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Investigating the Role of Wind in the Dispersion of Heavy Metals Around Mines in Arid Regions (a Case Study from Kushk Pb–Zn Mine, Bafgh, Iran)

Ahmad Reza Mokhtari[1] · Sadat Feiznia[2] · Mohammad Jafari[2] · Ali Tavili[2] · Mohammad-Javad Ghaneei-Bafghi[3] · Farah Rahmany[4] · Ruth Kerry[5]

Abstract
The Kushk Pb–Zn mine is located in Central Iran and it has been in operation for the last 75 years. To investigate the role of wind dispersion of heavy metal pollutants from the mine area, dust samples were collected during 1 year and topsoil samples were collected around the mine. Results showed that the topsoil is polluted with Pb and Zn to about 1500 m away from the mine. It was also found that there was not a significant difference between the metal concentrations in topsoil and dust samples. The Pb and Zn concentrations in the dust samples exceeded 200 mg kg^{-1} and their lateral dispersion via wind was estimated to be about 4 km away from the mine. It has been shown that a combination of mining activities and mechanical dispersion via water and wind have caused lateral movement of heavy metals in this area.

Keywords Dust · Mining · Marble dust collector · Heavy metals · Soil pollution · Wind dispersion

When extractable metals are present in the rocks, mining is one of the most lucrative uses of dry land which is limited in its agricultural productivity potential by the sparse supply of water. Unfortunately, mining also releases toxic substances and heavy metals and causes pollution. Economic and industrial developments in Iran have lead to the expansion of mines and they require meticulous environmental monitoring to ensure that heavy metal pollution does not result in degradation of ecosystems and the environment or to detrimental effects on plant, animal or human health. The World Health Organization (WHO) estimates that about a quarter of all diseases may occur as a result of prolonged exposure to environmental pollution (Comfort et al. 2013). Establishing the source of the toxic metals in dusts is important for developing policies that minimize their human exposure risks (Rout et al. 2015).

As a direct result of open-pit mining operations, soil is destroyed over a considerable area and what is left is generally degraded soil and mining waste which can cause environmental damage long after the mining period (Fernández-Caliani et al. 2009). In open-pit mining, large amounts of excavated sediments are dumped on the surface as mine waste or spoil. Most of the trace metals in these spoil heaps are toxic as the concentrations of pollutants exceed permissible limits and they affect the surface and subsurface environment. Weathering of mine spoils is likely to produce leachate which releases further heavy metals into the environment as they weather and release heavy metals from the sub-surface parent rocks. Surface runoff and wind erosion cause an increase in heavy metal concentrations in local

✉ Mohammad-Javad Ghaneei-Bafghi
  mjghaneib@ardakan.ac.ir

  Sadat Feiznia
  sfeiz@ut.ac.ir

  Farah Rahmany
  farahrahmany@gmail.com

  Ruth Kerry
  ruth_kerry@byu.edu

[1] Department of Mining Engineering, Isfahan University of Technology, Isfahan 8415683111, Iran

[2] Faculty of Natural Resources, University of Tehran, Karaj 3158777878, Iran

[3] Faculty of Agriculture and Natural Resources, Ardakan University, Ardakan, Iran

[4] Geological Survey of Iran, Azadi Square, Meraj Avenue, Tehran, Iran

[5] Department of Geography, Brigham Young University, Provo, UT, USA

biota which can have a severe effect on the ecosystem and may lead to geo-accumulation, subsequent bio-accumulation and bio-magnification in the food chain (Sadhu et al. 2012).

Enhanced heavy metal concentrations in the topsoil and sometimes in the deeper soil horizons often prevent otherwise productive land being used for agriculture (Vacca et al. 2002). Rills passing spoil heaps are important vectors for the dispersion of heavy metals and river bed sediments downstream of mines usually have elevated heavy metal concentrations (Riccardo et al. 2001). In addition, to runoff and transport via rills, wind can disperse dust containing heavy metals to places far from the mine. Soils located near tailing dams and in the main prevailing wind directions have been shown to have relatively high heavy metal concentrations in comparison to values for uncontaminated soil (Laghlimi et al. 2015). Sondergaard (2013) found that dust from mines was carried up to 5 km away from mines by wind and that wind is effective in dispersing heavy metals into the environment close to mines. Nevertheless, wind dispersal of heavy metals from mines has not received as much attention as dispersion by water even though it is likely that wind dispersal is of key importance in dryland areas.

The Kushk Pb–Zn mine is located in Central Iran, in the eastern part of Yazd Province and it has been in production for the past 75 years. Studies have shown that Pb concentrations in blood exceeded standard limits in 45.7% of workers (Aminipoor et al. 2008); that about 25% of workers have poor general health, 28.9% suffer from panic attacks, 43.6% are socially dysfunctional and 7.5% suffer from depression (Halvani et al. 2007). The main objectives of this study are:

(1) to assess the role of wind in dispersion of Pb and Zn around the Kushk Pb–Zn mine, (2) to describe the distribution pattern of Pb and Zn in top soils around the Kushk mine and (3) to investigate the main source of wind-blown dust containing heavy metals.

Materials and Methods

The Kushk Pb and Zn mine is located 45 km east of Bafgh and 165 km from the center of the Yazd Province in central Iran. This area ranges from 55°46′26″ to 55°44′10″ longitude and 31°44′19″ to 31°45′32″ latitude. The climate of the area is warm and dry with a Mediterranean climate, an average temperature of 21°C and an annual rainfall of 57 mm. There is minimal plant coverage on the plain downstream of the mine with less than 10% coverage overall. Average elevation is 2020 m from sea level with the general direction of slope being from east to west and there are mountains in the north and south of the basin (Fig. 1). The mine has been exploited since 1940 by traditional methods and from 1968 by new systematic methods. Heavy metals have been being dispersed into the adjacent environment for the past 75 years. The ore deposit is being exploited via underground tunnels as well as an open-pit at the surface.To determine the prevalent wind direction and the strongest winds for the area, seasonal and yearly wind roses of the area were plotted using wind data from the closest synoptic station. Due to the fact that the nearest synoptic station is 40 km from the study area, the data from the synoptic station were verified
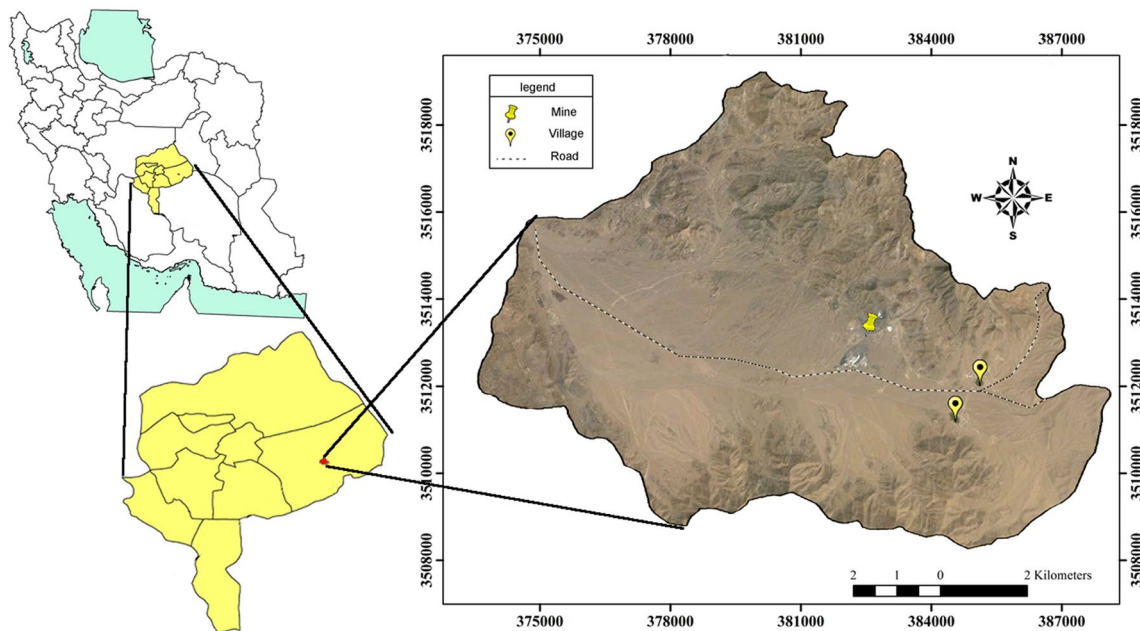

Fig. 1 Map of study area

using public questionnaires. To investigate the amount of Pb and Zn dispersion by wind as a result of mining activity, marble dust collectors (MDCO) (Goossens and Louis 2008) were used. Twenty-four MDCOs were placed 1000 m apart in an approximately regular network in the direction of the prevailing wind on the plain around the mine. During a one-year period, the sediments that accumulated in these traps were collected and stored in self-sealing plastic bags. The location of dust collectors is shown in Fig. 2.

To assess the dispersion of Pb and Zn into the environment around the mine after 75 years of operation, topsoil (0–5 cm depth) samples were collected (El Azhari et al. 2016; Zhang et al. 2012; Ettler et al. 2011) close to the dust collectors. To improve the representativeness of these samples and to avoid local variations at each location, the following bulking strategy was employed. A composite sample was obtained by mixing and homogenizing five topsoil sub-samples collected in crossing directions and spaced at approximately 2 m around a central point (Fernández-Caliani et al. 2009). As well as in order to compare the topsoil and subsoil concentration of Pb and Zn, and asses the anthropogenic activities for dispersion of contaminations, subsoil (5–30 cm depth) samples were collected and in order to compare the topsoil contamination with background, a sample were taken from out of basin boundary with the same geology and no water and wind relationship (EPA guideline 2008). The air-dry < 2 mm fraction of the soil samples was extracted for further analysis and stored in self-sealing plastic bags.

To determine total Pb and Zn contents, the soil and dust samples were digested using the four-acid digestion method (a mixed solution of HF–HCL–HNO$_3$–HCLO$_4$) according to ASTM standard practice D4698-92 (ASTM 2013) and were analyzed using inductively coupled plasma optical emission spectrometry (ICP-OES) in the Laboratory of the Geological Survey of Iran. Interpolation maps of Pb and Zn in topsoil and dust were produced using the inverse distance method of Arc GIS 10.1. Kolmogorov–Smirnov and Kruskal–Wallis tests were carried out using SPSS 23 and a 5% significance level.

Results and Discussion

Wind data were collected for a 14-year period (1997–2007) from the nearest synoptic station (Bafq station) (IRIMO 2007). During this period, meteorological statistics for this station revealed that wind gusts ranged from 0 to 20 m s^{-1}. An annual wind rose for the area is shown in Fig. 3. The dominant wind direction in the study area was NW–SE, but due to the effect of topography forming a natural wind corridor, the direction changed slightly to east–west. Mountains to the north and south of the mine also changed the wind direction slightly locally. The questionnaire results also showed the general wind direction to be east–west.

In Table 1, the summary statistics for topsoil, subsoil and dust samples are shown. The coefficients of variation (CV) indicates greater variability in Pb and Zn for the dust samples than the topsoil and subsoil samples. Figure 4 shows the relationship between Pb and Zn content for the soil samples showing a considerable correlation ($r = 0.88$) between these two elements. The strong
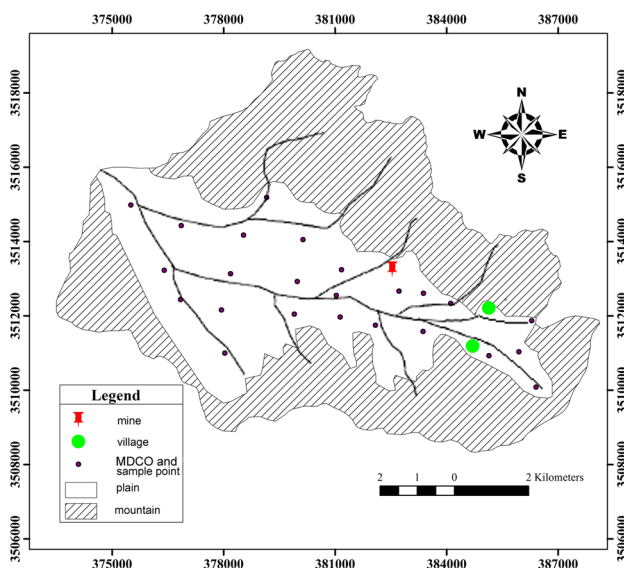

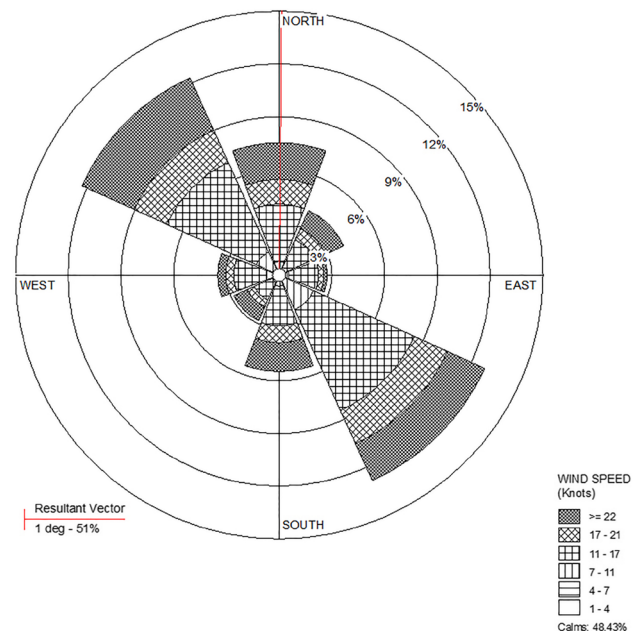Fig. 2 Map showing location of mine and sampling sites

Fig. 3 Annual wind rose

Table 1 Summary statistics for Pb and Zn in topsoil samples and dust

| Parameter	Pb			Zn		
	Topsoiloiloil	Subsoil	Dust	Topsoil	Subsoil	Dust
N	24	24	24	24	24	24
Minimum (mg kg^{-1})	25.2	17.1	27.9	98.7	41.8	78.3
Maximum (mg kg^{-1})	380.5	49.1	262.7	750.4	286.98	773.8
Mean (mg kg^{-1})	73.3	31.47	105.4	177.4	137.53	285.9
Median	55.3	28.3	60.3	155.5	1133.8	195.0
Standard deviation (mg kg^{-1})	85.9	9.2	71.2	159.2	70.4	210.9
First quartile	34.4	25.3	52.02	107.8	94.7	149.8
Third quartile	108.27	37.6	135.0	243.0	178.3	395.5
CV	0.82	0.29	1.5	1.11	0.51	1.4
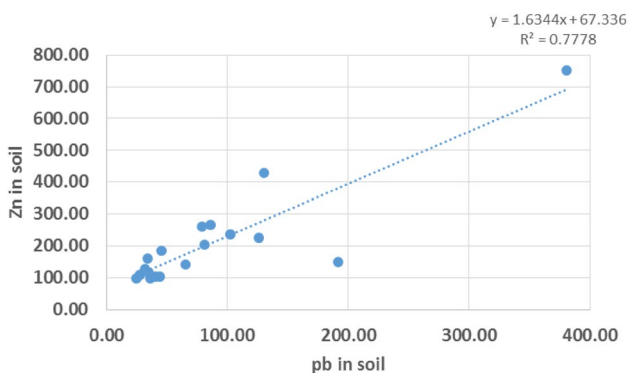
Fig. 4 Simple linear regression between Pb and Zn

Table 2 Kolmogorov–Smirnov test for normality results

Data	K–S value	Df	Sig.
Pb topsoil	0.236	23	0.009
Pb subsoil	0.152	23	0.158
Pb dust	0.261	23	0.002
Zn topsoil	0.249	23	0.004
Zn subsoil	0.304	23	0.00
Zn dust	0.261	23	0.002

Table 3 Kruskal–Wallis test results comparing Pb concentrations in topsoil and dust samples

Group		Mean ± std. error	Df	Sig.
Pb	Topsoil	73.31 ± 8.57	23	0.00
	Subsoil	31.47 ± 2.03	23	
Pb	Topsoil	73.31 ± 8.57	23	0.296
	Dust	105.36 ± 13.14	23	

Table 4 Kruskal–Wallis test results comparing Zn concentrations in topsoil and dust samples

Group		Mean ± std.	Df	Sig.
Zn	Topsoil	177.36 ± 19.86	23	0.011
	Subsoil	137.53 ± 12.36	23	
Zn	Topsoil	177.36 ± 19.86	23	0.184
	Dust	285.93 ± 49.71	23	

correlation between Pb and Zn suggests a single dominant source contributing to both, which is consistent with the nearby Pb–Zn mine excavating ores of both elements.

Given that many statistical techniques require data to be normally distributed, the Kolmogorov–Smirnov test was used to determine whether data were normally distributed or not (Table 2). Table 2, shows that except subsoil Pb data all data had distributions that were significantly different from normal. Consequently, the non-parametric Kruskal–Wallis H test was used to investigate the difference between Pb and Zn in topsoil and subsoil samples and topsoil and dust samples. Results showed that the amounts of Pb and Zn in the topsoil and subsoil were significantly

different while in the topsoil and dust were not significantly different (Tables 3, 4).

Kruskal–Wallis tests showed significant differences between the concentrationis of Pb and Zn in the topsoil and subsoil samples suggests that the topsoil contamination is due to recent human activities. Moreover The local background concentrations of Pb and Zn in the topsoil and subsoil were determined through analysis of samples with similar geology to the study area, but collected from outside the basin boundary. The concentrations of Pb and Zn were 29.2 and 91.1 ppm respectively for the topsoil and 19.83 and 102.0 ppm for the subsoil, respectively. The greater difference between the topsoil and background concentrations compared with subsoil and background concentrations of Pb and Zn suggest that Pb and Zn are being enhanced by deposition at the surface by wind or water carrying material from mining activities in the study area.

The lack of significant difference between the Pb and Zn concentrations in the topsoil and dust samples suggests that

the source of Pb and Zn in dust is the topsoil materials or that the dust contributes to the topsoil Pb and Zn concentration. The latter seems more likely as the concentrations of both Pb and Zn are higher in the dust samples than the topsoil samples.The interpolated maps of Pb and Zn in topsoil and dust samples (Figs. 5, 6) suggest that the distribution of Pb and Zn in the topsoil was influenced by runoff and wind as the main direction of elevated Pb and Zn concentration followed the direction of the corridor of the valley and which is the same of main wind direction and where the main runoff takes place. However, although the direction of flow of the main river is in the same corridor as the prevailing wind direction, lateral dispersion of Pb and Zn away from the immediate vicinity of the river and dispersion of metals to locations upstream of the mine suggest that wind plays a major role in dispersing polluted sediments in the vicinity of the mine in this arid environment.Dispersion of Pb and Zn to locations downstream of the mine could be due to the activity of wind and water.
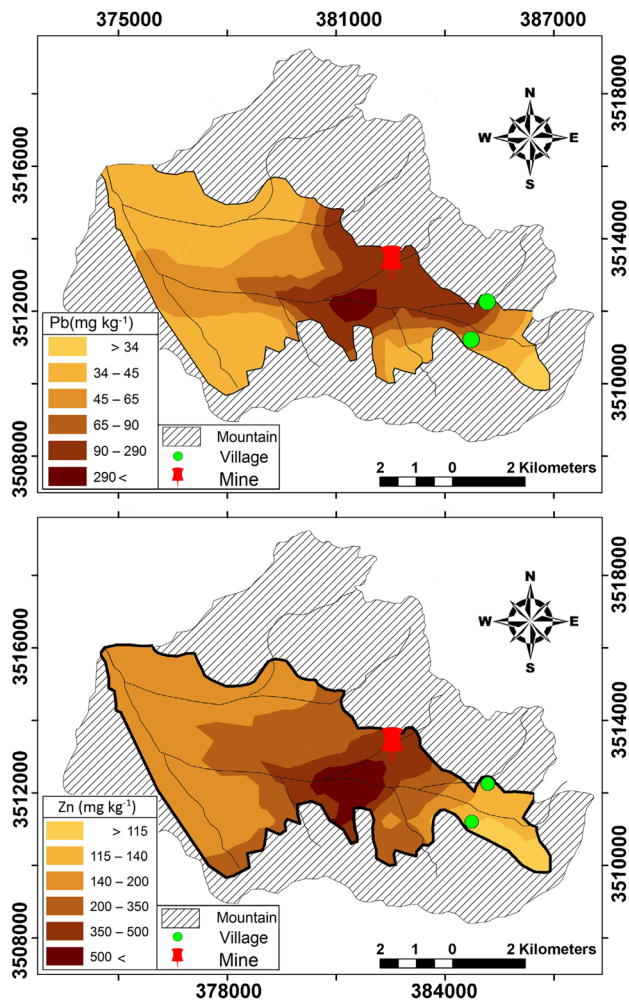

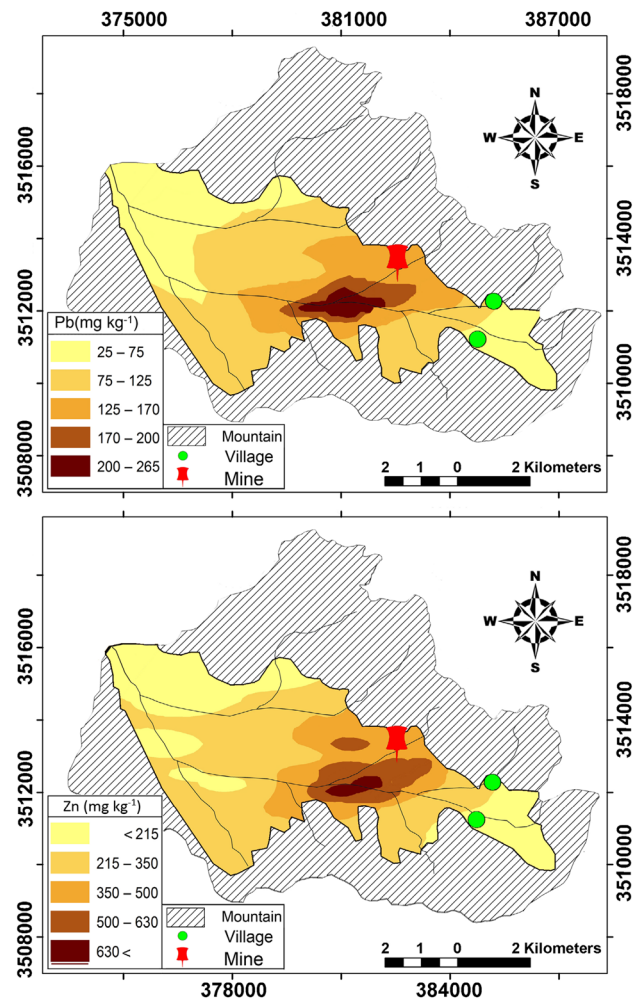**Fig. 5** Interpolation map for Zn and Pb concentrations in topsoil

Fig. 6 Interpolation map for Zn and Pb concentrations in dust samples

The maximum concentration of metals in the topsoil was close to the riverbed and the concentrations of Pb and Zn along the riverbanks were higher than the neighboring topsoil suggesting that the river definitely plays a roll in dispersing sediments from the mine. This result is in line with previous research results reported by Riccardo et al. (2001), Bister et al. (2015) and Ding et al. (2016). The concentration of metals along the river, just down-stream of the mine were above the standard levels published by the Bureau of Soil Conservation, an environmental organization in Iran. The allowable limits of Pb and Zn for rangeland soils are 290 and 500 mg kg^{-1}, respectively (Iranian Department of Environment 2013).

For comparison, maximum amounts of Zn and Pb in contaminated topsoil are presented from different locations around the world in Table 5. The heavy metal concentrations in topsoil and dust were higher than some studies and lower than others (Table 5). Two main factors influenced the level of soil contamination. The first factor was distance from the

Table 5 Maximum amounts of Zn and Pb in topsoil around the world

Location	Pb (mg kg^{-1})	Zn (mg kg^{-1})	References
Northern Idaho, USA	12,000	13,000	De Volder et al. (2003)
Kohistan region, Pakistan	1337	1072	Muhammad et al. (2011)
Copperbelt province, Zambia	480	450	Ettler et al. (2011)
Murcia Region, Spain	11,600	20,600	Conesa et all. (2011)
Rookhope Burn, UK	27,586	……	Chenery et al. (2012)
Tunisia	17,229	4813	Boussen et al. (2013)
France	75.2	327	Marchand et al. (2014)
Bestari Jaya, Selangor, Malaysia	17.52	116.09	Madzin et al. (2015)
Korea	885	1600	Kwon et al. (2017)
High Moulouya, Morocco	830.95	206	El Azhari et al. (2016)
Kolubara lignite basin, Serbia	64	66.5	Licina et al. (2017)
Suxian District of Hunan Province, China	222.61	215.73	Ding et al. (2016)

mine and river and the second one was wind deposition. This is similar to the findings of the studies conducted by Laghlimi et al. (2015) in High Moulouya, Morocco.

High levels of Pb and Zn in dust samples were mainly found around the river bed. Considerable concentrations of Pb (> 262 mg kg^{-1}) and Zn (> 773 mg kg^{-1}) in the collected dust samples were also found near the main river, which is dry for most of the year. The study area is located in a dry region of central Iran and its annual rainfall is about 50 mm. Most rainfall occurs in the winter and watercourses are filled only for several hours after large rainfall events. In such conditions, river bed deposits that have a small particle size are left without vegetation cover and easily eroded by the wind. This result indicates that not only the mine and mining processes are important sources for pollution in dust, but also river deposits can release heavy metals and pollution via wind erosion of these deposits. The direction of Pb and Zn dispersion was the same as wind direction (east–west) and also polluted dust was carried up to 4 km to the west far from the mine. This result is in line with the research results reported by Sondergaard (2013) where dispersion of heavy metals by wind was the main environmental concern during mining activities and dispersion of heavy metals was observed at distances up to 5 km from the mine.

This research targeted a mining district and adjacent areas in which mining activities have taken place for decades. The ore bodies are exploited through underground and open pit mining for Pb and Zn mineralization. To find out whether the area has been affected by mining activities and to determine the extent of contamination, geochemical sampling including soil and windborne materials were sampled. Spatial variations of Pb and Zn in soil samples revealed that the concentrations of these elements were elevated around the stream channel extending to the west from the mine locality. The dry river is one of the main features in the study area which carries runoff waters and considering the elevation of elements in the top soil near to the river it can be inferred

that water is a significant agent of transport of elements downstream. Similar patterns were observed for Pb and Zn in the dust samples and the highest concentration of these elements was detected on the margin of the river bed. So, considering these spatial coincidences between top soil and dust samples it can be inferred that both water and wind are the major transporting agents with wind being responsible for lateral dispersion around the river and dispersion to locations upstream of the mine. So, in this study area wind acts as an agent for more general dispersion and dispersion over larger distances. This was confirmed by elevated concentrations of Pb and Zn in the top soil and wind sediments are located at some distance from the mine in the river bed. However, the primary dispersion of fine particles from mining activities, i.e. tailings and open pit spoils, through wind is another complementary scenario. If particles in the dust and soil samples were examined using laser diffraction and a scanning electron microscope, the size and shape characteristics and surface markings could be examined to show how they had been transported, by water or wind. Such confirmatory analysis is needed to back up our hypotheses. Also additional samples could be collected in the 5 km radius around the mine to allow more accurate mapping of the patterns in this area and give more insight into the likely dispersal processes.

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