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Impact of Coal Mining on River Sediment Quality in the Sydney Basin, Australia

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Abstract**—**The environmental impacts arising from mining activities affect the air, water, and soil quality. Impacts may result in unexpected and adverse environmental outcomes. This study reports on the impact of coal production on sediment in Sydney region of Australia. The sediment samples upstream and downstream from the discharge points from three mines were taken, and 80 parameters were tested. The results were assessed against sediment quality based on presence of metals. The study revealed the increment of metal content in the sediment downstream of the reference locations. In many cases, the sediment was above the Australia and New Zealand Environment Conservation Council and international sediment quality guidelines value (SQGV). The major outliers to the guidelines were nickel (Ni) and zinc (Zn).

Keywords**—**Coal mine, environmental impact, produced water, sediment quality guidelines value.

I. INTRODUCTION

EXPONENTIAL increase in the energy demand has made extensive use of fossil fuels [1]. Extreme interdependency of energy generation and water consumption has evolved the term Water-Energy Nexus [2] which suggests that water used in and disposed of as part of energy generation would contain a variety of materials that eventually if not treated and disposed adequately would affect water and sediment quality in downstream environments. The nuisance of coal mining has been documented as early as 1620 [3]. In Australia, coal was used by Aborigines for cooking purposes in pre-1788 era [4] and was ‘discovered’ by Lieutenant John Shortland in 1797. The mining and export of coal began in 1799 and it remains the major source of energy and a key export commodity [4]. Coal is extracted in Australia by both open cut and underground methods. Wastewater is discharged under a pollution license issued by the State environment agency [5] and is typically treated to manage acid mine drainage and dissolved minerals [6]. The acidity caused by the geochemical process of mineral ion exchange and oxidative weathering from coal waste water produces acid generating salt (AGS) which has become a significant parameter in sedimentology [7] due to the process of converting a spoiled heap of coarse fragment of rock from coal mine into disaggregated mud and sand. The weathering effect ends into layers of sediment deposits in natural process of storm and wind.

The discharge of coal mine wastewater and associated sediments is a source of contamination. Contaminants may be associated with the sediment grains, which in turn can impact on flora and fauna and bioaccumulate [8]. The sediment holding the inactive contaminants can release into the water due to disturbance and affect the ecosystem [9]. It has become essential to study the sediment quality to effectively manage the environment.

There are always risks of environmental deterioration if a site goes under redevelopment or remediation. For a sustainable environment, an assessment of potential toxicity, bio-accumulation, and fate of contaminants must be studied. Environmentalists are looking for the ways to incorporate the latest science into the assessment of contaminated sediments. Some techniques work for the marine water sediment, but may not equally work for the freshwater. In past, focus was more on costal marine environment, and freshwater study was limited. A total chemical contamination analysis had always been a step forward to assess the contaminants. A sediment quality guidelines value (SQGV) for contaminants have been proposed [10], and Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand (The ANZECC/ARMCANZ 2000a) has published and revised these SQGVs for the assessment [11].

Apart from bulk analysis of individual contaminants, sediment quality was evaluated by ecotoxicity [12]. A bioavailability assessment approach and bioanalytical approaches were applied as an indicative tool for the quality assessment [13], [14]. Bioavailability, which is the fraction of contaminants available for uptake by an organism of interest, is assessed by leaving the organism in the sediment in the laboratory. Bioanalytical approach is the analysis of endocrine disrupting chemicals (EDC) using mechanism based biological screening tools. Toxicity identification evaluation (TIE) for dissolved toxicants has also been tried for the sediment evaluation [15]. Bioaccumulation in the tissues of organisms with contaminated sediment was used as quality indicator for the sediment [16]. Biomarker is a chemical or non-chemical response to single or multiple environmental stressors within an organism and was used for the quality assessment of sediment [17]. Sediment contamination assessment by potential ecological risk index (PERI) of toxic substances and water analysis based on USEPA criteria with equilibrium partitioning (EqP) of contaminants was

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considered for certain period of time [18]. Ecosystem stressors were also applied to evaluate the sediments quality [19]. Having all the technological developments applied to evaluate the sediment, it was always accepted that total contaminants analysis correlates with the sediment quality. This study revolves around analysis of different parameters of sediments near coal mining area in the Sydney basin, based on contaminants concentration.

TABLE I
SAMPLE AND SITE IDENTIFICATION

Study Area	Mines / Industry	Sample Collection Site	Sample Identification	Coordinates		**Site I.D.**
1	Ash Dam, Angus Place and Springvale	Coxs River, upstream	W1	33°18'0.64"S	150° 5'49.30"E	W1
		Sawyers Swamp, downstream	W2	33°22'50.74"S	150° 5'11.63"E	W2
		Sawyers Swamp, upstream	W3	33°23'37.40"S	150° 7'28.12"E	W3
		Springvale discharge	W4	33°24'6.55"S	150° 5'39.55"E	W4
2	Centennial Coal Mine	Wollangambe River, upstream	W5	33°27'19.94"S	150°15'26.64"E	W5
		Wollangambe River, downstream	W6	33°27'53.63"S	150°15'49.68"E	W6
		Wollangambe River, discharge	W7	33°27'52.26"S	150°15'33.73"E	W7
3	Canyon Coal Mine	Dalpura creek, upstream	W8	33°32'24.67"S	150°18'22.19"E	W8
		Dalpura creek, downstream	W9	3°32'27.75"S	150°18'25.71"E	W9
		Dalpura creek, further downstream	W10	3°32'18.58"S	150°18'5.55"E	W10

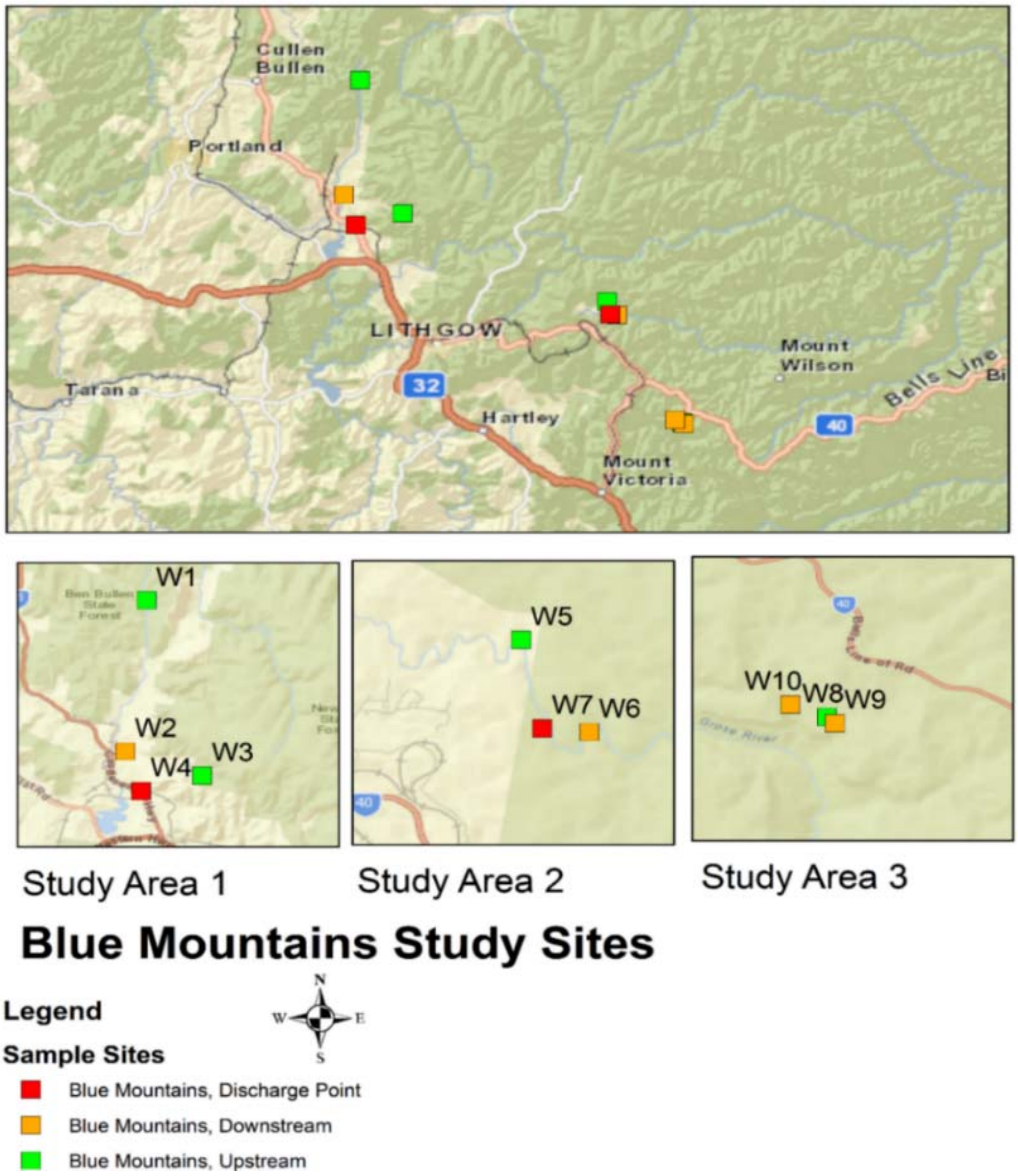

Fig. 1 Mapping nonlinear data to a higher dimensional feature space

TABLE II
SEDIMENT QUALITY PARAMETERS

Study Area		SQGV	Study Area 1				Study Area 2			Study Area 3		
Sample Location			W1	W2	W3	W4	W5	W6	W7	W8	W9	W10
Analytes	DL (mg/kg)		U	D	U	D	U	D	DP	U	D	DD
Phosphorus	10 mg/kg		440	360	40	490	10	140	70	<10	60	550
Aluminium	1 mg/kg		5800	27000	1500	8200	800	5400	3800	190	12000	6500
Arsenic	4 mg/kg	20	16	41	<4	26	<4	<4	<4	<4	28	18
Barium	1 mg/kg		120	220	23	610	36	59	44	1	510	260
Calcium	5 mg/kg		830	17000	61	3900	260	360	250	<5	1300	3500
Chromium	1 mg/kg		8	10	2	9	<1	5	4	<1	1	10
Cobalt	1 mg/kg		66	180	3	51	310	5	59	<1	3600	470
Copper	1 mg/kg	80	5	17	2	22	2	21	7	<1	87	180
Iron	1 mg/kg		300000	27000	9200	21000	1800	10000	7600	870	360000	310000
Lead	1 mg/kg	65	6	24	3	23	2	13	7	<1	37	130
Magnesium	5 mg/kg		520	990	30	810	20	180	99	<5	480	1300
Manganese	1 mg/kg		3200	3800	64	8600	2800	160	750	2	38000	4700
Nickel	1 mg/kg	21	13	210	2	59	260	13	53	<1	2300	870
Potassium	10 mg/kg		320	1100	50	1200	40	290	130	10	2300	800
Sodium	10 mg/kg		350	2200	10	860	<10	40	20	<10	210	60
Silicon	10 mg/kg		1800	380	80	730	80	370	220	110	8000	1500
Zinc	1 mg/kg	200	43	650	8	380	360	31	91	<1	3500	1800

D = downstream, DD = further downstream, DP = discharge point, and U= upstream, DL = detection limit

II. MATERIAL AND METHODS

A. Study Area and Site Description

This paper covers three sites in Blue Mountain area of Western Sydney region located 85 to 140 km west of Sydney. Extensive coal mining activities in the region prompted the selection of the area where water resources were affected by three coal mines namely Canyon, Centennial, and Springvales collieries. These mines are affecting the quality of Coxs River, Wollangambe River, Grose River, Dalpura creek, and Sawyers Swamp's sediment quality. It is worth mentioning that the Canyon Colliery was an underground coal mine operated from 1930 to 1997. Drainage shaft carries the drainage to Dalpura creek at high flow which contributes to 65% of the water flow in the upper Grose River. It has been reported that the water was highly contaminated with acid mine drainage (AMD), and after the closure of mine, the ground water was continuously flowing through the mine to the Dalpura creek [20]. The drainage falling into Wollangambe River comes from coal washing dewatering and surface storage at mine site of Clarence Colliery. Table I shows the detail of the coordinates and sampling locations. Sample location points are further depicted in Fig. 1. This region has 150-year history of coal mining activities [21]. The sediment sampling locations were selected to represent sediment before and after the discharge points of industrial wastewater.

B. Sampling and Analysis

A clean screw capped glass jar was used to collect sediment samples from the sampling points. Samples were kept in an ice box without addition of any preservatives during the period of July 2014 to September 2015 with the favorable weather for accessibility to the remote sites. A National Association of Testing Authorities (NATA) accredited external laboratory, Envirolab, was used for the analysis of samples. USEPA 200.8, USEPA 6020A, USEPA 7471A, USEPA 3051A, and APHA 3125 as standard reference methods were used for the analysis of sediment samples. The parameters analyzed by external laboratory for the study included polyatomic non-metals, most transition metals, alkali metals, and alkaline earth metals metalloids.

Thermo-gravimetric and computer aided thermal analysis of sediments were performed using Mettler Toledo thermo-gravimetric analyzer (TGA/DSC 1 STARe system). Weight changes of the samples with the change in temperature were analyzed by using STARe software. The carrier gas nitrogen with flow rate of 20 mL/min was used for approximately 20 g of sample heated to the maximum temperature of 1000 °C at the rate of 10 °C /min.

Fourier transform infra-red spectroscopy (FTIR) was used to monitor the abundance of functional groups with the changing location of sediments. Nicolet 6700 FTIR spectrometer was used with 32 number of scans and spectral resolution of 4 cm^{-1}. Attenuated total reflectance (ATR) with a diamond crystal was used for the analysis.

III. RESULT AND DISCUSSION

The sediment samples were analyzed for 37 trace element parameters. The results for each site are presented in Table II with detectable elements only. Concentrations range of sodium in downstream samples varied from 10 mg/kg to 2200 mg/kg, while upstream samples had concentration ranging from undetected to 350 mg/kg. The increment sodium indicated a significant impact of the release of salts from the coal mine produced water. Study Area 3 revealed that many of the parameters which were not detected in the upstream sample were in very high concentration in the downstream sediment sample. Arsenic, cobalt, copper, lead, nickel, zinc, calcium, and magnesium were among those that exceeded the available SQGVs. Most of the study areas revealed elevated

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levels of sodium, cobalt, iron, barium, and nickel in the downstream and indicated an effect of the coal mining activities. Sawyers Swamp (W2) and other downstream discharge sampling points W4, W6, W7, W9, and W10 showed high aluminum levels. Although the ANZECC guidelines do not report trigger values for aluminum in sediments, high concentrations of aluminum are of concern as Dalpura Creek falling into the river (W3) carried 12,000 mg/kg of aluminum which is a continuous process for years without any regulatory restriction.

Elevated concentrations of nickel, calcium, and potassium were also detected in most of the downstream sediment samples. The highly toxic substance, arsenic, was found to be above the ANZECC trigger value of 20 mg/kg for Sawyers Swamp (W2 = 41 mg/kg), Springvale (W4 = 26 mg/kg), and Dalpura creek (W9 = 28 mg/kg). Cadmium in Swayer Swamp and Dalpura Creek was also higher than the trigger value of 1.5 mg/kg SQGV (W2 = 2 mg/kg & W9 = 2 mg/kg). Nickel was also highly elevated downstream of the Blue Mountains area (W2 = 210 mg/kg, W4 = 59 mg/kg, W7 = 53 mg/kg, W9 = 2300 mg/kg, and W10 = 870 mg/kg) with concentrations in the sediments above the trigger value of 21 mg/kg. Zinc was highly elevated in many of the downstream locations. The trigger value of zinc SQGV is 200 mg/kg, while the measured values in W2 = 650 mg/kg, W4 = 380 mg/kg, W5 = 360 mg/kg, W9 = 3500 mg/kg, and W10 = 1800 mg/kg were well above the trigger values. It is important to note that the iron levels were found to be very high in all cases and varied from 870 mg/kg to 300,000 mg/kg. Iron does not have ANZACC guidelines trigger value but in several cases (W1, W9, and W10) the concentrations of iron ranged over 30% of the sediment chemistry. Calcium, potassium, magnesium, and sodium in the collected sediments exhibited strong contamination trends at the mine discharge locations. The results clearly indicated that the sediments in the vicinity of coal mines in the Blue Mountains area were subjected to higher environmental impact.

Fig. 2 represents general outlook to the trend in the presence of contaminants before and after the discharge point. The data were collected from the sediment samples of Dalpura creek. Upstream sample was clean sand, and selected parameters Ni, Co and Zn were not detected in the sediment sample. The downstream sample was collected from a place close to the discharge point of the abandoned coal mine, and further down sample was collected from a distant place to the discharge point. All the three contaminants selected in Fig. 2 are highly toxic, and their sudden increment from absence to nearly 3500 mg/kg was found to be potentially highly damaging to the inhabitants.

Zinc deficiency has been an issue in the past, but in recent research work, it was found to affect the inhabitants adversely as it affects the enzymes that regulate RNA and DNA [22]. Cobalt poses adverse effect on kidney and eye sight, and the magnitude of increment in the samples was considered a threat to the inhabitants [23]. Nickel is listed in the European Commission List, World Health Organization as Group 1 (human carcinogen) [24], and its increment downstream was found to be very high.

High phosphorous presence can affect the biological productivity of freshwater ecosystem [25], [26]. Downstream samples of Centennial coal mine (W6) and Canyon coal mine (W10) showed a significantly high presence of phosphorous, though the increment of phosphorous content in other downstream samples was not very high. Significant increment in nitrogen value of Canyon coal mine's Dalpura creek was also observed.

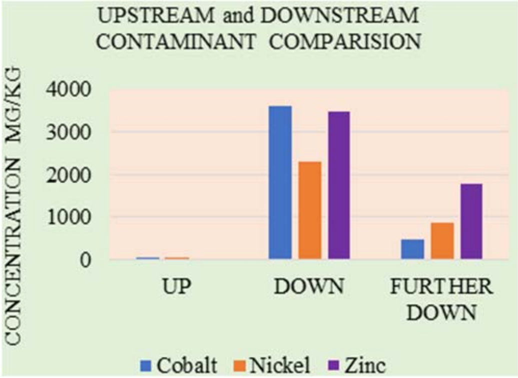

Fig. 2 Comparison of upstream to downstream contaminants in Dalpura creek sediments

Fig. 3 shows the FTIR of the sediment samples. The side peak at 1162 cm^{-1} and a large peak centering at around 1060-1080 cm^{-1} for sample W1 are ascribed to quartz and aluminosilicate clay minerals (e.g., kaolinite), respectively. This information matched with the abundance of aluminum in the sediment analysis. Double peaks at 796 and 777 cm^{-1} correspond to the inorganic materials, such as clay and quartz minerals, while the peak at 692 cm^{-1} is attributed to anthophylitte. The existence of quartz is also confirmed by the peak at 467 cm^{-1} which is the result of Si-O and O-Si-O bending vibrations. This information revealed that the abundance of contaminants discharge had contributed in the natural process of quartz formation.

The additional small peaks at 3696 cm^{-1} and 3619 cm^{-1} appeared in the IR spectrum of W2, which was related to Al-O–H stretching and Si-O and O-Si-O bending vibrations and/or Al-O–H (inter-octahedral), respectively. The peak at 1595 cm^{-1} became more intensive, demonstrating the increased content of Si–O–C bond. More intense bonding has indicated that the downstream sample has more minerals to form Si-O-C bonds. Similar results can be obtained when comparing W4 with W3, W6 with W5, and W9 with W8, respectively.

The mass loss of the samples when heated at 10 °C/min is presented in Fig. 4. The differential thermogravimetry (DTG) analyses for samples indicated distinct discrete stages of degradation to reflect their thermal dynamics. Most of them are characterized by the initial loss of inherent moisture followed by the devolatilisation of primary volatiles. For instance, upstream sample of Sawyer swamp, W3 illustrated initial DTG peak centered at 60-90 °C can be assigned to inherent moisture loss followed by a broad peak at 300-350 °C

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which started declining at 220 °C for water soluble materials. Further temperature increment yielded a broader peak from 370 °C through to 480 and slightly dipped at 450 °C which stabilized at 550 °C. At the temperature of 620 °C, another decline started yielding into a very sharp peak at 640-650 °C and finally got stable at 740 °C.

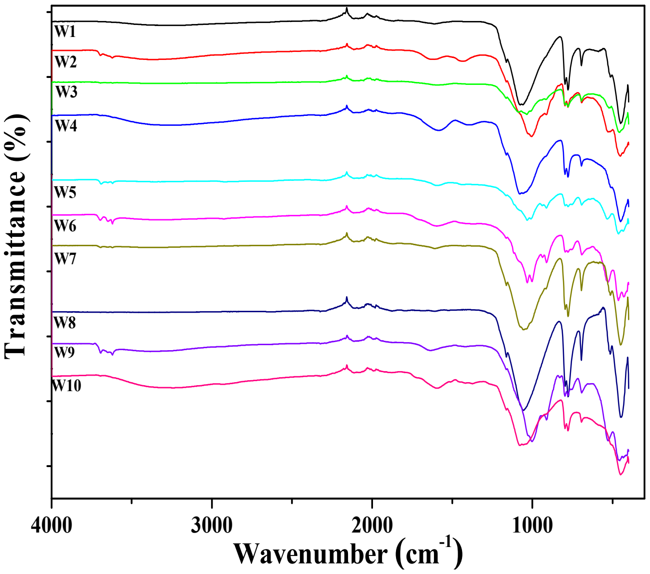

Fig. 3 FTIR of sediment samples from Blue Mountain area

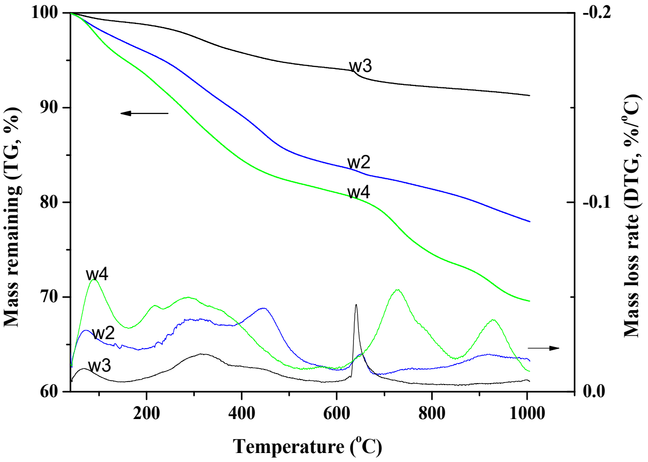

Fig. 4 DTG curves of sediments from Blue Mountain area

Downstream sample of the Sawyer swamp W2 initially exhibited the same pattern and the slight dip of W3 at 450 °C became a prominent peak reducing the size of sharp peak at 640-650 °C. When discharge point sample of Springvale was subjected to the DTG analysis, an additional peak at 280 °C was observed, and the sharp peak of W3 at 640-650 °C became more intense and broad which further showed a very prominent peak 940-960 °C indicating a highly stable compound.

IV. CONCLUSION

This project helped in studying the chemical contaminants and toxicity increment in the sediment of Blue Mountain region near coal mine activities. The sediments have been seriously affected by the mine discharge breaching the ANZECC guideline limits. The exceedance of toxic elements to SQGV indicated the possible adverse contaminant-induced impact on resident benthic communities in the region. Continuous trace element buildup and accumulation could have resulted in catalyzing the natural process of quartz and clay formation in the sediment which was confirmed by FTIR of the samples. TGA analysis indicated the discharge of thermally high stability compounds from coal mines or catalisation of their natural formation by discharged material. This work has provided a baseline of contaminants for the region and regulatory authority can design remedial system for future resource utilization. This study revealed that an independent monitoring schedule should be in place to avoid uncontrolled continuous environmental impact compromises.

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