RESEARCH ARTICLE



The occurrence and potential ecological risk assessment of bauxite mine-impacted water and sediments in Kuantan, Pahang, Malaysia

Faradiella Mohd Kusin^{1,2} · Muhammad Syazwan Abd Rahman¹ · Zafira Madzin¹ · Shamshuddin Jusop³ · Ferdaus Mohamat-Yusuff^{1,2} · Mariani Ariffin^{1,2} · Mohd Syakirin Md Z¹

Received: 29 July 2016 / Accepted: 3 October 2016 © Springer-Verlag Berlin Heidelberg 2016

Abstract Recent bauxite mining activities in the vicinity of Kuantan, Pahang, have been associated with apparent environmental quality degradation and have raised environmental concerns among the public. This study was carried out to evaluate the overall ecological impacts on water and sediment quality from the bauxite mining activities. Water and sediment samples were collected at seven sampling locations within the bauxite mining areas between June and December 2015. The water samples were analyzed for water quality index (WOI) and distribution of major and trace element geochemistry. Sediment samples were evaluated based on geochemical indices, i.e., the enrichment factor (EF) and geoaccumulation index (I_{geo}). Potential ecological risk index was estimated to assess the degree to which sediments of the mine-impacted areas have been contaminated with heavy metals. The results showed that WQIs of some locations were classified as slightly polluted and contained metal contents exceeding the recommended guideline values. The EFs indicated minimal to moderate enrichment of metals (Pb, Cu, Zn, Mn, As, Cd, Cr, Ni, Co, and Sr) in the sediments. Igeo showed slightly to partially polluted sediments with respect to As at some locations. The potential ecological risk index (RI)

Responsible editor: Philippe Garrigues

Faradiella Mohd Kusin faradiella@upm.edu.my

- ¹ Department of Environmental Sciences, Faculty of Environmental Studies, Universiti Putra Malaysia, UPM, 43400 Serdang, Selangor, Malaysia
- ² Environmental Forensics Research Centre (ENFORCE), Faculty of Environmental Studies, Universiti Putra Malaysia, UPM, 43400 Serdang, Selangor, Malaysia
- ³ Department of Land Management, Faculty of Agriculture, Universiti Putra Malaysia, UPM, 43400 Serdang, Selangor, Malaysia

showed that As posed the highest potential ecological risk with RI of 52.35–60.92 at two locations, while other locations indicated low risk. The findings from this study have demonstrated the impact of recent bauxite mining activities, which might be of importance to the local communities and relevant authorities to initiate immediate rehabilitation phase of the impacted area.

Keywords Bauxite · Mine water · Sediment · Heavy metal · Ecological risk index · Geochemical index

Introduction

Malaysian mining industry is expected to remain on a growth path driven by the ongoing demand for mineral supply both nationally and globally. Metallic mineral sector in Malaysia includes bauxite, iron ore, manganese, gold, tin, and other byproducts of tin and gold mining (Majid et al. 2013). As of 2013, bauxite production has greatly increased and the only bauxite mine in operation was in Pengerang, Johor. Kuantan, Pahang, a district in eastern Peninsular Malaysia, has become a hot spot for new bauxite mines in Malaysia when bauxite mining in Indonesia ceased operation. Bauxite in Kuantan area is formed from basalt. The area in Kuantan including Bukit Goh (an area which is heavily mined for bauxite) occupied by basalt is about 18,000 ha (Paramananthan 2000). The basalt in Kuantan area is composed of 12-13 % Al₂O₃, 3-6 % Fe₂O₃, 7-8 % FeO, 1-2 % $TiO_2,\ 0.02\ \%\ Cr_2O_3,\ and\ 0.01\ \%$ NiO (Paramananthan 1977; Senathi 1986).

Bauxite contains precious metal called Al that is widely used for manufacturing many industrial goods. The materials having the ore contain minerals which could be similar to those occurring above it—the soil of Kuantan Series contains gibbsite [Al(OH)₃] mixed with goethite (FeOOH), hematite (Fe₂O₃), and kaolin (Tessens and Shamshuddin 1983; Shamshuddin and Fauziah 2010). The red coloration of the bauxite in Kuantan is due to the presence of mineral hematite. A small amount of anatase (TiO₂) could possibly be present in the bauxite, which is a source of Ti, an even more precious metal. Bauxite is an ore formed from severely weathered rocks, which are leached of and other soluble materials in a wet tropical and sub-tropical climate (Gow 1993). Bauxite is typically reddish brown in color with a pisolitic structure, earthy luster and a low specific gravity. Lateritic bauxite (silicate bauxites) ores are largely formed in tropical regions by the weathering of silicate rocks and tends to contain the highest concentration of aluminum ores compared to karst bauxite (carbonate bauxites) (Zhukov and Bogatyrev 2012).

However, bauxite mining is not without its challenges, especially the open cast mining activity. Bauxite is usually stripmined because it is typically found below soil layer, 1 or 2 m below the surface. Mining bauxite may cause great disruption as it has detrimental impacts on water, air, land, aquatics, wildlife, and other biological resources as well as human life if the mining activities are not properly controlled (Saxena and Singh 2000; Abdullah et al. 2016). Mining activities in general have been known to generate environmental impacts such as degradation of water quality and spreading of spoils that forms wastelands (Lamare and Singh 2014). Open cast mining also creates socioeconomic impacts, as seen when the quarrying is carried out unsystematically, not as per prescribed rules and regulation (Lad and Samant 2014). The presence of metals for instance may introduce impacts in the aquatic ecosystem with regard to environmental persistence, toxicity, and ability to be assimilated into the food chain (Ololade et al. 2008; Ahanger et al. 2014; Shaari et al. 2015).

Ecological contamination such as heavy metal pollution may also exist through natural processes aside of the anthropogenic activities. The natural sources such as erosion, weathering process, and acidification are common sources for heavy metals being brought into the environment (Tajam and Kamal 2013; Demirak et al. 2013). Heavy metal pollution is one of the major concerns in the natural environment due to its features of being destructible and the toxicity effect it imposes on living organisms when it exceeds permissible levels (Mmolawa et al. 2011). The importance of ecological impact assessment due to bauxite mining activities might be of interest to the local communities and relevant authorities partly because the impacted water bodies could be the source for raw water supply (Kusin et al. 2016a). Given the extent of recent environmental degradation due to such mining activities, it is important that the occurrence of the pollution be investigated. Therefore, this study was undertaken to evaluate the overall ecological impacts due to bauxite mining activities in the vicinity of Kuantan, Pahang, on water ecosystems and within the mine water environments. Specifically, evaluations were made based on several hydrogeochemical indices such as water quality index, enrichment factor and geoaccumulation index of selected heavy metals in sediments,

and potential ecological risk index, as well as comparison with the regulatory requirement guidelines. With recent public outcry over apparent environmental impacts associated with bauxite mining activities in Pahang and southern Terengganu, this study can provide significant inputs for policy-makers in reviewing the existing laws and other stakeholders interested in the issue.

Materials and methods

Study area

Kuantan District (2960 km²) is the state capital of Pahang, which is located at latitude 3° 45' 0" N, and longitude 102° 30' 0" E. The National Physical Plan 2005 has identified Kuantan as one of the future growth centers and a hub for trade, commerce, transportation, and tourism in Malaysia. Kuantan is considered a social, economic, and commercial hub for the East Coast of Peninsular Malaysia due to its strategic location, while rapid development has transformed and modernized the city. The bauxite mining operation is progressively occurring in the vicinity of Bukit Goh Kuantan, but the ore deposits were then transported to temporary storage area within Kuantan Port prior to being exported to China for mineral processing. Monitoring of the mine-impacted areas was conducted at seven sampling locations within the bauxite mining areas in Kuantan including Bukit Goh before the moratorium, i.e., temporary cessation of the bauxite mining activities (Fig. 1). Sampling was carried out thrice (between June and December 2015). The sampling locations were at Bukit Goh, Sungai Panching Intake, Pengorak River, and Kuantan Port including the stockpile areas, which are the most affected sites due to bauxite mining activities (Table 1).

Water and sediment sampling

The physico-chemical characteristics and mineral composition of water and sediment were investigated to evaluate the effect of bauxite mining on water and sediment geochemistry of the areas. On-site measurements of water physico-chemical parameters (pH, electrical conductivity (cond.), E_h (redox potential), total dissolved solids (TDSs), and temperature) were taken using a calibrated Myron L Ultrameter 6P. Alkalinity was measured in the field using a HACH Alkalinity Kit (AL-AP) by means of titration against sulfuric acid with phenolphalein and bromcresol green-methyl red indicators. On-site turbidity measurement was undertaken using an Orion Aquafast turbidity meter. Samples for water quality analysis were collected in pre-washed polypropylene bottles (soaked overnight in 10 % v/v nitric acid (HNO₃), washed three times with tap water, then three times with 18.2- Ω Milli-Q deionized water). For total cations and metal analysis, water samples were collected in 125-mL bottles, filtered through a 0.2- μ m filter paper and acidified with 1 % v/v concentrated HNO₃, and unacidified for anion analysis. All samples were kept



Source: Jabatan Mineral & Geosains

Fig. 1 a Mining areas in the state of Pahang, b sampling locations in Bukit Goh, and c Kuantan Port

in the cold room at 4 °C prior to analysis. Major cations (Ca, Mg, Na, K) and metals (Fe, Mn, Al, Zn, Cu, Pb, As, Cr, Cd, Co, Ni, Sr) were analyzed using an inductively coupled plasma–optical emission spectrometer (ICP-OES), Optima 8300, Perkin Elmer. Anion (Cl) was analyzed using titration method, and SO₄ was determined using turbidimetric method by HACH meter. Reliability of sample analyses was tested by charge balance calculations. An electro-neutrality within ±5 % was considered to be of suitable accuracy, but up to ±10 % are acceptable (Appelo and Postma 2005).

For laboratory analyses of BOD, COD, TSS, and NH₃-N, all the laboratory analyses and the sample preservation were carried out according to APHA Standard Methods for the

examination of water and wastewater (APHA 2012). All samples were kept cool at 4 °C prior to analysis. Samples for COD and NH₃-N were acidified with 0.35 % by weight of H₂SO4 to pH < 2, while samples for BOD were collected in 300-mL BOD bottles, kept in the dark, and analyzed within 48 h after sampling. COD and NH₃-N were determined using a UV-visible detector (DR900 HACH) with a COD test reagent based on dichromate method using potassium dichromate and an NH₃-N test reagent (Nessler reagent), respectively. Dissolved oxygen level for BOD test was measured using a DO probe for initial DO and DO after 5-day incubation at 25 °C, BOD₅. TSS was measured by measuring the weight

	-		
Table 1	Description of sampling		

locations

Station	Sampling site	Location	Description
S1	Bukit Goh	3° 52′ 36.0″ N, 103° 15′ 47.1″ E	Mine drainage at Bukit Goh
S2	Bukit Goh	3° 52′ 44.6″ N, 103° 15′ 22.3″ E	Mine drainage at Bukit Goh
S3	Sg. Panching Water Intake	3° 50′ 47.7″ N, 103° 11′ 60.0″ E	Water intake point to water treatment plant at Sg. Panching
S4	Kuantan Port	3° 59′ 23.9″ N, 103° 24′ 58.3″ E	Drainage area nearby bauxite stockpile area
S5	Kuantan Port	3° 59′ 39.4″ N, 103° 24′ 53.0″ E	A stream nearby bauxite stockpile area
S6	Kuantan Port	3° 58' 22.8" N, 103° 24' 44.9" E	A stream nearby bauxite stockpile area
S7	Pengorak River	3° 58' 08.2" N, 103° 24' 35.9" E	Estuary from Pengorak River to South China Sea

of remaining portion of the filtered samples before and after ignition at 105 °C in an oven.

Sediment samples were collected at the same sites as with the water samples. All of the samples were bagged, labeled, and sealed in clean polyethylene bags and were transported to the laboratory for analysis. Sample preparation was performed according to EPA method 3050B (USEPA 1996) prior to heavy metal analysis by means of acid digestion, using nitric acid-hydrogen peroxide digestion. The sample was air-dried, crushed, and sieved through a 500-µm mesh sieve (IAEA 2003). Of the sample, 1.0 g was digested for a total volume of 50 mL. The supernatant sample was then filtered with 0.45-µm membrane filter and analyzed using ICP-OES for metal elements.

For quality assurance/quality control (QA/QC), all the laboratory apparatus and glassware used were cleaned with 5 % ν/ν HNO₃ and rinsed with 18.2- Ω Milli-Q deionized water. The reagents used were all of analytical grade. To ensure accuracy and precision of the ICP-OES performance, a series of standard solutions were prepared using the ICP multielement stock solution for generating the standard calibration curves. Sample blanks were used to ascertain the background correction. All sample tests were run in triplicate during ICP-OES analysis. Analytical accuracy was also checked with standard reference material NIST, SRM 1646a (estuarine sediment). The percentage of recoveries for the metals studied ranged between 86 and 115 %.

Water quality index

Water quality index (WQI) ascribes water quality value to an aggregate set of measured parameters (Table 2). It consists of sub-index values assigned to each pre-identified parameter by comparing its measurement with a parameter-specific rating curve, optionally weighted, and combined, resulting in the final index. The assessment of water quality parameters with their respective guideline standards is the basis of water quality index (Khan et al. 2003). The WQI was calculated based on the concentrations of DO, BOD, COD, NH₃-N, SS, and pH of the water (Mustapha 1981; Haque et al. 2010). Once the respective sub-indices have been calculated, the WQI can then be calculated as the following (DOE 2008):

$$DOE-WQI = 0.22 \times SIDO + 019 \times SIBOD + 0.16$$
$$\times SICOD + 015 \times SIAN + 0.16 \times SISS$$
$$+ 0.12 \times SPIH$$
(1)

where the sub-indices of the parameters were obtained from a series of equations.

Geochemical indices

In order to evaluate the geochemical characteristics with respect to metal contamination in sediments, geochemical

 Table 2
 Water quality classification of selected parameters according to National Water Quality Standards (NWQS) for Malaysia

Parameter	Class						
	Unit	Ι	IIA	IIB	III	IV	V
pН		6.5-8.5	6–9	6–9	5–9	5–9	_
DO	mg/L	7	5-7	5-7	3-5	<3	<1
BOD	mg/L	1	3	3	6	12	>12
COD	mg/L	10	25	25	50	100	>100
TSS	mg/L	25	50	50	150	300	300
AN	mg/L	0.1	0.3	0.3	0.9	2.7	>2.7

Source: DOE (2008)

Class I conservation of natural environment, water supply I—practically no treatment necessary, fishery I—very sensitive aquatic species; *class IIA* water supply II—conventional treatment required, fishery II—sensitive aquatic species; *class IIB* recreational use with body contact; *class III* water supply III—extensive treatment required, fishery III—common of economic value and tolerant species, livestock drinking; *class IV* irrigation; *class V* none of the above

indices were used including enrichment factor (EF) and geoaccumulation index (I_{geo}) .

EF

The enrichment factor for Fe-normalized data is defined as [16]

$$EF_{metal} = [Mx/Fex]_{sample} / [Mc/Fec]_{background}$$
(2)

where Mx is the concentration of metal in the examined sample, Fex is the concentration of Fe in the examined sample, Mc is the concentration of metal in the average shale or undisturbed sediment, and Fec is the concentration of metal in the average shale or undisturbed sediment that acts as a normalizer. Fe was chosen as the element of normalizer because it is a natural resource vastly dominated in input. The main advantages of using Fe as a normalizer are (1) Fe is associated with fine solid surface, (2) its geochemistry is close to that of many trace metals, and (3) its natural sediment concentration tends to be uniform. Fe has been used successfully by researchers to normalize metal contamination in river and coastline sediments (Baptista-Neto et al. 2000; Zhang et al. 2009; Amin et al. 2009; Cevik et al. 2009). The background concentrations of Pb, Cu, Zn, Mn, Fe, As, Cd, Cr, Ni, Co, and Sr in the average shale obtained from Smith and Huyck (1999) were used in this study. According to Sutherland (2000), EF can be categorized as follows: EF < 2 is deficiency to minimal enrichment, EF 2-5 is moderate enrichment, EF 5-20 is significant enrichment, EF 20-40 is very high enrichment, and EF > 40 is extremely high enrichment.

Igeo

 I_{geo} as described by Muller (1969) is to estimate the enrichment of metal concentrations above background or baseline

concentration. I_{geo} is a quantitative approach to measure heavy metal pollution in sediments or soils. The index is mainly a single metal approach to calculate metal accumulation in sediment when the concentration of toxic heavy metal is 1.5 or greater than their lithogenic background values (Gaur et al. 2005).

The I_{geo} is expressed by the following formula:

$$I_{\text{geo}} = \log_2 \left[C_n / 1.5 B_n \right] \tag{3}$$

where C_n is the measured concentration of metal in sediment n, B_n is the geochemical background value of element n, and factor 1.5 is the coefficient variation of the background data due to lithogenic impacts. The background values of the heavy metals are the same as applied in the enrichment factor calculation.

Potential ecological risk index

Potential ecological risk index was used to evaluate the potential ecological risk considering the content and toxic response factors of trace elements in the sediment samples (Sun et al. 2010; Liu et al. 2016). Potential ecological risk index (PERI) was calculated based on the following formula (Hakanson 1980):

$$\mathbf{RI} = \sum E_f$$
 (4)

where RI is the sum of all the potential risk factors for heavy metal in soil. E_f^i is the potential ecological risk index for single heavy metal pollution that can be calculated as

$$E_f^i = C_f^i \times T_f^i \tag{5}$$

 T_f^i is the response coefficient for the toxicity of the single metal contamination. C_f^i is the pollution index for a given heavy metal and can be defined as

$$C_f^i = C_s^i / C_n^i \tag{6}$$

where C_s^i is the present concentration of heavy metal in the sediment and C_n^i is the reference natural background concentration of heavy metal in the sediment that can be referred to as the background values of the heavy metals, which are the same as applied in the enrichment factor calculation. Based on the previously published values, the toxicity coefficients of Pb, Cu, Zn, As, Cd, Cr, Ni, and Co used were 5, 5, 1, 10, 30, 2, 5, and 5, respectively (Zheng-Qi et al. 2008; Mamat et al. 2016). Based on the E_f^i and RI formula, the classification of potential ecological risk of the selected heavy metals can be obtained.

Table 3 Mean physico-	chemica	al parameters of	the water	rs and water quali	ity classifica	tion based on DOE-	-WQI								
Location	Hd	Temperature	SQT	Conductivity	E_{h} (mV)	Alkalinity	Turbidity	DO	SSL	BOD	COD	NH ₃ -	ΝQΙ	Class	Status
			(mg/	(1112/241)		(IIIB/L as cacu3)		(mg/L)	_			2			
S1-Bukit Goh	5.95	33.3	219	234	150	103	872	7.89	7.04	1.2	12	1.53	87	Π	Clean
S2-Bukit Goh	6.43	31.1	23	37	347	5	41	7.10	0.15	1.7	11	0.28	91	Π	Clean
S3-Sungai Panching Intake	5.10	31.1	54	87	180	42	80	7.03	0.20	5.8	7	0.19	86	Π	Clean
S4-Kuantan Port	6.44	31.8	254	392	302	207	55	6.40	5.45	1.5	12	1.72	83	Π	Clean
S5-Kuantan Port	6.69	31.1	234	314	189	131	53	5.85	0.13	2.5	16	0.76	85	Π	Clean
S6-Kuantan Port	4.96	30.0	272	416	208	105	928	4.02	4.04	2.7	73	1.37	99	Ш	Slightly
															polluted
S7-Pengorak River	6.16	31.0	245	311	304	115	164	4.31	1.04	4.5	16	1.07	74	III	Slightly polluted
Mean data for each locatic	n is pre	sented $(n = 9)$													





Results and discussion

Assessment of WQI

For water quality index assessment, the WOI was calculated for all the monitored locations. The water quality index classification is shown in Table 3. It is noted that the lowest WQI was found at location S6 with value of 66 followed by S7 (74). The WQI was found to be in the order of S6 > S7 > S4 > S5 > S3 > S1 > S2(lowest to highest). WQI indicates that the surface water quality of the mine-impacted water was found slightly polluted in some locations (i.e., S6 and S7 were categorized as class III, slightly polluted). The water sampled at S6 was from the stockpile area of bauxite mine storage, which is in the vicinity of Kuantan Port and is near to other industrial areas. S7 was also found polluted as a result of direct discharge from the stockpile area into the river. Based on current water quality status, the water from these locations can only be used as a source of raw water supply after extensive treatment and the water is only suitable for tolerant fish or aquatic species (DOE 2008). For S1 to S5 the water quality is in class II, which is considerably clean but will require further treatment if it is intended for potable water use.

Notwithstanding the WQI classification, the variations of selected water quality parameters are illustrated in Fig. 2. pH was found in circum-neutral range to slightly acidic pH (at S1, S3, and S6). The relatively acidic pH at S6 was apparently associated with the uncontrolled discharge from the stockpile area and is coupled with notably low dissolved oxygen and high turbidity and COD (Fig. 2). S1 indicated the highest TSS value among stations but was still below the recommended acceptable value of the NWQS. Even though S3 was generally categorized as clean, it was noted that the slightly acidic pH and high BOD level (approximately class III) could be an indication of water quality degradation. Mining significantly changes the natural water conditions when oxygen enters a formerly reducing environment during the excavation processes causing the weathering of disulfide (Wolkersdorfer 2008). The weathering reaction produces protons and thus releases acid into the mine water. In the absence of buffering minerals, pH of mine water can be extremely low. Therefore, further water quality evaluation is required because WQI does not include major and trace element geochemistry in the assessment so as to understand contaminant behavior in the mine water environments (Kusin et al. 2016b).

Major and trace elements in water

Further discussion on the major and trace element geochemistry of the waters is presented here. The results are demonstrated by comparing the mean values of the variables according to the recommended guideline values of the Ministry of Health Malaysia (MoH), World Health Organization (WHO), US Environmental Protection Agency (USEPA), and EU

Mean major and trace elements of the waters

Fable 4

Location	SO_4	CI	Ca	Mg	Na	К	Al	Fe (mg/L)	Mn	Zn	Sr	As	Cr	Cd	Ni	Cu	Co	Pb
S1-Bukit Goh	69	2.2	20.93	1.19	8.19	6.88	0.182	0.125	0.050	0.009	0.033	<tod< td=""><td><lod< td=""><td>0.002</td><td><lod< td=""><td>0.002</td><td>0.001</td><td>0.002</td></lod<></td></lod<></td></tod<>	<lod< td=""><td>0.002</td><td><lod< td=""><td>0.002</td><td>0.001</td><td>0.002</td></lod<></td></lod<>	0.002	<lod< td=""><td>0.002</td><td>0.001</td><td>0.002</td></lod<>	0.002	0.001	0.002
S2-Bukit Goh	87	8.3	2.17	0.65	1.50	4.50	0.110	0.155	0.097	0.039	0.007	0.004	<lod< td=""><td><lod< td=""><td>0.005</td><td>0.004</td><td>0.001</td><td><lod< td=""></lod<></td></lod<></td></lod<>	<lod< td=""><td>0.005</td><td>0.004</td><td>0.001</td><td><lod< td=""></lod<></td></lod<>	0.005	0.004	0.001	<lod< td=""></lod<>
S3-Sungai Panching Intake	94	6.8	2.33	0.69	7.60	21.60	0.013	0.108	0.102	0.019	0.007	<10D	<lod< td=""><td><10D</td><td>0.013</td><td>0.004</td><td>0.001</td><td>0.001</td></lod<>	<10D	0.013	0.004	0.001	0.001
S4-Kuantan Port	86	2.13	41.92	1.45	3.78	5.60	0.172	0.177	1.646	0.013	0.087	<lod< td=""><td><lod< td=""><td>0.001</td><td><lod< td=""><td>0.005</td><td>0.001</td><td>0.009</td></lod<></td></lod<></td></lod<>	<lod< td=""><td>0.001</td><td><lod< td=""><td>0.005</td><td>0.001</td><td>0.009</td></lod<></td></lod<>	0.001	<lod< td=""><td>0.005</td><td>0.001</td><td>0.009</td></lod<>	0.005	0.001	0.009
S5-Kuantan Port	80	6.18	128.37	167.21	56.45	10.25	0.100	0.209	0.648	0.021	0.512	<l0d< td=""><td><lod< td=""><td>0.001</td><td><lod< td=""><td><lod< td=""><td><lod< td=""><td>0.071</td></lod<></td></lod<></td></lod<></td></lod<></td></l0d<>	<lod< td=""><td>0.001</td><td><lod< td=""><td><lod< td=""><td><lod< td=""><td>0.071</td></lod<></td></lod<></td></lod<></td></lod<>	0.001	<lod< td=""><td><lod< td=""><td><lod< td=""><td>0.071</td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td>0.071</td></lod<></td></lod<>	<lod< td=""><td>0.071</td></lod<>	0.071
S6-Kuantan Port	43	211.4	42.84	7.49	44.73	6.93	0.720	0.732	1.904	0.061	0.131	0.019	0.001	0.003	0.012	0.01	0.004	0.007
S7-Pengorak River	59	222.6	119.48	173.00	230.3	52.20	0.050	0.174	0.796	0.077	0.062	0.092	0.001	0.003	0.006	0.009	0.002	0.011
MOH (untreated raw water)	250	250	I	150	200	I	I	1.00	0.20	3.00	I	0.01	0.05	0.003	Ι	1.00	I	0.05
MOH (treated water)	250	250	I	150	200	I	0.20	0.30	0.10	3.00	I	0.01	0.05	0.003	I	1.00	I	0.01
WHO and USEPA	400	250	I	I	200	I	0.20	0.30	0.05	5.00	I	0.01	0.05	0.01	0.02	1.00	I	0.05
EU drinking water standards 98/83/EC	250	I	I	I	I	I		0.25	0.05	I	I	0.01	0.05	0.005	0.02	2.00	I	0.01
Mean data for each location is presen	ted $(n =$	6)																

Not specified

drinking water standard (EU directive 98/83/EC) (Table 4). These guidelines describe the national or regional standards for reasonable minimum requirements of safe practice to protect the health of consumers and/or derive numerical "guideline values" for constituents of water or indicators of water quality. The compositions of SO₄, Cl, Ca, K, Zn, Sr, Cr, Cd, Ni, Cu, and Co suggested that all these element concentrations were within the recommended guideline values at all sampling locations. However, the concentrations of Mg, Na, Al, Fe, As, and Pb were above the standard guideline values at some locations as shown in Fig. 3. Sampling locations S5 and S7 were high in Mg with 167.21 and 173.0 mg/L, respectively (compared to recommended acceptable value of 150 mg/L). Mg in freshwater is typically present at concentrations ranging from <10 to 50 mg/L (Hem 1992). Anthropogenic sources of Mg include fertilizers, liming, and chemical industries (Reimann and de Caritat 2005). Apparently, surface mining soils that were being disturbed due to open cast bauxite mining excavation which discharge into nearby rivers could be a significant source of Mg release in this case. Relatively high Na of 230.30 mg/L (compared to recommended acceptable value of 200 mg/L) at S7 was notably due to the influence of seawater as with its location, i.e., mix of salt water from the sea and the estuarine water of Pengorak River. Overall, the hydrochemical signatures of the waters are illustrated in the piper diagram (Fig. 4). Most of the water samples plot in the Ca range on the cation triangle, and in the $CO_3 + HCO_3$ range on the anion triangle. This is indicative of large contribution of dissolved bicarbonate in the water that may originate from the dissolution of carbonate minerals of the host rocks and the bicarbonate-rich surface runoff. Despite this, it was noticeable that the waters sampled within Kuantan Port were mostly dominated by cation Mg and anion Cl, suggesting the influence of seawater mixing.

On the other hand, Al content was found within the recommended acceptable value for most sampling locations. However, S6 indicated Al concentration of 0.72 mg/L, exceeding the recommended values of MOH, WHO, and USEPA guidelines (0.2 mg/L). It is important to note that the higher values of Al and Fe in the water at the stockpile area were due to the fact that bauxite ores contain Al_2O_3 , Fe_2O_3 (hematite), and SiO₂ (quartz). All has been recognized as an important toxic agent to large parts of aquatics as well as terrestrial ecosystems (Rosseland et al. 1990). The Fe concentration in the water at S6 was relatively high and has been indicated by the reddish color of the sediments, i.e., precipitated Fe. The Fe concentration of 0.73 mg/L exceeded the recommended value of MOH for treated water and all other standards (0.3 mg/L). Mn concentration was expected to be high as with the presence of Fe in the water, i.e., values of 1.65, 0.65, 1.90, and 0.80 mg/L at S4, S5, S6, and S7, respectively, which were above the guideline values. The concentrations of As at S6 and S7 were 0.019 and 0.092 mg/L,



respectively, which were above permissible levels of all the standard guidelines (0.01 mg/L). The high value of As at S6 was potentially associated with the leaching of the composition of stockpiles of bauxite that directly enters the river. Consequently, this has also resulted in high As concentration as the water flows to S7. Additionally, As might as well be released due to natural processes of abundant crust (Chen et al. 2007) or from palm oil plantations along the areas. Pb concentration was 0.072 mg/L at S5, above the recommended values of all the standard guidelines (0.05 mg/L). The high concentration of Pb in the water at S5 can be related with the discharge from another bauxite stockpile area and other industries near the site. Although the impact from bauxite storage area is apparent here, anthropogenic sources of Pb in surface water can also result in an order of magnitude higher concentration compared to background values, which also includes cargo shipping activities and other industrial activities (Patterson 1965) near the Kuantan Port. Additionally, Pearson's correlation analysis showed strong positive correlations between Al-Fe, Mn, Co; Fe-Mn, Co; Zn-As, Cr, Cu; As-Cr; Cr-Cd, Cu, Co; and Cu-Co (r above 0.70, p < 0.01) (Table 6), suggesting that these heavy metals were discharged from a similar anthropogenic source or origin and had a similar behavior within their environments. The strong correlations between Fe, Pb, Zn, Cu, Al, Cd, and SO₄ can be associated with the presence of sulfide minerals like sphalerite (ZnS), galena (PbS), and chalcopyrite (CuS) because there is interaction between sulfide minerals and pyrite (FeS₂) (Taylor 1971; Gomez et al. 2016).

Fig. 3 Variation of selected

major and trace elements in water







Sediment geochemistry

The potential ecological impacts of heavy metals in sediments are important reference indicator to water quality (Chen et al. 2007; Kusin 2013). The concentration of most heavy metals in sediments for Pb, Zn, Cd, Cr, and Ni were within the recommended guideline values (i.e., sediment quality guidelines (SQGs) of the Hong Kong Environmental Protection Department, Canadian Council of Ministers of the Environment, and the UK Environmental Agency) (Table 5) except for Cu and As. Most of the sampling locations have sediment metal contents within recommended values except for S1 and S2 as illustrated in Fig. 5. S1 was found to be high in Cu, i.e., 53.45 mg/kg exceeding the permissible level as suggested by the SQGs (35.7 mg/kg). Apart from the mining activities, the contribution of Zn in agricultural soils such as from oil palm plantation might have promoted the concentration of Cu in the sediment. Stations S1 and S2 were high in As, i.e., about 8 mg/kg, which was greater than the permissible level of SQGs (5.9 mg/kg), potentially due to bauxite mining exploration, with arseniccontaining minerals mobilized during mining activities and deposited onto the sediments (Toevs et al. 2008). Further evaluation of the sediment quality is presented below with respect to the level of heavy metal enrichment and accumulation in the sediments ("EF" and "Igeo" sections).

On the other hand, the findings from this study were also compared to other relevant studies with respect to sediment/soil contamination that have been reported previously (Table 5). Although the ranges of heavy metal values vary between studies, generally, the heavy metal contents in the sediments found in this study were within the values reported in previous relevant studies in Malaysia. When compared with other bauxite mining-related studies around the world, the major elements in sediment such as Fe and Mn were generally lower than reported elsewhere. Trace elements such as Pb, Zn, As, Cr, and Sr were also lower than most reported values, while Cu, Cd, Ni, and Co were generally within the ranges reported elsewhere around the world (Table 6).

EF

EF is a geochemical tool that is widely used to categorize the metal fractions associated with sediments. Mine-impacted sediments have been associated with high metal and metalloid enrichment, suggesting strong influence of ore deposits on the mineralogy of the sediments (Gomez et al. 2016). The distributions of calculated EF for each of the studied metals are displayed in Fig. 6. Some of the metals have EFs higher than 1.5, showing strong human influence to the metal pollution in sediment. Sampling locations S1 and S6 indicated that the surface sediments were attributed to minimal enrichment of metals, where the EF values were below 2. The high values of EF shown for

Table 5 Mean heavy metal composition of the sedime	ients										
Location	Pb	Cu	Zn	Mn	Fe	As (mg/ kg)	Cd	Cr	Ni	Co	Sr
S1-Bukit Goh	10.00	53.45	60.65	203.05	22,675.00	8.01	<lod< td=""><td>0.69</td><td>0.98</td><td>12.8</td><td>5.20</td></lod<>	0.69	0.98	12.8	5.20
S2-Bukit Goh	11.00	26.60	31.45	78.55	9422.75	8.15	0.06	<lod< td=""><td>1.54</td><td>1.40</td><td>2.65</td></lod<>	1.54	1.40	2.65
S3-Sungai Panching Intake	13.40	18.85	24.95	66.40	18,144.95	<lod< td=""><td><pre><pre>TOD</pre></pre></td><td>0.97</td><td>3.67</td><td>1.05</td><td>3.65</td></lod<>	<pre><pre>TOD</pre></pre>	0.97	3.67	1.05	3.65
S4-Kuantan Port	7.25	23.75	63.20	146.35	10,765.00	<lod< td=""><td><tod< td=""><td>1.37</td><td>1.17</td><td>5.05</td><td>4.05</td></tod<></td></lod<>	<tod< td=""><td>1.37</td><td>1.17</td><td>5.05</td><td>4.05</td></tod<>	1.37	1.17	5.05	4.05
S5-Kuantan Port	5.20	9.50	13.35	33.45	8413.30	4.50	<lod< td=""><td>1.34</td><td>2.77</td><td>0.85</td><td>4.90</td></lod<>	1.34	2.77	0.85	4.90
S6-Kuantan Port	19.42	15.00	34.82	336.42	47,396.00	1.72	0.04	0.89	4.52	5.93	14.15
S7-Pengorak River	17.58	9.60	28.20	181.58	27,311.00	2.39	0.08	0.98	3.99	4.18	11.15
Hong Kong Environmental											
Protection Department											
ISQG-low	75	65	200	Ι	I	8	Ι	80	40	Ι	Ι
ISQG-high	218	270	270	Ι	Ι	70	I	370		Ι	I
Canadian Council	35	35.7	123	I	I	5.9	0.6	37.3	18	I	Ι
of Ministers of the Environment											
UK Environment Agency											
Threshold effect level (TEL)	35	36.7	123	I	I	5.9	0.596	37.3	18	I	I
Predicted effect level (PEL)	91.3	197	315	I	I	17	3.53	Ι	I	I	I
Crust average	13	70	132	950	50,000	1.8	0.2	100	80	38	350
Comparison with other relevant											
studies in Malaysia											
Shaari et al. (2015)—marine	I	17.48	63.01	273.4	7.56^{a}	I	I	I	I	9.3	I
sediments of east coast											
Malaysia											
Abdullah et al. (2014)—soils	24	34	Ι	125	Ι	Ι	I	Ι	11	I	Ι
in Gebeng, Kuantan											
Kamaruzzaman et al. (2010)-Pahang river	I	18.65	I	517.9	I	I	I	I	I	15	I
Kamaruzzaman and Ong (2009)-Kemaman river	Ι	48.8	I	597	I	I	I	I	I	16	I
Comparison with other studies associated with bauxite mini	ing activities										
Renforth et al. (2012)-sediments impacted by bauxite	<1-79.8	9.3-60.3	26.3-	292.8–2565.8	11,100-	1.7–78.5	- <u> </u> V	27.7-810.7	7.6–291.7	6.0–97.1	91.5-335.9
processing			173.2		210,300		4.0				
residue											
Zhengwei et al. (2013)-bauxite ore deposits	I	I	I	I	$0.5-24.8^{a}$	I	I	210-720	6-43	0.7 - 4.5	31–243
Radusinović et al. (2017)—karstic	T	I	I	I	$13.41 - 22.69^{a}$	I	I	342595	51-298	17.6-208.7	51.3-774
bauxite deposits											
Pappa et al. (2016)-marine sediments	570-1700	30-210	940 - 4100	3840-26,000	I	320-4100	I	I	I	I	I
associated with mining activities											
Mišík et al. (2014)—soils impacted	22.2-	26.0-112.1	42.0-	Ι	Ι	17.8-201.1	Ι	40.0-703.3	12.5-283.1	7.3-54.6	161.2 -
by red mud	143.0		123.4								357.6
Machado et al. (2013)—soils	32.97	13.76 -	46.9-	344.92 -	182,305 -	55.7-77.18	I	264.35 -	26.43 -	20.19 -	35.09-
associated with abandoned		25.55	62.05	1738.8	260,678			429.89	58.66	26.56	69.71
bauxite mine											
Mean data for each location is presented $(n = 9)$											
Mot monthed											
-INOL Specified											
^a Fe reported in percent											

🖄 Springer

Environ Sci Pollut Res





locations S2, S3, S4, S5, and S7 vary with each heavy metal elements. The findings showed high values of EF for Pb in locations S2, S3, S4, S5, and S7, which were 4.49, 2.84, 2.59, 2.38, and 2.48, respectively, under moderate enrichment. Apart from the bauxite mining activities, high value of Pb can also be related with domestic and industrial discharges (Ma et al. 2013) near the sampling locations. The EF for Cu recorded moderate enrichment of 2.02 at S2, possibly due to open cast bauxite mining and use of fertilizers in agricultural soils. Although high EF is a first indication of potential anthropogenic influence for an element, some natural sources can also cause the observed enrichment (Atgin et al. 2000). In S4, EF for Zn was classified as moderate enrichment, which indicates relatively high anthropogenic source with EF value of 2.22. The EF values of As were recorded as having significant enrichment at sampling location S2, S5, and S1, while S7 has moderate enrichment with values of 24.03, 14.86, 10.00, and 2.43, respectively. The high EF for As were related with anthropogenic activities such as the bauxite mining activities and palm oil plantation surrounding the sampling sites (Amin et al. 2009).

Igeo

The analysis also showed that the value of I_{geo} of heavy metals, i.e., Pb, Cu, Zn, Mn, Fe, As, Cd, Cr, Ni, Co, and Sr, in the surface sediments of the sampling location were relatively low, indicating clean status and no pollution with respect to heavy metals $(I_{geo} < 0)$ except for sampling locations S1, S2, and S5 with high values of As. The sampling locations of S1 and S2 indicated the highest values of Igeo for As compared to other locations, i.e., values of 1.56 and 1.59, respectively, showing partially polluted status in (class 2, $1 < I_{geo} < 2$). The sampling location of S5 has I_{geo} value for As of 0.74, which is classified as slightly polluted (class 1, $0 < I_{geo} < 1$). None of the trace metals in this study belong to the last four classes that are strongly polluted (class 3, 4, 5, and 6). Therefore, the high As accumulation in the sediments suggested that it comes from anthropogenic sources, where mining activities could be a significant source of the contaminant.

PERI

In order to evaluate the ecological impact with respect to heavy metal contamination in the sediments, potential ecological risk index was applied (Diami et al. 2016). The potential ecological risk index (Eir) for individual element and total risk index (RI) of heavy metals in the sediments of the bauxite mining areas have been calculated. The risk indices are as listed in Table 7, and the contribution from each metal element to total RI is presented in Fig. 7. As shown in the table, except for As at sampling locations S2 and S3, the Eir of Pb, Cu, Zn, Cd, Cr, Ni, and Co were lower than 40, indicating a slight potential ecological risk. Two stations, S2 and S3, have equally higher values of Eir of 45.28. Other sampling locations have low ecological risk with Eir values below 40. As noted earlier, the higher content of As in surface sediments as observed in this study can be attributed to anthropogenic activities such as the open cast bauxite mining and also due to palm oil plantation near the area (Chen et al. 2007). Natural processes can also be a significant source as As are abundant in Earth's crust and are naturally deposited onto sediments. The highest RI value of 60.93 was recorded at sampling location S2, and the lowest was recorded at sampling station S4 with RI value of 5.7. Notably, As constituted the greatest proportion of Eir to total RI at S2, S3, and S5, while contributions of Pb, Cu, and Cd were equally important at other locations (Fig. 7). Metals such as Cu, Zn, Pb, Cd, and Cr have been found to be two to five times as high as their background levels in mine-impacted sediments, suggesting anthropogenic sources of the metals (Pan and Li 2016), and have contributed to large proportions in potential ecological risk from mining activities (Pan and Li 2016; Pandey et al. 2016). Notwithstanding this, in general, the sediment samples of the mine-impacted areas were in low ecological risk level (RI <50) except for S2 and S3, which were in moderate potential ecological risk levels with $50 \le RI < 200$.

Table	e Dearso	on's correlat	ion matrix	among wat	er quality va	ariables												
	SO_4	CI	Ca	Mg	Na	K	Al	Fe	Mn	Zn	Sr	As	Cr	Cd	Ni	Cu	Co	Pb
SO_4	1.00																	
C	-0.79**	1.00																
Ca	-0.33	-0.02	1.00															
Mg	-0.20	-0.17	0.95^{**}	1.00														
Na	-0.48*	0.05	0.73^{**}	0.79^{**}	1.00													
К	-0.22	-0.14	0.51*	0.64^{**}	0.91^{**}	1.00												
Al	-0.76^{**}	0.95^{**}	-0.09	-0.29	-0.13	-0.36	1.00											
Fe	-0.77**	0.99**	0.05	-0.12	0.03	-0.21	0.97^{**}	1.00										
Mn	-0.54*	0.67^{**}	0.26	0.00	0.13	-0.09	0.70^{**}	0.73^{**}	1.00									
Zn	-0.68^{**}	0.53*	0.38	0.42*	0.77^{**}	0.63^{**}	0.33	0.48*	0.33	1.00								
\mathbf{Sr}	-0.04	0.02	0.72^{**}	0.63^{**}	0.08	-0.14	0.05	0.14	0.18	-0.12	1.00							
\mathbf{As}	-0.53*	0.12	0.57*	0.62^{**}	0.97^{**}	0.91^{**}	-0.05	0.07	0.17	0.83^{**}	-0.14	1.00						
\mathbf{C}	-0.87^{**}	0.71^{**}	0.39	0.33	0.72^{**}	0.56^{*}	0.55*	0.66^{**}	0.54^{*}	0.92^{**}	-0.09	0.79^{**}	1.00					
Cd	-0.94^{**}	0.58*	0.47*	0.34	0.63^{**}	0.40*	0.56^{*}	0.57*	0.52^{*}	0.63^{**}	0.03	0.67^{**}	0.84^{**}	1.00				
ïŻ	-0.23	0.56^{*}	-0.32	-0.24	0.08	0.25	0.34	0.46^{*}	0.10	0.46^{*}	-0.37	0.18	0.47*	0.06	1.00			
Cu	-0.68^{**}	0.68^{**}	0.03	-0.03	0.50*	0.44*	0.55*	0.62^{**}	0.60^{**}	0.82^{**}	-0.43*	0.65^{**}	0.89^{**}	0.64^{**}	0.59	1.00		
Co	-0.83^{**}	0.92^{**}	-0.08	-0.20	0.25	0.13	0.84^{**}	0.86^{**}	0.62^{*}	0.69^{**}	-0.31	0.39	0.84^{**}	0.69^{**}	0.62^{**}	0.89^{**}	1.00	
Ъb	0.06	-0.13	0.75**	0.70^{**}	0.15	-0.05	-0.12	-0.01	0.06	-0.13	0.99**	-0.09	-0.15	-0.03	-0.42*	-0.50*	-0.43*	1.00
*Sigr	ufficant at p	< 0.05																
**Sig	mificant at 1	v < 0.01																

Fig. 6 a Enrichment factor (EF) and **b** geoaccumulation index (I_{geo}) values for heavy metals in surface sediments of sampling location



Conclusions

Generally, the compositions of the bauxite mineimpacted water and sediments in the studied area have been thoroughly investigated. Results of the WQI indicated that some locations were classified as slightly polluted and have metal contents exceeding the recommended guideline values. It was found that the concentrations of Al, Fe, Mn, As, and Pb in the mine-impacted water were slightly higher than the recommended guidelines values, while the concentrations of Pb, Cu, Zn, and As in sediments were high at some sampling locations. The analysis of water samples showed that the bauxite stockpile areas and nearby streams are the most affected sites with low water quality index and have several metal contents, which were above the recommended values.

Sampling station	Potent	ial ecolog	gical risk	indices fo	r single he	eavy meta	al (Eir)		Total ecological
	Pb	Cu	Zn	As	Cd	Cr	Ni	Co	risk index (RI)
S1	3.85	3.82	0.46	45.12	_	0.01	0.06	1.68	9.88
S2	4.23	1.90	0.24	45.28	9.00	_	0.10	0.18	60.93
S3	5.15	1.35	0.19	-	-	0.02	0.23	0.14	52.35
S4	2.79	1.70	0.48	_	_	0.03	0.07	0.66	5.73
S5	2.00	0.68	0.10	25.00	_	0.03	0.17	0.11	28.09
S6	7.47	1.07	0.26	9.56	7.05	0.02	0.28	0.78	26.50
S7	6.76	0.69	0.21	13.28	13.05	0.02	0.25	0.55	34.81

Grade of ecological risk of single metal: Eir < 40 shows low risk, $40 \le \text{Eir} < 80$ shows moderate risk, $80 \le \text{Eir} < 160$ shows considerable risk, $160 \le \text{Eir} < 320$ shows high risk, and $\text{Eir} \ge 320$ shows very high risk. Grade of potential ecological risk of environment: $\text{RI} \le 50$ shows low risk, $50 \le \text{RI} < 200$ shows moderate risk, $200 \le \text{RI} < 300$ shows considerable risk, and $\text{RI} \ge 300$ shows very high risk.

 Table 7 Potential ecological risk

 indices of heavy metals





Based on the estimated EF, all sampling locations were found minimally to moderately enriched with heavy metals in sediments. The I_{geo} indicated slightly to partially polluted sediments with respect to As at some locations. Meanwhile, the potential ecological risk index demonstrated low to moderate ecological risk with respect to heavy metal contamination in the sediments. The findings have highlighted the importance of an appropriately managed mining operation as with the role of relevant agencies in coordinating more holistic strategies to mining industry. This will aid in terms of evaluating the security and safety of river quality, especially when it is intended for use as raw water resource for potable water consumption. Despite the findings from this study, it is still recommended that further studies and monitoring be conducted to assess long-term impact of mining inputs on the quality of river ecosystem and potentially on human health.

Acknowledgments Funding for this research was provided through the FRGS (5524757), Putra IPM/IPS (9433300 and 9453700) research grants funded by the Universiti Putra Malaysia (UPM), and Ministry of Higher Education, Malaysia (MOHE). The authors would also like to acknowledge technical assistance of the laboratory staffs of the Faculty of Environmental Studies, UPM.

References

- Abdullah MZ, Azhar NF, Kadir SMA (2014) Deposition of heavy metals in soil and higher plant related to rare-earth processing activities. J Ind Control Pollut 31(2):315–321
- Abdullah NH, Mohamed N, Sulaiman LH, Zakaria TA, Rahim DA (2016) Potential health impacts of bauxite mining in Kuantan. Malays J Med Sci 23(3):1–8
- Ahanger FA, Sharma HK, Rather MA, Rao RJ (2014) Impact of mining activities on various environmental attributes with special reference to health impacts in Shatabdipuram, Gwalior, India. Int Res J Environ Sci 3(6):81–87

- Amin B, Ismail A, Arshad A, Yap CK, Kamarudin MS (2009) Anthropogenic impacts on heavy metal concentrations in the coastal sediments of Dumai, Indonesia. Environ Monit Assess 148:291–305
- APHA (2012) Standard methods for the examination of water and wastewater, 22nd edn. American Public Health Association, American Water Works Association, Water Environment Federation, Washington
- Appelo CAJ, Postma D (2005) Geochemistry, groundwater and pollution, 2nd edn. Balkema Publishers, Leiden, The Netherlands
- Atgin RS, El-Agha O, Zararsız A, Kocataş A, Parlak H, Tuncel G (2000) Investigation of the sediment pollution in Izmir Bay: trace elements. Spectrochim Acta Part B 55:1151–1164
- Baptista-Neto JA, Smith BJ, McAllister JJ (2000) Heavy metal concentrations in surface sediments in a nearshore environment, Jurujuba sound, Southeast Brazil. Environ Pollut 109: 1–9
- Cevik F, Goksu M, Derici O, Findik O (2009) An assessment of metal in surface sediments of Seyhan dam by using enrichment factor, geoaccumulation index and statistical analyses. Environ Monit Assess 148:291–305
- Chen CW, Kao CM, Chen CF, Dong CD (2007) Distribution and accumulation of heavy metals in the sediments of Koahsiung Harbor, Taiwan. Chemosphere 66:1431–1440
- Demirak A, Yilmaz F, Tuna AL, Ozdemir N (2013) Heavy metals in water, sediment and tissues of *Leuciscus cephalus* from a stream in southwestern Turkey. Chemosphere 63(9):1451–1458
- Diami SM, Kusin FM, Madzin Z (2016) Potential ecological and human health risk of heavy metals in surface soils associated with iron ore mining in Pahang, Malaysia. Env Sci Pollut Res. doi:10.1007 /s11356-016-7314-9:1-12
- DOE (2008) Department of Environment Malaysia, Interim National Water Quality Standards for Malaysia. Kuala Lumpur
- Gaur VK, Gupta SK, Pandey SD, Gopal K, Misra V (2005) Distribution of heavy metals in sediment and water of river Gomti. Environ Monit Assess 102(1–3):419–433
- Gomez P, Valente T, Braga MAS, Grande JA, de la Torre ML (2016) Enrichment of trace elements in the clay size fraction of mining soils. Environ Sci Pollut Res 23:6039–6045
- Gow NN (1993) Bauxite. Geosci Can 20(1):9–16
- Hakanson L (1980) An ecological risk index for aquatic pollution control: a sedimentological approach. Water Res 14(8):975–1001
- Haque MA, Huang YF, Lee TS (2010) Seberang Perai rice scheme irrigation water quality assessment. J Institution of Engineers Malaysia 71:42–49

- Hem JD (1992) Study and interpretation of the chemical characteristics of natural water, 3rd edn. In: U.S. Geological Survey Water-Supply Paper, 2254, p 263
- IAEA (2003) Collection and preparation of bottom sediment samples for analysis of radionuclides and trace elements. Nutritional and healthrelated environmental studies section. International Atomic Energy Agency, Vienna, Austria
- Kamaruzzaman Y, Ong MC (2009) Geochemical proxy of some chemical elements in sediments of Kemaman River estuary, Terengganu, Malaysia. Sains Malaysiana 38(5):631–636
- Kamaruzzaman Y, Siti WA, Ong MC, Bidai J (2010) Spatial distribution of lead and copper in the bottom sediments of Pahang River estuary, Pahang, Malaysia. Sains Malaysiana 39(4):543–547
- Khan F, Husain T, Lumb A (2003) Water quality evaluation and trend analysis in selected watersheds of the Atlantic region of Canada. Environ Monit Assess 88:221–242
- Kusin FM (2013) A review of the importance of hydraulic residence time on improved design of mine water treatment systems. World Appl Sci 26(10):1316–1322
- Kusin FM, Zahar MSM, Muhammad SN, Mohamad ND, Zin ZM, Sharif SM (2016a) Hybrid off-river augmentation system as an alternative raw water resource: the hydrogeochemistry of abandoned mining ponds. Environ Earth Sci 75(3):1–15
- Kusin FM, Muhammad SN, Zahar MSM, Zin ZM (2016b) Integrated river basin management: incorporating the use of abandoned mining pool and implication on water quality status. Desalin Water Treat. doi:10.1080/19443994.2016.1168132
- Lad RJ, Samant JS (2014) Environmental and social impacts of stone quarrying—a case study of Kolhapur district. Int J Current Res 3(8):39–42
- Lamare R, Singh OP (2014) Degradation in water quality due to limestone mining in east Jaintia Hills, Meghalaya, India. Int Res J Environ Sci 3(5):13–20
- Liu L, Zhang X, Zhong T (2016) Pollution and health risk assessment of heavy metals in urban soil in China. Hum Ecol Risk Assess 2(2): 424–434
- Ma Z, Chen K, Yuan Z, Bi J, Huang L (2013) Ecological risk assessment of heavy metals in surface sediments of six major Chinese freshwater lakes. J Environ Qual 42:341–350
- Machado NAM, Leite MGP, Figueiredo MA, Kozovits AR (2013) Growing *Eremanthus erythropappus* in crushed laterite: a promising alternative to topsoil for bauxite-mine revegetation. J Environ Manag 129:149–156
- Majid AA, Shaharudin HM, Alias S, Adnan E, Hassan AIA, Ali MZ (2013) Malaysian mining industry. Minerals and Geoscience Department Malaysia, Kuala Lumpur, p. 152
- Mamat Z, Haximu S, Zhang Z, Aji R (2016) An ecological risk assessment of heavy metal contamination in the surface sediments of Bosten Lake, northwest China. Environ Sci Pollut Res DOI. doi:10.1007/s11356-015-6020-3
- Mišík M, Burke IT, Reismüller M, Pichler C, Rainer B, Mišíková K, Mayes WM, Knasmueller S (2014) Red mud a byproduct of aluminum production contains soluble vanadium that causes genotoxic and cytotoxic effects in higher plants. Sci Total Environ 493:883–890
- Mmolawa KB, Likuku AS, Gaboutloeloe GK (2011) Assessment of heavy metal pollution in soils along major roadside areas in Botswana. Afr J Environ Sci Technol 5(3):186–196
- Muller G (1969) Index of geoaccumulation in sediments of the Rhine River. GeoJournal 2(3):108–118
- Mustapha N (1981) Indices for water quality in a river. Master's thesis, Asian Institute of Technology, Bangkok
- Ololade IA, Lajide L, Amoo IA (2008) Seasonal metal distribution in Ondo coastal sediment, Nigeria. J Appl Sci Environ Manage 12(4):11–18

- Pan Y, Li H (2016) Investigating heavy metal pollution in mining brownfield and its policy implications: a case study of the Bayan obo rare earth mine, Inner Mongolia, China. Environ Manag. doi:10.1007 /s00267-016-0658-6
- Pandey B, Agrawal M, Singh S (2016) Ecological risk assessment of soil contamination by trace elements around coal mining area. J Soils Sediments 16:159–168
- Pappa FK, Tsabaris C, Ioannidou A, Patiris DL, Kaberi H, Pashalidis I, Eleftheriou G, Androulakaki EG, Vlastou R (2016) Radioactivity and metal concentrations in marine sediments associated with mining activities in Ierissos gulf, north Aegean Sea, Greece. Appl Radiation and Isotopes 116:22–33
- Paramananthan S (1977) Soil genesis on igneous and metamorphic rocks in Malaysia. DSc Thesis, Ghent University, Belgium
- Paramananthan S (2000) Soils of Malaysia: their characteristics and identification. Academy of Sciences Malaysia, Kuala Lumpur, Malaysia
- Patterson CC (1965) Contaminated and natural lead environments of man. Archives of Environmental Health: An International Journal 11(3):344–360
- Radusinović S, Jelenković R, Pačevski A, Simić V, Božović D, Holclajtner-Antunović I, Životić D (2017) Content and mode of occurrences of rare earth elements in the Zagrad karstic bauxite deposit (Nikšić area, Montenegro). Ore Geol Rev 80: 406–428
- Reimann C, de Caritat P (2005) Distinguishing between natural and anthropogenic sources for elements in the environment: regional geochemical surveys versus enrichment factors. Sci Total Environ 337(1):91–107
- Renforth P, Mayes WM, Jarvis AP, Burke IT, Manning DAC, Gruiz K (2012) Contaminant mobility and carbon sequestration downstream of the Ajka (Hungary) red mud spill: the effects of gypsum dosing. Sci Total Environ 421-422:253– 259
- Rosseland BO, Eldhuset TD, Staurnes M (1990) Environmental effects of aluminium. Environ Geochem Health 12(1–2):17–27
- Saxena NC, Singh G (2000) Environment and ecoplanning of mining of sedimentary deposits in forest areas. Indian J Environ Plan 3(3):49– 446
- Senathi RS (1986) Bauxite in the Kuantan area, peninsular Malaysia. GEOSEA V Proceedings Vol I, Bulletin of the Geological Society of Malaysia 19:315–325
- Shaari H, Azmi SNHM, Sultan K, Bidai J, Mohamad Y (2015) Spatial distribution of selected heavy metals in surface sediments of the EEZ of the East Coast of Peninsular Malaysia. Int J Oceanography Article ID 618074
- Shamshuddin J, Fauziah CI (2010) Weathered tropical soils: the Ultisols and Oxisols. UPM Press, Serdang, Malaysia
- Smith KS, Huyck HL (1999) An overview of the abundance, relative mobility, bioavailability, and human toxicity of metals. Environ Geochem Miner Deposits 6:29–70
- Sun Y, Zhou Q, Xie X, Liu R (2010) Spatial, sources and risk assessment of heavy metal contamination of urban soils in typical regions of Shenyang, China. J Hazard Mater 174(1): 455–462
- Sutherland RA (2000) Bed sediment-associated trace metals in an urban stream, Oahu, Hawaii. Environ Geol 39(6):611–627
- Tajam J, Kamal ML (2013) Marine environment risk assessment of Sungai kilim, Langkawi, Malaysia: heavy metal enrichment factors in sediments as assessment indexes. Int J Oceanography 2013:1–6 Article ID 482451
- Taylor D (1971) An outline of the geology of the Bukit Ibam orebody, Rompin, Pahang. Bulletin of the Geological Society of Malaysia 4: 71–89

- Tessens E, Shamshuddin J (1983) Quantitative relationship between mineralogy and properties of tropical soils. UPM Press, Serdang, Malaysia
- Toevs G, Morra MJ, Winowiecki L, Strawn D, Polizzotto ML, Fendorf S (2008) Depositional influences on porewater arsenic in sediments of a mining-contaminated freshwater lake. Environ Sci Technol 42(18):6823–6829
- USEPA (1996) Acid digestion of sediments, sludges and soils. Method 3050B
- Wolkersdorfer C (2008) Water management at abandoned flooded underground mines. Springer
- Zhang W, Feng H, Chang J, Qu J, Xie H, Yu L (2009) Heavy metal contamination in surface sediments of Yangtze River

intertidal zone: an assessment from different indexes. Environ Pollut 157:1533-1543

- Zheng-Qi X, Shi-Jun N, Xian-Guo T, Cheng-jiang Z (2008) Calculation of heavy metals' toxicity coefficient in the evaluation of potential ecological risk index. Environ Sci Technol 31(2): 112–115
- Zhengwei Z, Lingjie Z, Yujiao L, Chengquan W, Chaofei Z (2013) The "coal-bauxite-iron" structure in the ore-bearing rock series as a prospecting indicator for southeastern Guizhou bauxite mines. Ore Geol Rev 53:145–158
- Zhukov VV, Bogatyrev BA (2012) Dynamic models of lateritic bauxite formation. Geol Ore Deposits 54(5):370–397