The distribution of some potentially harmful elements (PHEs) in the Krugersdorp Game Reserve, Gauteng, South Africa: Implications for wildlife health

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Abstract. The Krugersdorp Game Reserve (KGR) is down-gradient to the Mintails Mogale Gold (MMG) mining outfit on the West Rand of the Witwatersrand Basin in Gauteng, South Africa. The soils and waterways of the KGR have developed a signature accumulation of potentially harmful elements (PHEs) over several years due to emanations from gold mining and processing activities at MMG. In order to decipher the migration characteristics and concentration levels of PHEs in soils of the study areas, a total of 31 samples were collected from Krugersdorp, Mogale City, Gauteng, South Africa. Twenty three soil samples were taken from the KGR, four samples from the surrounding smallholdings and two samples each from Rand Uranium (RU) and MMG. Samples were analysed by both Inductively Coupled Plasma Emission Spectrometry (ICP-ES) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) for 36 elements. The concentration levels of these elements in the study areas are reported, with particular reference to the effect of toxic levels (of these elements) on nutrition and health of wildlife communities in the KGR.
Keywords. Potentially harmful elements (PHEs), heavy metal contamination, Krugersdorp Game Reserve, wildlife nutrition, integrated pollution index (IPI).

1 Introduction

Mining in Krugersdorp is an expanding industry that contributes significantly to the economic activity of the Gauteng region. However, mining has had a devastating impact on the land, water, fauna, flora and the surrounding communities. Environmental impacts include land degradation, acid mine drainage, heavy metal contamination and erosion, with serious health and ecological implications (Singo *et al*., 2013). Erosion of exposed soils, extracted mineral ores, tailings and fine material in waste rock piles can result in substantial sediment loading in surface waters and drainage ways. In addition, spills and leaks of hazardous materials and the deposition of contaminated windblown dust can lead to soil contamination (Davydova, 2005).

Heavy metals are commonly found in the environment all around the world, their presence being associated with natural occurrence (from the pedogenetic processes of weathering of parent materials at levels that are regarded as trace, $<1000\ \mathrm{mg\ kg^{-1}}$ and rarely toxic) or as a result of anthropogenic activities (Pereira *et al*., 2006). In the biogeochemical cycles, the pollution sources of heavy metals in the environment are mainly derived from anthropogenic sources through emissions from the rapidly expanding industrial areas, mine tailings, disposal of high metal wastes and atmospheric deposition (Khan *et al*., 2008; Zhang *et al*., 2010). The metals commonly found in soil as a result of anthropogenic activities include copper (Cu), lead (Pb), zinc (Zn), nickel (Ni), cobalt (Co), mercury (Hg) and cadmium (Cd). Although some of these metals are required in small amounts by living organisms for their normal physiological functioning, excessive concentrations destabilise ecosystems because of their bioaccumulation in organisms and toxic effects on biota through metabolic interference and mutagenesis (Saxena *et al*., 1999; Battaglia *et al*., 2005; Madejón *et al*., 2006). In addition, their total concentration in soils persists for a long time after their introduction (Adriano, 2003; Kirpichtchikova *et al*., 2006).

Mintails Mogale Gold (MMG) and Rand Uranium (RU) are active in re-mining of old tailing dams and dumps in the West Rand Basin. Past mining in the basin has created an underground mine void volume of approximately 43 million m^3 at Environmental Critical Level (ECL). The cessation of mining in the basin has resulted in progressive flooding of the void since 1997, until water started to decant from a number of boreholes and an old shaft in September 2002 (Hobbs and Cobbings, 2007). The decants are all located in the north western section of the Old Randfontein Estates Mine. A portion of the decanting mine water is intercepted at Black Reef Incline Shaft (BRI) and pumped to a mine water treatment facility, before being released into the Tweelopiespruit that runs through the KGR (Hobbs and Cobbings, 2007).

Due to the deterioration of water and soil quality and the impacts of acid mine drainage (AMD) from the West Rand Basin, there was a need to study the distribution characteristics and fate of the heavy metals around the mining area at Krugersdorp and to establish their levels of concentration in the area.

The KGR is in close proximity and lies immediately down-gradient (< 1000 m) to the locus of AMD originating largely from the MMG setting. Other potential receptors of AMD include neighbouring smallholdings and, further afield, the Cradle of Humankind World Heritage Site. It is imperative, therefore, that the hydrogeological environment which hosts mine water decant and is the potential recipient of AMD, is understood with regard to all potential impacts and contaminant migration pathways (Hobbs and Cobbings, 2007).

This study reports on the distribution and concentration levels of heavy metals from mining in the

Krugersdorp region (RU and MMG) and its migration to surrounding smallholdings and the KGR. In addition, this study also determines the extent to which these elements could influence the health of the wildlife population in the KGR. This information is vital in formulating intervention measures such as mitigation (AMD neutralisation), rehabilitation and soil amendment.

2 Geological Setting

The Witwatersrand Basin occupies a central portion of the Archaean Kaapvaal Craton in South Africa extending from the east of Johannesburg in the north, to the southern Free State in the south west. This Basin is approximately 300 km long and 160 km wide and is divided into the East Rand Basin, Central Rand Basin and West Rand Basin. The Witwatersrand Basin comprises granitoids and greenstones, as well as sedimentary and volcanic rocks (Robb and Meyer, 1995; Abiye *et al*., 2011).

3 The Study Area

The present study was conducted in the KGR, Mogale City on the West Rand Basin.

3.1 Geology

The KGR is characterised on the surface by dolomitic strata of the Chuniespoort Group, and in particular the Malmani Subgroup within this lithostratigraphic unit (Hobbs and Cobbing, 2007). The key underlying geology of the Krugersdorp Game Reserve comprises the Government Subgroup quartzite running through the study area.

3.2 Hydrology

Groundwater occurs in the weathered and fractured sedimentary rocks of the Witwatersrand Supergroup. The dolomitic strata from the Malmani Subgroup represents a karst aquifer characterised by transmissivity values ranging from <100 m^2/d to > 1000 m^2/d (Bredenkamp *et al*., 1986; Leskiewicz, 1986; Hobbs 1988; Kuhn, 1989; Hobbs and Cobbing, 2007) and according to Bredenkamp et al., (1995), having modest storativity values. The Black Reef Formation from the study area is associated with fractured aquifers characterised by low transmissivity (<10 m^2/d) and storativity values of <1% (Hobbs and Cobbing, 2007).

More importantly, following cessation of mining in the area in 1997, the mine void in the West Rand Basin filled with water and finally began to decant onto the surface in 2002. The initial surface decanting took place from a water borehole situated alongside the Tweelopiespruit, just below the position of the Black Reef Incline (BRI) portal. This was followed by decant from the BRI and finally the two winzes (number 17 and 18) as the water level in the void continued to rise (Department of Water Affairs, 2012). This finally resulted in a rise in the water table and the development of a permanent water body in the Hippo Dam further downstream in the southern part of the KGR. The Tweelopiespruit, in its lower reaches then becomes an influent stream losing water to the karst aquifer (Hobbs and Cobbing, 2007).

4 Methodology

4.1 Soil Sampling

A total of 31 soil samples were collected randomly (Figure 1); twenty three were acquired from the KGR, four samples from surrounding smallholdings and two samples each from RU and MMG. At each sampling site, a 1m X 1m pit was dug to a depth of 40 cm using the pick and shovel. A composite near-surface soil sample (30 cm below A_0) was collected and stored in pre-labelled Kraft paper envelopes in accordance with IGCP 259 recommendations (Darnley *et al*., 1995). After every 6^{th} soil sample a duplicate was collected. In addition, the GPS coordinates as well as other geoenvironmental characteristics (geology, topography, vegetation, pedology and hydrology) at each sampling site were recorded.

4.2 Sample Preparation and Geochemical Analysis

Each soil sample was oven-dried (30°C) for about 12 h, homogenised and then quartered in the Biochemistry Laboratories, Mangosuthu University of Technology. A split fraction of approximately 50 g was sent to a commercial laboratory (ACME Laboratories in Vancouver, Canada), where the sediments were air-dried at 60°C, disaggregated, sieved to <180 µm (80 mesh), and pulverised. A 30 g split was then weighed and digested with a modified *Aqua Regia* solution of equal parts concentrated HCl, HNO_3 and de-ionised H_2O.

Following sample digestion, analyses of 36 minor and trace elements, including a number of PHEs were determined by both Inductively Coupled Plasma Emission Spectrometry (ICP-ES) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Duplicate samples comprised 16% of total samples. The data were accepted if the relative standard deviation was <15% at five times the limit of detection for the duplicate samples.

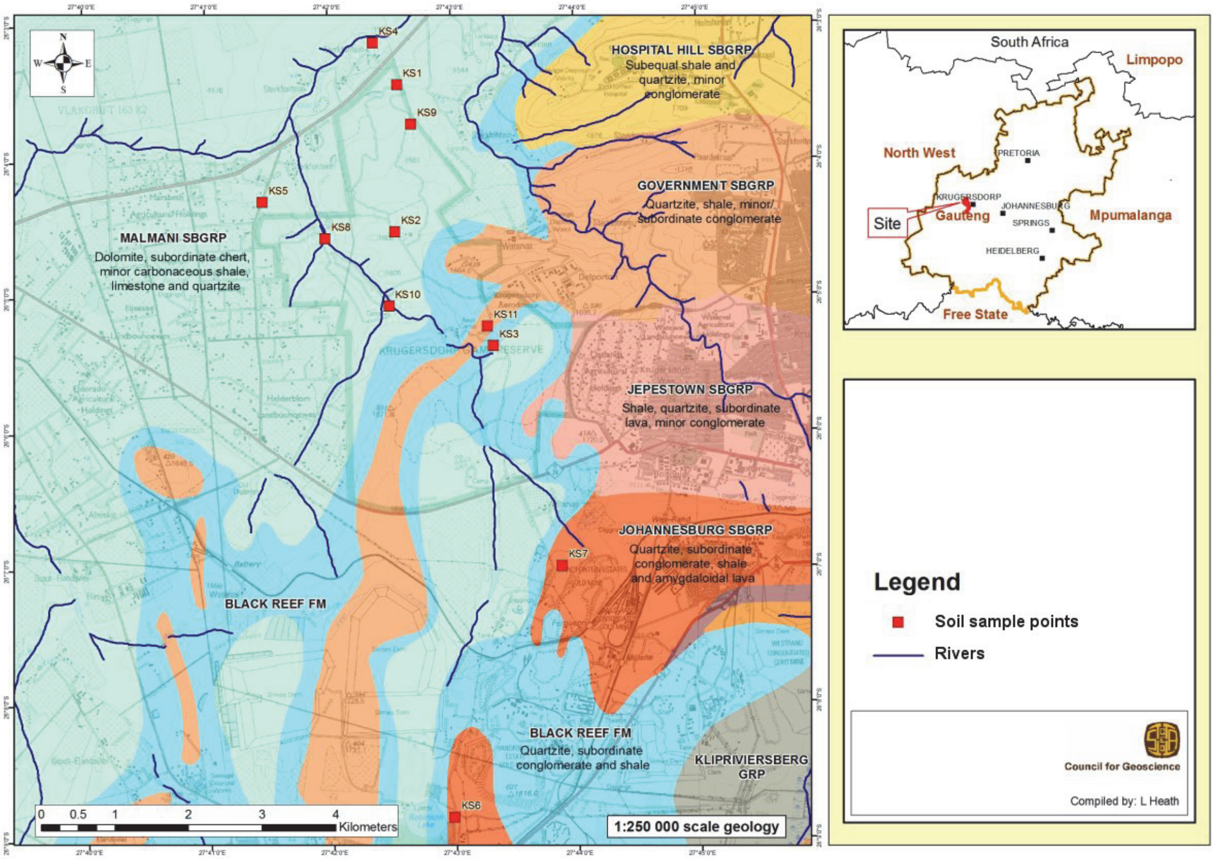

Figure 1. Soil sampling points in the Krugersdorp Game Reserve (n=23), surrounding smallholdings (n=4), Rand Uranium (n=2) and Mintails Mogale Gold (n=2). Soil sampling points KS1, KS2, KS3, KS8, KS9, KS10 and KS11 were from the Krugersdorp Game Reserve, KS4 and KS5 from the surrounding smallholdings and KS6 and KS7 from Rand Uranium and Mintails Mogale Gold respectively.

5 Results and Discussion

5.1 Total Content of Heavy Metals

A comparative analysis of heavy metal concentration in soil samples from the respective study sites are indicated in Table 1. These concentrations obtained in the study sites are compared with the reference values for background concentrations (Clarke values) after Wedepohl (1995).

In the KGR, surrounding smallholdings and RU, Mn had the highest mean concentration followed by Cr. These three study sites also had a similar trend for the four lowest heavy metal concentrations, Pb > As > Cd > Hg (Table 1). The soil samples from the KGR had mean heavy metal (and As) concentrations of 93.41; 4280.33; 17.37; 64.73; 35.07; 88.56; 0.17; 0.12; 11.55 and 7.56 mg.kg^{-1} for Cr; Mn; Co; Ni; Cu; Zn; Cd; Hg; Pb and As respectively. The trend of heavy metal (and As) concentration in this site was Mn > Cr > Zn > Ni > Cu > Co > Pb > As > Cd > Hg. In the soils from MMG, the trend was Mn > Zn > As > Cr > Cu > Ni > Pb > Co > Cd > Hg (Table 1). The higher standard deviation reveals higher variations in heavy metal distributions from the point source of discharge to the adjacent areas.

The sampling sites in the KGR (Table 2) showed a distinct migration pattern of heavy metal concentrations. Sampling sites KS 8 and KS 10 displayed higher mean concentrations than the other sampling sites in the KGR. This is interesting since KS 8 and KS 10 were located in close proximity to the Tweelopiespruit (Figure 1). The higher mean concentrations are to be expected since AMD first decanted into this waterway in September 2002 (Hobbs and Cobbings, 2007). The sampling site KS 1 in the KGR had predominantly the lowest mean heavy metal concentrations (Table 2). Again, this is to be expected, since this sampling site was the furthest from the point source of discharge (Figure 1).

5.2 Assessment of Soil Contamination

To assess the contamination levels of the heavy metals, an integrated pollution index (IPI) was calculated. The IPI is defined as the mean value of the pollution index (PI) of an element. In this study, the PI of each element is defined as the ratio of the metal concentration in the study site to the background concentration (Clarke value) of the corresponding metal using the following formula (Hakanson, 1980; Chen *et al*., 2005 Wei and Yang, 2010):

$$PIi = Ci / Bi$$

where C_i is the concentration of element in environment, B_i is the background value. The IPI is classified where: IPI≤1 (low level of pollution); 1<IPI≤2 (moderate level of pollution); 2<IPI≤5 (high level of pollution); IPI>5 (extreme high level of pollution). The IPI assessed using the single index method is presented in Table 3.

Table 1. Mean heavy metal (and As) concentrations ($mg.kg^{-1}$) in the four study sites compared to reference values for background concentrations (Clarke values) after Wedepohl (1995).

Heavy Metal		Study Sites				Mean Clarke values in mg.kg-1 after Wedepohl (1995)
		Krugersdorp Game Reserve	Smallholdings	Rand Uranium Mine	Mintails Mogale Gold	
Cr	Mean	93.41	96.50	86.00	102.33	35.000
	SD	49.34	9.68	18.39	16.26	
	Min	38.00	84.00	73.00	88.00	
	Max	233.00	107.00	99.00	120.00	
	n	23	4	2	2	
Mn	Mean	4280.33	3377.50	631.50	3938.00	527.000
	SD	3621.13	2989.20	255.27	2801.97	
	Min	115.00	1082.00	451.00	1717.00	
	Max	10000.00	7644.00	812.00	7086.00	
	n	23	4	2	2	
Co	Mean	17.37	30.30	31.10	41.20	11.600
	SD	19.45	41.86	21.07	12.38	
	Min	2.80	6.40	16.20	26.90	
	Max	102.30	93.00	46.00	48.40	
	n	23	4	2	2	
Ni	Mean	64.73	84.40	45.60	81.33	18.600
	SD	81.65	125.81	22.49	19.58	
	Min	13.90	19.60	29.70	59.60	
	Max	444.80	273.10	61.50	97.60	
	n	23	4	2	2	
Cu	Mean	35.07	19.88	16.10	99.73	14.300
	SD	23.21	7.15	3.39	33.76	
	Min	10.10	13.50	13.70	61.00	
	Max	93.20	29.80	18.50	115.30	
	n	23	4	2	2	
Zn	Mean	88.56	59.75	23.50	657.33	52.000
	SD	162.40	94.84	12.02	488.82	
	Min	10.00	12.00	15.00	153.00	
	Max	736.00	202.00	32.00	1129.00	
	n	23	4	2	2	
Cd	Mean	0.17	0.20	0.10	0.50	0.102
	SD	0.18	0.20	0.00	0.27	
	Min	0.10	0.10	0.10	0.30	
	Max	0.70	0.50	0.10	0.80	
	n	23	4	2	2	
Hg	Mean	0.12	0.03	0.02	0.25	0.056
	SD	0.27	0.01	0.01	0.09	
	Min	0.02	0.02	0.01	0.15	
	Max	1.36	0.04	0.02	0.26	
	n	23	4	2	2	
Pb	Mean	11.55	8.63	9.35	71.67	17.000
	SD	14.26	2.87	4.31	21.17	
	Min	3.60	5.90	6.30	50.00	
	Max	79.60	12.40	12.40	92.30	
	n	23	4	2	2	
As	Mean	7.56	4.33	3.95	130.07	2.000
	SD	3.54	1.41	1.49	46.47	
	Min	3.20	3.30	2.90	79.20	
	Max	16.80	6.40	5.00	170.30	
	n	23	4	2	2	

Table 2. Mean heavy metal (and As) concentrations (mg.kg^{-1}) from the sampling points in the Krugersdorp Game Reserve. The mean concentrations were compared to reference values for background concentrations (Clarke values) after Wedepohl (1995).

Heavy Metal		Sampling Points in Krugersdorp Game Reserve							Mean Clarke values in mg.kg-1 after Wedepohl (1995)
		KS1	KS2	KS3	KS8	KS9	KS10	KS11	
Cr	Mean	56.25	61.00	113.20	88.00	74.25	113.00	140.00	
	SD	17.02	7.31	9.83	11.31	11.76	N/A	81.99	
	Min	38.00	52.00	100.00	80.00	64.00	N/A	49.00	35.000
	Max	67.00	71.00	123.00	96.00	91.00	N/A	233.00	
	n	4	5	5	2	4	1	6	
Mn	Mean	2564.00	9011.20	4635.00	8578.00	1980.75	8990.00	502.17	
	SD	553.94	2211.02	2596.11	1006.92	667.08	N/A	425.64	
	Min	1801.00	5056.00	2956.00	7866.00	1122.00	N/A	115.00	527.000
	Max	3128.00	10000.00	9233.00	9290.00	2628.00	N/A	1273.00	
	n	4	5	5	2	4	1	6	
Co	Mean	10.78	14.62	11.76	75.50	11.58	39.40	9.57	
	SD	1.01	2.69	1.36	37.90	2.29	N/A	6.81	
	Min	9.30	10.50	10.80	48.70	9.00	N/A	2.80	11.600
	Max	11.60	18.00	14.10	102.30	13.70	N/A	20.60	
	n	4	5	5	2	4	1	6	
Ni	Mean	24.05	153.74	55.08	93.80	29.75	117.60	30.52	
	SD	5.58	164.56	5.47	23.19	1.73	N/A	15.16	
	Min	16.40	38.50	49.30	77.40	27.50	N/A	13.90	18.600
	Max	29.50	444.80	61.40	110.20	31.60	N/A	51.90	
	n	4	5	5	2	4	1	6	
Cu	Mean	13.43	28.82	43.44	85.70	20.05	93.20	31.17	
	SD	2.94	9.21	3.34	8.06	2.81	N/A	17.79	
	Min	10.10	16.00	40.60	80.00	17.60	N/A	11.10	14.300
	Max	16.00	42.00	49.00	91.40	24.00	N/A	55.30	
	n	4	5	5	2	4	1	6	
Zn	Mean	17.75	91.60	38.00	508.50	18.25	446.00	22.67	
	SD	3.77	73.38	14.71	321.73	2.22	N/A	10.58	
	Min	15.00	25.00	25.00	281.00	16.00	N/A	10.00	52.000
	Max	23.00	216.00	54.00	736.00	21.00	N/A	36.00	
	n	4	5	5	2	4	1	6	
Cd	Mean	0.10	0.20	0.10	0.55	0.10	0.70	0.10	
	SD	0.00	0.17	0.00	0.21	0.00	N/A	0.00	
	Min	0.10	0.10	0.10	0.40	0.10	N/A	0.10	0.102
	Max	0.10	0.50	0.10	0.70	0.10	N/A	0.10	
	n	4	5	5	2	4	1	6	
Hg	Mean	0.03	0.14	0.04	0.23	0.03	1.36	0.04	
	SD	0.01	0.20	0.01	0.01	0.01	N/A	0.01	
	Min	0.02	0.03	0.03	0.22	0.02	N/A	0.03	0.056
	Max	0.04	0.50	0.04	0.24	0.04	N/A	0.06	
	n	4	5	5	2	4	1	6	
Pb	Mean	5.20	13.66	8.14	16.50	6.00	79.60	7.57	
	SD	0.82	3.61	2.09	2.69	2.02	N/A	3.36	
	Min	4.60	7.50	6.30	14.60	3.60	N/A	3.60	17.000
	Max	6.40	16.40	10.60	18.40	8.20	N/A	13.20	
	n	4	5	5	2	4	1	6	
As	Mean	5.83	6.30	7.04	15.45	4.13	15.90	8.48	
	SD	0.78	1.66	0.55	1.910	0.72	N/A	2.79	
	Min	5.20	4.10	6.40	14.10	3.20	N/A	4.20	2.000
	Max	6.80	8.60	7.60	16.80	4.70	N/A	11.60	
	n	4	5	5	2	4	1	6	

Table 3. Integrated Pollution Index (IPI) of heavy metals (and As) using the single index method. Low, moderate, high and extreme levels of pollution are indicated by white, green, orange and red respectively.

Study Sites	Cr	Mn	Co	Ni	Cu	Zn	Cd	Hg	Pb	As
Krugersdorp Game Reserve	2.669	8.122	1.498	3.480	2.452	1.703	1.707	2.130	0.679	3.781
Smallholdings	2.757	6.409	2.612	4.538	1.390	1.149	1.961	0.491	0.507	2.163
Rand Uranium Mine	2.457	1.198	2.681	2.452	1.126	0.452	0.980	0.268	0.550	1.975
Mintails Mogale Gold	2.924	7.472	3.552	4.373	6.974	12.641	4.902	4.405	4.216	65.033

Analysis of the soil sediments from MMG showed extremely high levels of contamination for Mn, Cu, Zn and As and high levels for the remaining six heavy metals (Table 3). The KGR had 60% of the heavy metal (and As) contamination levels ranging from extremely high (Mn) to high (Cr; Ni; Cu; Hg; As). The surrounding smallholdings had 50% of the heavy metal contamination values ranging from extremely high (Mn) to high (Cr; Co; Ni; As). According to Chao *et al.* (2007), fugitive dust can pose significant environmental problems at some mines. The inherent toxicity of the dust depends on the proximity of environmental receptors and the type of ore being mined. It was important to note that both these study sites were down-gradient (< 1000 m) from MMG.

The mean chromium (Cr) concentration trend (Table 1) was MMG (102.33 $mg.kg^{-1}$) > Smallholdings (96.50 $mg.kg^{-1}$) > KGR (93.41 $mg.kg^{-1}$) > RU (86.00 $mg.kg^{-1}$). The highest concentration recorded for Cr was 233.00 $mg.kg^{-1}$ from the KGR (Table 1). All four study sites had a high IPI level of Cr contamination (Table 3). According to Govind and Madhuri (2014), chronic exposure to Cr in animals can produce kidney and liver damage and also affect the circulatory and nerve tissues.

Manganese (Mn) is one of the most abundant metals in soils. In all study sites, Mn was recorded with the highest mean concentration of all heavy metals analysed (Table 1). Also, the highest and lowest mean Mn concentration was at the KGR and RU respectively (Table 1).

High exposure to Co may adversely affect heart and lung function. In addition, Co is present in vitamin B_{12} and plays a biological role in N_2-fixation (Spitz and Trudinger, 2009; Hamman, 2012).

The mean copper (Cu) concentration trend (Table 1) was MMG (99.73 $mg.kg^{-1}$) > KGR (35.07 $mg.kg^{-1}$) > Smallholdings (19.88 $mg.kg^{-1}$) > RU (16.10 $mg.kg^{-1}$). The integrated pollution index (IPI) for copper (Cu) concentrations indicated pollution levels of extreme (6.974) and high (2.452) for MMG and the KGR respectively (Table 3). Copper can be found in cytochrome and hemocyanin and in cellular molecules that are involved in respiration (Spitz and Trudinger, 2009; Hamman, 2012). In wildlife, chronic Cu toxicity causes liver cirrhosis and tubular necrosis in the kidney (Gaetke and Chow, 2003; Barceloux, 1999; Ikenaka *et al.*, 2010; Govind and Madhuri, 2014). In addition, elevated concentrations of Cu may cause increased oxidative damage to lipids, proteins and DNA in animals.

Zinc (Zn) is essential in several enzymes that catalyze the metabolism of proteins and nucleic acids. Toxicity of Zn can cause irritation of the digestive system and is toxic to some plants and fish (Spitz and Trudinger, 2009; Hamman, 2012).

In all study sites, mercury (Hg) was recorded with the lowest mean concentration of all heavy metals analysed (Table 1). The IPI for Hg (Table 3) was high for MMG (4.405) and the KGR (2.130). The surrounding smallholdings and RU had a low IPI for Hg (0.491 and 0.268 respectively). The implications of Hg toxicity in wildlife includes kidney damage, disruption of the nervous system, damage to the CNS and chromosomal and DNA damage (Govind and Madhuri, 2014).

Elements such as nickel (Ni), cadmium (Cd), lead (Pb) and arsenic (As) pose a carcinogenic and mutagenic risk (ATSDR, 2008; IARC, 2010).

The mean nickel (Ni) concentration trend (Table 1) was smallholdings (84.40 $mg.kg^{-1}$) > MMG (81.33$mg.kg^{-1}$) > KGR (64.73 $mg.kg^{-1}$) > RU (45.60 $mg.kg^{-1}$). Interestingly, the KGR had both the highest (444.80 $mg.kg^{-1}$) and lowest (13.90 $mg.kg^{-1}$) concentration of Ni. All four study sites had a high IPI level of Ni contamination (Table 3). Nickel (Ni) is an essential element and is needed in small amounts to produce red blood cells (RBCs), but it becomes slightly toxic in excess quantity. Its chronic exposure to animals can cause decrease in body weight, heart and liver damage, and skin irritation (Spitz and Trudinger, 2009; Hamman, 2012; Govind and Madhuri, 2014).

The mean cadmium (Cd) concentrations (Table 1) for all study sites were low, ranging from 0.10 $mg.kg^{-1}$ to 0.50 $mg.kg^{-1}$. The Cd concentrations were only higher than that for Hg. This heavy metal has mainly an anthropogenic origin and accumulates predominantly in the kidneys and liver. Lower Cd concentrations have been recorded in the brain and bones (Eisler, 1985; Garcıa-Fernandez *et al.*, 1996). High exposure to Cd in wildlife may be linked to kidney dysfunction, pulmonary disease and lung cancer. Bone defects, increased blood pressure and myocardial disease in animals have also been reported (Govind and Madhuri, 2014).

Mintails Mogale Gold had a high IPI level (4.405) for lead (Pb) contamination (Table 3). The remaining study sites had low IPI levels of 0.550, 0.507 and 0.679 for RU, the surrounding smallholdings and the KGR respectively. Lead is a cumulative body toxin and has been shown to affect virtually every organ and body system in humans and animals. Chronic exposures may affect the kidneys, cardiovascular system, blood, immune system and central and peripheral nervous systems in animals (Spitz and Trudinger, 2009; Newman, 2010; Hamman, 2012; Govind and Madhuri, 2014).

The mean arsenic (As) concentration trend (Table 1) was MMG (130.07 $mg.kg^{-1}$) > KGR (7.56 mg.kg-1) > Smallholdings (4.33 $mg.kg^{-1}$) > RU (3.95 $mg.kg^{-1}$). The IPI levels for As (Table 3) were extreme (65.033) for MMG, high for both the KGR (3.781) and the surrounding Smallholdings (2.163) and moderate for RU (1.975). Chronic As toxicity is mostly manifested in weight loss, mucosal lesions, mouth ulceration and reduced milk yield in ruminants (Raikwar *et al*., 2008). Long-term exposure causes skin disturbances, circulatory and peripheral nervous disorders and a possible increase in the risk to gastrointestinal tract and urinary system cancers. In addition, high concentrations of As can result in the decreased formation of red blood cells and white blood cells in animals (Govind and Madhuri, 2014).

6 Conclusions

Wildlife populations in the KGR are steadily decreasing due to a high incidence of disease. Several studies have shown the adverse effects of high heavy metal concentrations on animal health. Evidence continues to mount that many diseases in populations from the KGR may be related to the trace metal status of the surrounding ecosystems, a status shaped largely by the behaviour of PHEs released from the numerous mine settings in the Municipality.

The legacies of mining sites will remain problematic for many years to come due to the magnitude of the environmental impacts, as well as the serious health and ecological implications. The introduction of best practice techniques in mining and mineral processing should be made mandatory in order to achieve sustainability in the maintenance of environmental integrity.

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