

The impacts of alkaline mine drainage on Ba, Cr, Ni, Pb and Zn concentration in the water resources of the Takht coal mine, Iran

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ABSTRACT

Keywords: heavy metals, groundwater, surface water, sediment, alkaline mine drainage, coal-mining.

The release of heavy metals into the environment represents one of the most important environmental effects involved in extracting coal; it needs to be studied more fully. The present research investigated the effects of coal-mining in an alkaline environment and alkaline mine drainage in the Takht coal mine regarding the distribution of selected heavy metals (Zn, Pb, Ni, Cr and Ba) on the region's surface and ground water. The mine is located 12 Km southeast of Minoodasht, in Golestan province in northern Iran. Samples were collected from groundwater and surface water resources upstream and downstream of the mine. The elements' concentrations were measured by the inductively-coupled mass spectrometry (ICP-MS) method. The results showed that an alkaline environment was responsible for producing alkaline mine drainage due to the presence of limestone; this caused high pH (8.41) in the area's groundwater resources. Mining activities increased Ba, Cr, Ni, Pb and Zn concentration in the groundwater from 3.39, 0.5, 0.2, 0.5, 9.2 ppb to 83.52, 2.2, 0.6, 2.6, 48.3 ppb and from 68.7, 0.5, 1.3, 0.8, 172.6 ppb to 91, 1.2, 4.5, 1.3, 27.6 ppb in surface water, respectively. Due to the basic environment, heavy metal accumulation in the bed sediment for both tunnel effluents and runoffs was higher than during the soluble phase. pH was the main controlling factor in elements' solubility and their distribution in the environment. Increased Ba concentration in water resources was due to high Ba concentration in the coal, coal tailing and in quarry tailings.

RESUMEN

Palabras claves: metales pesados, aguas subterráneas, aguas superficiales, sedimentos, drenaje alcalino en minería, minería de carbón.

La liberación de metales pesados en el medio ambiente representa uno de los efectos ambientales más importantes en la extracción de carbón, lo cual necesita ser estudiado con mayor profundidad. El presente estudio investigó los efectos de la minería del carbón en un ambiente alcalino y en el drenaje de la mina de carbón Takht, con respecto a la distribución de determinados metales pesados (Zn, Pb, Ni, Cr y Ba) en superficie y en las aguas subterráneas de la región. La mina está ubicada a 12 km al sureste de Minoodasht, en la provincia de Golestán en el norte de Irán. Se recogieron muestras de aguas subterráneas y aguas superficiales aguas arriba y aguas abajo de la mina. Las concentraciones de los elementos se midieron mediante la espectrometría de masa de acoplamiento inductivo (ICP-MS). Los resultados indican que un ambiente alcalino produjo drenaje de minas alcalinas debido a la presencia de la piedra caliza; esto causó altos niveles de pH (8,41) en las fuentes de aguas subterráneas de la zona. La actividad minera incrementó los niveles de concentración de Ba, Cr, Ni, Pb y Zn en las aguas subterráneas de 3,39, 0,5, 0,2, 0,5, 9,2 ppb a 83,52, 2,2, 0,6, 2,6, 48,3 ppb y de 68,7, 0,5, 1,3, 0,8, 172,6 ppb a 91, 1,2, 4,5, 1,3, 27,6 ppb en el agua de la superficie. Debido al ambiente básico, la acumulación de metales pesados en el lecho sedimentario, tanto para los efluentes del túnel como para las aguas de escorrentía, fueron mayores que durante la fase soluble. El pH fue el principal determinante en la solubilidad de los elementos y su distribución en el medio ambiente. El aumento de la concentración de Ba en los recursos hídricos se debió a la alta concentración de Ba en el carbón, carbón de relaves y colas en cantera.

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Introduction

Coal is a heterogeneous material which is formed through plant decomposition in a variety of conditions regarding moisture, temperature and pressure. The diversity of elements in coal's compositions as well as the complex process of the coal forming are responsible for the existence and accumulation of light elements (e.g. Li, Be), non-metallic elements (e.g. Se, As, Bi) and heavy metals (e.g. Cu, Pb, Co, Cr) in coal. These elements can be released into the environment during coal extraction, its preparation, processing, transportation and combustion (mainly in power plants) thereby causing environmental pollution (Finkelman *et al.*, 2002; Swaine and Goodarzi, 1995; Yiwei *et al.*, 2007).

Geochemical characteristics of coal in the Alborz region of Iran have been thoroughly investigated. The findings have shown that aluminium silicates and sulphide minerals are heavy metals' main hosts. According to the chemical and physical weathering of excavated materials (coal and its wastes), elements are released from various complexes and then transported or precipitated due to their geochemical properties. After tunnel effluent transportation from a reduced to an oxidised environment, the elements' oxidation state becomes changed and some heavy metals become precipitated (i.e. Pb, Ni and Zn). Reaction oxidation and reduction potential, pH, colloid materials in transporting media and transferred materials' ion potential

are the main factors controlling materials' transportation and precipitation (Northeast Alborz Mining Co., 2009).

The Takht coal mine is located at 37° 2' 10" N and 37° 10' 35" N latitude and 55° 22' 30" E and 55° 27' 40" E longitude, lying 12 km southeast of Minoodasht, Golestan, in Iran (Figure 1). Extraction started from 2001 onwards with horizontal tunnels being bored on the south side of the area (Minoodasht Water Office, 2003a). Summer in the area is warm and humid whilst the winter involves a large amount of precipitation, mostly in the form of snow in the mountainous areas. The temperature varies from -10°C to 35°C. The basin's annual average rainfall is about 500 mm. Runoff feeds the Chehel-Chay River which is located downstream of the mine (Minoodasht Water Office, 2003b).

This research investigated the effects of alkaline mine drainage on heavy metals' distribution (namely Ba, Cr, Ni, Pb and Zn) on groundwater and surface water in the vicinity of the Takht coal mine in Minoodasht, Iran, regarding environmental concerns.

Materials and methods

Triplicate samples were collected from coal, coal and quarry tailings tunnel effluent, tailing leachate and surface and ground water as well as bed sediments from tunnel effluent and runoff to assess the effects of coal min-

Table 1. Coal sample characteristics (Northeast Alborz Coal Mining Co. 2009).

Parameter	From	To
Coal moisture	1.2%	1.8%
Ash content	11.2%	44.7%
Volatile compounds	34.2%	37.5%
Heat value	7.985 kcal/kg	8.132 kcal/kg
Carbon content	79.99%	84.24%
Hydrogen content	4.7%	5.77%
Oxygen + Nitrogen content	10.72%	15.34%
Phosphorus content	0.04%	0.31%.
Sulfur content	0.56%	1.3% (mostly in the form of pyrite)

Table 2. Sampling locations and the samples' EC and pH.

No.	Place of sampling	Longitude	Latitude	pH	EC($\mu\text{S}/\text{cm}$)
1	Tunnel effluent	361608	4112469	8.41	1451
2	Tailing leachate	361244	4113631	8.12	2620
3	Upstream groundwater	361940	4111490	7.23	219
4	Downstream groundwater	356526	4115781	7.58	726
5	Upstream runoff	361494	4112509	8.21	536
6	Downstream runoff	361451	4112539	8.29	828
7	Downstream river	357480	4114509	8.31	654
8	Tunnel effluents' bed sediments	361509	4112506	7.63	-
9	Upstream runoff bed sediments	361494	4112509	7.53	-
10	Downstream runoff bed sediments	361451	4112539	7.77	-
11	Downstream river bed sediments	357480	4114509	7.37	-

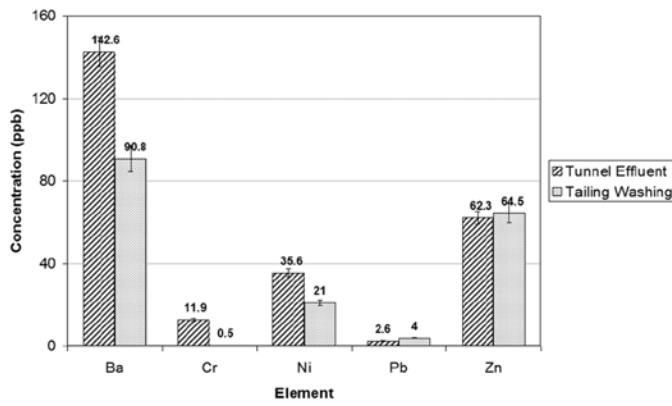


Figure 1. Overall view of the study area's location.

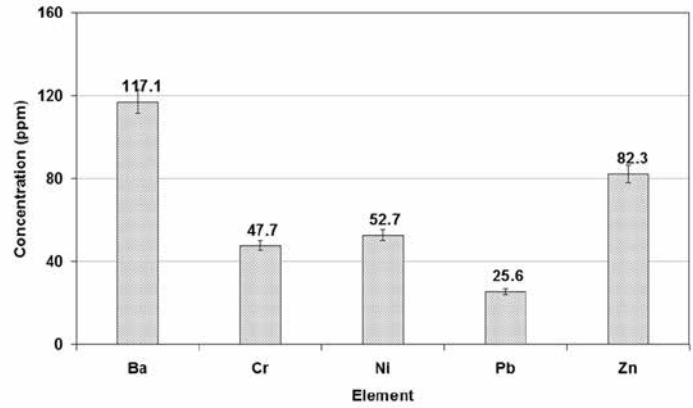


Figure 2. Heavy metals' concentrations in tunnel effluent and tailing leachate.

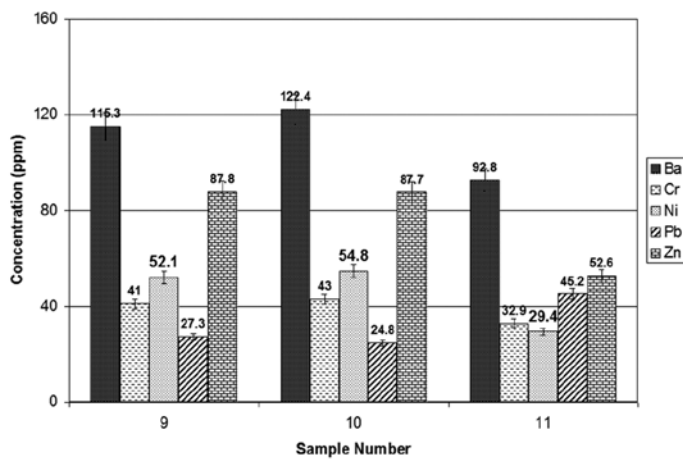


Figure 3. Heavy metals' concentration in tunnel effluent bed sediment.

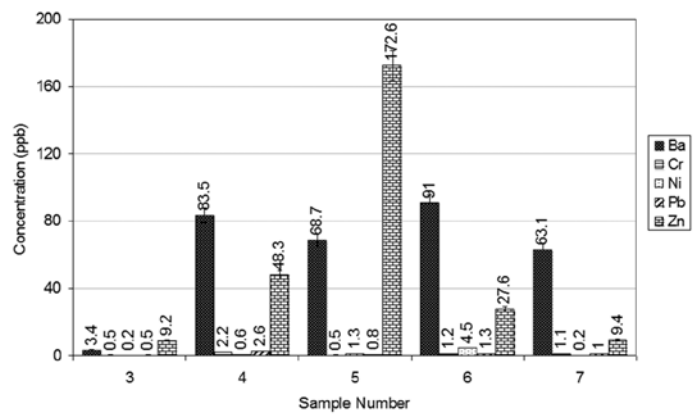


Figure 4. Heavy metals' concentration in bed sediment samples (Sample 9: upstream runoff sediments, Sample 10: downstream runoff sediments, Sample 11: downstream river sediments)

ing on heavy metals' distribution in surface and ground water. Sampling was done in October 2009 at the end of the dry season to find the worst conditions. Table 1 gives the coal samples' characteristics. Sediments were air dried at room temperature and passed through #80 mesh (180 μm opening size) to measure the heavy metals' concentrations. Samples were analysed at the ACME Lab, Vancouver, Canada using inductively-coupled mass spectrometry (ICP-MS) techniques. The water's pH and EC were measured on site using a Jenway pH meter (model 3510) and Jenway EC meter, respectively. For the sediments, pH was measured referring to the EPA SW-846 Method 9045. Table 2 shows sampling locations, pH and EC.

Results and discussion

Alkaline mine drainage has resulted from the neutralisation of acidic mine drainage (AMD) by carbonate minerals and low grade pyrite rocks. The basic tunnel effluent (pH 8.4) indicated the presence of alkaline mine drainage (Table 2) due to the highly alkaline environment. This alkalinity was responsible for the sedimentation of most elements in tunnel effluent bed sediments.

EC tended to increase downstream of the mine which could have been due to the high concentration of heavy metals and ions. Sample 4 (taken from groundwater 7 km downstream of the mine) had an EC which was 3.3 times higher than that of sample 3 (taken from groundwater upstream of the mine). This increase could have resulted from tunnel effluent and tailing leachate entering the environment (1,451 and 2,620 μS/cm EC, respectively) and causing an increased EC in surface water (from 536 μS/cm in upstream runoff to 828 μS/cm in downstream runoff). A rise in surface

and ground water pH was also observed (Table 2). The results indicated that sulphate concentration in surface water increased from zero to 48 mg/L due to pyrite oxidation and sulphate complex entering the environment which facilitated the retention of heavy metals in solution phase. The present research's findings agreed with Anderson *et al.*, (2005) who noted that concentrations of sulphate, iron, manganese and other constituents can increase, even in the presence of alkaline mine drainage.

Coal, coal tailing and quarry tailing analysis revealed high concentrations of heavy metals (especially Ba) in all three contaminant sources. Comparing these three contaminant sources indicated that coal tailings had the maximum Zn, Pb, Ni and Cr concentrations while maximum Ba concentration occurred in quarry tailings (Table 3). Washing and the consequent leaching of coal, coal tailings and quarry tailings were the main factors for contaminants entering water.

Tunnel effluent and drainage of tailing washing were the main sources of pollution, containing heavy metals Ba, Cr, Ni, Pb and Zn. Ba had the highest concentration due to its high solubility in an alkaline environment (Figure 2). Barium also had the maximum concentration in tunnel effluent

Table 3. The heavy metals' concentration in coal and tailings (in mg/Kg).

Sample	Zn	Pb	Ni	Cr	Ba
Coal	33.8	21.76	28.4	18.1	118.8
Coal tailing	128.4	46.66	70.8	43.3	54.8
Quarry tailing	80.3	32.95	60.5	42.8	146.4

Table 4. The heavy metals' concentration in the region's water resources (in µg/L).

Sample	Place	Ba	Cr	Ni	Pb	Zn
3	Upstream groundwater	3.4	0.5	0.2	0.5	9.2
4	Downstream groundwater	83.5	2.2	0.6	2.6	48.3
5	Upstream runoff	68.7	0.5	1.3	0.8	172.6
6	Downstream runoff	91	1.2	4.5	1.3	27.6
7	Downstream river	63.1	1.1	0.2	1	9.4
	Min	3.4	0.5	0.2	0.5	9.2
	Max	91,0	2.2	4.5	2.6	172.6
	Mean	61.94	1.1	1.36	1.24	53.42
	Standard Deviation	34.6	0.7	1.8	0.8	68.5

bed sediment compared to the other heavy metals (Figure 3). Regarding pH 8.4, the heavy metals in the bed sediment had much higher concentrations than in the tunnel effluent. In other words, heavy metals' concentrations in solid phase were higher than in the aqua phase when pH was 8.4 (Figures 2 and 3, Table 2). Figure 4 shows that heavy metals' concentration in bed sediments from upstream and downstream runoff had the following order: Ba > Zn > Ni > Cr > Pb. Ion exchange, adsorption and complexation are the main known mechanisms for heavy metals' accumulation in sediment (Dahrazma and Mulligan, 2007). Smith (1999) mentioned that increased pH enhances cation sorption and decreases anion sorption. The high Ba concentration in upstream runoff bed sediment could have been due to a carbonated environment and Ca exchange with Ba; this finding agreed with that of Hem (1985). Concentrations of heavy metals in downstream river bed sediments (except for Pb) became decreased, due to drained water becoming diluted in the river.

Contaminants entering the environment through mining activities (as mentioned above) changed the area's heavy metals' distribution in groundwater and surface water (Table 4). Ba concentration in downstream groundwater was 24.6 times greater than upstream due to high Ba concentration in tunnel effluent (142.6 µg/L) and tailing leachate (90.8 µg/L). Mining activities also caused increased Ba concentration in downstream runoff compared to upstream (Table 4).

The results showed that Cr, Ni, Pb and Zn concentrations in groundwater increased 4.4, 2, 5.3, and 5.5 times, respectively, from upstream to downstream. In terms of runoff, Cr, Ni and Pb concentrations from 0.5, 1.3 and 0.8 upstream reached 1.2, 4.5 and 1.3 (all in µg/L) downstream, respectively. Zinc did not increase in downstream runoff (comparing Figure 2 and Table 4) since its concentration in tunnel effluent and tailing leachate (62.3 and 64.5 µg/L, respectively) was lower than its concentration in upstream runoff (172.6 µg/L). It should be noted that the concentration of heavy metals in the river was generally lower than in downstream runoff due to dilution. This was clearly an indication of the adverse effect of mining activities on the region's groundwater and surface water. It can thus be concluded that alkaline mine drainage being released into the environment increased Ba, Zn, Pb, Cr and Ni concentration (in descending order) in groundwater and Ni, Cr, Pb and Ba in surface water.

Conclusion

Alkaline mine drainage rarely occurs in coal mines throughout the world. The Takht coal mine is one of the few coal mines where alkaline mine drainage occurs. The mining activities started in 2002 and have already had adverse effects on the quality of water resources in the area since the concentration of heavy metals in downstream groundwater is higher than in upstream water. Tunnel effluent and tailing leachate entering the environ-

ment were the main causes of such increases. An alkaline environment was responsible for the heavy metals' solubility and distribution in surrounding water resources. Heavy metals' concentration was much higher in tunnel effluent bed sediments and upstream and downstream runoff than in the aqua phase due to the alkaline environment reducing solubility.

Mining activities increased Ba, Cr, Ni and Pb concentration in the area's surface water and groundwater. Alkaline mine drainage has led to increased Zn concentration in downstream groundwater compared to upstream groundwater (5.2 times greater) while it decreased Zn concentration in surface water. The rate of coal-mining-related alkaline mine drainage effects on the environment should be investigated more fully to prevent further damage in the foreseeable future.

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