waterways affected by coal mine activity in the Freeport coal seam of the Appalachians (USA) where Petty *et al.* (2010) reported salinity increased from unmined areas (mean 98 µS/cm) increased at streams exposed to high-intensity mining (mean 734 µS/cm).

The pH of rivers and streams, below mine drainage inflows, was significantly lower than upstream (Table 3,

Fig. 2). In seven of eight cases, the pH of rivers/streams increased because of the influence of the mine drainage (Table 3). On average, the pH below the mine discharge increased by more than two pH units (mean 5.74 upstream versus 7.85 downstream) below the entry of mine discharges (Table 3). The largest increase in pH was detected in Sawyers Swamp Creek (mean of 4.69 upstream and 8.52 downstream; Table 3). The Wingecarribee River was the only waterway that had lower pH below the mine (mean 7.25), compared to a mean of 7.25 upstream.

One of the well-known triggers of water pollution from coal mines is the generation of acidic waste water because of the influence of acid mine drainage (AMD). This is caused by the oxidisation of sulphur compounds in the coal, disturbed by the mining process (Robb, 1994; Banks *et al.*, 1997; Tiwary, 2000). In contrast to many other studies, our study revealed that the discharge of coal mine wastes alkalised rather than acidified downstream streams or rivers. The acidic pH levels recorded at upstream sites are typical of the naturally acidic and poorly buffered waterways in the Sydney Basin in minimally disturbed catchments (Hayes and Buckney, 1995; Wright *et al.*, 2011). An additional factor contributing to the higher pH is that many of the mines provide treatment to their wastes and this often increases the pH of the wastewater to promote precipitation of dissolved metals. For example, an earlier investigation of Clarence Colliery by Cohen (2002) reported that calcium oxide was added in the wastewater treatment process to increase water pH to promote oxidation of the iron and manganese. The largest increase in pH in a waterway was detected in Sawyers Swamp (mean 4.70 upstream and 8.42 downstream). These results contrast with most international coal mine studies which typically report that low pH is often due to coal mines generating acidic wastes (Banks *et al.*, 1997; Verb and Vis, 2000; Brake *et al.*, 2001; Tiwary, 2000; Johnson, 2003; Petty *et al.*, 2010). There was only one location in this current study where river pH declined due to a coal mine discharge, and that was Berrima Colliery where the pH of the Wingecarribee River declined slightly from a mean of 7.48 upstream to 7.25 downstream. These data were collected after the Berrima Colliery workings were partially flooded, which caused a drop in the mine drainage pH (Wright *et al.*, 2018).

A contributing factor to the absence of major pH reductions is that coal in the study area (Sydney Basin) has lower sulphur content than many other coal fields. Sydney Basin coal has a reputation for having a lower sulphur content (Huleatt, 2012). For example, the sulphur content of coal from the Katoomba Seam (Clarence Colliery and Canyon Colliery) was reported to have low pyritic forms of sulphur of 0.02%, which is much lower than is generally found internationally (Cohen, 2002). The lower sulphur content of coal is reflected in the sulphate concentrations in mine discharges in this study which were generally lower than many international studies. This reinforces the observation that acid mine drainage (AMD) was not a major problem in these coal mines.

However, sulphate was significantly elevated in waters downstream of coal mine discharges, compared to upstream, at all eight discharges. The mean sulphate concentration in waterways receiving mine discharges increased more than 10 times from 4.12 mg/L upstream to 46.9 mg/L downstream. The steepest increase in sulphate concentration was found below the Springvale mine (0.8 mg/L upstream compared to 104 mg/L downstream; Table 4). Comparable to our current study were results from an Appalachian (USA) catchment (Petty *et al.*, 2010) with sulphate in unmined streams (mean 14 mg/L) increasing in intensively mined areas to a mean of 22 mg/L (of Killanning geology) and 338 mg/L in the mined stream in the other area of that study (Freeport geology; Petty *et al.*, 2010).

The concentration of all major anions increased because of the inflow of mine discharges into streams or rivers (Table 3, Fig. 3). The anion composition of waterways upstream of mines was co-dominated by chloride and bicarbonate, with sulphate subdominant (Table 4, Fig. 3). On average, water samples collected downstream of mines revealed that bicarbonate was dominant, with sulphate subdominant, followed by carbonate and chloride was lowest. The largest overall increase was measured for bicarbonate concentrations, which increased by nearly 22 times (upstream mean 15.0 mg/L, downstream mean 342.0 mg/L; Table 3). The largest mean bicarbonate increase was recorded in the Georges River where the bicarbonate concentration increased from 18.0 mg/L upstream, rising by 35 times to 526 mg/L downstream, due to waste from the West Cliff mine (Table 4). Bicarbonate has been identified as pollutant that can contribute to ecotoxicology of coal mine wastewater (Vera *et al.*, 2014). The waterways receiving waste water from four active and one closed mine had mean bicarbonate concentrations above 225 mg/L. This level of bicarbonate (225 mg/L) has been recommended as a trigger value by NSW OEH (2012) to protect aquatic ecosystems. NSW OEH conducted an ecotoxicology investigation on wastewater discharged from the West Cliff Colliery in 2012 and identified bicarbonate as a key pollutant of concern (in that mine discharge) in 2012 (NSW OEH, 2012). The OEH report quoted research by Farag and Harper (2012) on bicarbonate and recommended trigger values for 80–95% protection of aquatic species of 225–319 mg/L (NSW OEH, 2012). The largest increase in the mean bicarbonate concentration in this study was found in Sawyers Swamp Creek, which increased from 4.2 mg/L upstream to 597.7 mg/L downstream. None of the EPA licence for collieries in this study specify a discharge limit for bicarbonate.

Thermal water pollution was detected downstream of several coal mines in this investigation (Table 3). Overall, the mean temperature of receiving waterways increased by 2.48°C, with the largest increase measured was a (mean) 10.2°C increase in the water temperature of Sawyers Swamp Creek (Table 3). The second highest increase in water temperature was found in Dalpura Creek, which recorded a mean increase in water temperature of 3.2°C downstream of the mine drainage inflow from the closed Canyon Colliery (Table 3). The thermal pollution of streams detected in this study is an important finding. It is the first Australian investigation to link the discharge of waste water from coal mines to thermal water pollution of waterways receiving the coal mine wastes, although the phenomenon of higher temperatures of flooded mines is internationally well known (Ramos *et al.*, 2015). None of the EPA licence for collieries in this study specify any discharge limit for water temperature (EPA, 2018).

The study's findings are a reminder that active and closed coal mines can both be a major source of water pollution. Berrima and Canyon Collieries both demonstrate that ecologically hazardous water pollution may occur for years after underground coal mines ceased mining. Unlike the United Kingdom or United States (Robb, 1994; Verb and Vis, 2000; Younger, 2004), there has been limited study of the water pollution legacy from closed coal mines in Australia. Battaglia *et al.* (2005) studied residual pollution and ecological degradation from a waterway affected by a closed coal mine. Two of the closed mines in this study have previously been investigated. Canyon Colliery ceased mining in 1997 and previous studies have documented aspects of the water pollution caused by this mine (Wright and Burgin, 2009; Price and Wright, 2016) and degradation of the ecology of the receiving waterway (Wright and Burgin, 2009; Wright *et al.*, 2011; Wright and Ryan, 2016). The Berrima Colliery was still in the closure process when it was investigated in a 12-month study, by Wright *et al.* (2018). This mine discharged higher concentrations of zinc, nickel, salinity and manganese after it ceased mining and was partially flooded, compared to when it was operating (Wright *et al.*, 2018). Whilst water pollution and ecological impairment impacts from closed coal mines has not been commonly studied in Australia, it has been the focus for many studies internationally (e.g. Cairney and Frost, 1975; Younger, 1993; Brake *et al.*, 2001; Johnson, 2003).

Many of the EPA licences for the collieries in this study have been progressively modified to reduce the pollution of waste-receiving waterways. For example, the Clarence Colliery EPA licence was modified in July 2017 to reduce the concentration of several pollutants permitted to be discharged into the Wollangambe River. An earlier study of this mine and high-conservation value river had documented water pollution and severe ecological damage extending 22 km below the mine (Belmer *et al.*, 2014; Wright *et al.*, 2017). The new EPA licence reduced the permitted concentration of zinc in the colliery waste water by 99.5%, from 1500 μg/L permitted in the previous licence to 8 μg/L (EPA, 2018). The new EPA licence also specified a permitted concentration for nickel of 11 μg/L. The previous licence had not specified any discharge limit for nickel (EPA, 2018). It is anticipated that the colliery will upgrade the treatment of their wastewater to conform to the requirements of the new licence.

Conclusion

(1) Both active and closed coal mines can both modify downstream water quality and generate pollutant concentrations that are hazardous to the receiving river and stream ecosystems.

(2) The current study provides a reminder that closed coal mines can continue to generate a difficult long-term water pollution legacy.

(3) Tighter and consistent environmental regulations are needed to reduce pollutants that are hazardous to river and stream ecosystems (particularly salinity, zinc and nickel) in waste discharges from coal mines.

(4) Long-term rehabilitation strategies to reduce the emission of ecologically hazardous pollutants are needed to avoid further legacy pollution problems from closed coal mines.

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