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14-Month Water Quality Investigation of Coal Mine Discharge on Two Rivers in NSW, Australia: Implications for Environmental Regulation

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Abstract Ineffective environmental regulation of effluent discharged from an underground coal mine operation has enabled water pollution within two highly valued Australian rivers. This study investigated the impacts on water chemistry of the Bargo and Nepean rivers as a result of the continuous disposal of mine effluent from Tahmoor Colliery over a 14-month period. Coal mine effluent was saline (2180 µS/cm) and alkaline (8.7 pH), and strongly modified the ionic composition within both rivers. Ecologically hazardous concentrations of several metals were found in mine effluent, including aluminium (858 µg/L), arsenic (59.7 µg/L), nickel (60.7 µg/L), and zinc (49.4 µg/L). The effluent also contained elevated total nitrogen (2.89 mg/L) and the waste discharge contributed 67% of the median flow volume in the Bargo River below the discharge point. The plume of saline- and metal-enriched contamination extended at least 9 km downstream past the discharge point, impairing water quality in both the Bargo and Nepean rivers. This study reveals more than a decade of ineffective regulatory and governance systems that enable Tahmoor Colliery to continually release inadequately treated mine effluent.

Keywords Environmental regulation · Environmental management · Water quality · Metals · Nutrients · Ionic composition

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1 Introduction

Coal mining and the deliberate or accidental release of water contaminated by mine activities (termed *coal mine effluent*) to surface waters are a widespread source of water pollution across the world. Entry of coal mine effluent to waterways can cause a diverse range of adverse impacts to river water chemistry, sediment chemistry, and ecology (Tiwary 2001). The release of coal mine effluent to waterways is often linked to unnatural changes to water quality with typical symptoms including increased salinity, concentrations of heavy metals such as nickel and zinc and changes to pH and ionic composition (Banks et al. 1997; García-Criado et al. 1999; Verb and Vis 2000). There have been many studies showing water pollution from coal mining around the globe, including from the USA (Brake et al. 2001; Pond et al. 2008; Griffith et al. 2012), Brazil (Lattuada et al. 2009), the UK (Jarvis and Younger 1997; Younger 2001; Johnson 2003) and New Zealand (Winterbourn 1998; Gray and Harding 2012). Chemical composition of coal mine effluent and the resulting impacts to river water chemistry are often variable depending on the local geology, mining methods and hydrology of the area (Banks et al. 1997; Gombert et al. 2018). Coal mine effluent is often generated through groundwater that enters coal mine workings, which is then pumped to the surface to be treated and discharged to the environment, often to river systems (Younger 2004).

Contaminants commonly found in coal mine effluent such as nickel, zinc, aluminium and lead are known to be hazardous to aquatic flora and fauna (Brake et al. 2001). Studies have documented the bioaccumulation of metals from coal mine wastes in aquatic food webs (Bharti and Banerjee 2011; Belmer et al. 2019). Decreased river biodiversity was found in coal mine–impacted streams compared to non-impacted streams within the USA, with a 32% reduction in taxonomic richness and a 53% reduction in total abundance across all taxa investigated (invertebrates, fish and salamanders; Giam et al. 2018). Steep reductions in biodiversity have also been recorded in waterways suffering impaired water quality due to coal mine wastes in the Sydney Basin. For example, stream invertebrate taxonomic richness declined by 63% below a recently closed underground coal mine (Wright et al. 2018) and an 88% reduction in stream invertebrate abundance was measured below the waste outfall from an active coal mine (Wright et al. 2017).

Despite the environmental impacts of coal mining on its waterways, Australia has increased coal production in recent decades due to international trade in metallurgical and thermal coal (Mudd 2009). Australia is now one of the world's leading exporters of coal (Mudd 2009) and coal exports are now Australia's second largest resource export after iron ore (Cunningham et al. 2019). Historically, much of Australia's coal was used for domestic industry, particularly with coal as the energy source for about 60% of the nation's electricity generation (Geoscience Australia 2013). However, the proportion of Australian coal exported has risen from 55% in 1990 to 75% in 2018 (Cunningham et al. 2019). With increasing demand for Australian coal, the mining industry continues to grow in Australia, including many active underground mines to the south and west of Sydney, Australia's largest metropolitan area (Cunningham et al. 2019). There are heightened community concerns about the environmental impact of coal mining on Australia's water resources (Daniel et al. 2010). For example, an underground coal mine in the catchment of Sydney's largest drinking water reservoir released contaminated drainage into a catchment river (Wright et al. 2018) and several longwall mines have damaged to Sydney's 'protected' drinking water catchments (Krogh 2007).

Water quality impacts have been documented from effluent discharge from active and closed coal mines in the southern and western coalfields of the Sydney Basin (Battaglia et al. 2005; Wright and Burgin 2009a, b; Wright 2012; Price and Wright 2016; Ali et al. 2017). Several active and closed coal mines in the Sydney Basin have reported water pollution problems, such as elevated salinity and modified ionic composition, changes to pH, increased concentrations of several metals and associated impairment of aquatic ecosystem, largely based on surveys of river invertebrates (Wright and Burgin 2009a, b; Wright 2012; Price and Wright 2016; Wright and Ryan 2016; Belmer and Wright 2019).

Water pollution from point source wastewater discharges, including effluent generated from coal mining operations, is regulated by the NSW Government. This was historically done using the repealed Clean Water Act (1971), now replaced by the Protection of the Environment Operations Act (1997). The legislation for the majority of commercial coal mines is enforced by the NSW Government's Environment Protection Authority. Their approach to regulation and control of water pollution from waste discharges relies on a 'command and control' approach (Graham and Wright 2012). This is through an individual permit system for each premise called an environment protection licence (EPL) that specifies the permitted concentration and associated metrics for a range of pollutants in the effluent point source discharges from that premise into waterways (Graham and Wright 2012). This is very similar to the permit approach that is used to regulate wastewater discharges in the United States of America (USA) under the USEPA (2020; Rich 2016). Water pollution is prohibited by the USEPA (2020) without a permit, generally obtained under the National Pollutant Discharge Elimination System programme (NPDES; Rich 2016). The USEPA, or approved state agencies, issue permits for premises to discharge pollutants at prescribed levels designed to maintain water quality in the receiving waters (Rich 2016).

The Bargo River is a small upland river with a variable flow that declines and sometimes ceases to flow in an extended drought (*personal observation*). Water quality and ecological health of many Australian rivers and streams have declined in association with diminished river flows caused by prolonged drought conditions (Lake 2003; Mosley 2015). It appears likely that climate change is reducing rainfall and stream flow across many regions of southern Australia (CSIRO and BOM (Bureau of Meteorology) 2020) and it is predicted that future climate change will have impacts to Australian river flows by reducing them (10–25%) by 2030 in some regions (Prosser 2011). Lower river flows are important as dilution of wastes that are released into flowing waters is an important factor influencing water pollution impacts. Currently, almost all NSW EPA licences for industry wastewater discharges that release wastes to rivers do not vary according to the degree of dilution offered by river flow. However, in south western Sydney, Picton sewage treatment plant (STP) is only permitted to discharge treated effluent when there is sufficient flow volume of the small receiving water (EPL 10555). The NSW EPA also limits the discharge volume from Picton STP to ensure that the effluent comprises less than 25% of the stream flow (EPL 10555). Drought and lower river flows have been linked to increased concentration of pollutants from human activities in European (Zwolsman et al. 2011) and North American waterways (Murdoch et al. 2000). A study on the Lower Cheat River Basin, located between Pennsylvania and West Virginia, has also linked coal mining activity with increased stream contamination in dry weather conditions (Williams et al. 1999). Williams et al. (1999) described low flow conditions as providing evidence of the 'worst-case scenario' for stream water quality in waterways affected by coal mining activity.

There are relatively few studies that have investigated the role of environmental regulation in the resulting water pollution in rivers receiving coal mine effluent (Wright et al. 2011; Graham and Wright 2012; Belmer and Wright 2020). This current study investigated the water quality impacts within the Bargo River and the Nepean River resulting from the EPA licenced discharge of coal mine effluent from Tahmoor Colliery. The study was designed to measure any changes to water chemistry from the mine effluent discharge by using a temporally replicated water sampling method covering more than 9 km downstream in the Bargo River and into the Nepean River. This investigation was framed around answering four questions. The first three relate to assessment of the nature of the colliery waste and the impact of its release on water quality in Bargo and Nepean rivers. The fourth question relates to the management of river water quality and the effectiveness of environmental regulations imposed on the colliery effluent discharge.

1. What is the water chemical composition of the coal mine effluent discharge?
2. What are the key water quality changes that could be ecologically hazardous resulting from the mine effluent discharge to the Bargo River and Nepean River downstream of the mine?
3. Does the Bargo River and the Nepean River show any downstream signs of 'recovery' from any water pollution impacts from the mine effluent discharge?
4. Are the environmental regulations imposed on the discharge of mine effluent from Tahmoor Colliery effective in protecting the river from water pollution that could contribute to ecological harm?

The study design anticipated that mine effluent discharges could cause a water quality impact downstream of the discharge point to the Bargo River. However, the focus included an investigation of the nature, severity and spatial extent of any water quality impacts caused by the waste discharge. The outcome of the research was also positioned to inform future pollution licencing by environmental regulators to protect highly valued aquatic environments.

2 Methods

2.1 Study Area

This study investigated the water quality impacts of a single coal mine effluent discharge from Tahmoor Colliery to the Bargo River, via a small stream Tea Tree Hollow. The sampling area is within the Bargo River catchment, a small sub-catchment of the Hawkesbury-Nepean catchment. The Bargo River is a tributary of the Nepean River in NSW, one of the longest coastal rivers in south eastern Australia (Markich and Brown 1998). Both rivers are on the outskirts of the Sydney metropolitan area and are both important and highly valued for the community for recreational fishing, bushwalking, birdwatching, swimming, for potable water supply and for irrigation (Healthy Rivers Commission of NSW 1998; Pinto and Maheshwari 2015; Wollondilly Shire Council 2020). The Bargo River catchment includes the small townships of Tahmoor and Bargo and is situated on the outer south western urban fringe of Sydney, approximately 75 km from its CBD (Fig. 1) (34° 14′ 34.84″ S 150° 35′ 17.27″ E). Tributaries of the Nepean River are impounded to supply Sydney's drinking water supply (Krogh 2007; Markich and Brown 1998). The surrounding landscape is peri-urban and includes a broad combination of natural vegetation, mixed agricultural holdings and small urban townships. Water quality in the Nepean River has been extensively monitored but this is the first study that has investigated the contribution of the Bargo River. Most studies (e.g. Sydney Water 2018) report data for Nepean River at Maldon Weir as the most upstream of sampling sites. Maldon Weir is about 4 km downstream of the confluence of Bargo River. Median flow data (see Section 2.1 Study Area) suggests that Bargo River accounts for about 25% of the Nepean River flow immediately below the inflow.

The environmental values of the Bargo River were assessed by the former Hawkesbury-Nepean Catchment Management Authority as part of their River Health Strategy (2007). They reported that the Bargo River is popular for recreation, fishing and for conservation of native species. The River Health Strategy (2007) also found that the Bargo subcatchment is largely undisturbed bushland, with the exception of Picton Weir, located on Bargo River 6.1 km upstream of Tea Tree Hollow (Fig. 1). The Bargo River and surrounding lands are important habitats for native flora and fauna, such as eucalypts and lyrebirds, and are known to be important habitats for platypus (NSW National Parks and Wildlife Service 2015).

Tahmoor Colliery is an underground coal mine that has been operating since 1979, near the township of Tahmoor (AECOM 2018). The mine extracts 3 million tonnes per year of mainly high-quality metallurgical coal and lesser amounts of thermal coal from 1.7- to 2.3-m-thick Bulli coal seam of the Southern Coalfields in the lower Sydney Basin of NSW (Huleatt 1991; Tahmoor Coal 2019). For more than 30 years, the mine has been using longwall mining technology and operates at a depth of 400–450 m below the surface and is seeking to extend its mining operation for a further 15 years proposing to mine up to 4 million tonnes per year of coal (DPIE 2020).

Coal mine wastewater is generated through both the coal mining and coal washing operations. Groundwater seepage accumulates in the underground mine workings (Tahmoor Coal 2019). The mine water is pumped to the surface where the mine's wastewater is treated and some is reused onsite (DPIE 2020; Appendix J). A median volume of 5.3 ML of wastewater per day is discharged from the mine to receiving surface waters (DPIE 2020; Appendix J). The wastewater is released to a small drain which flows overland to a small stream (Tea Tree Hollow), which enters Bargo River about 900 m from the waste discharge point. In median flow conditions, mine wastes contribute approximately 67% of the median flow of the Bargo River, downstream of the Tea Tree inflow. This was calculated from flow gauging results on Bargo River, upstream of Tea Tree Hollow, which reported the median river flow, above the mine discharge, to be 2.6 ML/day (DPIE 2020; Appendix J). Maldon Weir is on the Nepean River approximately 4 km downstream of the entry of Bargo River. The median flow of the Nepean River at Maldon Weir over an 8-year period (April 2006 to May 2014) was 29.3 ML/day (Sydney Catchment Authority 2015). Based on these median flow statistics, the Bargo River accounts for about 25% of the volume of the Nepean River downstream of the Bargo/Nepean junction.

2.2 EPA Regulation of Tahmoor Colliery's Mine Effluent

The disposal of Tahmoor Colliery's effluent to local waterways is regulated by the NSW Environment Protection Authority (EPA) under the Protection of the Environment Operations (1997) Act (POEO Act 2018). The EPA regulates the effluent discharge using an Environment Protection Licence (EPL) number 1389 (Graham and Wright 2012; Belmer and Wright 2020). Up until December 2011, the EPL specified discharge limits for only the following five pollutants in the mine effluent (chemical oxygen demand 30 mg/L; oil and grease 10 mg/L; pH 6.5–8.5; turbidity 150 NTU; total suspended solids 30 mg/L). The EPL does not permit Tahmoor Colliery to discharge any other pollutants in the mine effluent, and the licence states this explicitly: 'To avoid any doubt, this condition does not authorise the pollution of waters by any pollutant other than those specified in the table/s' (Clause L2.3, EPL 1389).

The EPA was aware of unauthorised pollutants in Tahmoor Colliery's mine effluent that were of environmental concern and were not being regulated by the previous EPL. In December 2011, a notice from the EPA to the colliery states: 'Tahmoor Coal has measured levels of salinity and the metals arsenic, nickel and zinc in discharges from the premises over a number of years' (NSW EPA 2011). From December 2012, the EPL for Tahmoor Colliery specified discharge limits for eight pollutants only (electrical conductivity 2600 μS/cm; oil and grease 10 mg/L; pH 6.5–9.0; turbidity 150 NTU; total suspended solids 30 mg/L; nickel 200 μg/L; arsenic 200 μg/L; zinc 300 mg/L). The same EPA notice also acknowledged that the colliery was, at that time in late 2011, constructing an advanced wastewater

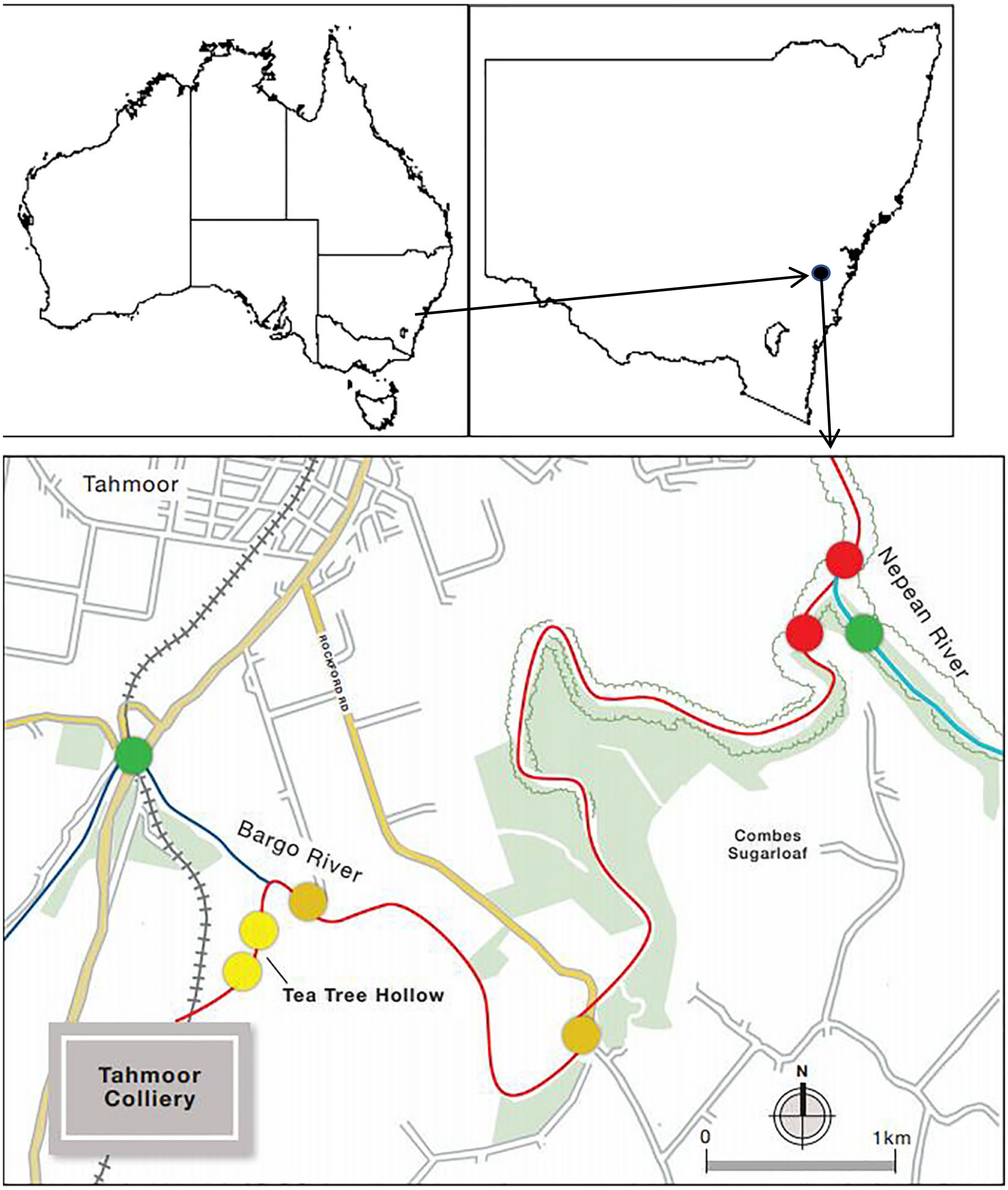

Fig. 1 Map of sampling sites used to investigate the impact of mine effluent discharge from Tahmoor Colliery to the Bargo River and Nepean River, via Tea Tree Hollow. The two reference sites (REFS) are green circles, two mine effluent sites (WASTE) are yellow circles, two Bargo River downstream sites (DS1) are orange circles, and the two sites furthest from the mine discharge are red (DS2). Discharge pathway of mine waste from Colliery is shown by red line

treatment plant to reduce salinity and the concentration of metals, including arsenic, nickel, and zinc in the colliery wastes (NSW EPA 2011). The EPA notice considered the pollutant discharge limits that first applied in December 2011 to be *interim* as the treatment plant was to be completed and commissioned 12 months later (31 December 2012; NSW EPA 2011). Once the new waste treatment plant was operating, the EPA notice advised that they would apply revised discharge limits for arsenic, zinc and nickel that would be based on Australian water quality guidelines (ANZECC (Australian and New Zealand Environment and

Conservation Council). 2000). A series of EPA notices from the EPA regarding EPL 1389 in 2013, 2015 and 2017 contain various reasons why the treatment plant was slow to be constructed and had multiple issues over many years that prevented it from treating waste effectively (NSW EPA (Environment Protection Authority) 2017). The interim pollutant limits issued by the EPA in December 2011 were still in force during the current study in 2019–2020.

2.3 Water Quality Assessment

This study was conducted over a 14-month period (16 April 2019 to 24 June 2020) to investigate the water quality impacts of wastewater discharge from Tahmoor Colliery on the Bargo River and the Nepean River. Samples were collected from eight individual sampling sites representing four groupings (as pairs of sites) for the basis of this study. The first group (REF) included two reference sites not receiving any coal mine wastewater discharge. The two reference sites were situated on the two rivers including the Bargo River 1 km upstream of the Tea Tree Hollow mine discharge, and the Nepean River upstream of the entry of Bargo River (Fig. 1). The second group (WASTE) included two sites collected from the coal mine wastewater discharge from Tahmoor Colliery. One WASTE site was the undiluted waste drain near the coal mine discharge point and the second site was from Tea Tree Hollow, which is predominantly mine wastewater (AECOM Appendix J EIS 2018; Fig. 1). The third group of sites (DS1) comprised two sites from the Bargo River downstream of entry of mine wastes from Tea Tree Hollow. One site was 80 m downstream of Tea Tree Hollow (entry of mine effluent) and the other was 2 km downstream of Tea Tree Hollow. The inclusion of the two sites in the DS1 category that cover a total of 2 km of the Bargo River was designed to allow for a mixing zone near the entry of the mine effluent immediately below Tea Tree Hollow (ANZECC (Australian and New Zealand Environment and Conservation Council) 2000). The fourth group of sites (DS2) included one Bargo River site, 9 km downstream of Tea Tree Hollow, immediately upstream of the Nepean River junction. The second DS2 site was the Nepean River, just downstream of the Bargo River confluence, 9.2 km downstream of Tea Tree Hollow (Fig. 1).

The first six sampling occasions (16 April; 24 June; 5 August; 27 September; 8 October; 11 November) were in 2019. Due to dangerous weather conditions (bushfire and flood) and access difficulties, sampling was then suspended until April 2020. Sampling was conducted on five occasions in 2020 (April 17; April 26; May 15; May 28; June 24 2020). On four of these five occasions in 2020, samples were collected from the group of three sites further downstream (DS2) and the reference site on the Nepean River, upstream of Bargo River. Over the sampling period, the monthly rainfall recorded at the Camden Automatic weather station located 22 km from the study area (BOM 2021) was dryer than normal and resulted in a total of 875.6 mm. This was less than the long-term average of 944.3 mm. There was one period of very heavy rain in 7 to 10 February of 2020 that recorded 320 mm of rainfall and resulted in minor flooding (personal observation). We suspended sampling for several weeks to avoid the post-flood conditions and recommenced sampling on 17 April 2020.

At each site, on each sampling occasion, physio-chemical water quality attributes of pH, salinity as electrical conductivity (EC), dissolved oxygen (DO), turbidity and water temperature were measured in situ using portable water quality metres. These included a YSI ProODO metre for measuring dissolved oxygen and water temperature, a TPS WP81 for electrical conductivity and pH and a HACH 2100P IS turbidity metre for turbidity. Each metre was checked for calibration and adjusted if necessary prior to use on each sampling day. Five replicated measurements of each of the above water quality attributes were recorded from each site on each sampling occasion, once the metre readings had stabilised.

Duplicate samples of water were collected at each site on each sampling occasion in unused sample containers provided by the commercial testing laboratory (Envirolab Services, Sydney). Water samples for metal determination were collected using unused bottles that had been pre-treated by nitric acid. Samples were chilled and delivered to the laboratory for analysis. All samples that were analysed in the laboratory used appropriate methods (APHA (American Public Health Association) 1998). The methods were ‘Metals-020’: inductively coupled plasma (ICP) atomic emission spectroscopy (ICP-AES); and ‘Metals-022’: ICP mass spectrometry (ICP-MS). The methods are endorsed by the National Associations of Testing Authorities (NATA) for determination of anions (method: ‘Inorg-081’), cations (calcium, potassium, sodium, magnesium, bicarbonate, carbonate, sulphate, chloride, phosphate); total nitrogen and nitrate (method 'Inorg-055/062/127') and total metals (arsenic, barium, cadmium, chromium, copper, cobalt, manganese, molybdenum, nickel, lead, titanium, strontium, lithium, aluminium, iron, zinc, uranium). Detection limits for metals were generally 1 μg/L for most metals. Lower detection limits are applied for cadmium (0.1 μg/L) and uranium (0.5 μg/L), and higher detection limits applied to manganese (5 μg/L), aluminium and iron (10 μg/L) and boron (20 μg/L).

Water chemical results were compared to Australian Water Quality Guidelines (ANZECC (Australian and New Zealand Environment and Conservation Council). 2000). The category of guidelines chosen was *protection of freshwater aquatic ecosystems* (ANZECC (Australian and New Zealand Environment and Conservation Council). 2000). This category reflects the community and stakeholder value for the conservation of the natural environmental qualities of the Bargo and upper Nepean rivers (Healthy Rivers Commission of New South Wales 1998; Hawkesbury-Nepean River Health Strategy 2007; Pinto and Maheshwari 2015; Wollondilly Shire Council 2020). For metal guidelines, the 95% protection of species was selected, as it is recommended for slightly/moderately disturbed systems (ANZECC (Australian and New Zealand Environment and Conservation Council). 2000). The water samples collected in this study represented total unfiltered metal concentrations. It is acknowledged that appropriately filtered samples can enable a more accurate estimation of metal bioavailability (Markich et al. 1998).

2.4 Data Analysis

Before conducting any statistical testing, each water quality variable was firstly examined for heterogeneity of variance using Levene's test. It was found that many variables were not normally distributed, resulting in a non-parametric statistical analysis technique used. The Kruskal-Wallis test was used to compare significant differences across the four sampling groups (REFS, WASTE, DS1 and DS2). Significant Kruskal-Wallis results were then followed with Dunn's post hoc pairwise comparison of site groups. All statistical analysis was performed using IBM SPSS Statistics version 25. Ionic strength calculations were performed using the PHREEQC programme (version 3.1.7.9213) with LLNL database utilising the Debye-Hückel approach (Parkhurst and Appelo 2013).

3 Results

The discharge of effluent from Tahmoor Colliery to the Bargo River resulted in a water contamination plume that stretched more than 9 km downstream. The effluent increased salinity in the Bargo River by five times, from a mean of 198.1 μS/cm at reference sites to 1200 μS/cm below the effluent entry (DS1; Table 1; Fig. 2). This exceeded the ANZECC (Australian and New Zealand Environment and Conservation Council) (2000) guidelines for salinity (< 350 μS/cm) by more than three times. Salinity at the furthest downstream sites (DS2, 9.0–9.2 km below waste inflow) remained elevated (mean 769.3 μS/cm) more than double the guideline. Salinity of Tahmoor Colliery effluent (mean 2181.3 μS/cm) was almost 10 times higher than that of reference sites (Fig. 2). Effluent from Tahmoor Colliery was alkaline (8.7 pH) and increased pH of the Bargo and Nepean rivers (Table 1). The pH of reference sites (mean 7.03) was nearly 1.7 pH units lower than the Bargo River below the mine waste (DS1 mean of 8.71), exceeding the maximum ANZECC (Australian and New Zealand Environment and Conservation Council) (2000) pH guideline (6.5–7.5) by more than 1 pH unit. The elevated pH persisted at the most downstream sites (DS2 mean 8.62), 9 to 9.2 km below the mine discharge point.

The ionic composition of both the Bargo River and the Nepean River was modified due to the inflow of effluent from Tahmoor Colliery (Fig. 3). The ionic strength at the reference site was 0.002 M (Table 1) and is indicative of a typical sodium chloride freshwater with intermittent local groundwater intrusion modulated by low to moderate flow ranges (Fig. 4). The entry of mine effluent increased the ionic strength to 0.026 M at the discharge site and this decreased with distance downstream to 0.010 M which is still five times greater than the reference values. Bicarbonate was the dominant anion in the coal mine wastes (mean 990.7 mg/L; Fig. 4). Mean bicarbonate concentration in the Bargo River increased by more than 60 times, from 10.2 mg/L at reference sites to 641.1 mg/L downstream of the waste discharge (Fig. 4). Elevated bicarbonate levels 9–9.2 km downstream of the discharge (DS2 mean 345.83 mg/L) was more than 30 times that of reference sites (Fig. 4). Sodium was the dominant cation in the coal mine wastewater (mean 487.4 mg/L; Fig. 5) which increased the Bargo River mean sodium concentration by more than 12 times, from 21.1 mg/L at reference sites to 306.9 mg/L below the mine discharge (DS1, Fig. 5).

Table 1 Water quality summary statistics including range (maximum to minimum) and mean (median). *p* values for differences according to sampling site category is provided. Across rows, mean values that are followed by one or more identical letters are not significantly different (*p* value > 0.05). Site locations are explained in methods (Bd, below detection)

		Ref		Waste		DS1 (80 m–2 km)		DS2 (9 km–9.2 km)	
	p value (K-W)*	Range	Mean (Median)	Range	Mean (Median)	Range	Mean (Median)	Range	Mean (Median)
Temperature (°C)	0.0001	9.9–19.1	14.4 ^{A}(13.3)	12.2–19	16.5 $^{\mathbf{B}}$ (17.1)	10.2–21.5	15.2 ^{A} (16)	10.3–17.8	13.4 ^{A} (12.65)
Dissolved oxygen (% saturation)	0.054	76.3–102.9	92.9 ^{A} (93.2)	68.2–109.8	94.2 ^{A}(92.9)	83.5–106.3	92.2 ^{A,C}(92.9)	89–106.2	97.7 ^{C}(97.3)
Turbidity (NTU)	0.0001	1.31–148	21 ^{A}(5.11)	2.23–319	77.4 ^{B}(29.65)	2.44–142	30.3 ^{C}(10.1)	1.65–20.7	8.8 ^{D,A}(4.09)
pH (pH units)	0.0001	6.02–7.74	7.03 ^{A}(7.07)	8.42-9.06	8.7 ^{B}(8.68)	8.25–9.08	8.71 ^{B}(8.73)	8.16–8.94	8.62 ^{B}(8.65)
Electrical conductivity (µS/cm)	0.0001	129.2–276.8	198.1 ^{A}(216.1)	1993–2481	2181.3 ^{B}(2182)	531.7–2010	1200 ^{C}(1122)	343.4–1236	769.3 ^{C}(785.15)
Arsenic (µg/L)	0.0001	Bd.	Bd.^{A}(Bd.)	31–85	59.75 ^{B}(60)	8–79	28.6 ^{C} (24)	7–13	8.86 ^{A,C}(8)
Barium (µg/L)	0.0001	12–48	20.9 ^{A}(16)	2400–4500	3434.4 ^{B}(3500)	590–3400	2000.5 ^{C}(1800)	480–940	650.7 ^{A}(570)
Cadmium (µg/L)	0.300	Bd.	Bd.(Bd.)	Bd.–0.5	0.085 (0.05)	Bd.–0.2	0.056 (0.05)	Bd.–1.1	0.125 (0.05)
Chromium (µg/L)	NA	Bd.	Bd.(Bd.)	Bd.	Bd.(Bd.)	Bd.–1	0.53 (0.05)	Bd.	Bd.(Bd.)
Copper (µg/L)	0.0001	Bd.	Bd. ^{A}(Bd.)	Bd.–4	2.1 ^{B}(2)	Bd.–4	0.89 ^{C}(0.5)	Bd.	Bd. ^{A,C} (Bd.)
Cobalt (µg/L)	0.0001	Bd.–2	0.66 ^{A}(0.5)	6–8	6.75 ^{B}(7)	2–7	3.94 ^{C}(4)	1–4	2.14 ^{A,C}(2)
Manganese (µg/L)	0.0001	20–390	150.8 ^{A}(150)	Bd.–69	32.8 ^{B}(30)	Bd.–93	32.6 ^{B}(29)	Bd.–39	13.4 ^{B}(14)
Molybdenum (µg/L)	0.0001	Bd.	Bd. ^{A}(Bd.)	16–27	23 ^{B}(24)	3–24	12.69 ^{C}(14)	5–10	7.07 ^{A,C}(7)
Nickel (µg/L)	0.0001	Bd.–3	1.18 ^{A}(1)	50–72	60.78 ^{B}(60)	14–70	37.3 ^{C}(38)	13–32	20.85 ^{A,C}(20)
Lead (µg/L)	0.0001	Bd.	Bd. ^{A}(Bd.)	Bd.–5	1.89 ^{B}(1.5)	Bd.–3	0.74 ^{A}(0.5)	Bd.	Bd. ^{A}(Bd.)
Titanium (µg/L)	0.147	Bd.	Bd.(Bd.)	Bd.–1.7	0.59(0.5)	Bd.–3	0.8(0.5)	Bd.	Bd.(Bd.)
Strontium (µg/L)	0.0001	23–42	30.2 ^{A} (28)	560–870	687.18 ^{B}(660)	150–690	423.8 ^{C} (450)	150–270	194.3 ^{A,C}(170)
Lithium (µg/L)	0.0001	Bd.–7	2.4 ^{A}(2)	660–1800	1331.2 ^{B}(1300)	290–1600	765.1 ^{C}(620)	320–590	435 $^{A, C}$(415)
Aluminium (µg/L)	0.0001	5–60	29.4 ^{A}(30)	20–4000	858 ^{B}(135)	20–2500	241.7 ^{B,C}(80)	40–260	70.7 ^{C,A} (50)
Iron (µg/L)	0.001	Bd.–2500	679 ^{A}(420)	Bd.–680	165.1 ^{B}(86)	Bd.–1500	390.1 ^{B,C}(130)	88–870	357.1 ^{C,A}(315)
Zinc (µg/L)	0.0001	Bd.–10	3.7 ^{A}(4)	22–99	49.4 ^{B} (44)	11–54	24.8 ^{C}(24)	6–16	10 ^{A}(9)
Uranium (µg/L)	0.0001	Bd.	Bd. ^{A}(Bd.)	3.7–10	6.94 ^{B}(7.1)	1–6.8	3.93 ^{C}(4.1)	1.3–2.4	1.87 ^{A,C}(1.9)
Calcium (mg/L)	0.0001	2.7–4.7	3.4 ^{A} (3.35)	10–26	16.8 ^{B}(16)	7.1–18	12.3^{B}(12.5)	6.9–10	8.05^{A}(7.85)
Potassium (mg/L)	0.0001	1.7–3.4	2.46 ^{A}(2.5)	20–31	24.1^{B}(23)	6.9–28	16.6 ^{C}(17.5)	7.8–12	9.4 ^{A,C}(9.05)
Sodium (mg/L)	0.0001	12–34	21.1 ^{A}(22.5)	390–600	487.4 ^{B}(490)	110–550	306.9^{C}(305)	120–250	165 ^{A,C}(145)
Magnesium (mg/L)	0.0001	2.9–8.3	5.28 ^{A}(5.5)	10–17	12.85 ^{B}(12)	6.2–16	10.9 ^{B}(12)	6–8.8	7.3 ^{A}(7.45)
Bicarbonate (mg/L)	0.0001	Bd.–18	10.2 ^{A}(12.5)	540–1200	990.7 ^{B}(1050)	230–1300	641.1 ^{C}(655)	260–510	345.8 ^{A,C}(310)
Carbonate (mg/L)	0.0001	Bd.	Bd. ^{A} (Bd.)	21–99	67.3 ^{B}(68)	2.5–89	48.05 ^{C}(52)	2.5–42	19.6 ^{A,C}(16.5)
Total alkalinity (mg/L)	0.0001	Bd.–18	9.9 ^{A} (12)	600–1300	1054.2 ^{B}(1100)	230–1300	686.6 ^{C}(705)	260–550	365 ^{A,C}(325)
Sulphate (mg/L)	0.0001	4–6	4.32 ^{A}(4)	7–37	20.5 ^{B}(18)	7–27	11.83 ^{C}(11)	9–16	10.91 ^{B,C}(10)
Chloride (mg/L)	0.0001	24–82	48.1^{A}(50)	82–110	92.7 ^{B}(94)	53–100	76.2 ^{C}(78)	50–72	62.1 ^{A,C} (61)
Nitrate (mg/L)	0.0001	Bd.–0.44	0.215 ^{A} (0.25)	Bd.–2.50	1.58 ^{B}(1.80)	Bd.–1.50	0.737^{A,C}(1.0)	0.56–0.99	0.712^{B,C}(0.67)
Nitrite (mg/L)	0.0001	Bd.–0.02	0.005 ^{A} (Bd.)	Bd.–2.0	0.519 ^{B}(0.19)	Bd.–1.90	0.517^{C}(0.096)	Bd.	Bd. ^{A,C}
Fluoride (mg/L)	0.0001	Bd.–0.05	0.041 ^{A} (Bd.)	0.027–0.5	0.387 ^{B}(0.5)	Bd.–0.4	0.21^{A,C}(0.2)	0.1–0.2	0.15^{B,C}(0.15)
Total nitrogen (mg/L)	0.0001	0.3–0.6	0.43 ^{A} (0.4)	0.05–4.0	2.73 ^{B} (2.40)	0.9–2.3	1.44 ^{C}(1.35)	0.05–1.3	0.858 ^{A,C} (0.9)
Phosphate (mg/L)	0.005	Bd.–0.05	0.013 ^{A} (Bd.)	0.01–0.5	0.063 ^{B}(0.019)	Bd.–0.2	0.039 ^{A,B} (0.008)	Bd.–0.025	0.009 ^{A,C}(Bd.)
Ionic strength (M)			0.002		0.026		0.017		0.010

Total nitrogen concentrations in the Bargo River increased by more than three times, from 0.43 mg/L at reference sites to 1.44 mg/L in the Bargo River below the mine discharge (DS1; Fig. 6; Table 1). This exceeded the recommended guideline (< 0.25 mg/L) by almost five times (ANZECC (Australian and New Zealand Environment and Conservation Council) 2000). The total nitrogen concentration furthest downstream of the effluent inflow (DS2 mean 0.925 mg/L) was more than twice the mean recorded at reference sites and was several times above the guideline. The total nitrogen concentration of the mine waste varied from 2.1 to 4.0 mg/L, with a mean of 2.73 mg/L (Table 1). Nitrate was the dominant form of nitrogen

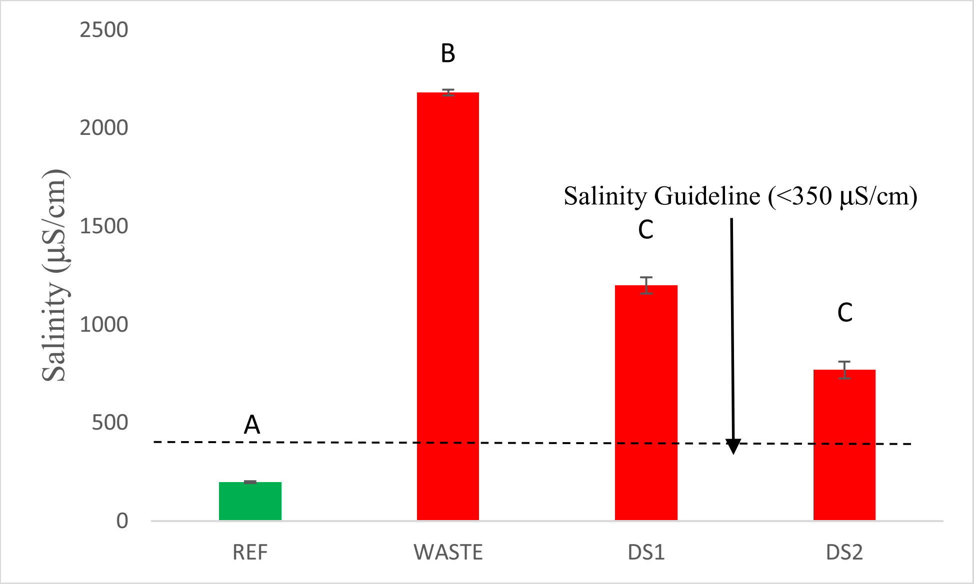

Fig. 2 Mean (± SEM) salinity, measured as electrical conductivity (µS/cm) at each sampling site category. The ANZECC (2000) guideline is indicated. Above each mean value is one letter. Mean values sharing identical letters are not significantly different (p value > 0.05)

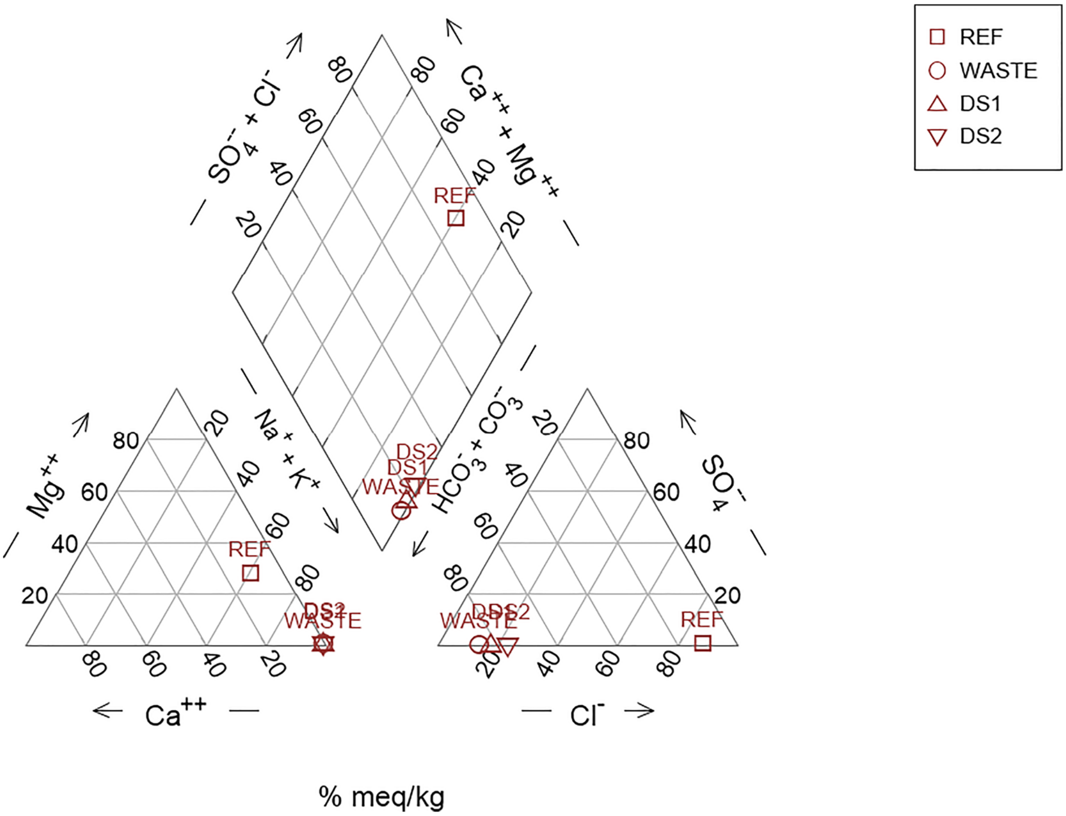

Fig. 3 Ternary diagram of dominant ions across each sampling site category

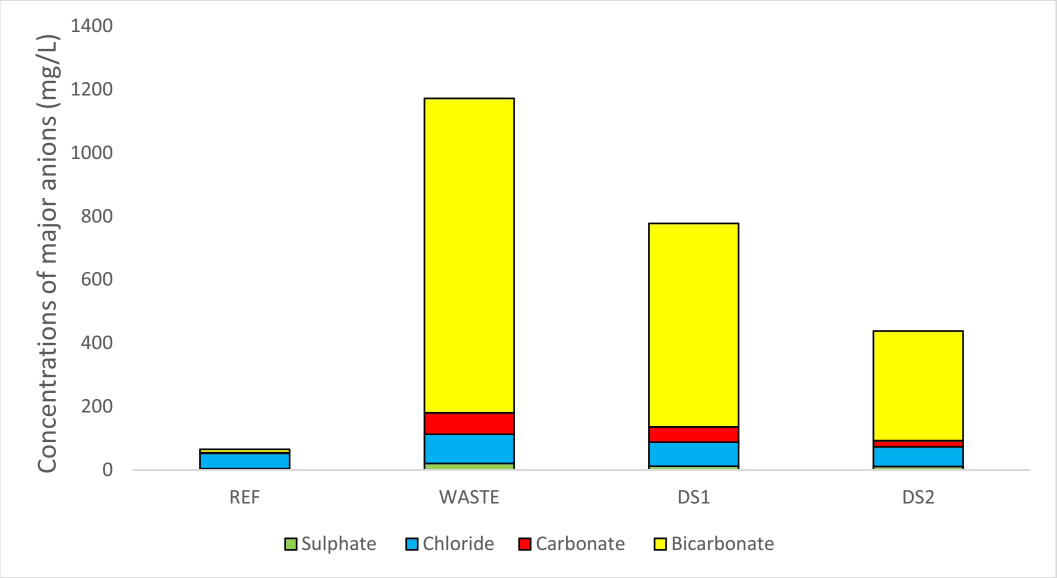

Fig. 4 Mean concentration of major anions at each sampling site category

in the mine effluent, at a mean of 1.58 mg/L compared to a mean of 0.519 mg/L for nitrite (Table 1). Mean nitrate was elevated in the Bargo River from 0.215 mg/L at reference sites to 0.737 mg/L below the mine discharge point (sites DS1), with elevated levels (mean 0.712 mg/L at sites DS2) persisting up to 9 km downstream (Table 1).

The metallic (excluding Ca^{2+}, K^{+}, Na^{+} or Mg^{2+}) content of the Bargo River and Nepean River was strongly influenced by the entry of the colliery effluent (Table 1; Fig. 7). The mean combined metal content in the Bargo River, immediately below the mine outfall, was 3968 μg/L (DS1; Fig. 7). This was more than four times higher than the combined metal content of water from reference sites (918.2 μg/L). Three metals (barium, strontium and lithium) accounted for an average 80.4% of the metal content in the Bargo River below the inflow of effluent (Fig. 7). Further downstream (DS2), these

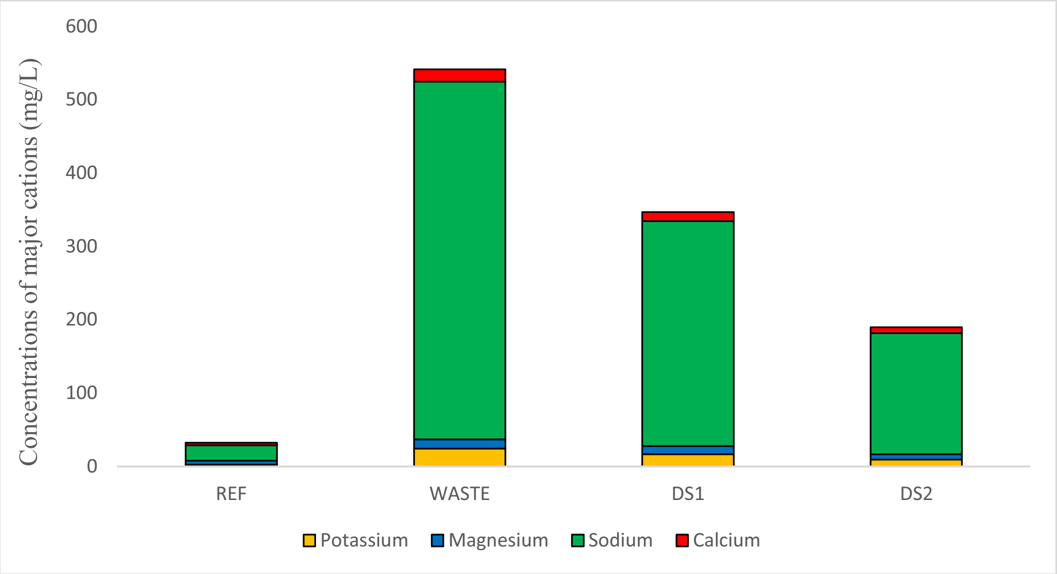

Fig. 5 Mean concentration of major cations at each sampling site category

three metals were still dominant and comprised 72.2% of the total mean metal content of water samples. In contrast, these three metals only contributed 5.8% of the mean metal content at reference sites. The mine wastes increased the mean concentration of barium in the Bargo River by nearly 100 times, from 20.9 μg/L at reference sites to 2000.5 μg/L below the mine discharge (DS1; Table 1; Fig. 7). Lithium in the Bargo River increased steeply, due to the entry of the mine wastes, rising by more than 300 times, from 2.4 μg/L at reference sites to 765 μg/L below the mine waste inflow (DS1; Fig. 7).

The inflow of the mine effluent reduced the relative abundance of three metals (iron, aluminium and manganese) that are common in natural unmodified waterways flowing in sandstone geology in the Sydney Basin (Price and Wright 2016). These three metals contributed a combined mean concentration of 859.2 μg/L in reference site water samples, accounted for 93.6% of the total mean metal content (Fig. 7). These three metals were less abundant in the Bargo and Nepean rivers, below the entry of the mine effluent, accounting for a much lower proportion (DS1 16.7% and DS2 24.9%) of the metal content.

Four metals (nickel, zinc, arsenic and aluminium) in the Bargo River, below the entry of mine effluent, were recorded at ecologically hazardous concentrations exceeding ecosystem protection guidelines (Table 1; Figs. 7, 8, 9, 10; 95% protection of species; ANZECC (Australian and New Zealand Environment and Conservation Council) 2000). The concentration of nickel in the Bargo River below the effluent outfall (DS1 mean 37.3 μg/L) was three times the maximum recommended guideline (< 11 μg/L) and 30 times higher than recorded at reference sites (mean 1.18 μg/L; Table 1; Fig. 8). Tahmoor Colliery effluent had a mean nickel concentration of 60.7 μg/L. Concentrations of nickel, greater than the guideline, persisted even at the most downstream sites (DS2) 9 km below the entry of mine effluent to the Bargo River. The effluent had a mean zinc concentration of 49.43 μg/L and its entry to the Bargo River increased mean zinc content from 3.7 μg/L at reference sites to 24.8 μg/L downstream (DS1; Table 1). The recommended guideline for zinc is < 8 μg/L (95% protection; ANZECC (Australian and New Zealand Environment and Conservation Council) 2000). Elevated zinc levels (mean 10 μg/L) persisted for up to 9 km below the entry of the effluent (DS2; Table 1; Fig. 9). Arsenic was not detected at reference sites (< 1 μg/L), but was recorded at a mean concentration of 28.6 μg/L in the Bargo River below the effluent discharge, more

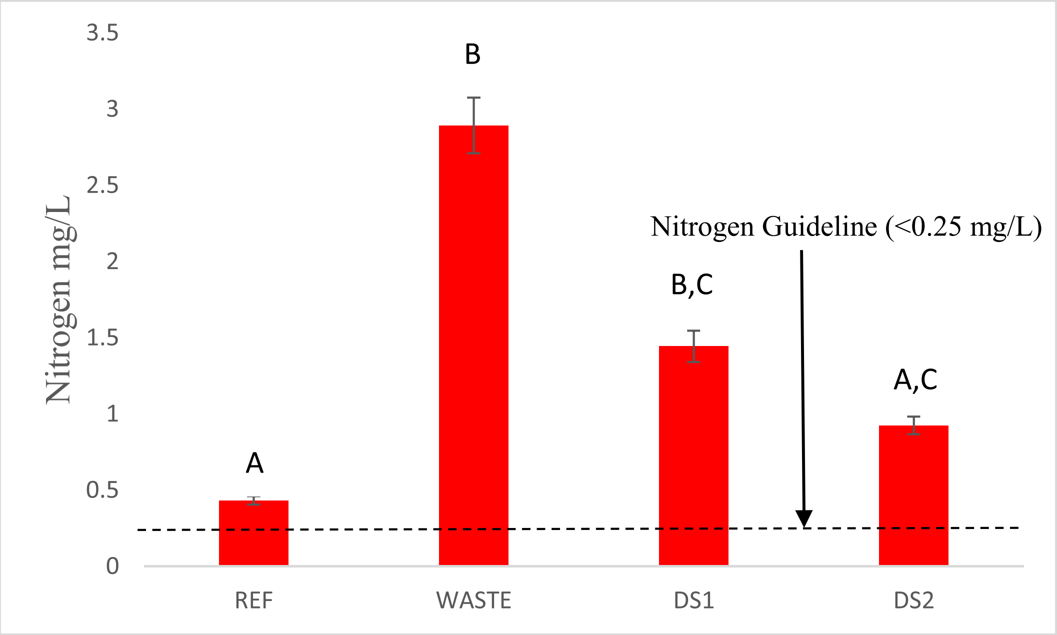

Fig. 6 Mean (± SEM) total nitrogen concentration at each sampling site category. The ANZECC (Australian and New Zealand Environment and Conservation Council). (2000) total nitrogen guideline is indicated. Above each mean value is one or two letters. Mean values sharing identical letters are not significantly different (*p* value > 0.05)

than twice the recommended guideline (< 13 µg/L arsenic V; Fig. 10). The effluent also increased the mean aluminium concentration of the Bargo River (mean 241.7 µg/L) by more than 25 times, compared to the level at reference sites (mean 29.4 µg/L; Table 1). The recommended guideline for aluminium (when pH > 6.5) is < 55 µg/L (95% protection; ANZECC (Australian and New Zealand Environment and Conservation Council) 2000).

4 Discussion

Water quality results from this 14-month study reveal that the overall impact of mine effluent discharged by Tahmoor Colliery to the Bargo River is consistent with *water pollution* as defined in the Protection of the Environment Operations (POEO) Act, 1997 (POEO 2018). This legislation empowers the NSW EPA to control the disposal of mine effluent. Environmental regulation of this mine fails one of the key aims of this legislation: 'to protect, restore and enhance the quality of the environment in New South Wales…' (POEO 2018). Further details are provided in the discussion for the pollutants in the colliery effluent that have been recorded at ecologically hazardous concentrations in this study. Comparison is made for a range of key pollutants found in this study in both the mine effluent and rivers with relevant Australian water quality guidelines (ANZECC (Australian and New Zealand Environment and Conservation Council) 2000) and also to the discharge limits imposed for that pollutant, under the mine's Environment Protection Licence (EPL 1389 2021).

Salinity of Tahmoor Colliery effluent (mean of 2181.3 µS/cm) was nearly 10 times higher than reference site samples (mean of 198.1 µS/cm). The mine effluent increased salinity in the Bargo River by five times (mean 1200 µS/cm) at DS1 below the entry point. These salinity levels are hazardous to aquatic ecosystems, exceeding the ANZECC (Australian and New Zealand Environment and Conservation Council) (2000) guideline for protection of ecosystems of 350 µS/cm. Horrigan et al. (2005) found that elevated salinity levels are hazardous to freshwater river biota as aquatic macroinvertebrate communities declined once salinity reached 800–1000 µS/cm. Sensitivity of aquatic biota to salinity was demonstrated in a study investigating aquatic mayfly species (Ephemeroptera) in the Appalachian region (Kentucky, USA; Pond 2010). Mayfly species were investigated across natural and disturbed (coal mine and residential development) streams and reported a steep decline in mayfly species at modestly increased salinity levels (200–300 µS/cm; Pond 2010). An earlier study investigating macroinvertebrates within the Bargo River also reported a decline of mayfly relative abundance below the entry of Tahmoor Colliery mine effluent, from comprising 15% of the community upstream, to 4.2% of the community downstream (Wright et al. 2015). This needs to be interpreted with caution as the difference was based on taxonomically coarse family-level data and the difference was not statistically different.

The increase of salinity in the Bargo River was one of the largest from a coal mine in the Sydney Basin (Belmer and Wright 2020). In comparison to the current study, the West Cliff Colliery mine effluent was marginally more saline (2319 µS/cm; Table 2; Price and Wright 2016). The West Cliff effluent discharged to the Georges River, increasing river salinity by 12 times, to 1228 µS/cm below the mine effluent entry point (Price and Wright 2016). Similar levels of salinity have been recorded in coal mine–affected UK waterways, such as in the Durham coalfield, with reported EC levels up to 2039 µS/cm (Jarvis and Younger 1997). The increased salinity of the Bargo River due to Tahmoor Colliery effluent was more than three times higher than the recommend water quality guideline (< 350 µS/cm) for south east Australian upland streams (ANZECC (Australian and New Zealand Environment and Conservation Council) 2000). During the current study, the EPL for Tahmoor Colliery had a maximum discharge limit for salinity of 2600 µS/cm (EPL 1389 2021). Most coal mines in the Sydney Basin do not have any discharge limits for salinity in their effluent discharges. Tahmoor Colliery is one of only two coal mines in the Sydney Basin with any discharge limit for salinity, the other (Springvale Colliery) has a maximum of 1200 µS/cm (Belmer and Wright 2020). The salinity discharge limit was added to the Tahmoor Colliery EPL, for the first time, in December 2011. This was added as an interim measure, until the planned wastewater treatment plant was operational, initially expected in late 2012 (NSW EPA 2011). Due to a series of problems with the new treatment facility, the interim salinity guideline (2600 µS/cm) remained the maximum permitted discharge limit during this study (EPL 1389 2021).

Tahmoor Colliery effluent contained elevated total nitrogen concentrations (mean of 273 mg/L), about five times higher than reference site samples (mean of 0.433 mg/L). Mine effluent discharged to the Bargo River more than doubled total nitrogen concentration (DS1 mean 1.44 mg/L). This result verifies the findings of an earlier study (Ali et al. 2017) that recorded elevated nitrogen concentrations (in the form of nitrite) in the Bargo River below the mine effluent discharge (Ali et al. 2017). Elevated nitrogen concentrations in the Bargo River are likely to contribute to the abundant growth of river algae. A previous study detected elevated concentrations of chlorophyll-*a* in the Bargo River downstream of the effluent entry point (Ali et al. 2018). Further downstream in the Nepean River elevated nitrogen and phosphorus concentrations have been frequently recorded, particularly due to the discharge of treated sewage wastes (Markich and Brown 1998; Sydney Water 2018). Currently, the EPL for Tahmoor Colliery has no discharge limits for any form of nitrogen (EPL 1389 2021). The lack of nitrogen discharge limits is puzzling as the EPA tightly controls the disposal of nitrogen-enriched waste to waterways in the Hawkesbury-Nepean catchment, which has a long history of problems associated with eutrophication (Markich and Brown 1998).

Nickel and zinc are potentially ecologically harmful metals often associated with coal mine effluent and contamination of waterways (Younger 1993; Brake et al. 2001; Griffith et al. 2012; Belmer and Wright 2020; Strosnider et al. 2020). Nickel concentrations in the Bargo River, below the effluent discharge, had a mean concentration of 37.3 μg/L, about 30 times above the concentration (mean 1.18 μg/L) in reference site samples. The mean nickel content of Tahmoor mine effluent was 60.78 μg/L. A similar trend was also detected for zinc, which increased from a mean of 3.73 μg/L at reference sites, rising to 24.8 μg/L below the entry of mine effluent (mean zinc 49.4 μg/L). The nickel and zinc concentrations recorded in the Bargo River downstream from the mine discharge were ecologically hazardous, on average, three to 3.5 times above the recommended guideline for protection of 95% of aquatic species (11 μg/L nickel, 8 μg/L zinc; ANZECC (Australian and New Zealand Environment and Conservation Council) 2000). Even at the most downstream sites (DS2) 9 km below the waste entry, the mean nickel and zinc concentrations remained higher than the ANZECC (Australian and New Zealand Environment and Conservation Council) (2000) guidelines and reference site results. However, it is important to note that the toxicity of both nickel and zinc are influenced by water hardness. As the DS1 sites (Bargo River) were classified as moderately hard, the hardness-corrected trigger value for nickel and zinc (according to ANZECC (Australian and New Zealand Environment and Conservation Council) 2000) were both 2.5 times higher (27.5 μg/L nickel, 20 μg/L zinc). All other river sites (reference and DS1) were classified as soft.

Currently, the EPL 1389 for Tahmoor Colliery has a maximum discharge limit for nickel of 200 μg/L and a maximum zinc discharge limit of 300 mg/L (EPL 1389 2021). Both discharge limits are well above the ANZECC guideline for each metal. The discharge limit for zinc of 300 mg/L seems extraordinarily hazardous, as it permits the discharge of zinc at concentrations approximately 37,000 times higher than the ANZECC (Australian and New Zealand Environment and Conservation Council) (2000) guideline (8 μg/L). In contrast, another Sydney Basin coal mine, Clarence Colliery, is only permitted to discharge effluent with a maximum of 8 (μg/L) of zinc and 11 (μg/L) for nickel (EPL 726; Belmer and Wright 2020).

The mean concentrations of nickel and zinc in Tahmoor mine effluent were compared to levels reported in an extensive study of European mine waters (Gombert et al. 2018). Nickel in Tahmoor effluent (60.8 μg/L) was about 62% higher than the average level in Europe mine effluent (37.4 μg/L; Gombert et al. 2018). Zinc, in contrast, was much lower in Tahmoor effluent (49.4 μg/L) compared to the Europe average (440 μg/L), although there was considerable variation in zinc levels across Europe, with mine drainage from Germany having the highest mean zinc content of 899 μg/L (Gombert et al. 2018). Much higher concentrations of nickel and zinc, than recorded in this study, were reported from waterways contaminated by the Green Valley coal mine (Indiana, USA) with nickel levels often above 500 μg/L and zinc often above 5000 μg/L (Brake et al. 2001). Nickel and zinc concentrations have been recorded at ecologically hazardous concentrations in effluent from active and closed mines in Sydney Basin (Table 2). Elevated levels of zinc may remain ecologically hazardous for years after coal mines cease operation. For example, a disused coal mine (Canyon Colliery), in the western coalfield of the Sydney Basin, continued to release highly elevated levels of zinc (mean 595 μg/L) via a small stream into the Grose River lifting zinc concentrations from < 5 μg/L, upstream, to 388 μg/L (Wright and Burgin 2009a). The highest mean nickel (418 μg/L) and zinc (1161 μg/L) concentrations reported in the Sydney Basin were both recorded in effluent from the Berrima (Medway) Colliery. This was three years after the mine closed and underground workings were flooded (Wright et al. 2018).

This investigation detected arsenic in Tahmoor Colliery effluent at the highest concentrations reported from Australian coal mines. The mean effluent concentration for arsenic (mean 59.75 μg/L) in this study was about five times greater than was reported in West Cliff Colliery effluent (Price and Wright 2016). The concentration of arsenic in Tahmoor Colliery effluent was about three times greater than the average concentration in samples from European coal mines (18.6 μg/L; Gombert et al. 2018). Gombert et al. (2018) reported the average arsenic content of French mine water samples of 60.5 μg/L, which is comparable to Tahmoor Colliery effluent. The species of arsenic in Tahmoor Colliery mine effluent was examined in March 2020 (Tia Richardson *personal communication*) and was found to be arsenic (V). The ANZECC (Australian and New Zealand Environment and Conservation Council). (2000) guideline for arsenic (V) for protection of 95% of species is 13 μg/L. Arsenic was not detected in any reference site samples in this study (< 1 μg/L). The mean concentration of arsenic in the Bargo River, below the discharge, was double the ANZECC guideline (mean 28.6 μg/L). Currently, the EPL 1389 for discharge of Tahmoor Colliery effluent allows a maximum arsenic concentration of 200 μg/L. In comparison, the EPL (EPL 2504) for West Cliff Colliery permits a much lower maximum concentration of 19 μg/L (Belmer and Wright 2020).

Table 2 Comparison of mean salinity and metal concentrations (for nine metals) recorded in coal mine effluent in this study (Tahmoor Colliery) with effluent from three other underground collieries in the Sydney Basin. Westcliff Colliery is an active coal mine located 21.6 km east of Tahmoor. The two other coal mines are closed with Berrima (Medway) Colliery located 38.8 km south west of Tahmoor and Canyon Colliery is 83.8 km north of Tahmoor. The data for Westcliff and Canyon mines is from Price and Wright (2016) and data for Berrima (Medway) is from Wright et al. (2017). The symbol NT represents 'not tested'

	Tahmoor	Westcliff	Canyon	Berrima
Salinity (μS/cm)	2181	2319	116.9	1000
Arsenic (μg/L)	59.75	8.86	Bd.	NT
Barium (μg/L)	3434.4	365.0	27.7	39.4
Manganese (μg/L)	32.8	74.6	417.5	11,939
Nickel (μg/L)	60.78	138.6	210.0	418.0
Strontium (μg/L)	687.18	211.7	21.7	250.0
Lithium (μg/L)	1331.2	NT	NT	57.3
Aluminium (μg/L)	858	557.1	6.25	42.7
Iron (μg/L)	165.1	439.1	310.0	10,939
Zinc (μg/L)	49.4	38.6	370.0	1161

The current EPL 1389 for Tahmoor Colliery does not specify discharge limits for the metals barium, lithium and strontium, despite these being the dominant metals found in the mine effluent, and also in the Bargo and Nepean river samples below the mine discharge (Fig. 7). A recent ecotoxicology study on barium reported that the water flea (*Ceriodaphnia dubia*) was sensitive to barium with an EC10 concentration of 1.7 mg/L (Golding et al. 2018). This concentration is lower than the mean concentration of barium in Tahmoor Colliery effluent (3.4 mg/L) and also is lower than mean concentration of barium in Bargo River (DS1) of 2.0 mg/L (Table 1). It is possible that such concentrations of barium recorded in this study may be hazardous for aquatic species. It is recommended that further investigation be conducted on the toxicity of barium to provide a recommended guideline for aquatic ecosystems, and also to guide revision of appropriate discharge limits for EPL 1389. Both strontium and lithium have both been reported to be toxic to freshwater species, but at concentrations greater than was recorded in this study (Aral and Vecchio-Sadus 2008; McPherson et al. 2014) (Fig. 7).

Barium, strontium and lithium have also been detected bioaccumulating within willow tissue grown in a laboratory study using Tahmoor Colliery effluent (*Salix babylonica*; Morrison et al. 2019). The study was conducted over 6 weeks and grew two groups of willow cuttings in a controlled environment. One was grown in Tahmoor effluent, and the other in water from the reference site, Bargo River upstream of the mine outfall (Morrison et al. 2019). That study revealed that barium, lithium and strontium accounted for 52.2 to 56.5% of all metals detected in mine effluent willow tissue, compared to 13.9–16.1% willow tissue grown in reference site water (Morrison et al. 2019). Whilst the broader ecological impacts are not well known, strontium has been found to bioaccumulate in some plant species (Burger and Lichtscheidl 2019). It is recommended that future mine effluent discharge limits be considered for barium, lithium and strontium and other elements based on further studies of ecotoxicology and

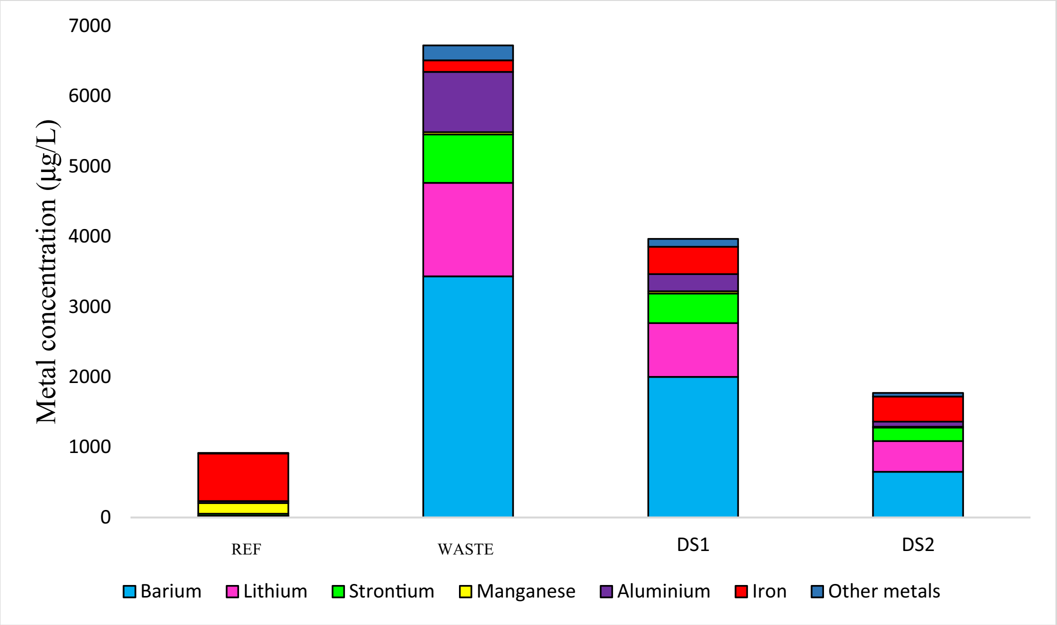

Fig. 7 Mean concentration of most abundant six metals and combined concentration of less abundant 11 'other metals' at each sampling site category. Not including Ca, K, Na or Mg

bioaccumulation of contaminants in plants and animals exposed to mine effluent (e.g. Zrinka et al. 2019).

The ionic composition of the Bargo and Nepean rivers was modified by the entry of Tahmoor Colliery mine effluent. Reference site water chemistry was dominated by sodium and chloride ions, which is typical of coastal streams in south eastern Australia (Hart and McKelvie 1986). Below the inflow of mine effluent, the order of major anion dominance changed from that found at reference sites (Cl^{-}>HCO_3^{-}>SO_4^{-}) to (HCO_3^{-}> Cl^{-}> CO_3^{2-}>SO_4^{2-}). The concentration of HCO_3^{-} in the Bargo River below the mine (DS1 mean 641.1 mg/L) was more than 60 times greater than was found at reference sites (mean 10.2 mg/L). Below the mine discharge, the order of cation dominance (Na^{+}>K^{+}>Ca^{2+}=Mg^{2+}) remained similar to that of reference site samples (Na^{+}>Mg^{2+}>Ca^{2+}>K^{+}). The major change was that the sodium concentration below the mine (DS1 mean 306.7 mg/L) was more than 20 times greater than at reference sites (mean 21.1 mg/L). The mean concentration of sulphate of Tahmoor Colliery effluent of 20.5 mg/L appears to be very low compared to other studies. An international comparison of coal mine drainage by Strosnider et al. (2020) reported the lowest average sulphate concentration of 144 mg/L (Greece) to the highest of 1931 mg/L (South Korea).

The contamination of the Bargo and Nepean rivers documented in this 14-month study reflects ineffective environmental governance. The colliery's environmental licence allows the discharge of effluent containing ecologically hazardous concentrations of salinity and three metals (arsenic, nickel and zinc). The NSW EPA use an individual licence for Tahmoor Colliery, called an *Environmental Protection Licence*. However, in reality, the very high concentrations of metals and elevated salinity that are permitted in the colliery's licence allow it to release effluent that legally pollutes the Bargo and Nepean rivers. Under NSW legislation (Protection of the Environment Operations Act) it is an offence to pollute the environment, unless the pollutant is within discharge conditions in an Environmental Protection Licence. It is noteworthy that the licence for this colliery allows a maximum concentration of zinc in colliery effluent of 300 mg/L. This is more than 30,000 times higher than the recommended guideline of 0.008 mg/L (ecosystem protection: ANZECC (Australian and New Zealand Environment and Conservation Council) 2000). The NSW EPA issued the colliery with interim licence conditions in December 2011 for an expected period of about 12 months (NSW EPA 2012). This was based on their expectation that improved waste treatment systems at the colliery would reduce the

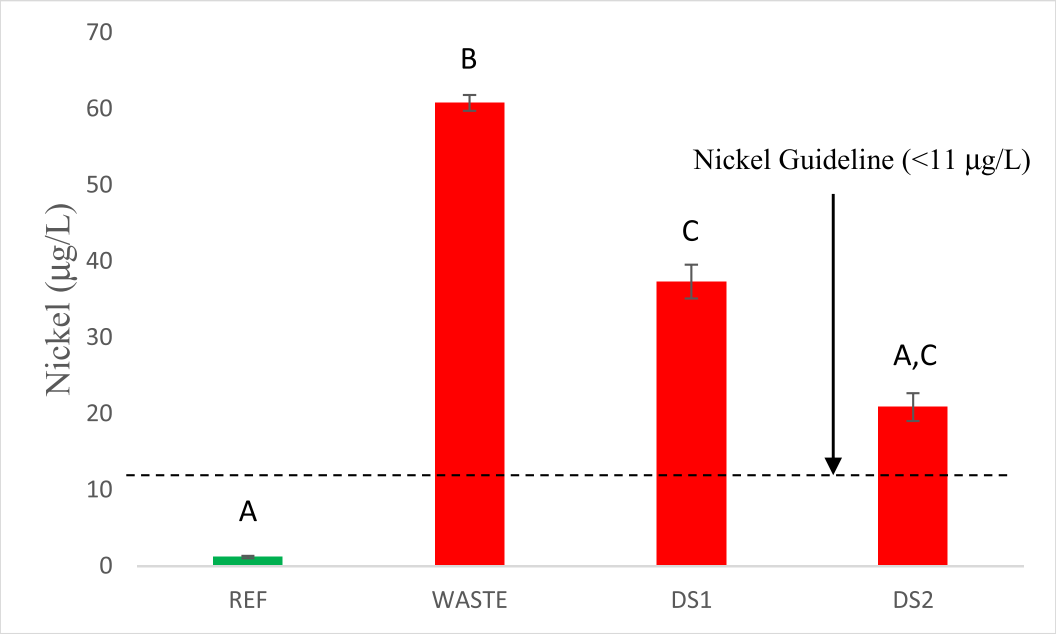

Fig. 8 Mean (± SEM) nickel concentration at each sampling site category. The ANZECC (Australian and New Zealand Environment and Conservation Council). (2000) nickel guideline is indicated. Above each mean value is one or two letters. Mean values sharing identical letters are not significantly different (*p* value > 0.05)

concentrations of arsenic, nickel, zinc and salinity to levels recommended in ANZECC (2000). This current study was conducted 7.5 to 8.5 years after the *interim* pollutant discharge limits were first enforced, which still remain in the EPA licence (EPL 1378). An additional regulation deficiency was that two ecologically

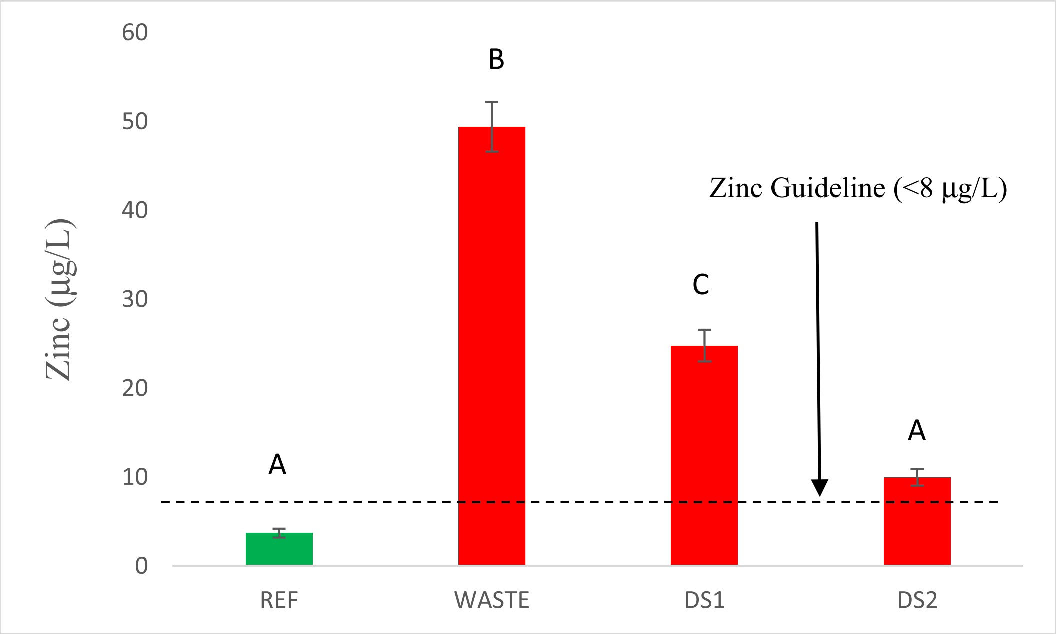

Fig. 9 Mean (± SEM) zinc concentration at each sampling site category. The ANZECC (Australian and New Zealand Environment and Conservation Council). (2000) zinc guideline is indicated. Above each mean value is one letter. Mean values sharing identical letters are not significantly different (*p* value > 0.05)

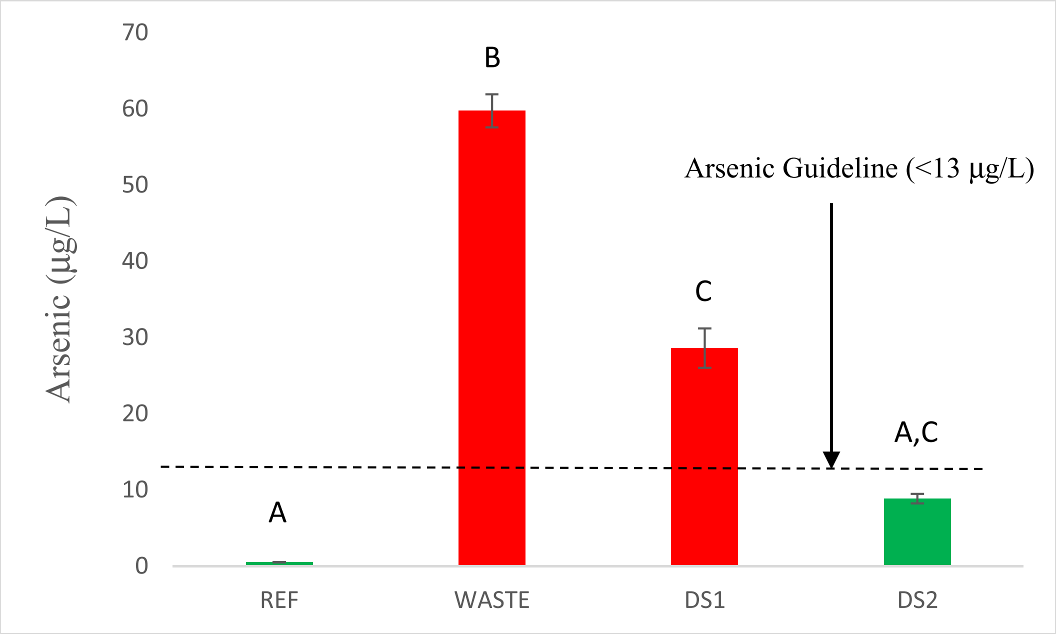

Fig. 10 Mean (± SEM) arsenic concentration at each sampling site category. The ANZECC (Australian and New Zealand Environment and Conservation Council). (2000) arsenic (V) guideline is indicated. Above each mean value is one or two letters. Mean values sharing identical letters are not significantly different (*p* value > 0.05)

hazardous pollutants revealed by this study (aluminium and nitrogen) were not specified in the licence.

Such deficiencies in Tahmoor Colliery's environmental licence (EPL 1389) are not isolated to this case study. Inadequate regulation of specific water pollutants in waste discharges has been found at many coal mine and other industrial discharges across NSW (Wright 2011; Wright et al. 2011; Graham and Wright 2012; Wright et al. 2018). The NSW Audit Office has also questioned the effectiveness of the NSW EPA's regulation of water pollution in Sydney's drinking water catchments (NSW Auditor-General 2018). However, improved regulation of pollution from coal mines has been enforced in at least one other coal mine in the Sydney Basin. The NSW EPA comprehensively addressed water pollution in the Wollongambe River caused by effluent discharged from Clarence Colliery. The EPA made comprehensive amendments to the environmental regulations applied to Clarence Colliery (NSW EPA 2017; Wright et al. 2017). The EPA updated the EPL 726 for Clarence Colliery and added new discharge limits for contaminants that were previously not included, along with reduced discharge limits on a range of pollutants. This included arsenic, nickel and zinc concentrations that conformed with the Australian ANZECC (Australian and New Zealand Environment and Conservation Council). (2000) guidelines for protection of aquatic ecosystems. Given the potentially serious risk to the ecological health of the Bargo and Nepean rivers identified in this study, it is recommended that the NSW EPA promptly revise the Tahmoor Colliery licence and require an urgent upgrade to its effluent treatment systems. It should also consider undertaking aquatic bioaccumulation investigations to refine the appropriate suite and concentration of pollutants to be included in future environmental protection licences for this and other coal mines.

Improved regulation of this effluent discharge should also consider how the water quality impact caused by discharge of effluent into waterways may be adversely affected by lack of dilution due to lower receiving river flow volumes. This is likely to be a growing issue in many parts of the world, such as many areas of southern Australia, which appear to be impacted by lower rainfall and lower river flows due to the influence of climate change (CSIRO and BOM (Bureau of Meteorology) 2020). An important example is a nearby waste discharge (7.4 km to the north east) where the discharge conditions do vary according to availability of dilution. At this site, the treated sewage wastes from the Picton sewerage treatment plant has an EPL licence (EPL 10555 2021) that does not permit the discharge of wastes in low flows (< 8 ML/day). The EPL also specifies that the discharge of treated sewage wastes can only occur when the volume released is less than 25% of daily creek flow. Given that the Tahmoor mine effluent in median flow conditions contributes approximately 67% of the median flow of the Bargo River (DPIE 2020; Appendix J), it would be appropriate to adopt discharge conditions that consider the supply of adequate dilution.

5 Conclusion

The study addressed each of the questions posed. It provides one of the most detailed investigations on the composition of coal mine effluent ever published on an Australian coal mine. The effluent is highly saline, and has an elevated suite of metals dominated by barium, strontium and lithium. The investigation is also one of the first in Australia to detect elevated concentrations of nitrogen in coal mine effluent. The study also revealed that the disposal of effluent from Tahmoor Colliery, over a 14-month period, to Bargo and Nepean rivers consistently increased salinity and pH, and modified the ionic composition at sampling sites within both rivers, below the entry of the mine effluent. The mine effluent also caused ecologically hazardous concentrations of salinity, nitrogen, aluminium, arsenic, zinc and nickel in the Bargo and Nepean rivers (ANZECC (Australian and New Zealand Environment and Conservation Council) 2000). The study did detect some improvement in water quality at the pair of sampling sites furthest (9 km) downstream from the effluent entry point. However, water quality at all sampling sites in Bargo River and Nepean River below the entry of mine effluent remained impaired and consistently exceeded safe levels for ecosystem protection for salinity, nitrogen and nickel. The environmental regulation of Tahmoor Colliery's mine effluent discharge has several deficiencies that fail to protect the Bargo and Nepean rivers from water pollution and potential ecological harm from the mine effluent. This study is based on assessment of water quality and further research to more completely document the impact of the effluent on the river should consider assessment of contaminants in river sediments and also on river biota. The future environmental regulation of treated effluent from mine should also consider protection of a broader range of community values for both waterways. For example, this should include conditions that protect primary and secondary contact recreational values of both waterways. It is also suggested that the dissolved metals be measured to evaluate the bioavailability of metals (ANZECC (Australian and New Zealand Environment and Conservation Council). 2000; Markich et al. 1998). It is also recommended that the speciation of arsenic should also be conducted to confirm the relative concentration of different forms of arsenic, such as the hazardous forms of arsenic (III) and arsenic (V) (Jain and Ali 2000).

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Declarations

Conflict of Interest The authors declare no conflict of interest.

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