



Regional Comparison of Impacts to Stream Macroinvertebrates from Active and Inactive Coal Mine Wastewater Discharges, Sydney Basin, New South Wales Australia

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Abstract: This study investigates macroinvertebrates from waterways receiving wastewater from coal mines in the Sydney Basin. Three of the coal mines were inactively mining and four actively mining during sampling. Macroinvertebrates were collected from each collieries receiving waterway upstream and downstream of all mine wastewater inflows. All the coal mines wastewater discharges are licensed and regulated by the New South Wales Environment Protection Authority (NSW EPA). Results of the study show that the coal mine wastewaters being discharged are having varying negative impacts to the receiving waterways aquatic ecosystem through macroinvertebrate biotic indices, despite whether mining is active or inactive. Biotic indices measured at active and inactive coal mines show that actively mined wastewaters are most likely causing less of an impact to the receiving waterways aquatic ecosystem than inactively mined wastewaters. All the waterways receiving untreated (inactively mining) wastewaters recorded statistical differences for all biotic indices when analysed between their upstream and downstream sample locations. This was in contrast to the actively mined (treated wastewaters) with only one of the streams sampled recording statistical differences for all biotic indices. Results suggest that once mining ceases and the treatment of the coal mine wastewaters subsequently ceases the receiving waterways aquatic ecosystem are clearly more degraded. This is of great concern as once mining ceases so does the treatment of their wastewaters. It is recommended that the NSW EPA further investigate measures of treatment post coal mining at these mines to ensure further degradation of the receiving waterways ecosystem does not occur.

Keywords: Benthic Macroinvertebrates, Coal Mine Wastewater, Coal Mining, Environmental Management, Coal Mine Regulation, Active Mines, Inactive Mines

1. Introduction

Coal mining practices are well documented to contribute to an array of differing environmental problems including air pollution, fire hazards, ground subsidence or deformation, surface and or ground water pollution. Surface water pollution is a major environmental problem associated with coal mining and occurs through the discharge of mine waters that are contaminated by various disturbances associated with mining practices [1-3].

Water pollution from coal mining occurs as large volumes of surface and groundwater are required to be removed from most underground coal mines. This is generally through the pumping of water to the surface as surface and groundwaters infiltrate the mine shafts through the local geological substrata and subsequently accumulates in the underground mine workings. Without this, groundwater would flood most sections of the underground mining operation [1, 4]. This practice of mine and wastewater discharge is licensed and regulated through contaminant limits in New South Wales by

the New South Wales Environmental Protection Authority [5].

Coal mine wastewater will often be contaminated due to the disturbance of the local geology associated with mining activities. The exact nature of the water contamination will vary depending on local factors such as groundwater geochemistry, hydrology and mineralogy of the local strata. In addition to the physical activity of the mining operation and the removal of the wastewater, other activities will also often contaminate water used throughout a mining plant which can include; coal washing and the inclusion of other wastes generated by the surface operation at the mine such as sewage wastes [4].

A widespread form of water pollution caused by coal and metalliferous mining is termed 'acid mine drainage' (AMD) and often occurs when wastewaters are not treated or when treatment ceases [6]. This arises when sulphur in coal (or other ores) is oxidised due to the disturbance associated with mining and its exposure to both air and water which triggers the formation of sulphuric acid of various strengths [2]. The AMD acid leaches and mobilises metals in mine water, depending on the sulphur content of the ore and the characteristics of the surrounding geology [2, 6, 7].

Water pollution impacts attributed to treated coal mine wastewaters discharged to surface waters often includes changes to pH, elevated salinity, modified stream ionic composition and elevated heavy metals [3, 8-14].

River sediments are also often heavily polluted from the mine wastewater discharges as the heavy metals become water soluble once oxygenated and discharged, often falling out of the water column and accumulating in river sediments contaminating them with many heavy metals [15-17].

A compounding effect of coal mining wastewater discharges into streams and rivers coupled with the eventual contamination of the receiving waterway is the impact on the freshwater ecosystems. Battaglia et al. 2005 concluded that increased heavy metals contributed to the degradation of stream macroinvertebrate assemblages. Wright & Burgin 2009 reported elevated zinc levels from drainage flowing from the closed coal mine (Canyon Colliery) impaired the downstream Grose Rivers stream ecosystems with reductions in macroinvertebrate taxonomic richness and abundance [9].

Similar studies by performed by Belmer et al. 2014 and Wright et al. 2017 reported that a coal mine (Clarence Colliery) wastewater discharge increased the Wollangambe Rivers salinity, pH, nickel and zinc levels which were concluded to have reduced macroinvertebrate taxonomic richness and abundance downstream of the mine discharge.

There is a rich literature on coal mines and water pollution in some parts of the world, such as the United States which includes many regional studies of active and inactive mines [3, 6, 20]. Many of these studies do not include sampling above the mining operation and, as a result, often do not illustrate the full extent of impact on the receiving waterways

and their ecosystems. One major data gap is that there have been very few studies (none in Australia) comparing impacts to coal mine wastewater receiving waterways aquatic ecosystems from a regional group of coal mines that discharge wastes from active (treated) and inactive mines (un-treated).

The relative lack of studies investigating aquatic ecosystem degradation from Australian coal mines is puzzling given the importance of the industry. Despite increased mining of coal in recent decades and coal becoming Australia's second highest value export, there are comparatively fewer studies on the impacts to aquatic ecosystems from coal mines in Australia [21].

Coal mine wastewater discharges in New South Wales are regulated by the New South Wales Environmental Protection Authority (NSW EPA) and environmental protection of receiving waterways is implemented through Environmental Protection Licenses (EPL), under the Protection of the Environment Operations Act 1997 (POEO Act). EPL's set discharge limits for water quality and chemical properties in which coal mine wastewaters discharge to the environment must adhere to [10, 14].

In many cases the EPL's for coal mine waste discharges are failing to protect the receiving waterways ecosystems by failing to identify ecologically hazardous chemicals in the waste discharges and often imposing water quality and chemical limits much higher or significantly different to the receiving waterway or local reference conditions [14, 20]. The research questioned posed for this research is; how does the receiving aquatic ecosystem (measured via aquatic macroinvertebrates) differ from a regional group of active (treated wastewaters) coal mines compared to inactive coal mines (un-treated wastewater)?

2. Methods

2.1. Sample Locations

This study investigates eight waterways receiving wastewater from seven coal mines in the Sydney Basin with three inactively mining coal and four actively mining coal during sampling. Four mines are located within the Greater Blue Mountains area. These include Angus Place Colliery (inactively mined), Canyon Colliery (inactively mined), Clarence Colliery (actively mined) and Springvale Colliery (actively mined) (Figure 1). Three mines are located in the Greater Southern Highlands area, those being Berrima (Medway) Colliery (inactively mined) Tahmoor Colliery (actively mined) and Westcliff Colliery (actively mined) (Figure 1). The geology of all mine locations share many similarities as they all extract coal from various seams within the Illawarra coal measures spanning the southern and western coalfields within the greater Sydney Basin [22, 23].

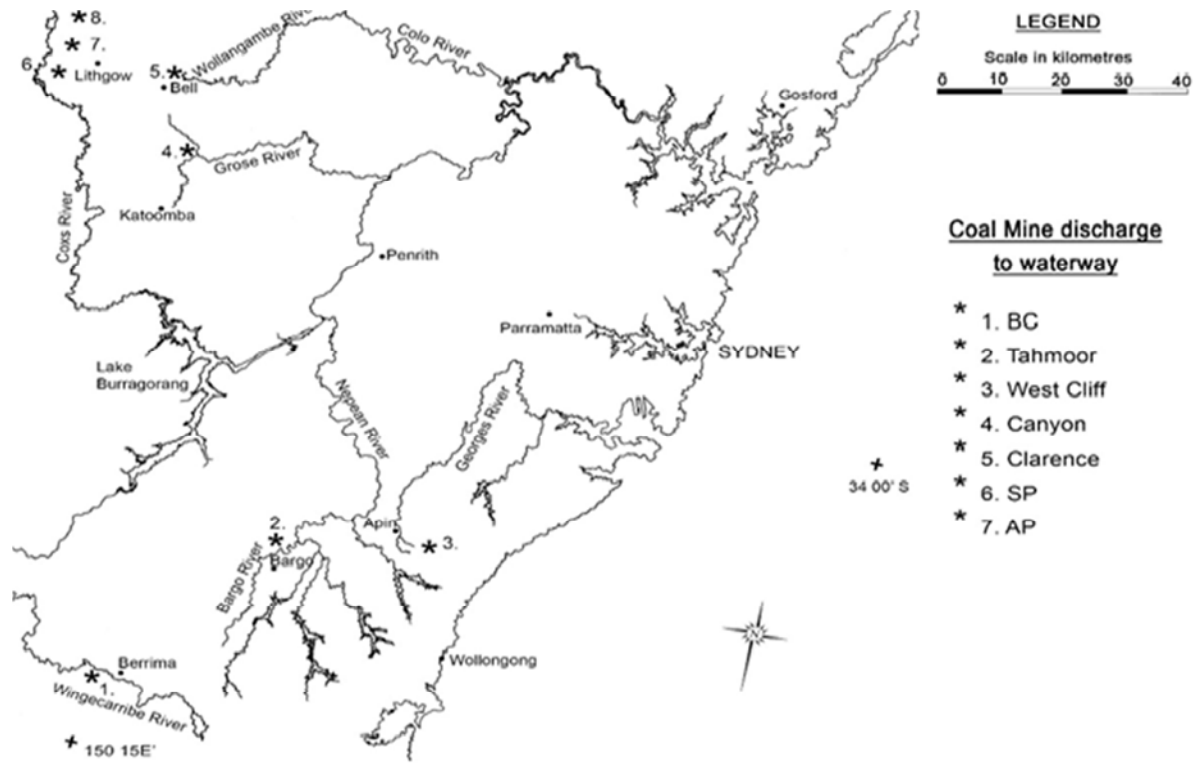


Figure 1. Map of lower Sydney basin, its major waterways and location of the seven coal mines (marked by * and numbered) investigated in this study that discharge waste water to nearby streams or rivers. (1 Berrima (Medway) Colliery, 2. Tahmoor Colliery, 3. Westcliff Colliery, 4. Canyon Colliery, 5. Clarence Colliery, 6. Springvale Colliery, 7. Angus Place Colliery).

Table 1. Colliery name, waterway name, approximate longitude and latitude and altitude (Metres above sea level) of collieries and waterways used in this study. Stream order is derived from the Strahler method [24].

Colliery name	Waterway name	Sample location	longitude	latitude	Altitude (ASL)	Stream order
Inactive mines						
Angus Place Colliery	Sawyers Swamp	Upstream	-33.396377 S	150.133510 E	1000 m	1
	Kangaroo Creek	Downstream	-33.349507 S	150.098834 E	915 m	1
Berrima (Medway) Colliery	Wingecarribee River	Upstream	-34.489611 S	150.261454 E	590 m	3
	Wingecarribee River	Downstream	-34.488328 S	150.255918 E	530 m	3
Canyon Colliery	Dalpora Creek	Upstream	-33.539753 S	150.308879 E	910 m	1
	Dalpora Creek	Downstream	-33.540910 S	150.308116 E	890 m	1
Active mines						
Clarence Colliery	Wollangambe River	Upstream	-33.455964 S	150.249101 E	1025 m	1
	Wollangambe River	Downstream	-33.455673 S	150.257359 E	960 m	2
	Springvale Creek	Upstream	-33.405991 S	150.125420 E	1020 m	1
Springvale Colliery	Springvale Creek	Downstream	-33.401727 S	150.094156 E	890 m	1
	Sawyers Swamp	Downstream	-33.380748 S	150.086568 E	895 m	1
Tahmoor Colliery	Bargo River	Upstream	-34.236946 S	150.579127 E	260 m	2
	Bargo River	Downstream	-34.244479 Ss	150.590146 E	250 m	2
Westcliff Colliery	Georges River	Upstream	-34.205055 S	150.798932 E	230 m	1
	Georges River	Downstream	-34.203947 S	150.798088 E	225 m	1

2.2. Macroinvertebrates

Aquatic macroinvertebrates were collected on one occasion. All paired upstream and downstream samples were collected on the same day from the respective receiving waterway upstream and downstream of each mines waste inflow (Table 1). A total of ten randomly selected, quantitative benthic macroinvertebrate samples were collected at five receiving waterways and 5 from the remaining three receiving waterways. For one sample stream (Kangaroo Creek) an upstream sample location was not

available due to extremely low flow. Due to this the use of Sawyers Swamp (reference site) was used as a paired reference site due to its close proximity to Kangaroo Creek (5 km). Samples were collected from flowing sections of each waterway. A ‘kick’ net (frame of 30 x 30 cm and 250 µm mesh) was used to collect invertebrates and sampling was achieved by disturbing stream substrate in a 30 cm by 30 cm quadrat upstream of the sample net for 30 seconds and collecting all the benthic materials that flowed into the net [25]. Net contents of each replicated sample were then placed into individual sample containers and preserved in 70%

ethanol.

Aquatic macroinvertebrates were counted and identified to the family level (for the majority of taxa) at the School of Science and Health laboratory facilities at the Western Sydney Universities Hawkesbury Campus using a Nikon stereo microscope 10x magnification and the identification keys [26, 27]. Family level macroinvertebrate identification has been found to be an adequate taxonomic resolution for coal mine impact assessment [28].

2.3. Data Analysis

For univariate data analysis (upstream compared to downstream) Students t-test were used to test for differences between aquatic macroinvertebrate community structure. Standard industry biotic indices for aquatic macroinvertebrates were used to infer differences in community structure from upstream and downstream of waste inflows, these include; Total Abundance and Family Richness, Ephemeroptera, Plecoptera and Trichoptera Abundance (EPT abundance), Ephemeroptera, Plecoptera and Trichoptera Family Richness and Ephemeroptera, Plecoptera and Trichoptera Percent (EPT%) [29].

Multivariate data analysis was used to compare community structure of macroinvertebrates with the software package PRIMER 6. PRIMER 6 was used to infer statistical differences in community structure of aquatic macroinvertebrates [30, 31, 32]. BIOENV (BEST) was also performed using PRIMER 6 to analyse which water quality and chemistry parameters (previously published by the authors) greatly contributed to the change in macroinvertebrate community structure between upstream and downstream sample locations.

3. Results

A combined total of 12866 individual macroinvertebrates were collected and identified from 8 waterways from 15 individual sample locations (7 upstream and 8 downstream). Of the total aquatic macroinvertebrates collected and identified 5853 were sampled from upstream locations and 7013 from downstream sample locations. Some 58% of the downstream macroinvertebrates were collected at one downstream sample location (Westcliff Colliery) which is some 85% of the total collected macroinvertebrates at

Westcliff Colliery. A similar trend was found for upstream samples with some 41% of all upstream macroinvertebrates collected from Tahmoor Colliery.

SIMPER results show combined inactive mines recorded the greatest dissimilarity between their paired upstream and downstream sample locations in comparison to combined actively mined results, inactive mines significance level of 0.5% (Global R): 0.274 and active mines significance level of 0.5% and (Global R) 0.122. Each individual inactive mine; Angus Place Colliery significance level of 0.1% (Global R) 0.949, Canyon Colliery significance level of 0.1% (Global R) 0.689 and Berrima (Medway) Colliery significance level of 0.1% (Global R) 0.594. Whilst each individual active mine recorded less dissimilarity; Springvale Colliery significance level of 0.1% (Global R) 0.940, Westcliff Colliery significance level of 0.1% (Global R) 0.394, Clarence Colliery significance level of 0.1% (Global R) 0.359, significance level of 0.1% (Global R) 0.394, Tahmoor Colliery significance level of 0.5% (Global R) 0.162.

Dissimilarities of macroinvertebrate community structure are depicted as two nMDS plot graphs divided into Blue Mountains mines and Southern Highlands mines (Figures 7 and 8). For the Blue Mountains mines nMDS the majority of the reference samples at both active and inactive mines show similarity to each other with the majority of replicates clustering together in the centre. Whilst in comparison downstream sample replicates are scattered from top to bottom and right, with a few Dalpura replicates (D) shifting far left. As for the Southern Highlands mines nMDS the Bargo river replicates are showing some similarity to each with both other collieries (Berrima (Wi) and Westcliff (G) showing less similarity to their paired sampled replicates (Figures 2 and 3).

Macroinvertebrate community structure was found to be statistically dissimilar when analysed for similarity through ANOSIM at all streams when compared between their upstream and downstream sample locations with a significance level of 0.5% (Global R) 0.033, between active mining upstream and active mining downstream with a significance level of 0.1% (Global R) 0.122, between inactive mining upstream and inactive mining downstream with a significance level of 0.1% (Global R) 0.274 and when compared between active mining downstream and inactive mining downstream with a significance level of 0.1% (Global R) 0.259.

Table 2. Macroinvertebrate total individual abundance, Family richness, EPT abundance, EPT percent (%) and EPT Family Richness, range, total counts and means for all mines inactive and active. * = $p < 0.05$; ** = $p < 0.001$; *** = $p < 0.0001$; ns = not significant.

Colliery	Biotic indices	Individual Abundance		Family Richness		EPT Abundance	
	Site	Range (Total)	Mean	Range	Mean	Range (Total)	Mean
	p value	**		*		**	
Angus Place	Sawyers Swamp Upstream (reference)	37 - 125 (363)	72.6	11-16	14	13 - 43 (121)	24.2
Colliery (Inactive)	Kangaroo Creek Downstream (impact)	22 - 65 (183)	36.6	6-15	10	3 - 7 (28)	5.6
	p value	***		***		***	
Berrima Colliery	Wingecarribee Upstream (reference)	18 - 121 (796)	79.6	11-27	18.5	4 - 5 (299)	29.9
(Inactive)	Wingecarribee Downstream (impact)	4 - 37 (188)	18.8	3-11	6.6	0 - 2 (7)	0.7
	p value	***		***		***	
Canyon Colliery	Dalpura Creek Upstream (reference)	22 - 100 (544)	54.4	4-14	9.1	4 - 72 (344)	34.4
(Inactive)	Dalpura Creek Downstream (reference)	0 - 13 (48)	4.8	0-6	3.1	0 - 4 (11)	1.1
	p value	*		***		***	

Colliery	Biotic indices	Individual Abundance		Family Richness		EPT Abundance	
	Site	Range (Total)	Mean	Range	Mean	Range (Total)	Mean
Clarence Colliery (Active)	Wollangambe River Upstream (reference)	52 - 166 (614)	97.4	10-13	11.4	0 - 87 (284)	23.9
	Wollangambe River Downstream (impact)	3 - 34 (373)	7.9	2-10	3.6	0 - 3 (160)	0.8
	p value	***		*		***	
Springvale Colliery (Active)	Springvale Creek Upstream (reference)	54 - 92 (348)	69.6	6-15	10.6	3-12 (36)	7.2
	Springvale Creek Downstream (impact)	28 - 50 (191)	38.2	6-8	13	0 - 4 (12)	2.4
	Sawyers Swamp Downstream (impact)	2 - 19 (64)	12.8	9-17	5.6	1 - 4 (13)	2.6
	p value	n/s		*		n/s	
Tahmoor Colliery (Active)	Bargo River Upstream (reference)	68 - 933 (2406)	240.6	5-14	8.8	11 - 64 (346)	34.6
	Bargo River Downstream (impact)	11 - 718 (1965)	196.5	4-10	6.9	5 - 67 (262)	26.6
	p value	***		*		n/s	
Westcliff Colliery (Active)	Georges River Upstream (reference)	41 - 155 (782)	78.2	4-18	11.4	0 - 53 (208)	20.8
	Georges River Downstream (impact)	130 - 889 (4065)	406.5	10-17	14.4	2 - 64 (345)	34.5

Table 2. Continued.

Colliery	Biotic indices	EPT %		EPT Family Richness	
		Range	Mean	Range	Mean
	p value	**		*	
Angus Place Colliery (Inactive)	Sawyers Swamp Upstream (reference)	27.4 - 44.4	34.4	1-4	2.6
	Kangaroo Creek Downstream (impact)	10.8 - 20.6	15.9	1 - 1	1
	p value	***		***	
Berrima Colliery (Inactive)	Wingecarribee Upstream (reference)	15.4 - 60.5	35.9	3 - 8	6.1
	Wingecarribee Downstream (impact)	0 - 11.1	3.9	0 - 1	0.6
	p value	**		***	
Canyon Colliery (Inactive)	Dalpura Creek Upstream (reference)	8.9 - 84.1	62.3	3 - 5	3.4
	Dalpura Creek Downstream (reference)	0 - 66.7	19.7	0 - 1	0.6
	p value	*		n/s	
Clarence Colliery (Active)	Wollangambe River Upstream (reference)	23.1 - 62.7	39.7	1 - 8	4.4
	Wollangambe River Downstream (impact)	0 - 26	6.6	0-6	3.1
	P value	***		*	
Springvale Colliery (Active)	Springvale Creek Upstream (reference)	4.3 - 16	10.8	1 - 3	1.8
	Springvale Creek Downstream (impact)	0 - 10	6	0 - 1	0.6
	Sawyers Swamp Downstream (impact)	15.4 - 50	25.6	0 - 1	0.2
	p value	n/s		n/s	
Tahmoor Colliery (Active)	Bargo River Upstream (reference)	6.7 - 4	21.2	3 - 6	4.2
	Bargo River Downstream (impact)	6.1 - 45.5	18.7	2 - 5	3.6
	p value	*		n/s	
Westcliff Colliery (Active)	Georges River Upstream (reference)	0 - 64.6	28	0 - 5	2.8
	Georges River Downstream (impact)	0.7 - 43.8	11.4	1 - 5	2.6

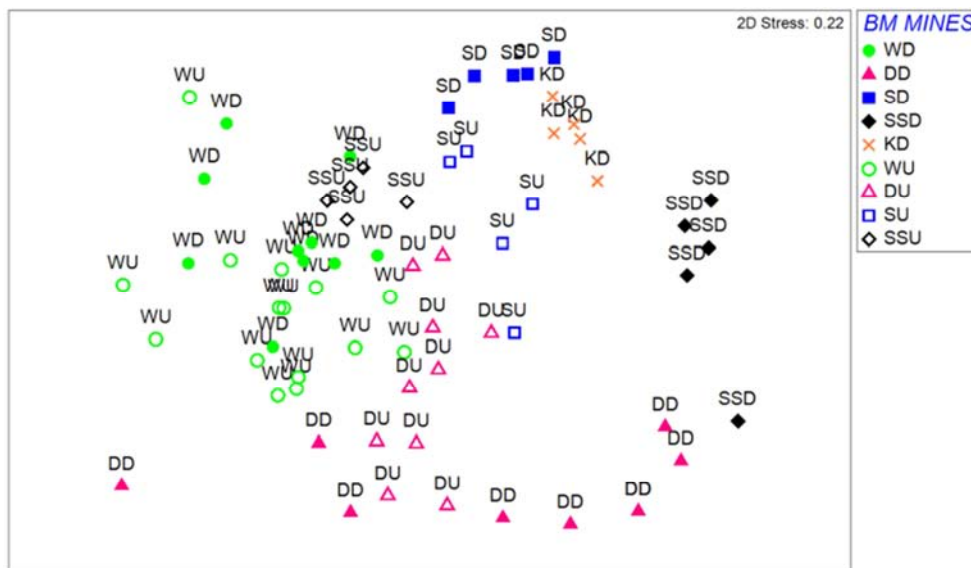


Figure 2. nMDS plot graph depicting Blue Mountains Collieries macroinvertebrate community structure. Solid shapes are downstream samples and outlined shapes are upstream samples. D = downstream, U = upstream. W (Circles) = Wollangambe River (Clarence Colliery), D (Triangle) = Dalpura Creek (Canyon Colliery), S (Square) = Springvale Creek (Springvale Colliery), SS (Diamond) = Sawyers Swamp (Springvale and Angus Place Colliery) and K (Cross) = Kangaroo Creek (Angus Place Colliery).

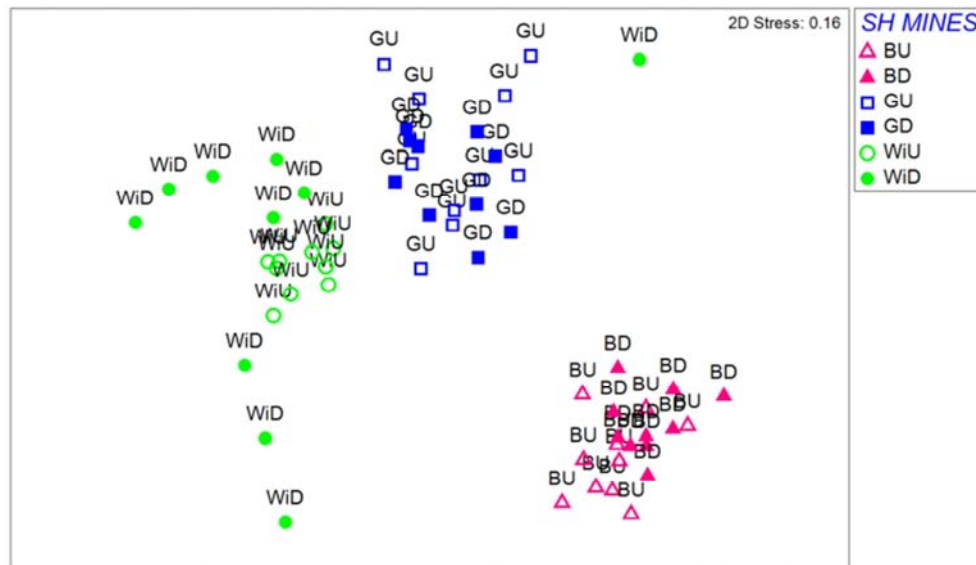


Figure 3. nMDS plot graph depicting Southern Highland Collieries macroinvertebrate community structure. Solid shapes are downstream samples and outlined shapes are upstream samples. D = downstream, U = upstream. B (Triangle) = Bargo River (Tahmoor Colliery), G (Squares) = Georges River (Westcliff Colliery) and WiD (Circles) = Wingecarribee River (Berrima (Medway) Colliery).

Reference Angus Place macroinvertebrate biotic indices were all found to be statistically different when compared to their paired impacted (downstream) sample. Total abundance for Angus Place Colliery reference site recorded a mean of 72.6 individuals per replicate and ranged between 37 and 125. In comparison, the total abundance downstream of Angus Place Collieries wastewater inflow was (mean of 36.6) nearly half of its paired reference sample. (Table 2 and Figure 4). Family richness for Angus Place Collieries reference site recorded a mean of 14 families per replicate and ranged between 11 and 16. In comparison, family richness downstream recorded a mean of 10 ranging between 6 and 15 families (Table 2 and Figure 5).

EPT abundance for the reference site recorded a mean of 24.2 EPT individuals per replicate and ranged between 13 and 43. In comparison, EPT abundance downstream of Angus Place Collieries wastewater discharge recorded a mean of 5.6 EPT individuals per replicate and ranged between 3 and 7 (Table 2 and Figure 6). %EPT for Angus Place Collieries reference site recorded a mean of 34.4 %EPT individuals and ranged between 27 and 44 %EPT. In comparison, %EPT downstream of Angus Place Collieries wastewater discharge recorded a mean of 15.9 %EPT individuals per replicate and ranged between 11 and 21 (Table 2 and Figure 7). EPT Family Richness upstream of Angus Place Colliery recorded a mean of 2.6 EPT families ranging between 1- 4 families whilst downstream only 1 family was recorded in each replicate (Table 2 and Figure 8).

Reference Springvale Colliery macroinvertebrate biotic indices were all found to be statistically different when compared to their paired impacted (downstream) sample. Total abundance for Springvale Colliery reference site recorded a mean of 69.6 individuals per replicate and ranged between 54 and 92. In comparison, the total abundance downstream of Springvale Collieries wastewater inflow was (mean 38.2 and 12.8 for both receiving waterways) and

ranged between 2 and 50, a 50% loss in abundance (Table 2 and Figure 4). Family richness for Springvale Collieries reference site recorded a mean of 10.6 families per replicate and ranged between 6 and 15. In comparison, family richness downstream recorded means of 5.6 and 13 ranging between 6 and 17 families (Table 2 and Figure 5)

EPT abundance for the reference site recorded a mean of 7.2 EPT individuals per replicate and ranged between 3 and 12. In comparison, EPT abundance downstream of Springvale Collieries wastewater discharge recorded means of 2.4 and 2.6 EPT individuals per replicate and ranged between 0 and 4 individuals per replicate (Table 2 and Figure 6). %EPT for Springvale Collieries reference site recorded a mean of 10.8 %EPT individuals and ranged between 4.3 and 16 %EPT. In comparison, %EPT downstream of Springvale Collieries wastewater discharge recorded means of 6 and 25.6 %EPT individuals per replicate and ranged between 0 and 50 %EPT (Table 2 and Figure 7). Although this is a higher percent of EPT taxa, it should be noted that this is represented by a less sensitive EPT community downstream. In contrast to the upstream sensitive taxa such as leptophlebiidae, Hydraboisidae and Philoptomidae the downstream community recorded none of these sensitive EPT taxa and appear to have been replaced with much less sensitive EPT taxa such as baetidae and hydroptilidae (Table 2). EPT Family Richness upstream of Springvale Colliery recorded a mean of 1.8 EPT families ranging between 1- 3 families in contrast downstream means of 0.6 and 0.2 families were recorded ranging between 0-1 at both downstream locations (Table 2 and Figure 8).

Macroinvertebrate biotic indices results for Clarence Colliery show statistically significant differences between upstream and downstream samples for Abundance, Family Richness, EPT abundance and %EPT (Table 2). Total abundance for the Wollangambe River reference site recorded a mean of 97.4 individuals per replicate and ranged

between 56 and 166. In comparison, mean total abundance for the paired impacted site was 7.9 and ranged between 3 and 34 individuals per replicate showing a decrease some 12 times from reference condition abundance (Table 2 and Figure 4). Family richness for the reference site recorded a mean of 11.4 families per replicate and ranged between 10 and 14. In comparison, the family richness at the paired impacted site was (mean 3.6) and ranged from 2 to 10 this is a loss over 3 times the family richness of reference streams (Table 2 and Figure 5).

EPT abundance for the reference site recorded a mean of 23.9 EPT taxa per replicate and ranged between 0 and 87. In comparison, the EPT abundance at the paired impacted site was (mean 0.8) and ranged from 0 to 3. This shows a decrease of nearly 30 times the abundance from reference conditions (Table 2 and Figure 6). EPT % at Wollangambe River reference site recorded a mean of 39.7% EPT taxa per replicate and ranged between 23.1 and 62.7. In comparison, the EPT % at the downstream impacted site was (mean 6.6%) and ranged from 0 to 26% (Table 2 and Figure 7). EPT Family Richness upstream of Clarence Colliery recorded a mean of 4.4 EPT families ranging between 1- 8 families whilst downstream a mean of 3.1 was recorded ranging between 0-6 (Table 2 and Figure 8).

Macroinvertebrate biotic indices results for Dalpura Creek show statistically significant differences between upstream and downstream samples for all biotic indices (Table 2). Total abundance for the reference site recorded a mean of 54.4 individuals per replicate and ranged between 22 - 100. In comparison, total abundance for the impacted site was (mean 4.8) some eleven times lower (Table 2 and Figure 4). Family richness for the reference site recorded a mean of 9.1 families per replicate and ranged between 4 and 14 families. In comparison family richness for the impacted site was 3.1 families per replicated sample and ranged from 0 to 6 families. This shows a decrease of family richness of nearly three times (Table 2 and Figure 5).

EPT abundance for the reference site recorded a mean of 34.4 EPT individuals per replicate and ranged between 4 and 72. In comparison, the EPT abundance for the impacted site was mean 1.1 ranging between 0 and 4 EPT individuals per replicate. This is a loss on average over 30 times (Table 2 and Figure 6). EPT % for the reference site recorded a mean of 62.3% EPT taxa per replicate and ranged between 8.9 and 84.1% EPT taxa per replicate. In comparison, EPT % for the impacted site (mean 19.7) ranging from 0 to 66.7% EPT taxa. On average this is a loss of over three times of EPT% between reference (upstream) and impacted (downstream) samples (Table 2 and Figure 7). EPT Family Richness upstream of Canyon Colliery recorded a mean of 3.4 EPT families ranging between 3 - 5 families in contrast downstream of Canyon Collieries wastewater inflow only 1 family was recorded (mean 0.6 EPT Families) (Table 2 and Figure 8).

Macroinvertebrate biotic indices results for Wingecarribee River show statistically significant differences between upstream and downstream samples for all biotic indices

(Table 2). Total abundance for the reference site recorded a mean of 79.6 individuals per replicate and ranged between 18 - 121. In comparison, total abundance for the impacted site was (mean 18.8) ranging from 4 -37 some four times lower (Table 2 and Figure 24). Family richness for the reference site recorded a mean of 18.5 families per replicate and ranged between 11 and 27 families. In comparison family richness for the impacted site was 6.6 families per replicated sample and ranged from 3 -11 families. This shows a decrease of family richness of nearly three times (Table 2 and Figure 5).

EPT abundance for the reference site recorded a mean of 29.9 EPT individuals per replicate and ranged between 4 and 52. In comparison, the EPT abundance for the impacted site recorded a mean of 0.7 ranging between 0 and 2 EPT individuals per replicate. This is a loss on average over 40 times (Table 2 and Figure 6). EPT % for the reference site recorded a mean of 35.9% EPT taxa per replicate and ranged between 15.4-60.5% EPT taxa per replicate. In comparison, EPT % for the impacted site recorded a mean of 3.9 ranging from 0 to 11.1% EPT taxa. On average this is a loss of over nine times of EPT% between reference (upstream) and impacted (downstream) samples (Table 2 and Figure 7). Family Richness upstream of Berrima (Medway) Colliery recorded a mean of 6.1 EPT families ranging between 3 - 8 families in contrast downstream of Canyon Collieries wastewater inflow only 1 family was recorded (mean 0.6 EPT Families) (Table 2 and Figure 8).

Macroinvertebrate biotic indices results for Bargo River show statistically significant differences between upstream and downstream samples for Family Richness only (Table 2). Total abundance for reference site recorded a mean of 240.6 individuals per replicate and ranged between 68 and 933. In comparison, mean total abundance for the paired impacted site was 196.5 and ranged between 11 and 718 (Table 2 and Figure 4). Family richness for the reference site recorded a mean of 8.8 families per replicate and ranged between 5 and 14. In comparison, the family richness at the paired impacted site was (mean 6.9) and ranged from 4 to 10 (Table 2 and Figure 5).

EPT abundance for the reference site recorded a mean of 34.6 EPT taxa per replicate and ranged between 11 - 64. In comparison, the EPT abundance at the paired impacted site was (mean 26.6) and ranged from 5 to 67. (Table 2 and Figure 6). EPT % for the reference site recorded a mean of 21.2% EPT taxa per replicate and ranged between 6.7 and ranged between 6.7 and 46. In comparison, the EPT % at the paired impacted site was (mean 18.7%) and ranged from 6.1 to 45.5% (Table 2 and Figure 7). Family Richness upstream of Tahmoor Colliery recorded a mean of 4.2 EPT families ranging between 3 - 6 families in contrast downstream 3.6 EPT families were recorded (range 2-5) (Table 2 and Figure 8).

Macroinvertebrate biotic indices results for Georges River show statistically significant differences between upstream and downstream samples for Abundance, Family Richness and EPT % (Table 2). Total abundance for reference site recorded a mean of 78.2 individuals per replicate and ranged between 41 and 155. In comparison, mean total abundance for the paired impacted site was 406.5 and ranged between 130 and

889 individuals per replicate of which the majority (nearly 50%) were chironomidae and simuliidae (1797 of 4065 total impacted macroinvertebrates sampled). Showing an increase over five times from reference condition abundance to impacted sampled abundance though nearly 50% of this sample was comprised of two Diptera (fly) families (chironomidae and simuliidae) (Table 2 and Figure 4).

Family richness for the reference site recorded a mean of 11.4 families per replicate and ranged between 4 and 18. In comparison, the family richness at the paired impacted site was (mean 14.4) and ranged from 10 to 17 an increase of three families from reference to impacted samples (Table 2 and Figure 5). EPT abundance for the reference site was not

found to be statistically different and recorded a mean of 20.8 EPT taxa per replicate and ranged between 0 and 53. In comparison, the EPT abundance at the paired impacted site was (mean 34.5) and ranged from 2 to 64 (Table 2 and Figure 6). EPT % for the reference site recorded a mean of 28% EPT taxa per replicate and ranged between 0 and 64.6. In comparison, the EPT % at the paired impacted site was (mean 11.4%) and ranged between 0.7 and 43.8% (Table 2 and Figure 7) on average a loss of 2.5 times the EPT % of replicates. EPT Family Richness upstream of Westcliff Colliery recorded a mean of 2.8 EPT families ranging between 0- 5 families whilst downstream a mean of 2.6 was recorded ranging between 1-5 (Table 2 and Figure 8).

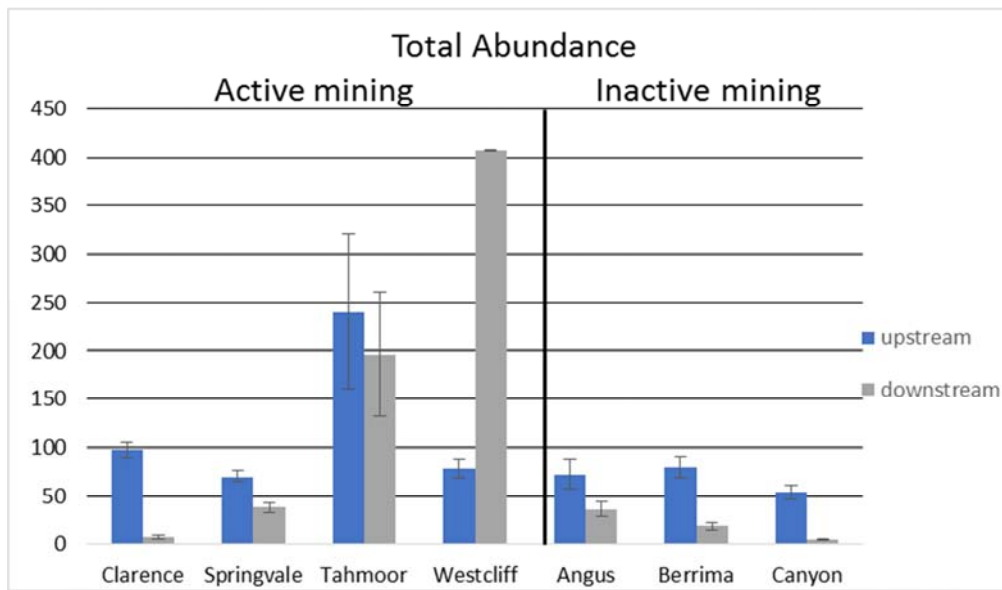


Figure 4. Macroinvertebrate total abundance. Left columns (Blue) are reference and right columns (Grey) are downstream of each respective coal mines waste water inflow. Left collieries are actively mining coal (treated wastewater) whilst the right collieries are inactively mining coal (un-treated wastewaters).

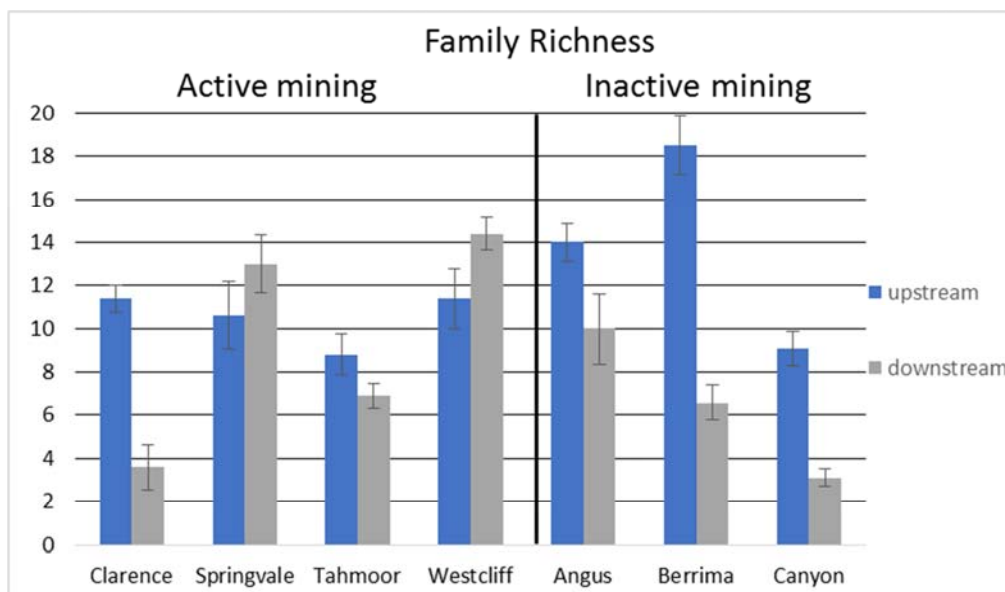


Figure 5. Macroinvertebrate family richness. Left columns (Blue) are reference and right columns (Grey) are downstream of each respective coal mines waste water inflow. Left collieries are actively mining coal (treated wastewater) whilst the right collieries are inactively mining coal (un-treated wastewaters).

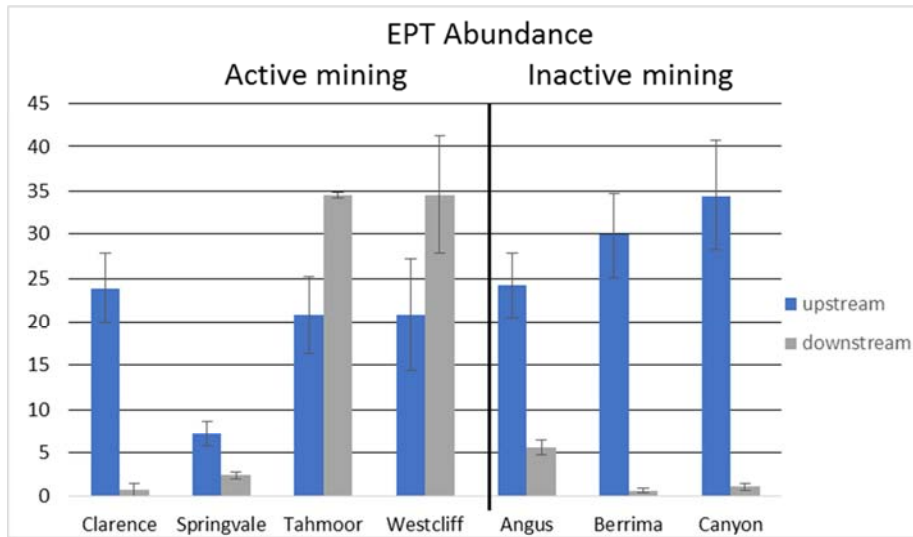


Figure 6. Macroinvertebrate EPT abundance. Left columns (Blue) are reference and right columns (Grey) are downstream of each respective coal mines waste water inflow. Left collieries are actively mining coal (treated wastewater) whilst the right collieries are inactive mining coal (un-treated wastewaters).

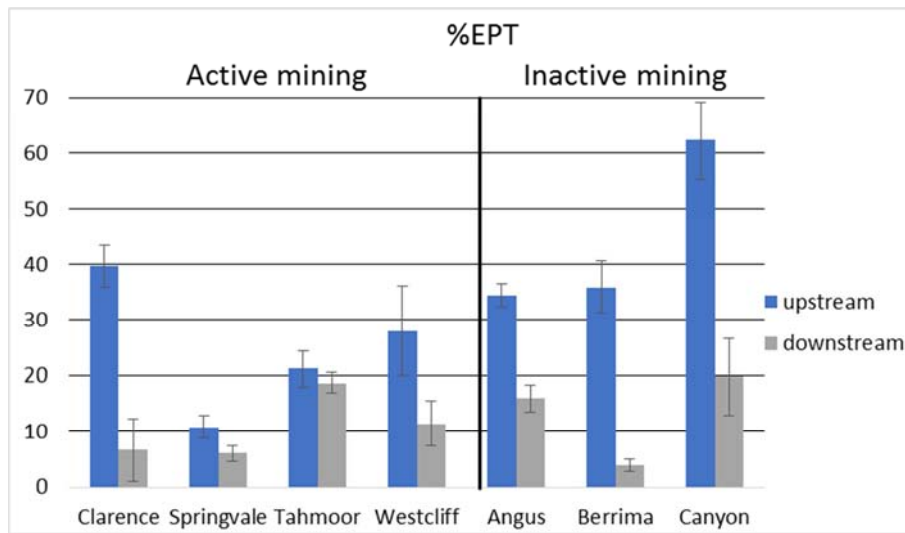


Figure 7. Macroinvertebrate %EPT. Left columns (Blue) are reference and right columns (Grey) are downstream of each respective coal mines waste water inflow. Left collieries are actively mining coal (treated wastewater) whilst the right collieries are inactive mining coal (un-treated wastewaters).

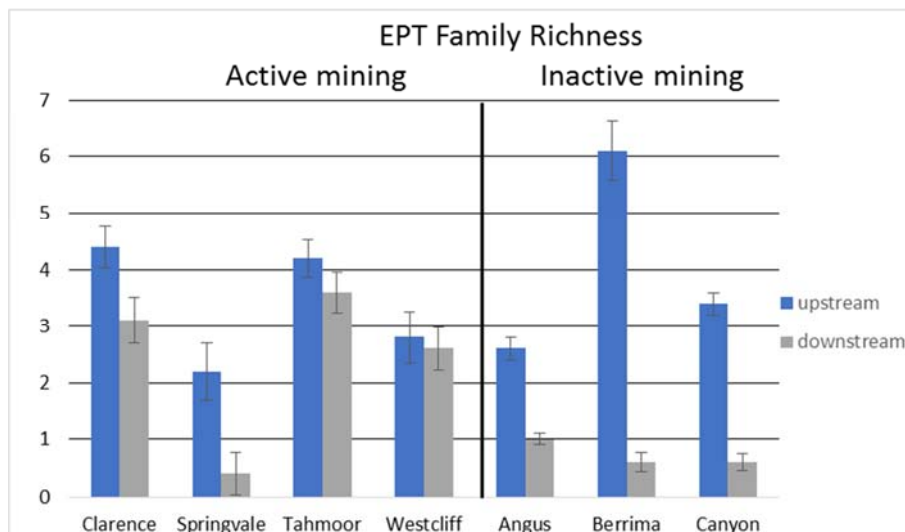


Figure 8. Macroinvertebrate EPT family richness. Left columns (Blue) are reference and right columns (Grey) are downstream of each respective coal mines waste water inflow. Left collieries are actively mining coal (treated wastewater) whilst the right collieries are inactive mining coal (un-treated wastewaters).

Table 3. List off macroinvertebrate taxa (order and family).

Order	Family	Impact	Reference
Ephemeroptera	Baetidae	X	X
	Coloburiscidae		X
	Leptophlebiidae	X	X
	Caenidae	X	X
Plecoptera	Eustheniidae		X
	Gripopterygidae	X	X
	Notonemouridae	X	X
	Hydrobiosidae	X	X
	Glossomatidae		X
	Hydroptilidae	X	X
	Hydropsychidae	X	X
	Ecnomidae	X	X
Trichoptera	Conoesucidae		X
	Calocidae		X
	Leptoceridae	X	X
	Philopotamidae	X	X
	Limnephilidae		X
	Helicopsychidae		X
	Philorheithridae		X
	Calamoceratidae		X
	Atriplectididae		X
	Hydraenidae	X	X
Coleoptera	Elmidae	X	X
	Scirtidae	X	X
	Hydrophilidae	X	X
	Curculionidae	X	X
	Gyrinidae	X	X
	Haliplidae		X
	Hydraenidae	X	
	Psephenidae	X	X
	Dytiscidae	X	
	Corixidae	X	X
Hemiptera	Gerridae	X	X
	Velidae	X	X
	Notonectidae		X
	Tipulidae	X	X
Diptera	Athericidae		X
	Ceratopogonidae	X	X
	Simuliidae	X	X
	Empididae	X	X
	Chironomidae	X	X
	Dolichopodidae	X	X
	Culicidae	X	
	Bithyniidae	X	X
	Hydrobiidae	X	X
	Planorbidae	X	X
Basommatophora	Physidae	X	X
	Lymnaeidae		X
	Viviparidae		X
	Aeshnidae	X	X
	Libellulidae	X	
	Odonata	Gomphidae	X
Veneroida	Diphlebiidae		X
	Corduliidae	X	
	Corbiculidae	X	X
	Sphaeriidae	X	X
Decapoda	Atyidae	X	
Megaloptera	Corydalidae	X	X
Neuroptera	Neurorthidae		X
Oligochaeta		X	X
Lepidoptera	Pyrilidae	X	X
Collembola		X	X
Tricladida	Dugesiiidae	X	X
Acarina		X	X
Cladocera			X
Isopoda		X	X

4. Discussion

Comparisons of the impacts between active and inactivity mined coal mines from their coal mine wastewater discharges to the receiving waterways through the use of benthic macroinvertebrates is not well studied. Results of this study show that both active and inactive upstream sample locations showed similarity between each other, other than the Bargo River whilst showing little similarity to active or inactive downstream sample locations. In comparison, active or inactive downstream sample locations shared little similarity with each other. Results suggest that the coal mine wastewaters being discharged are having varying negative impacts to the receiving waterways aquatic ecosystem whether mining of coal is active (treated wastewaters) or inactive (un-treated wastewaters).

The majority of biotic indices recorded at active and inactive mines shows that inactively mined wastewaters are causing a greater impact to the receiving waterways aquatic ecosystem than actively mined wastewaters. With all of the inactively mined locations recording statistical differences for all biotic indices when compared between their upstream and downstream sample location (Table 2). This contrasted to the actively mined locations with only one of the five streams sampled recording statistical differences for all biotic indices. Community structure of EPT taxa was also modified with known highly sensitive taxa of the EPT families often being replaced with a less sensitive EPT families at downstream locations (Table 3).

A loss of 18 potential “coal mine wastewater” sensitive taxa was observed from all seven mines. The loss of such individual taxa could lead to the implementation of a coal mine sensitive macroinvertebrate taxa list which could be used as rapid assessment tools for the assessment of coal mine wastewater impacts to their respective receiving waterways (Table 3).

A total of 66 different taxa were recorded at all sample locations (upstream and downstream) the majority of taxa were family level with the remaining order level. 48 total taxa were recorded at all downstream sample locations with a total of 60 being recorded at all upstream sample locations. Of the taxa recorded downstream a total of 6 taxa were not recorded upstream. Taxa were not recorded downstream included; *Coloburiscidae*, *Eustheniidae*, *Glossomatidae*, *Conoesucidae*, *Calocidae*, *Limnephilidae*, *Philorheithridae*, *Calamoceratidae*, *Atriplectididae*, *Haliplidae*, *Notonectidae*, *Athericidae*, *Lymnaeidae*, *Viviparidae*, *Diphlebiidae*, *Neurorthidae* and *Cladocera* (Tables 3 and 4).

BIOENV results (BEST) revealed that the greatest contributing water quality and chemistry parameters influencing the changes in macroinvertebrate community structure between upstream and downstream sample locations were electrical conductivity, lithium, nickel, sulfate and zinc in that respective order. Other contributing parameters though less influential included pH, temperature, calcium, chloride and cobalt.

Total abundance decreased downstream of each respective coal mines wastewater discharge at all sample streams other than one waterway, the Georges River (Westcliff Colliery). The decrease in abundance ranged between 18% and 90% across all the mines. Similar losses in abundance were recorded in the Wollangambe River in a previous study by Belmer et al (2014) with reductions of approximately 90%. Clements et al 2000 recorded similar decreases in total abundance in their study of mining impacts to rivers in the Colorado area of the USA. Georges River (Westcliff Colliery) abundance increased approximately 80% downstream of Westcliff Collieries wastewater inflow. The majority (nearly 50%) of the families that contributes to the increased abundance downstream were Chironomidae and Simuliidae (1797 of the 4065 total impacted sample location macroinvertebrates collected). Showing an increase over five times from reference condition abundance of the two Diptera (fly) families. Average decreases in abundance were reported by Giam et al. 2018 whom used results from eight different studies assessing the impacts from coal mining on stream ecosystem in North America. It was reported that abundance across the mines decreased by 53%.

Family richness decreased below all the coal mines wastewater discharges other than the Georges River (Westcliff Colliery). Declines in family richness for inactive mines was (30, 65 and 65%) whilst active mines recorded smaller declines in family richness (10, 20 and 60%). Similar decreases in family richness have been recorded in the USA by Pond et al 2008 with decreases in the order of 50% recorded in actively mined streams as well as the Colorado Rockies where decreases were significantly lower at mine impacted streams [33]. The Georges River in contrast recorded an increase from 11.4 families per replicate to 14.4 an increase in family richness of 25%. Giam et al. 2018 reported a 32% decrease in invertebrate richness across eight mines used in their study.

EPT abundance increased downstream of the actively mined Westcliff Colliery which recorded a 70% increase in EPT abundance. This increase was driven by the abundance of the less sensitive mayfly and caddisflies families Canidae, Hydroptilidae and Ecnomidae with downstream abundance recorded as (122, 79 and 79) respectively whilst upstream samples recorded three Canidae, eight Ecnomidae and 9 Hydroptilidae. This is in contrast to the abundance of the more sensitive mayfly Leptophlebiidae with only 42 recorded downstream of Westcliff collieries wastewater inflow compared to 157 collected upstream [25, 33].

All other downstream sample locations recorded decreases in EPT abundance with the inactively mined downstream sites showing greater decreases. Inactively mined downstream sample locations recorded 55, 70 and 85% decreases whilst downstream sample locations of actively mined coal mines recorded 10, 50 and 80% decreases in EPT abundance. The greater loss of EPT abundance in this study is similar to those decreases in EPT taxa found in Colorado [32] and New Zealand [33]. Decreases in EPT abundance

were reported by Clements et al. 2000 in the Rocky Mountains, North America to have decreased by 68% in streams polluted by heavy metals [32]. A comparatively smaller decline in EPT abundance was found in a study of West Virginia streams impacted by coal mines with the proportion of macroinvertebrates in EPT groups at unmined streams of 77.9% compared to 51.1% at mined streams [3].

EPT% decreased at all downstream sample locations other than Sawyers Swamp downstream of the waste inflow from the active Springvale Colliery. This increase of nearly 50% was mostly driven by the abundance of only two taxa the mayfly Baetidae and the caddisfly Hydropsychidae, whilst in comparison neither of the two EPT taxa were recorded at the paired upstream site. Mayflies and caddisflies were recorded upstream though the family structure was dominated by the much more sensitive mayfly Leptophlebiidae and the more sensitive caddisflies, Hydroptilidae, Philopotamidae and Calamoceratidae [25, 33]. Decreases in Ephemeroptera% from mined sites to unmined sites were recorded by Pond et al. 2008 and Pond 2010 [3, 29]. Pond et al. 2018 found decreases in the taxa Ephemeroptera from 45.6% of samples to 7.4% of samples from West Virginian mines which was similar to mines in the Kentucky region which found 51.5% in comparison to <6% downstream [29]. All the inactive mines recorded greater decreases in EPT% in comparison to actively mined downstream sample locations. Inactive mines recorded decreases of 55, 70 and 80% whilst downstream of the actively mining operations decreases of 10, 50 and 80% were recorded. Similar reductions in Ephemeroptera were recorded in Acid Mine Drainage effected streams in the River Avoca (Ireland) with upstream Ephemeroptera recording 43.8% of samples whilst downstream of the Acid Mine Drainage inflow only 5.1% of samples recorded Ephemeroptera taxa [33].

EPT Family Richness decreased at all downstream sample locations though this was only statistically significantly different at one of the four active mines whilst all three inactive mines downstream samples were statistically significantly different. Active mines recorded decreases from upstream to downstream samples of 7%, 14%, 30%, 66% and 88% Tahmoor, Westcliff, Clarence, Springvale Collieries respectively (Springvale Creek) (Sawyers Swamp), whilst in comparison inactive mines recorded decreases of 61%, 90% and 82% (Angus Place, Berrima (Medway) and Canyon Collieries respectively.

5. Conclusions

Results of this study show that the coal mine wastewaters discharged by all of the seven mines used in this study are having varying degrading impacts on their respective receiving waterways ecosystem. Whilst coal is still being actively mined water treatment processes of varying degrees to remove or reduce pollutants within the discharged wastewaters is occurring. This is not the case for the mines inactively mining oar in this study. At the stage of mine closure and the subsequent relinquishment of the wastewater

discharge licence the water treatment process ceases. This allows for groundwater to accumulate in the underground workings, eventually making its way through adits or discharge points back to the surface and into the original receiving waterway.

This untreated mine wastewater has higher concentrations of heavy metals and other contaminants, due to the Acid Mine Drainage process, than that of the actively mined treated wastewaters. This is of major concern as the impacts to the receiving waterways ecosystem at actively mined, licenced and regulated waterways is significant let alone once the mining operation is completed and water treatment ceases. Giam et al. 2018 found similar results for their study using eight mines in North America. Giam et al. 2018 also found slightly greater decreases in reclaimed mine sites in comparison to actively mined sites. Results show a slight decrease of 32% in taxa richness from actively mined sites in comparison to a decrease of 34% in reclaimed mine sites. Abundance recorded greater decreases from actively mined sites (53% decrease) whilst reclaimed mine sites recorded a decrease of 68% [19].

This research has allowed for a greater understanding of the failings of the NSW EPA to protect the aquatic environment through legislation and the regulation of contaminants within coal mine wastewaters in the Sydney Basin. At the active mines, large losses of biota have been observed, whilst the environmental protection licence is still in place, to ensure the receiving waterways ecosystem is protected. Measures to better protect waterways which receive untreated coal mine wastewaters must be undertaken by the NSW EPA to ensure that once coal is no longer mined the receiving aquatic ecosystem is still protected.

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