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Ecological and geochemical impact of an underground colliery waste discharge to a river

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Abstract. This study investigated the impact of mine wastewater disposal to a nearby river (the Bargo River). Mean electrical conductivity (EC) increased in surface waters below the mine discharge, rising more than six times from (219.5 µS/cm) upstream to 1551 µS/cm below the waste inflow. River pH increased from 7.12 (upstream) to 8.67 (downstream). The mine discharge strongly modified the ionic composition of the river. The mean concentration of several metals in the river were increased due to the mine wastewater. Nickel increased from 1.0 µg/L (upstream) to 32 µg/L (downstream). Zinc increased from 3.5 µg/L (upstream) to 23.5 µg/L (downstream). Our study also assessed the biological uptake of pollutants by growing weeping willow (*Salix babylonica)* cuttings in mine wastewater and contrasting to 'control' cuttings grown in river water from upstream of the mine. After growing in the laboratory for several weeks, the cuttings accumulated metals, dominated by barium, strontium and lithium. Results from the study constituted one of the most detailed geochemical and ecological studies investigating the impact of the coal mine waste discharge to an Australian river. Recommendations are suggested for improved regulation of the mine discharge to reduce its wastewater environmental impact.

1. Introduction

The discharge of liquid wastes from coal mines is frequently associated with pollution and associated degradation of waterways [1]. This study is the latest in a multi-year study and reveals that water quality of the Bargo River continues to be adversely affected from Tahmoor Colliery waste discharges [2,3]. The Tahmoor Colliery is one of several underground coal mines in the Sydney basin that dispose of wastewater into nearby waterways [3]. On multiple occasions, from July 2013 to April 2019, water quality in Bargo River was investigated to assess and measure changes resulting from wastewater discharged from an active underground coal mine (Tahmoor Colliery). The waste is released into Tea Tree Creek. Flow in this small stream is comprised mostly of wastes from the Tahmoor coalmine wastewater discharge. The coal mine waste discharge is licensed by the NSW Environment Protection Authority (EPA) under the legislation *Protection of the Environment Operations* Act (NSW) 1997 [4]. The EPA use an 'Environment Protection Licence (EPL)' that specifies the permitted concentrations of pollutants in colliery liquid wastes that can be discharged to the environment. The earlier phase of this investigation published its findings [2] based on collection of water and ecology samples from the Bargo River 1.1 km upstream and 2.9 km downstream of the inflow of the colliery wastes via Tea Tree Creek (figure 1). This current phase of this investigation (April 2019) collected samples of Tea Tree Creek, and from Bargo River upstream and 50 metres downstream of the Tea Tree Creek discharge. We have also examined water quality results of some pollutants in colliery waste reported by Tahmoor Colliery from 2012 to 2019, as part of its EPA licence [5,6].

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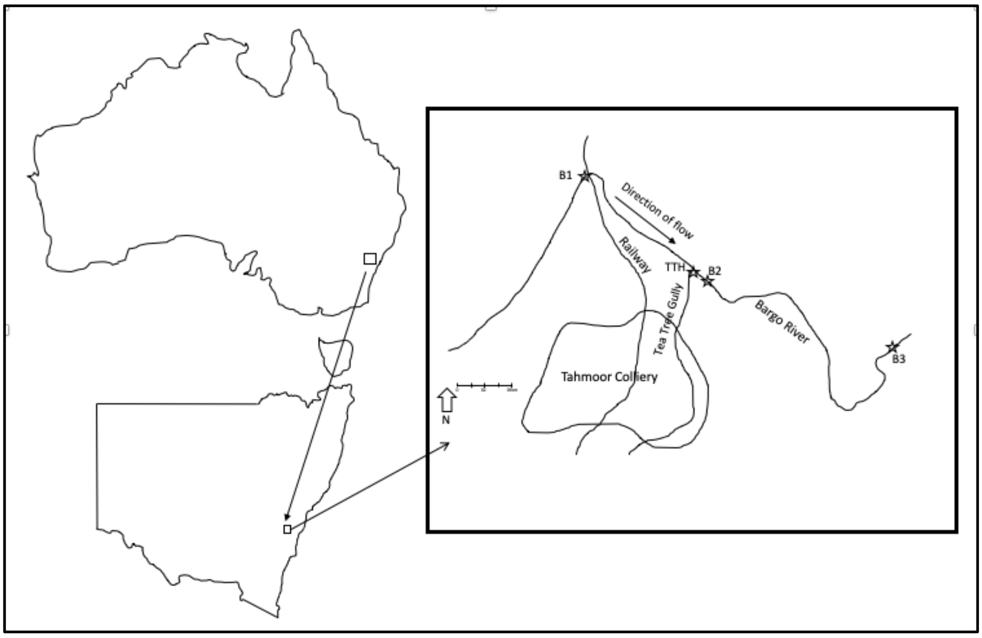

Figure 1. Location of sampling sites on the Bargo River. B1 is upstream of the mine, B2 is downstream and Tea Tree Creek comprises mostly mine wastes. B3 was sampled in an earlier study [2,3] and is 2.9 km downstream of Tea Tree Creek. The location of the study area in relation to NSW and Australia is indicated.

2. Methodology

The Tahmoor colliery discharges wastewater to the environment under specified conditions contained in the licence to the mine from NSW EPA [5]. The EPA licence permits the coal mine waste to be released to the environment and specifies only seven pollutants with maximum permitted discharge concentrations. They include pH (6.5 – 9.0), oil & grease (max. 10 mg/L), salinity (max. electrical conductivity of 2600 μS/cm), total suspended sediment (max. 30 mg/L), arsenic (max. 200 μg/L), nickel (max. 200 μg/L) and zinc (max. 300 μg/L) [5].

The discharge from the coal mine (of about five ML/day) to Tea Tree Hollow, a small tributary of Bargo River contributed about 50 % of the flow volume in April 2019. The dry weather flow in Tea Tree Creek is mostly attributed to the colliery waste discharge, but has not been quantified.

Water samples in April 2019 were collected from B1, B2 and Tea Tree Creek in duplicate, on one occasion (16 April 2019; figure 1). Water samples in an earlier phase of the study (July 2013 to December 2014) were collected on 11 occasions from B1 (upstream of the mine inflow) and B3 (2.9 km downstream of the mine inflow; figure 1) [2]. Macroinvertebrate samples were collected from B1 and B3 in 2013/2014 [2] to measure the ecological health of the river. At each sampling site, field meter results were obtained for stream pH, EC (electrical conductivity) and turbidity using field water testing instruments. They were tested for calibration (and adjusted if necessary) with reference solutions for pH and EC. pH and EC were measured using a TPS Aqua-CP/A meter and turbidity was measured using a HACH 2100P portable turbidity meter. At each site the meter was allowed to equilibrate before recording five replicate measurements. Weather conditions were assessed prior to collecting water samples to avoid periods of heavy rain, which could have caused confounded results.

Monthly water quality results for pollutants (arsenic, salinity, zinc and nickel) in Tahmoor Colliery wastewater were also examined over the period April 2012 to April 2019. This data was collected by the colliery and is publicly available [6], in compliance with the colliery's EPA licence [5].

To investigate ecological effects of the coal mine waste, willow cuttings were grown in water samples collected from Tea Tree Creek (colliery wastewater) and also from B1 (Bargo River upstream of the colliery). The willow cuttings were grown in a controlled environment for six weeks, with water levels topped-up with deionized water. At the end of the time the leaves were removed, dried, and the tissue powdered for metal analysis.

Water and willow tissue samples were tested the Envirolab laboratory. The laboratory is a National Association of Testing Authorities (NATA) endorsed commercial laboratory for analysis of water and sediment chemistry samples. They have NATA accreditation based on rigorous analytical testing methods within a quality assured chemistry environment.

3. Results and discussion

The water quality results from April 2019 show that the inflow of Tahmoor mine wastewater substantially modified water quality in the Bargo River (table 1; figure 2). The pH of the Bargo River increased by 1.55 pH units from 7.12 upstream to 8.67 downstream. The inflow of the mine wastes also changed the ionic composition of the Bargo River (table 1). Tea Tree Creek had highly elevated Na (540 mg/L). Bargo River Na increased from 2.9 mg/L, upstream, to 290 mg/L downstream. Tea Tree Creek also had highly elevated HCO_3 (990 mg/L). This increased the concentration of HCO_3 in the Bargo River from 12 mg/L upstream to 470 mg/L downstream.

This study found that lower river flows, after an extended period of dry weather, has reduced the dilution of mine wastewater and increased the impact, through higher downstream concentrations of pollutants. The sampling of the Bargo River and Tahmoor Colliery wastes in April 2019 was conducted in a period of drought and mine wastewater discharge resulted in an approximate 50% dilution of mine wastes by upstream flow.

Salinity of the Bargo River was increased by the mine discharge. The mean level of salinity in the Bargo River upstream (220 µS/cm) was lifted by more than six times to 1550 µS/cm due to the inflow of the saline mine wastes (mean 2061 µS/cm). The previous study (table 1; 2013/14) recorded a mean salinity of 1078 µS/cm at B3, 2.9 km downstream of the mine inflow [2]. Data reported by Tahmoor Colliery to the EPA [6] shows that over the last seven years the colliery has discharged wastes that have a mean annual salinity ranging from 1964 µS/cm to 2145 µS/cm (figure 2). Such increased salinity in the Bargo River is much higher than is recommended for protecting aquatic species. The recommended ANZECC [7] guideline is 350 µS/cm. Horrigan [8] found that aquatic macroinvertebrate communities declined at salinity levels above 1000 µS/cm. However, the Tahmoor Colliery EPA permits the discharge of such saline wastes with a maximum limit of 2600 µS/cm for salinity in its licence [5].

Of the 10 metals investigated in the current study, only five were detected in the Bargo River above the mine (table 1). In contrast, in the mine wastewater and the river downstream of the mine waste discharge, all 10 metals were detected. The five metals that the coal mine wastes introduced to the Bargo River were arsenic, cobalt, molybdenum, lithium and uranium. The largest increase was detected for lithium (table 1). Upstream of the mine lithium was <1 µg/L and it was measured at 670 µg/L downstream. The mine wastes contained 1300 µg/L of lithium.

Nickel was detected in the Bargo River, below the entry of the mine wastes, at concentrations that are considered hazardous [7] to aquatic ecosystems (figure 2; table 1). It was at a trace level (1 µg/L) in the Bargo River upstream of the mine and increased by more than 30 times to 32 µg/L, below the mine. The previous study (table 1; 2013/14) recorded a mean nickel concentration of 35.6 µg/L at B3, 2.9 km downstream of the mine inflow [2]. The mine wastes contained 61.5 µg/L, which was slightly lower than the mean monthly concentration of 66.5 µg/L of nickel in wastes discharge by the mine from 2012 to 2019 (figure 2) [6]. As the water hardness of the Bargo River is classified as ‘soft’, the ANZECC ecosystem protection guideline [7] for nickel is 2.4 µg/L, or 8 µg/L for 99% or 95% species protection. Although the nickel concentration in the Bargo River was four times higher than the ANZECC guideline, it was legally authorised as the EPA licence for the Tahmoor Coal Mine [5] which permits up to 200 µg/L of nickel in the Tahmoor Colliery wastewater. Other coal mines in the Sydney basin have more highly elevated nickel in their wastewater, with the highest being Dalpura

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Creek, below the closed Canyon coal mine containing 183 μg/L of nickel [9].

Zinc in Tahmoor wastewater (Tea Tree Creek) had a mean concentration of 43.5 μg/L in April 2019, and this increased the zinc concentration of the Bargo River from 3.5 μg/L (upstream) to 23 μg/L (downstream; table 1; figure 2). The previous study (table 1; 2013/14) recorded a mean zinc concentration of 38.6 μg/L at B3, 2.9 km downstream of the mine inflow [2]. As the water hardness of the Bargo River is classified as 'soft', the ANZECC ecosystem protection guideline [7] for zinc is 8 μg/L or 11 μg/L for 99% or 95% species protection. The colliery EPA licence for the colliery [5] currently has limit of 300 μg/L for zinc. Monthly data on zinc in the mine discharge (April 2012 to April 2019) reported by Tahmoor Colliery varied from 31 to 239 μg/L, with an overall mean of 79.3 μg/L [6].

Table 1. Mean water quality results collected from the three sampling sites in April 2019, Bargo River U/S ('B1'; 1 km upstream of the mine discharge), Bargo River D/S ('B2'; 50 metres downstream of the mine waste inflow) and Tea Tree Creek (Tahmoor Colliery waste discharge). Mean results for 'B3' 2.9 km downstream of mine waste collected in an earlier study (2013 to 2014) are provided [2]. Salinity is measured as electrical conductivity in µS/cm. Dissolved oxygen is measured as % saturation.

Water Chemistry	Bargo U/S (B1)	Tea Tree Creek	Bargo D/S (B2)	Bargo D/S (B3)
pH (pH units)	7.12	8.54	8.67	8.19
Salinity	219.5	2061.8	1550.6	1078
Temperature (℃)	18.7	18.8	18.5	14.96
Dissolved Oxygen (%)	102.9	100.24	101.4	89.5
Sodium (mg/L)	2.9	540	290	252
Calcium (mg/L)	2.7	6.8	4.2	11.3
Magnesium (mg/L)	4.5	9.2	5.2	9.28
Potassium (mg/L)	3	24	14	14
Sulphate (mg/L)	6	29	18	9.75
Chloride (mg/L)	45	78	62	48.6
Bicarbonate (mg/L)	12	990	470	439.2
Carbonate (mg/L)	<5	80	37	36.8
Alkalinity (mg/L)	12	1100	500	476
Arsenic (µg/L)	<1	31	12.5	-
Barium (µg/L)	16	2850	1500	-
Cobalt (µg/L)	<1	8	4	-
Manganese (µg/L)	94	12.5	37.5	28.2
Molybdenum (µg/L)	<1	9	18.5	-
Nickel (µg/L)	1	61.5	32	35.6
Strontium (µg/L)	28	615	320	-
Lithium (µg/L)	<1	1300	670	-
Uranium (µg/L)	<0.5	9.85	4.65	-
Zinc (µg/L)	3.5	43.5	23.5	38.6

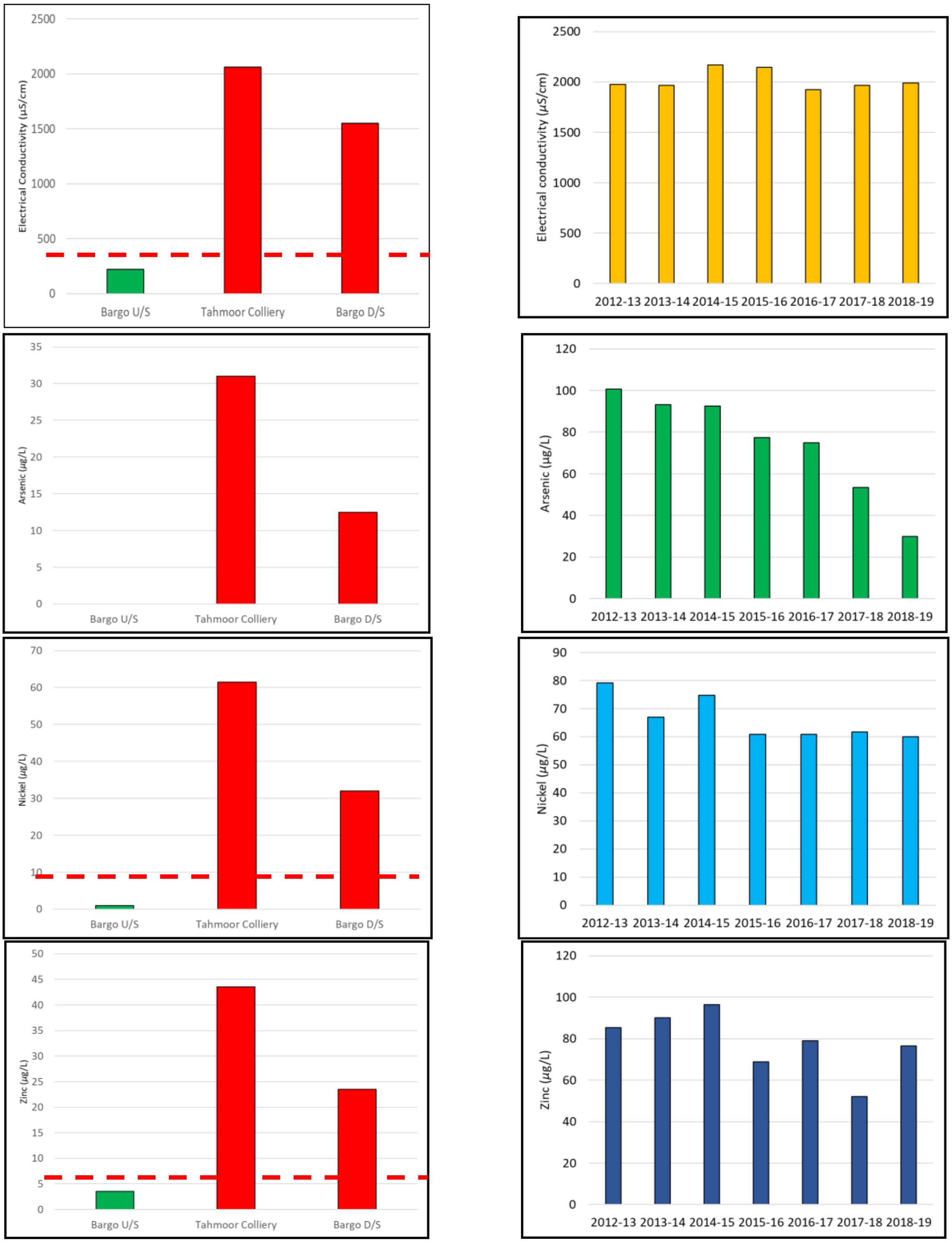

Figure 2. Mean water quality results collected from the current study (graphs on the left) for salinity (i and ii), arsenic (iii, iv), nickel (v, vi) and zinc (vii and viii). The mean values in the current study are for Bargo River upstream (U/S), Tahmoor Colliery waste and Bargo River downstream (D/S). The graphs on the right are the mean annual values (2012/3 to 2018/9) for these four pollutants in Tahmoor Colliery waste discharges [6]. The dotted red lines represent the ANZECC [7] guideline values for protection of aquatic species.

Arsenic in Tahmoor wastewater (Tea Tree Creek) had a mean concentration of 31 µg/L in April

2019 (table 1; figure 2). It was only found in Bargo River downstream of the waste inflow at 12.5 μg/L. Arsenic in the mine discharge (April 2012 to April 2019) declined from a mean of 100.7 μg/L in 2012/3 to 29.9 μg/L in 2018/9 (figure 2) [6].

The EPA licence currently provides no requirement for the colliery to improve their treatment of the colliery wastewater. The regulation of water pollution in NSW currently has an 'end of pipe' [5,9] focus, and this fails to recognise and measure the actual impact of the waste on the river environment.

Macroinvertebrate samples collected upstream of the mine compared to B3 2.9 km downstream of the mine wastes showed that the Bargo River had a modified community structure, indicative of mild ecological impairment [2,10]. In 2019 our bioassay using willow cuttings investigated the bioaccumulation of metals from mine wastewater into plants. Willow cuttings were grown in Tahmoor Colliery wastewater bioaccumulated barium, strontium and lithium metals in their leaves (figure 3). Together these three metals accounted for 52.2 and 56.5% of the metal content of the cuttings grown in mine wastewater. In contrast, the cuttings grown in Bargo River (upstream) water had no lithium detected. And the tissue from cuttings grown in Bargo River (upstream) water had smaller concentrations of strontium and barium. They accounted for 13.9 – 16.1 % of the metal content detected in their leaves (figure 3).

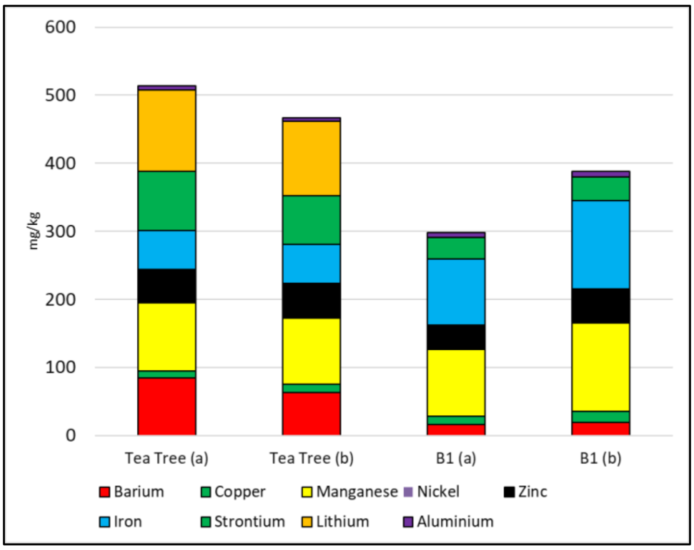

Figure 3. Concentration of nine metals detected in willow leaf tissue. Tea Tree (a) and (b) were from cuttings both grown in Tahmoor Colliery wastewater. B1 (a) and (b) were from cuttings grown in Bargo River water collected upstream of the coal mine.

4. Conclusions

This case study demonstrates how the disposal of wastewater from a coal mine can pollute rivers with an environmental licence of limited environmental effectiveness. Similar conclusions have been made about other coal mines in the Sydney area which have continue to discharge ecologically damaging wastes containing metals, even after mines close [3,9,11,12].

This study also contributes to international studies on water quality impacts from coal mines. For example, the sulphate concentration of the mine wastes in this study are unusually low (table 1; 29 mg/L). A group of coal mine discharges in England had sulfate ranging from 380-1170 mg/L [13]. A group of Indian coal mines also had much higher sulfate concentrations (400-1948.9 mg/L) [14]. Some of the most extreme sulfate results were from coal mines in f Brazil at up to 8412 mg/L [15]. One of the implications of the relatively low sulfate concentration was the absence of 'acid mine drainage'

(AMD). AMD is triggered by the oxidisation of sulfur compounds [1,16,17]. In our study, the discharge of coal mine wastes alkalized rather than acidified the river receiving coal mine wastewater. The pH of the Bargo River was generally increased by 1.5 pH units (table 1). This contrasts with many coal mine studies that often report coal mines generating acidic wastes [3,9,11,12].

The data presented in this study shows that the coal mine is polluting the Bargo River, but we were not able to document the downstream extent of the pollution. Future studies will examine the downstream extent of the water pollution plume from this coal mine discharge. We predict that the ecologically hazardous pollutants (salinity, zinc and nickel) are elevated to dangerous concentrations for many km downstream of the mine. The EPA licence [5] permits the discharge of only a select few of the pollutants that we measured in the in the colliery wastewater. The licence allows highly elevated pollutant concentrations for zinc (<300 μg/L) and nickel (<200 μg/L). Because the colliery wastes contributed about 50% of the flow in the Bargo River in April 2019, we suggest that ecologically safe concentrations of zinc, nickel and salinity should be much lower [7].

5. Recommendations
It is recommended that the pollutant concentrations for nickel, zinc and salinity in the EPL licence are reviewed and reduced by the EPA to improve water quality for aquatic life in the Bargo River. It is also recommended that the EPL licence imposes concentration limits on barium, strontium and lithium given the increased bioaccumulation of the three metals in plant leaves grown in colliery wastewater. The EPA should require the colliery to monitor and report pollutant concentrations in the river above and below the inflow of its wastes. This would enable measurement of the scale of water quality impairment resulting from its waste discharge.

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