Human health risks associated with historic ore processing at Berg Aukas, Grootfontein area, Namibia

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Berg Aukas once served as a mining town, where ores of lead, vanadium, and zinc were mined and roasted on site until 1979. Roasting of ores produced an unknown hazard in the surrounding area. For this study, soil, crops, and water from the Berg Aukas area were analysed for various pollutants. The main pollutants are metals such as Pb, Zn, Cu, Cd, As, Hg and Mo. They are bound to layered silicates, to sulphide minerals, or occur as elements.

The analytical results point to severe heavy metal contamination of the surface soils south and east of Berg Aukas. Crops grown at the National Youth Service, like sweet potatoes, cabbage, and Irish potatoes, accumulate heavy elements that are deleterious to health. Prolonged exposure to heavy metals in concentrations as found in the soils and some crops in Berg Aukas can cause severe health problems like diabetes, skin lesions, bladder problems, neurological effects, as well as skin, kidney or lung cancer.

The severely contaminated area at Berg Aukas, as a zone of high hazardous risk, represents an ellipsoid with diameters of approximately 3.5 km (E-W) and 2.5 km (N-S). Decision-makers in the Namibian Government were informed that the area should be avoided for any further residential or agricultural developments. As an immediate response, the hostel of the vocational school was moved to an uncontaminated area near Rietfontein. The farm management was informed to either diversify the crops grown on contaminated soils to crops that are less vulnerable to high heavy metal contents in soils or to transfer farming activities to less contaminated soils in the eastern portion of the farm.

Introduction

In 2005 and 2007 comprehensive environmental-geochemical surveys were conducted at the abandoned Berg Aukas mining district. The aim of the surveys were to gauge the contamination of water, soils, and agricultural plants by toxic elements, to determine the effect of mining and processing on the environment and to formulate recommendations and concepts that should ensure protection of the residents and students as well as the environment at large.

Over twenty different toxic heavy metals exist that can impact human health and each toxin will produce different behavioral, physiological, and cognitive changes in an exposed individual. The degree to which a system, organ, tissue, or cell is affected by a heavy metal depends on the toxicological potential of the substance and the individual's degree of exposure to the toxin. Our research therefore is aimed at creating awareness, support decision-making and working out measures of remediation in areas where critical heavy metal contaminations have been identified.

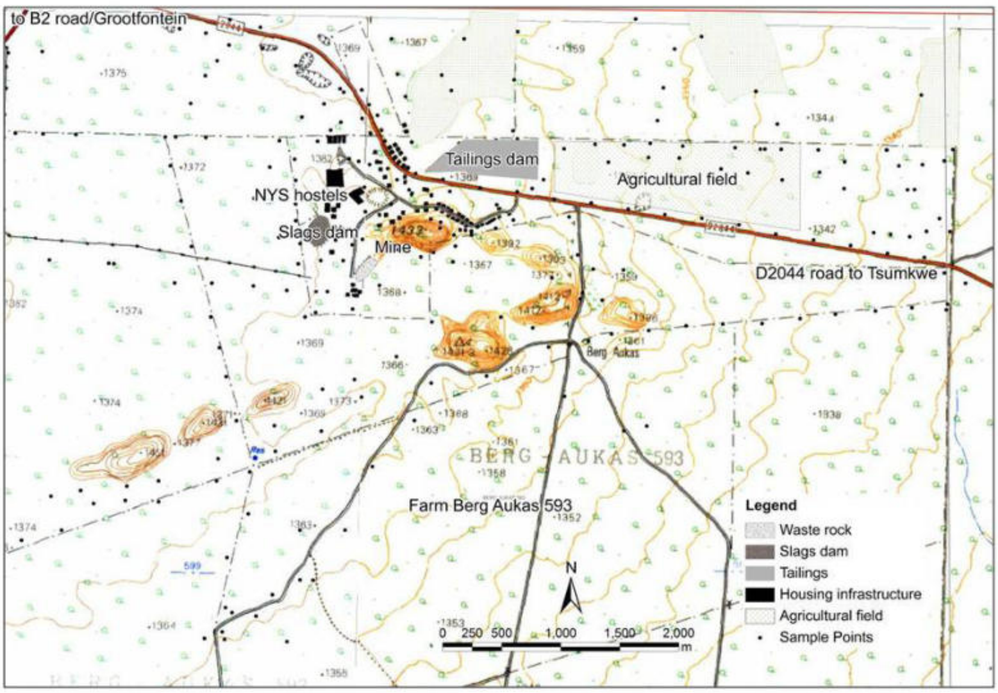

Figure 1: Map of the Berg Aukas settlement

Geology of Berg Aukas area

Berg Aukas is located 15km east of Grootfontein on the farm Berg Aukas 593, in the Otavi Mountain Land, Namibia (Figure 1). The area is located on good loamy soils that are underlain by carbonates. Currently the National Youth Service (NYS) uses most of the residential houses, workshops and hostels of the former mine as an agricultural vocational school and the farmland to the east of the tailings dump as an experimental crop farm.

The Berg Aukas mine is situated on the northern limb of the Berg Aukas Syncline. The syncline structure consists of dolostones, limestones and shales of the Berg Aukas Formation (at the base of Abenab Subgroup/Otavi Group). The Berg Aukas Formation is part of the Neoproterozoic sedimentation on the Otavi Platform. The sedimentary rocks were folded during the Pan-African Event.

Two types of lead-zinc-vanadium mineralization occur at the Berg Aukas mine (Misiewicz, 1988):

(i) The Northern Ore Horizon consists of a series of lenses with oxidized ore of sulphide replacement bodies. The ore occurs along the contact between two texturally distinct varieties of grey dolomite. The zone of mineralization strikes roughly east-west and dips about 50° to the south. In the topmost lens, the sulphides are confined to massive, fine-grained replacement bodies in which sphalerite, galena and subordinate pyrite are the only visible primary sulphides. Common secondary minerals are descloizite, willemite, cerussite, smithsonite and goethite.

(ii) The complex Central Ore Body, Intermediate and Hanging Wall Ore Body are located in recrystallised dolomite, in which they follow solution cavities that are controlled by steeply dipping north-south striking fractures. Ore bodies are arranged in an en echelon pattern, and dip almost vertically. In addition, the bodies are extremely irregular in outline and frequently contain blocks of barren dolomite. Galena and sphalerite, partly oxidized, are disseminated in layers of clay, mud and sand of varying dolomite content. The contacts between the ore bodies and country rocks are sporadically lined with crystalline willemite.

Mining and mining remnants

The lead-zinc-vanadium deposit of Berg Aukas was discovered in 1913, when the apex of the Central Ore Body on top of a hill was located. Mining started in 1920 and was terminated at the groundwater level in 1928. In 1950 the mine was re-opened and vanadinite and sulphide concentrate was produced and roasted on the spot. The ore reserves at the time of mine closure in 1978 were estimated as 1.65 Mt grading 0.6% V_2O_5, 5% Pb and 17% Zn (Misiewicz, 1988).

Remnants of two waste rock heaps are located directly on the area of the former mining and metallurgical complex (Figure 1). The waste dumps are not stable and in some places, slumping of large blocks and water erosion furrows can be observed. Access to some galleries of the old mine is not secured. The total amount of material deposited in waste rock heaps is estimated at 91,680 m^3.

The slag deposit is located within the central mining area (Figure 2). The slag was used for the construction of local roads and therefore this material is widely disseminated throughout the area. The surface of the slag deposit was covered by a mixture of concrete and slag. At present the sealing is eroded and the slag deposit represents an important source of dust.

The tailings (slimes) dam is located north of the mining area (Figure 2). The total volume of slimes is estimated at 343,500 m^3. The tailings dam is not fenced and poses a hazard to children playing in the area. Tailings material has been spilled in larger quantities into adjacent ephemeral streams. The eastern part of the tailings dam is partly covered by vegetation (grass and acacia).

Hydrogeological aspects, water sampling and analyses

Deeper parts of the Berg Aukas mine were spontaneously flooded after mine closure. Between 1981 and 1987, the Grootfontein-Omatako canal was built in or-

Figure 2. Tailings (slimes) dump (left) and waste rock dump (right) at Berg Aukas.

der to supply water from Berg Aukas, Kombat and other mines in the Otavi Mountain Land to Windhoek. The mines in the Otavi Mountain Land can supply a total of 15 Mm^3 water per year (Ploethner *et al.*, 1998). The groundwater from the underground mine of Berg Aukas is currently used for the water supply of the town itself and for irrigation of surrounding farming projects.

Water samples were collected from nineteen sites including boreholes (14), open wells (3), springs (1) and the NYS irrigation project (1) (Figure 3). Boreholes were sampled at different levels depending on the overall depth of the borehole. The water levels were measured with a dip meter that has a light sensor.

In total thirty (30) water samples were collected. The boreholes were first pumped for 5 to 20 minutes (using an MP pump powered by a generator) in order to get representative samples of the aquifer. This was done at each sampling depth. Duplicate water samples were collected in polyethylene bottles. One was unfiltered and unacidified for the analysis of anions and major cations. The other sample was filtered through a 0.45 µm membrane and acidified to pH <2.0 with 10% HNO_3 for the analysis of minor cations and trace elements.

Water analyses of groundwater from the shaft were carried out at the laboratories of BGR, Hanover, Germany. Concentrations of Al, Ca, Fe, K, Mg, Mn, Na, Si and Ti were analysed from acidified solution with ICP-AES (Inductively Coupled Plasma Atomic Emission Spectrometry) based on standard DIN EN ISO 11885 (1998). For the determination of the anions F-, Cl-, Br-, NO^3-, NO^2-, SO_4^{2-} an IC method (Ionic Chromatography) based on DIN EN ISO 10304-1 (1995) was used. Phosphate and ammonium were determined photometrically as a complex based on DIN EN 1189 (1996) and DIN 38406 (1983), respectively. Hydrogen carbonate was determined by titrimetric testing based on DIN EN 26777 (1993).

Concentrations of the trace elements As, B, Ba, Be, Cd, Co, Cr, Cu, Li, Ni, Pb, Sc, Sr, V and Zn were analysed from acidified solution with ICP-AES based on standard DIN EN ISO 11885 (1998). For the determination of alkalinity (acid neutralizing capacity) a 10 ml aliquot of the unfiltered sample was titrated with 0.02 N HCl to pH=4.3. (DIN 38409, 1979). The final point is determined potentiometrically using a 2-cell pH-glass electrode.

Results of water analyses

The pH of the water samples ranges from 6.8 to 8.1. The Namibian Guideline Values for drinking water (DWA, 1999) range between pH 6 and 9.

The water samples show electrical conductivities (EC) ranging from 74 to 393 mS/m. The limits for water of excellent quality (Group A) and of good quality (Group B) are 150 mS/m and 300 mS/m, respectively. Consumption of water above 300mS/m (Group C) is considered as low health risk.

Almost all the water samples from Berg Aukas are of excellent quality in terms of conductivity with the exception of three water samples, i.e. samples from borehole 63400 (15 m and 30 m sampling depth) and borehole 81270. The EC of the samples from the 15 m sampling depth of boreholes 63400 and 81270 fall into Group B (i.e. 207 and 172 mS/m, respectively),

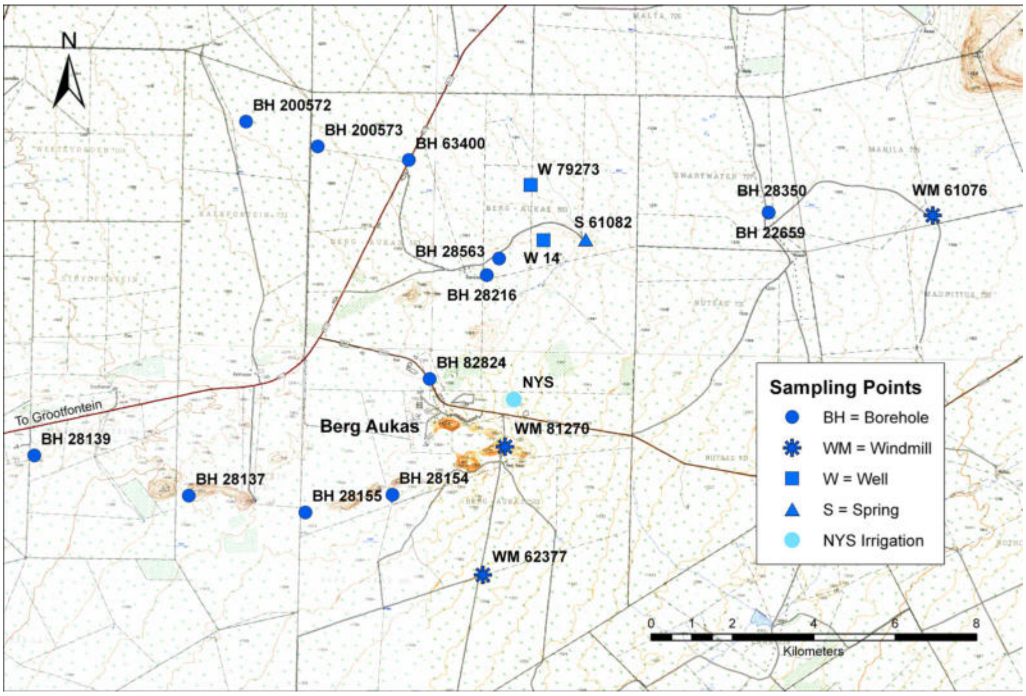

Figure 3. Location of water sampling in the surroundings of Berg Aukas

while the sample from 30 m sampling depth of borehole 63400 has an EC of 393 mS/m, indicating a low health risk.

The sample from the NYS irrigation scheme has an EC of 85 mS/m. This is in the same range as previous analyses in June 2005 (85 mS/m) and in August 2007 (89 mS/m) (GSN Environmental Monitoring Series, No18).

Conclusion on groundwater quality

In general, the groundwater in the Berg Aukas and the surrounding areas does not show any significant signs of contamination from the past mining activities. It is of excellent to acceptable quality according to the Namibian Guideline Values for drinking water. Although the soil in the mining area is highly contaminated, the groundwater does not reflect those contaminants. The groundwater is naturally protected by the carbonate containing host rocks. The metals are kept immobile in the upper soil horizons due to the relatively high pH of the soil.

Trace metals are only detectable in the water which is pumped directly from the old Berg Aukas mine shaft, and which is used for irrigation at the National Youth Service agricultural fields and human consumption in the settlement. However, arsenic, cadmium and lead values are far below the limits of Group A ("excellent quality") of the Namibian Guideline Values for drinking water. Only zinc values are with 1.7 mg/l slightly elevated in one water sample, marking it as Group B ("acceptable quality"). Based on the analysed metal concentrations, the Berg Aukas tap water is safe for human consumption and no health risks can be expected by using the water for vegetable irrigation.

The water quality is compromised by elevated salinity in some of the boreholes. Magnesium and sodium chloride are naturally occurring and can not be attributed to contamination of groundwater by human activities.

Soil sampling and analytical methods

Mining and processing activities at Berg Aukas altered the soil composition of the area. The northern and northeastern parts of the area are covered by soils that contain massive layers of slag and tailings (Figure 4).

Six tailings and slag samples as well as 19 soil samples were collected around Berg Aukas in 2005, using the methodology recommended for the regional geochemical mapping by the FOREGS Geochemistry Working Group (Salminen *et al.*, 1998). Reference to the sampled areas is done in two parts reflecting how the soil samples were obtained, i.e. a lower and an upper soil horizon was collected.

The sampling in 2007 was carried out by the GSN (Geological Survey of Namibia) with the support of 45 geology students from the University of Namibia. Soil sampling took place in six teams of 3-5 third year students headed by a 4th year team leader. Two types of soil samples were collected: top soil samples and background samples.

240 top soil samples (marked with "t") were taken according to accessibility at average intervals of 300 m within a radius of 3 km around Berg Aukas and at intervals of 500 m to 1,000 m in the wider area up to 6 km from the settlement. A top soil sample is collected from the first 3 cm on the surface with organic matter cleared away. At each collecting site, a sample consisted of soil taken from three points at intervals of about 2 m. The collected sample was then homogenized to give a good representation of the sampling spot. A GPS reading was taken at the centre of the triangle formed by the three points. The upper soil horizon reflects possible contamination by dumping, spilling and airborne transport.

Twenty background samples (marked with "d") were collected at every fifth top soil sampling spot, thus at intervals of approximately 1500 m. A background sample is taken at a depth of 60 to 80 cm. The background samples are necessary for the determination of the seepage of contaminants through the top soil (mobility) and the detection of natural mineralisations (deposits).

The analytical data are shown on two maps per element for the lower and upper soil horizons, respectively.

Approximately 0.5 kg of each soil sample was sieved

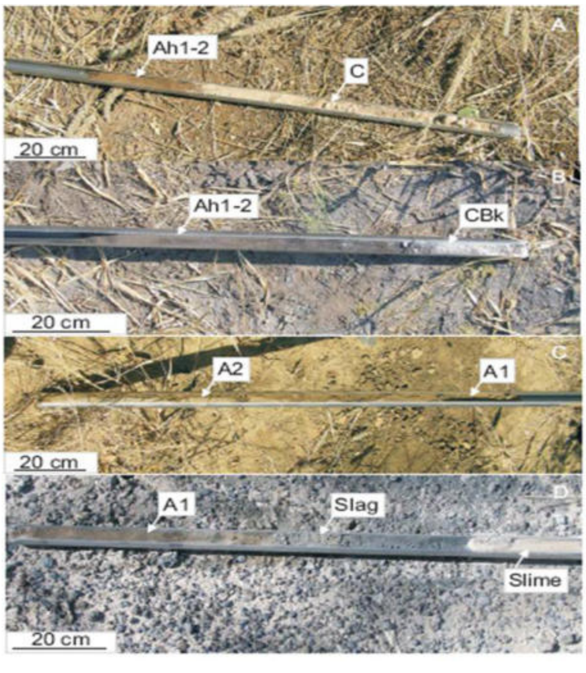

Figure 4. Variety of soils in the Berg Aukas Area: A: Calcic regosol; Ah1-2 horizon: Light brownish sandy clay; C horizon: weathered carbonate (caliche); B: Calcic cambisol; Ah1-2 horizon: Dark grey, granular loam with common roots and calcareous pseudomycelia; CBk horizon: Whitish weathered limestone; C: Pelitic vertisol; A1 horizon: Dry, dark brownish-grey clay; A2 horizon: Dark-grey, moisture clay with slickenside surfaces; D: Pelitic vertisol, covered by slag and slime.

to <0.2 mm. The fraction of < 0.2 mm was homogenized in an agate ball mill and the fraction < 0.063 mm was used for analyses. One gram of sample and 50 ml of a solution of HNO_3 and HCl in the ratio 1:9 were used to prepare a leachate.

Trace elements of 19 soil samples were determined in the laboratory of the Czech Geological Survey (after the methodology of Dempírová and Vitková, 2002), and at Charles University, Prague. Fe, Cd, Cu, Mo, Pb and Zn were analysed using flame atomic absorption spectroscopy (FAAS) with a PE 4000 spectrometer. Arsenic was determined by hydrite generation atomic absorption spectrometry (HGAAS) using the PE 503 equipment. Hg was analysed mercurometrically, using an AMA 254 analyser. The amount of total carbon was determined using the ELTRA CS 500 equipment. Samples were combusted, and the quantity of the resulting CO_2 was measured using an IR detector. The amount of carbonate carbon was determined using the Coulomat 7021 equipment. Samples were decomposed in the concentrated solution of H_3PO_4, and the amount of liberated CO_2 was recalculated to that of carbonate carbon (Ccarb). The amount of organic carbon (Corg) was determined by subtraction of carbonate carbon from total carbon content (Ctot): Corg = Ctot – Ccarb. Total sulphur (Stot) was determined on the ELTRA CS 500 equipment. Samples were combusted at a temperature of 1450°C, and the amount of released SO_2 was determined by an infrared detector.

The 260 soil samples of the sampling campaign in 2007 were analysed using a portable x-ray fluorescence (XRF) spectrometer XLt 700 Series Environmental Analyzer Version 4.2 of NITON Corporation, USA. The instrument is pre-calibrated by the manufacturer, and the measurements taken were compared with readings from international standard samples (NIST 2709, NIST 2710, RCRA and others). The samples were analysed for As, Cu, Pb, V and Zn only. The detection limits vary between 10 and 30 mg/kg for the elements of concern. The confidence intervals (2 sigma; 95%) depend on the measuring time and typically range from ±5 to ±50% for a measuring time of 60 seconds.

Results of soils analyses

The tailings material contains very high amounts of zinc, vanadium, cadmium, arsenic and mercury (Table 1). In contrast, the lead concentrations are low. Approximately 18 wt. % of the tailings consists of particles of less than 8 µm in diameter (PM_8). These particles pose the most serious health effects as they enter the lungs.

The slag is rich in zinc, lead, vanadium, copper and arsenic (Table 1). The amount of PM_8 particles in the slag dust is low (1.3 wt.%).

The analytical results for the soil samples are presented in the form of distribution maps of the pollutants. The maps for As, Cd, Hg and V were produced with SURFER of Golden Software Inc. ArcGIS was used to produce distribution maps for Cu, Pb and Zn.

Table 1: Average chemical composition of tailings and slags at Berg Aukas

	tailings	slags
Ctot (wt. %)	10.5	5.1
Stot (wt. %)	0.034	0.110
CO_2 (wt. %)	37.16	6.04
Corg (wt. %)	0.42	0.00
V (ppm)	704	832
Fe (wt. %)	1.68	3.98
Cu (ppm)	184	640
Zn (ppm)	52,100	22,400
Mo (ppm)	< 5	13
Cd (ppm)	352	< 0.8
Pb (ppm)	< 10	11,600
As (ppm)	109.1	383.7
Hg (ppm)	2.228	0.028

Arsenic

In the lower soil horizon, contents of arsenic are generally low (median: 0.89 ppm, maximum: 9.62 ppm) (Figure 5). Higher concentrations (> 2.6 ppm) were detected in the area of the former mining and processing complex and eastward (downwind) of the slime dams. The elevated concentrations trace back to an infiltration of arsenic-rich solution from the top soil. The median content of As in the top soil is one order higher (4.99 ppm) compared with the lower soil horizon, and maximum values are two orders higher (363 ppm) (Figure 6).

Cadmium

Concentrations of cadmium in the lower soil horizons are very low (median: >0.8 ppm, maximum: 7.8 ppm) (Appendix 2). Two areas of slightly higher cadmium values (from 2.3 to 5.3 ppm Cd) are located in the former mining and metallurgical complex. The cadmium concentration in the upper soil horizon is much higher (median: 5.4 ppm, maximum value: 387 ppm) (Appendix 2). It is important to note that elevated concentrations of cadmium in the upper soil horizon encircle the whole area of Berg Aukas and extend towards the east. The large-scale contamination can not be explained by dust fall-out from mining operations and slime deposits. It is probably a result of emissions from the roasting of ores in the past.

Copper

Contents of copper in the lower soil horizon are relatively low (median: 14 ppm), which corresponds to the low values of copper in ores. Concentrations of copper in surface soils range from 6 to 327 ppm (median: 28 ppm), and are only slightly higher compared with the lower soil horizon. The distribution of Cu can reflect both the position of ore bodies as well as the extent of contamination from the surface (Figure 7).

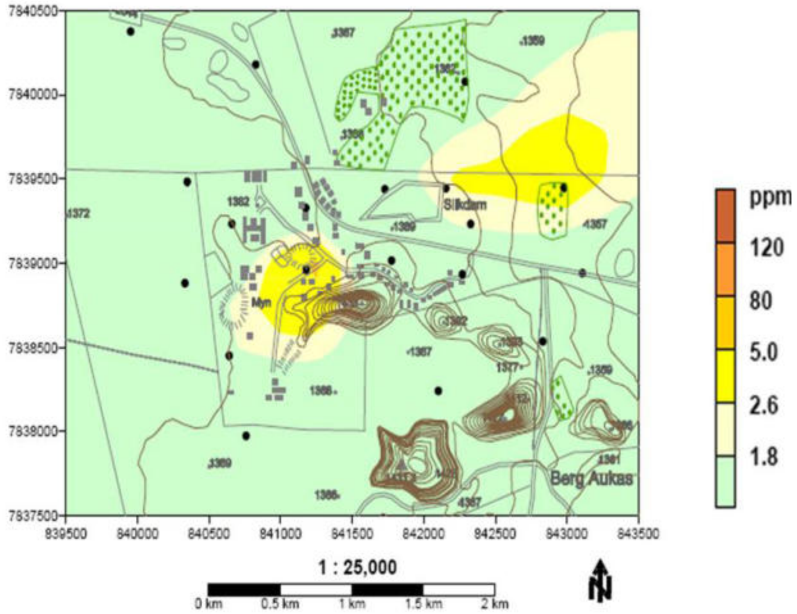

Figure 5. Arsenic in lower soil horizons (19 samples)

Lead

Lead concentration varies in the top soil of the study area from background values of approximately 20 ppm to more than 33,800 ppm.

The highest concentrations above 10,000 ppm (1% to 3,4% Pb) are restricted to an area of 800 m x 600 m in the central and southwestern part of Berg Aukas. This spot of extreme contamination (red colour in figure 8) is situated in the central part of the National Youth Training Centre including its sports field, dining hall, hostels and classrooms. The contamination traces back to mainly gaseous and particle emissions derived from processing, roasting and smelting of ore during the operational years of the Berg Aukas mine.

This area is surrounded by a halo of severe lead contamination with concentrations between 400 and 10,000 ppm, which extends for approximately 1 km to the east, south and west (light and dark purple in figure 8). Towards the northeast, the zone of severe lead contamination extends for approximately 2 km due to additional contamination from the tailings dump.

Both zones (red and purple colours) are not suitable for residential purposes according to the German Guideline Values. An additional zone of 300 to 800 m (orange and yellow colours with 140 to 400 ppm Pb; Figure 8) must be considered as not suitable for residen-

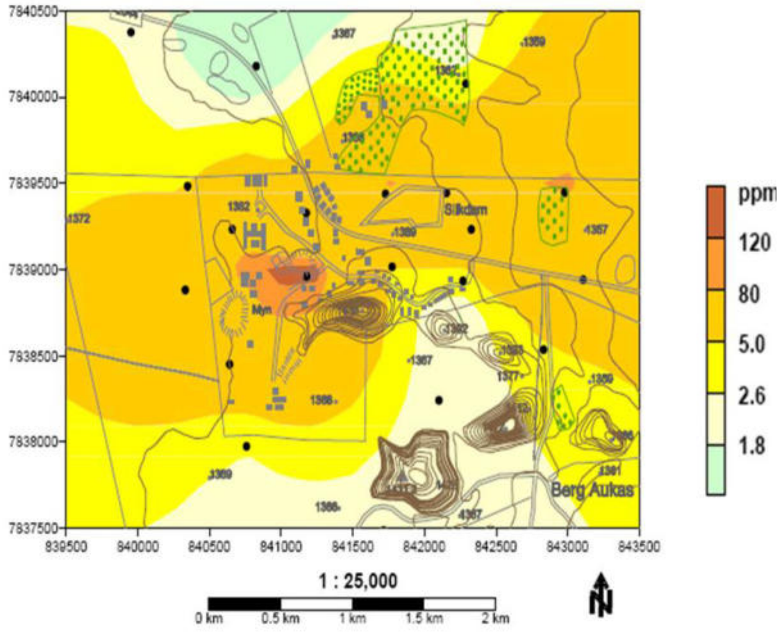

Figure 6. Arsenic in upper soil horizons (19 samples)

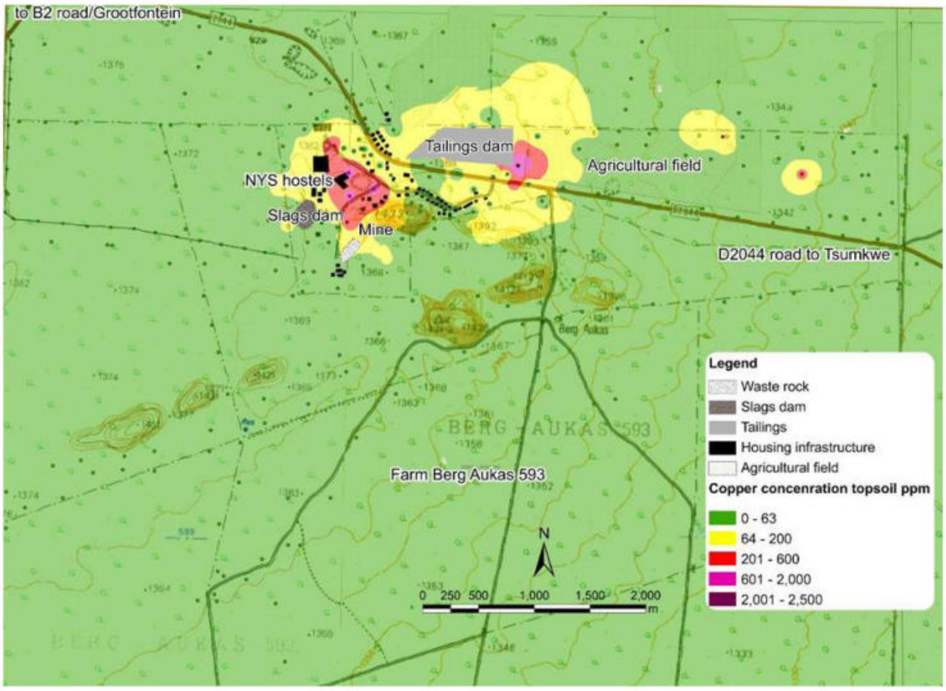

Figure 7. Copper in upper soil horizon (249 samples)

tial land use if the assessment is based on the Canadian Soil Quality Guideline (Table 2).

Lead contamination decreases gradually in all directions except northeast. The abrupt decrease towards the northeast traces back to predominantly water-borne contaminant transport in the area of the tailings dump. Areas affected by spillages (improper disposal of processing slurry and recent rainwater spillages) appear as severely contaminated patches, whereas adjacent areas might show lead concentrations close to natural background values. In contrast, the gradually decreasing lead concentrations in the surface soil towards all other directions are caused by predominantly wind-borne contaminant transport of smelter dust and slag particles.

The relatively clear picture of lead distributions in top

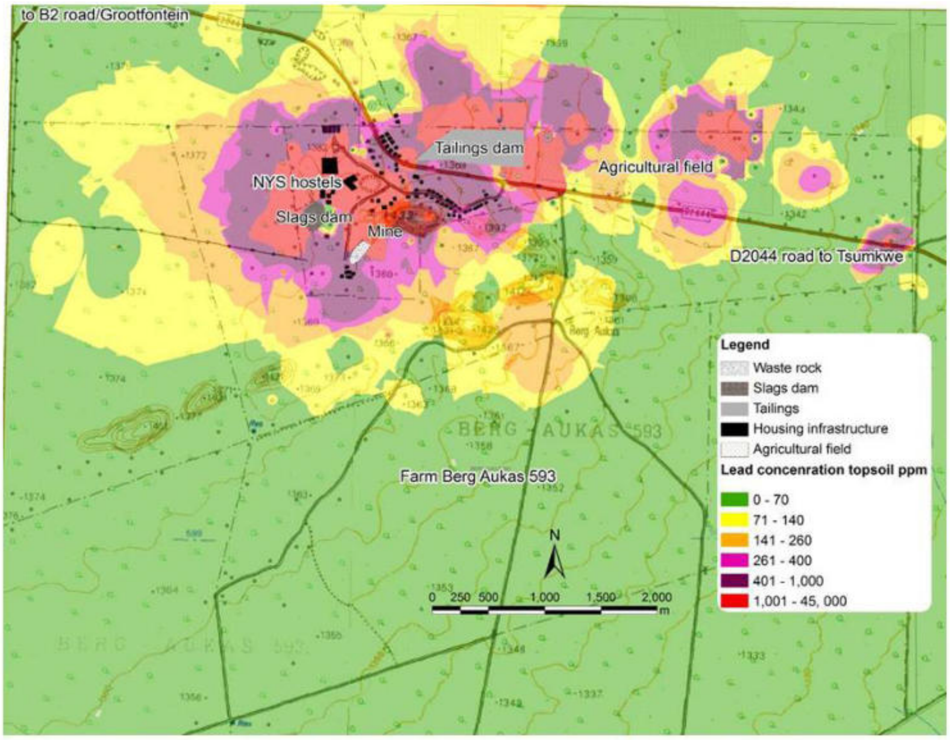

Figure 8. Lead in upper soil horizon (249 samples)

Table 2: Canadian and German guideline values (in ppm; 1 ppm = 1 mg/kg soil)

	Canada				Germany		
	Agricul-ture	Residential	Commer-cial	Industry	Play-ground children	Residential	Industrial
As	12	12	12	12	25	50	140
Cd	1.4	10	22	22	10	20	60
Cu	63	63	91	91	-	200	2000
Pb	70	140	260	600	200	400	1000
V	130	130	130	130	-	-	-
Zn	200	200	360	360	-	600	3000

soils around the old smelter site and the tailings dump is complicated by three features (Figure 8). These features are as follows: tailings material has been spilled far eastwards following the morphology through the agricultural fields; spots of severe soil contamination are caused by using slag and partly tailings material for road construction (e.g. southeastern and southern part of the agricultural fields and roads passing by the old Berg Aukas farm houses); natural mineralisation occurring at Heinitzberge, 3 km to the north of Berg Aukas, and possibly in the northern part of the agricultural fields.

Lead concentration varies widely in soils of the agricultural fields due to tailing spillages and dumping of slag. Areas which occur in light green are suitable for agricultural purposes. Dark green, yellow and orange colours are conditionally suitable depending on (i) vulnerability of crops to lead uptake, and (ii) bio-availability of lead in the area.

The contents of lead in the lower soil horizon are relatively high (median: 54 ppm; maximum 1,157 ppm) compared to other contaminants. The elevated lead concentrations in the lower soil horizon are located in heavily contaminated areas in the processing and smelting area and to the east of the tailings dump.

It can be concluded that anomalous contents of lead in the lower soil profile are predominantly constrained by a descending transport of the metal from contaminated top soil. This is generally supported by correlating values of lead in the upper soil horizon. However, it can not be excluded that the high lead values to the east of the tailings dump are at least partly caused by natural mineralisation.

Mercury

Slightly elevated values of mercury occur in the lower soil horizon (0.08–0.19 ppm) (Appendix 3). No relation is observed between the distribution of mercury and of the position of ore bodies. Mercury concentration in the upper soil reaches a maximum value of 6.9 ppm. Mercury is known to represent highly volatile products of ore roasting and smelting. Elevated concentrations of mercury in the upper soil horizon predominantly reflect in-situ roasting. Fossil fuels used for ore roasting might be a source of the mercury in soils.

Vanadium

Contents of vanadium in the lower soil horizon are low (median: 24 ppm; maximum value: 163 ppm), although Berg Aukas ores were mined for vanadium. No relationship was found between the distribution of vanadium in the lower soil horizons and the position of ore bodies. The concentrations of vanadium in top soil (median: 61 ppm; maximum value: 2,114 ppm) are much higher (Appendix 4). The maximum value of vanadium in surface soil (2,114 ppm) is relatively lower than the maximum value for Zn (216,000 ppm) or Pb (34,400 ppm), which can be explained by the low volatility of vanadium during ore roasting.

Zinc

While the average background value is 75 ppm, the values vary between 107,000 and 377,000 ppm for the historical smelting area in central Berg Aukas. The top soil of the smelting area contains with 10 to 38 % zinc up to three times more zinc than the originally mined ores. Concentrations are very high in the whole National Youth Training Centre and the settlement (1,000 to 50,000 ppm). Large-scale contamination of the whole Berg Aukas area can be attributed to the roasting of ores in the past and by dust fall-out from slimes dams and slag deposits. The zone in which zinc occurs in hazardous concentrations (with the risk of causing adverse health effects) is almost identical with that of high lead contamination (purple colours in figure 9). Thus, land use recommendations are identical to those for lead.

In the absence of guideline values for soil contamination in Namibia, criteria from Canada, Germany and the Netherlands have been used in this publication. The guideline values refer to the allowable and acceptable concentrations for the intended use of a particular site.

The concentrations of trace metals in soils in the study area were compared with the guideline or trigger values from Canada (Canadian Environmental Council of Ministers of the Environment, 2000) and Germany (1999). The guidelines vary for agricultural, commercial and industrial land uses. Concentrations of metals above these limits are likely to be associated with adverse health effects.

Analyses of plant samples

Agriculture in the Berg Aukas area is mostly based on livestock and crop farming. Therefore different grass species were collected from pasturelands. Samples of maize (grains), cassava (leaves and bulbs) and sweet potatoes (leaves and bulbs) were collected from agricultural fields to the east of the settlement irrigated by shaft water. Additionally 30 rhizosphere samples were collected from a depth of 0-30 cm.

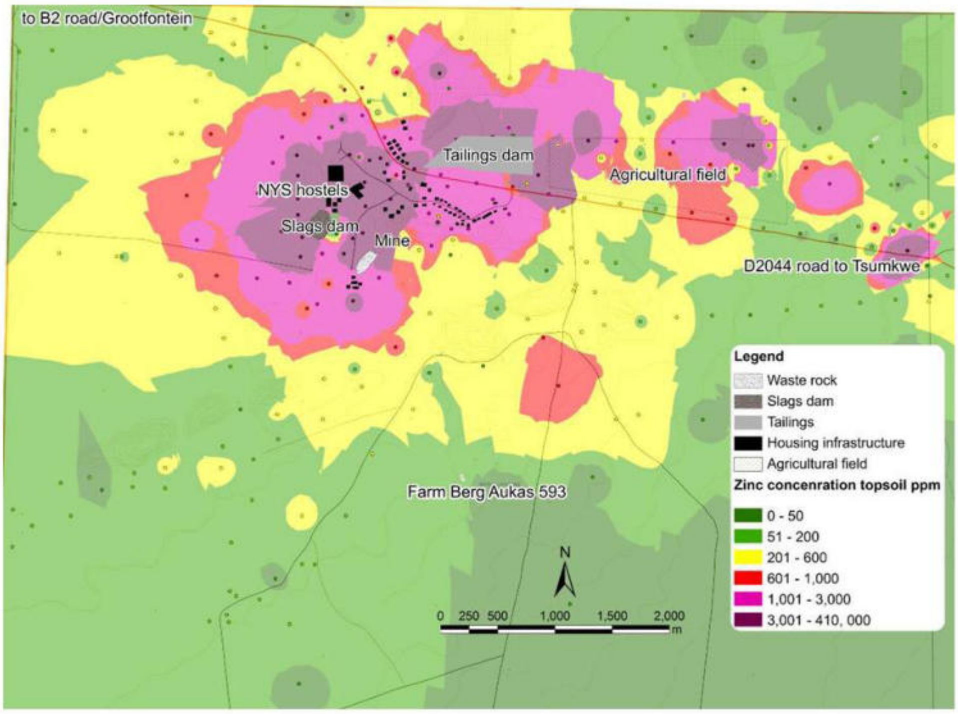

Figure 9. Zinc in upper soil horizon (249 samples)

The samples were combusted in a muffle oven at a temperature of 400°C. The amount of ash was scaled and the metals were analytically determined in HNO_3 and HCl leachate as described for the soil samples. Some results were recalculated on dry-weight basis to compare with the Czech limits for dry forage (As = 6 ppm, Mo = 3 ppm and Pb = 20 ppm; Kribek *et al.*, 2006). Concentrations of As, Cu, Pb and Zn were compared to World Health Organisation limits (WHO 2002: As = 0.5 ppm, Cu = 20 ppm, Pb = 0.4 ppm and Zn = 50 ppm) after recalculation to wet fresh matter.

The median value for Zn in the set of grass samples (202 ppm) and the maximum value of Zn (818 ppm) are in excess of the Czech limits for permanent grass cover (Zn = 35.2 ppm; Kribek *et al.*, 2006). More than a third of the sampled grass species show Pb concentrations above the Czech limits for dry forage. The highly contaminated samples were collected mainly in the vicinity of the slime deposit and the former processing plant.

The analysed cassava and sweet potato leaves as well as roots are characterized by As, Pb and Zn values in excess of WHO limits for food. The maximum concentrations in cassava leaves are 185 times higher for Pb, almost 9 times higher for Zn and for As almost 2 times higher than the WHO limits. Maximum values in sweet potato leaves exceed the WHO limits for Pb (460 times), Zn (17 times) and As (almost 5 times). All cassava and sweet potato roots have Pb contents above the WHO limits and two thirds of cassava root samples are characterized by Cu values above the WHO limits. Furthermore, WHO limits for As and Zn are exceeded for two thirds and one third of the sweet potatoes, respectively.

Generally, higher concentrations of metals occur in leaves than in roots, and the concentrations of heavy metals in potatoes are higher than in cassava roots.

Health effects of the major pollutants

The analytical results demonstrate contaminations with respect to arsenic, cadmium, copper, lead, mercury and zinc.

Health effects of a permanent exposure to arsenic are among others skin damages like keratosis and blackfoot disease, (skin, lung, bladder, kidney) cancer, increased infant mortality, and neurological problems.

Cadmium occurs as minor constituents in sulphide ores, mainly sphalerite. Cadmium is an acute toxin and carcinogen, whereby poisoning is experienced in lungs, kidneys and bones. Cadmium causes a disease which is known in Japan as “Itai-itai” (pain). Patients suffer from pain in joints, lumbago pains, pseudo-fracturing of bones, skeletal deformation and renal dysfunction.

Once absorbed, copper is distributed primarily to the liver, kidneys, spleen and heart. Individuals with copper toxicity show an abnormally high level of copper in the liver, kidneys, brain, eyes and bones (ATSDR 1990a). Acute toxicity of ingested copper is characterized by abdominal pain, diarrhea, vomiting, tachycardia and a metallic taste in the mouth.

Lead is absorbed into the body following inhalation or ingestion. Children absorb lead much more efficiently than adults after exposure, and ingested lead is more readily absorbed in a fasting individual (U.S.EPA 1986). Adults distribute about 95% of their total body lead to their bones, while children distribute about 73% of their total body lead to their bones (U.S. EPA, 1986a). Lead poisoning can cause irreversible brain damage (encephalopathy), seizure, coma and death, if not treated immediately (U.S. EPA, 1986). The Central Nervous System (CNS) becomes severely damaged at lead concentrations starting at 40 mcg/dl in blood, causing a reduction in nerve conduction velocities and neuritis (ATSDR 1993).

Mercury exposure can result in a wide variety of human health conditions. The degree of impairment and the clinical manifestations that accompany mercury exposure largely depend upon its chemical state and the route of exposure. While inorganic mercury compounds are considered less toxic than organic mercury compounds (primarily due to difficulties in absorption), inorganic mercury that is absorbed is readily converted to an organic form by physiological processes in the liver.

Zinc is a trace element essential in plants and animals, but high exposure may cause neuropathy, dehydration, growth retardation, anemia, and nausea.

Conclusions

The study shows that most parts of Berg Aukas are severely contaminated with lead, zinc, cadmium, arsenic and vanadium. The analytical results point to critical contamination of the surface soils in the historical processing area where the ores were smelted. Besides that, contaminants are spread by wind erosion of the slag and tailings dumps as well as water erosion of the tailings. The use of slag and tailings for road construction contributes to the problem in the wider area.

The historical processing area is nowadays part of the town centre and the National Youth Training Centre (NYTC). For example, NYTC accommodation is located close to the former mining and smelter complex, where top soil exhibits concentrations of 5 ppm arsenic, 5.4 ppm cadmium, 130 ppm copper, 1500 ppm lead, 50,000 ppm zinc, and 1.5 ppm mercury.

The people living and working in Berg Aukas face health risks from inhalation and ingestion of the dust as well as by ingestion of crops grown on the contaminated soils. If humans are exposed for longer periods to these hazardous elements, they risk various heavy metal triggered diseases and disorders. Prolonged exposure to heavy metals in concentrations as found in the soils in Berg Aukas can cause diabetes, neurological effects as well as skin, kidney or lung cancer. Lead affects the mental development of children and leads to brain retardation.

The severely contaminated area at Berg Aukas, as a zone of high hazardous risk, represents an ellipsoid with diameters of approximately 3.5 km (E-W) and 2.5 km (N-S). The zone is relatively small compared to other mining and processing sites and should be avoided for any further industrial, residential, or agricultural developments.

The contamination decreases rapidly in all directions, which opens options for future developments on farm Berg Aukas. An alternative site for development would be the site of the old Berg Aukas farm houses, which are protected from contamination by the Berg Aukas Mountains. Likewise, the agricultural fields could be extended to the south of the current fields.

There is an urgent need to react to the results of this study. The authors recommend the following measures:

(A) To stop additional contamination:

(1) Stop using slag and tailings material for construction purposes (roads). Fence off slag and tailings dump sites.

(2) Prevent wind erosion from the smelter site and slag dump by soil and vegetation coverage.

(3) Stop further use of the tailings dump as 4x4 driving trail to allow vegetation growth.

(4) Prevent further spilling of tailings material into the agricultural area by spillage control.

(B) Farming:

(5) The major part of the agricultural fields is suitable for crop farming, but the soil has to be studied in a 25 m x 25 m grid due to contamination hot spots derived from tailings spilling and dumped slag material.

(6) Cease crop production up to 1.8 km to the east of the tailings dump (slikdam) northeast of Berg Aukas.

(7) Avoid growing of potatoes, melons, pumpkins and root vegetables, in the moderately contaminated areas.

(8) Change crops to less vulnerable types like maize and stem vegetables (tomato, pepper) in the moderately contaminated areas.

(9) Restrict growing of root vegetables and limit crop farming in the settlement.

(10) Cattle pasturing is not recommended in an area 2 km around Berg Aukas due to high lead concentration in grasses. The rest of the farm Berg Aukas is excellent pasture land.

(C) Human health

(11) Harnessing of awareness about the hazards among the residents. Start awareness campaigns on the soil-human and soil-plant pathways of the dangerous substances.

(12) Conduct medical tests (lead in blood) to delineate highly vulnerable groups and risk zones.

(13) Especially children should not eat fruits and vegetables grown in the gardens of the settlement.

(D) Infrastructural measures

(14) Immediately restrict use of the sports field.

(15) Any new development (industry, residential, agricultural) has to be avoided in red and purple zones.

(E) Trigger remediation

(16) Contaminated urban areas have to be rehabilitated, if they are intended for future use as residential areas, e.g. by covering top soils with organic matter and vegetation.

(17) Removal of the severely contaminated top soil seems an option in some parts of the settlement, which are affected by airborne pollution. Here, the highly contaminated top soil can be removed and properly disposed.

(18) Soil removal and re-disposal is not an option in the central processing and smelting zone due to a deep penetration of the contaminants in the soil horizon, and thus, a tremendous volume of contaminated soil. Rehabilitation by reprocessing of the extremely contaminated soil (3% Pb, 30 % Zn) might be viable.

The Government of Namibia reacted without delay on the results of this study. After presentation of the results by the Ministry of Mines and Energy, Cabinet decided to take immediate action by evacuation of the hostels of the vocational school. Students are now accommodated in a safe environment at Rietfontein near Grootfontein. The follow-up on all measures (e.g. agricultural land use, food security, and remediation) is regularly monitored by Cabinet.

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Appendix 1: Water analyses for shaft water from Berg Aukas and groundwater from farm Dornhügel in comparison with Namibian guideline values for drinking water

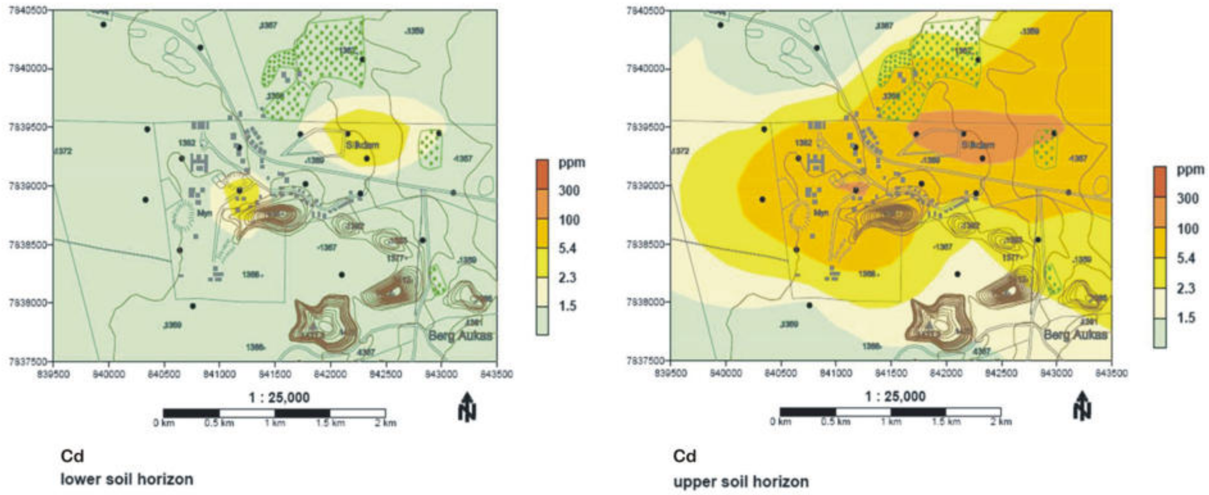
ID		pH field	pH	EC field	EC	total hardness	total dissolved solids (TDS)
				µS/cm	µS/cm	mg/L CaCO3	mg/L
B1	Berg Aukas Mine, shaftwater	7.25	7.3	857	838	465	855
D1	Farm Dornhügel, western borehole	7.5	7.6	976	997	543	668
	Namibia guideline values					mg/L CaCO3	
	Group A: excellent quality	6	9	1500	1500	300	
	Group B: acceptable quality	5.5	9.5	3000	3000	650	
	Group C: low health risk	4	11	4000	4000	1300	
	Group D: high health risk, or unsuitable for human consumption	4	11	4000	4000	1300	
	standard for effluent water (maximum levels)						500+influent

ID	K	Na	Cl	Mg	Ca	SO4	HCO3	Fe(II)	Mn	NO3	Br	NH4	NO2	F	PO4
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
B1	3.00	6.2	5.76	57.1	92.5	61.3	511	0.020	0.009	5.93	0.03	<0.01	<0.01	0.148	0.05
D1	0.08	16.0	22.0	84.0	79.0	29.0			<0.01	6.67			0.02	0.300	
Group A	200	100	250	70	150	200		0.1	0.05	44	1			1.5	
Group B	400	400	600	100	200	600		1	1	88	3			2	
Group C	800	800	1200	200	400	1200		2	2	176	6			3	
Group D	800	800	1200	200	400	1200		2	2	176	6			3	
Effluent		90+in												1	

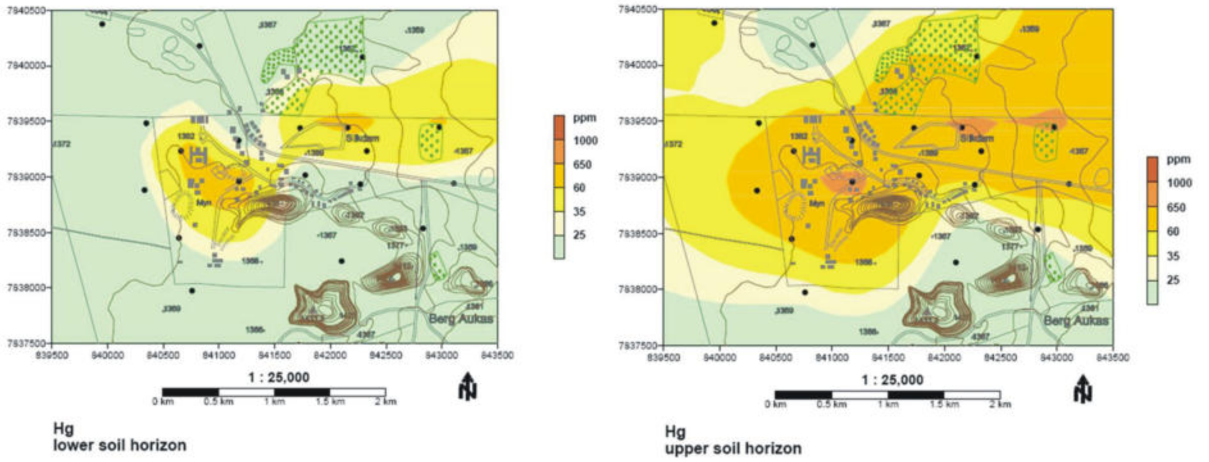
ID	Al	As	BO2	Ba	Be	Cd	Co	Cr	Cu	Li	Ni
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
B1	<0.003	<0.02	0.14	0.127	<0.0005	0.007	<0.005	<0.005	0.007	0.003	<0.005
D1		<0.01	<0.01			<0.01		0.01	0.02		
Group A	0.15	0.1	2	0.5	0.002	0.01	0.25	0.1	0.5	2.5	0.25
Group B	0.5	0.3	8	1	0.005	0.02	0.5	0.2	1	5	0.5
Group C	1	0.6	16	2	0.01	0.04	1	0.4	2	10	1
Group D	1	0.6	16	2	0.01	0.04	1	0.4	2	10	1
Effluent		0.5						0.5	1		

ID	Ni	Pb	Sc	SiO2	Sr	Ti	V	Zn
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
B1	<0.005	0.04	<0.001	14.5	0.183	<0.001	<0.005	2.34
D1		0.02						0.08
Group A	0.25	0.05				0.1	0.25	1
Group B	0.5	0.1				0.5	0.5	5
Group C	1	0.2				1	1	10
Group D	1	0.2				1	1	10
Effluent		1						5

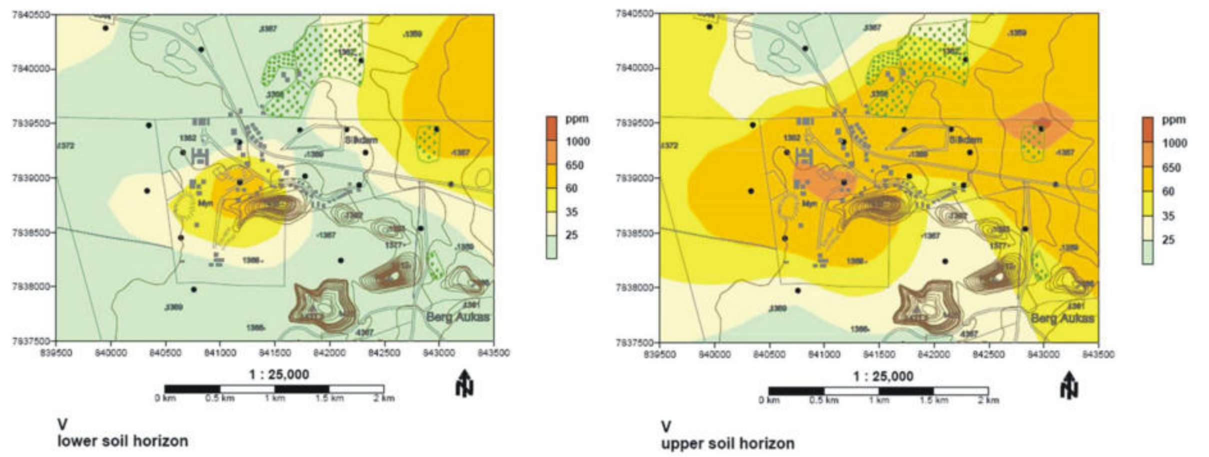
Appendix 2. Cadmium in lower (left) and upper (right) soil horizons (19 samples)



Appendix 3. Mercury in lower and upper soil horizons (19 samples).



Appendix 4. Vanadium in lower (left) and upper (right) soil horizons (19 samples)



Annex 1: Field parameters for the water samples in Berg Aukas and the surrounding farms.

Borehole No	Old No	Latitude	Longitude	Borehole Depth (m)	Collar Height (m)	Rest Water Level (RWL) (m)	Sampling depth (m)	Sample Date	Sample Time	Colour	Odour	pH	EC	T
22659	3	-19.46870	18.32743	18.01	1.02	15.05	17	27/08/'08	12h45	Clear	None	6.76	1324	28.4
28137	148	-19.53397	18.19302	134.01	1.00	27.74	40	27/08/'08	08h55	Clear	Rotten egg	6.65	997	26.5
28137	148	-19.53397	18.19302	134.01	1.00	27.74	80	27/08/'08	09h05	Clear	Rotten egg	6.65	993	26.1
28139		-19.52567	18.15665	70.26	0.34	3.5	10	27/08/'08	16h40	Clear	None	7.07	799	25.7
28139		-19.52567	18.15665	70.26	0.34	3.5	50	27/08/'08	16h46	Clear	None	7.15	802	25.3
28154	155	-19.53291	18.24067	120.04		44.86	60	26/08/'08	14h45	Clear	None	6.75	823	27.3
28154	155	-19.53291	18.24067	120.04		44.86	80	26/08/'08	14h50	Clear	None	6.81	876	27.5
28155	105	-19.53720	18.22038	144.12	0.36	30.12	50	26/08/'08	16h30	Clear	None	6.83	838	27.3
28155	105	-19.53720	18.22038	144.12	0.36	30.12	80	26/08/'08	16h45	Clear	None	6.86	840	26.4
28216		-19.48378	18.26177	55.01	1.05	5.83	10	28/08/'08	10h45	Greyish	Rotten egg	7.15	762	27.5
28216		-19.48378	18.26177	55.01	1.05	5.83	40	28/08/'08	10h50	Clear	Rotten egg	7.25	790	27.4
28350	98	-19.46868	18.32745	117.90		5.17	15	27/08/'08	11h40	Clear	None	6.93	954	27.1
28350	98	-19.46868	18.32745	117.90		5.17	40	27/08/'08	11h45	Clear	None	6.95	1009	26.4
28563	100	-19.48005	18.26458	8.78	0.4	3.4	5	28/08/'08	11h23	Clear	None	7.14	766	26.9
61076	88	-19.46861	18.36585			3.45		27/08/'08	10h53	Clear	None	7.03	978	27.5
61082	107	-19.47549	18.28474					28/08/'08	12h55	Clear	None	7.24	768	25.2
62377	80	-19.55029	18.26221	45.00		27.93	30	26/08/'08	13h29	Clear/ dust	None	6.86	1284	26.6
62377	80	-19.55029	18.26221	45.00		27.93	40	26/08/'08	13h40	Milky	None	6.87	1176	26.2
63400	5	-19.45856	18.24301	42.74		8.17	15	27/08/'08	17h30	Light brown	None	7.11	2.01 mS/cm	25.2
63400	5	-19.45856	18.24301	42.74		8.17	30	27/08/'08	17h35	Milky brown	None	6.94	3.74 mS/cm	24.8
79273	12	-19.46361	18.27165	12.01		8.66	10	28/08/'08	11h58	Faint yellow	None	8.00	1292	25.0
81270	82	-19.52179	18.26683	10.25		7.95	9.95	26/08/'08	11h33	Yellow/ brown	Rotten egg	7.48	1687	24
81637	14	-19.47579	18.27492					28/08/'08	12h40	Clear	None	7.11	754	32
82824	79	-19.50708	18.24887	50.40		12.37	20	27/08/'08	13h15	Clear	None	6.97	299	26.7
82824	79	-19.50708	18.24887	50.40		12.37	30	27/08/'08	13h30	Clear	None	6.98	826	26.1
200572		-19.45075	18.20476	149.56		7.35	30	28/08/'08	09h15	Clear	Rotten egg	7.35	1388	27.1
200572		-19.45075	18.20476	149.56		7.35	80	28/08/'08	09h25	Grey	Rotten egg	7.24	1378	27.0
200573		-19.45595	18.22165	37.45	0.8	7.05	15	28/08/'08	08h05	Clear	None	6.97	952	26.2
200573		-19.45595	18.22165	37.45	0.8	7.05	30	28/08/'08	08h15	Clear	None	6.93	1004	25.9
NYS Project	Tap	-19.51127	18.26865					28/08/'08	15h00	Clear	None	7.46	847	25.4

Annex 2: Analytical results for the groundwater samples from Berg Aukas.

Borehole ID	Old Number	Description	Sample depth	Coordinates		pH	EC	Total Hardness	TDS	K	Na	Cl	Mg	Ca	SO_4
			m	Lat	Long		mS/m	mg/L	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
22659	3	Berg Aukas Borehole	17	-19.46870	18.32743	7.10	137.00	663	918	0.4	65	82	93	112	25
28137	148	Berg Aukas Borehole	40	-19.53397	18.19302	7.00	100.70	540	675	3	8.8	19	59	119	3
28137	148	Berg Aukas Borehole	80	-19.53397	18.19302	6.80	100.40	564	673	2.9	9	20	63	122	3
28139		Struikfontein Borehole	10	-19.52567	18.15665	7.50	82.20	473	551	1	6.6	14	59	92	8
28139		Struikfontein Borehole	50	-19.52567	18.15665	7.60	82.20	505	551	1.1	6.7	13	59	105	8
28154	155	Berg Aukas Borehole	60	-19.53291	18.24067	7.20	84.90	534	569	0.5	3.7	7	66	105	4
28154	155	Berg Aukas Borehole	80	-19.53291	18.24067	7.20	85.30	505	572	0.5	3.9	7	59	105	4
28155	105	Berg Aukas Borehole	80	-19.53720	18.22038	7.20	86.60	506	580	0.4	3.9	6	61	102	3
28155	105	Berg Aukas Borehole	50	-19.53720	18.22038	7.80	85.40	503	572	0.4	3.5	7	64	96	2
28216		Berg Aukas Borehole	10	-19.48378	18.26177	7.20	74.10	433	496	1.6	4.7	10	62	71	3
28216		Berg Aukas Borehole	40	-19.48378	18.26177	7.70	79.10	453	530	1.4	4.7	10	62	79	1
28350	98	Swartwater Borehole	15	-19.46868	18.32745	7.80	97.40	594	653	1.2	6.3	11	89	91	7
28350	98	Swartwater Borehole	40	-19.46868	18.32745	7.70	103.60	640	694	0.6	6.4	13	96	98	6
28563	100	Berg Aukas Borehole	5	-19.48005	18.26458	7.10	78.40	492	525	0.5	2.4	5	60	98	3
61076	88	Farm Manilla Windmill		-19.46861	18.36585	7.30	101.00	592	677	0.5	7.1	17	88	92	7
61082	107	Berg Aukas Spring		-19.47549	18.28474	7.60	77.70	474	521	0.4	2.4	5	58	94	3
62377	80	Berg Aukas Borehole	40	-19.55029	18.26221	7.20	115.60	657	775	2.2	11	7	91	113	2
62377	80	Berg Aukas Borehole	30	-19.55029	18.26221	7.00	127.30	710	853	2.9	12	9	104	113	1
63400	5	Berg Aukas Borehole	15	-19.45856	18.24301	7.30	207.70	890	1392	1.6	120	311	155	101	28
63400	5	Berg Aukas Borehole	30	-19.45856	18.24301	7.40	393.00	1522	2633	1.6	181	807	255	189	32
79273	12	Berg Aukas Borehole	10	-19.46361	18.27165	8.10	133.70	759	896	4.1	26	35	134	83	<1
81270	82	Berg Aukas Open well	10.45	-19.52179	18.26683	7.60	172.30	635	1154	16	15	34	76	129	<1
81637	14	Berg Aukas Borehole		-19.47579	18.27492	7.30	77.60	520	520	0.5	2.6	6	59	93	2
82824	79	Berg Aukas Borehole	30	-19.50708	18.24887	7.40	84.50	527	566	0.6	5.5	12	65	104	14
82824	79	Berg Aukas Borehole	20	-19.50708	18.24887	7.30	96.10	521	644	0.9	5.5	14	64	103	12
200572		Berg Aukas Borehole	30	-19.45075	18.20476	7.40	143.20	959	959	2.7	40	49	138	73	8
200572		Kalkfontein Borehole	80	-19.45075	18.20476	7.50	142.10	777	952	3.4	44	50	139	82	12
200573		Berg Aukas Borehole	15	-19.45595	18.22165	7.30	98.70	661	661	0.3	17	16	91	87	<1
200573		Berg Aukas Borehole	30	-19.45595	18.22165	7.10	104.00	588	697	0.3	17	25	93	82	<1
		Berg Aukas NYS Irrigation Project		-19.51127	18.26865	7.60	85.90	486	0	3.8	6.1	8	58	99	59
Current Namibia Guideline Values for Drinking Water								mg/l $CaCO_3$							
Group A: excellent quality					6	9	150	300		200	100	250	70	150	200
Group B: acceptable quality					5.5	9.5	300	650		400	400	600	100	200	600
Group C: low health risk					4	11	400	1300		800	800	1200	200	400	1200
Group D: high health risk, or unsuitable for human consumption					4	11	400	1300		800	800	1200	200	400	1200
Standard for effluent water (maximum allowable levels)									500+in fluent		90+in				

Annex 2: Continued

ID Bore-hole	Old Num-ber	Sample depth	NO_3	Fe(II)	Mn	Mo	NO_2	F	As	B	Cd	Cr	Cu	Hg	Pb	Se	SiO_2	U	V	Zn
			mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
22659	3	17	<0.5	0.05	0.08	<0.01	<0.1	0.2	<0.01	0.1	<0.01	<0.01	<0.01	<0.05	<0.01	0.01	27	<0.2	<0.01	<0.01
28137	148	40	<0.5	3.4	0.2	<0.01	<0.1	0.1	0	0.02	<0.01	<0.01	<0.01	<0.05	<0.01	0.02	28	<0.2	<0.01	<0.01
28137	148	80	<0.5	3.9	0.2	<0.01	<0.1	0.1	0	0.01	<0.01	<0.01	<0.01	<0.05	<0.01	0.01	28	<0.2	<0.01	<0.01
28139		10	4	0.02	<0.01	<0.01	<0.1	0.1	0	<0.01	<0.01	<0.01	<0.01	<0.05	<0.01	0.01	16	<0.2	<0.01	0.02
28139		50	4	0.03	<0.01	<0.01	<0.1	0.1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.05	<0.01	<0.01	16	<0.2	<0.01	0.01
28154	155	60	2.1	0.05	0.01	<0.01	<0.1	0.2	0	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	20	<0.2	<0.01	0.03
28154	155	80	2.3	0.03	<0.01	<0.01	<0.1	0.2	<0.01	0.01	<0.01	<0.01	<0.01	<0.05	<0.01	0.01	20	<0.2	<0.01	0.01
28155	105	80	1.4	0.02	<0.01	<0.01	<0.1	0.1	<0.01	0.01	<0.01	<0.01	<0.01	<0.05	<0.01	0.02	20	<0.2	<0.01	0.01
28155	105	50	1.6	0.03	<0.01	<0.01	<0.1	0.2	0	<0.01	<0.01	<0.01	<0.01	<0.05	<0.01	<0.01	20	<0.2	<0.01	0.01
28216		10	<0.5	11	0.05	<0.01	<0.1	0.1	0	0.03	<0.01	<0.01	<0.01	<0.05	<0.01	<0.01	20	<0.2	<0.01	0.01
28216		40	<0.5	6.4	0.02	<0.01	<0.1	0.1	0	0.01	<0.01	<0.01	<0.01	<0.05	<0.01	<0.01	21	<0.2	<0.01	<0.01
28350	98	15	<0.5	0.03	0.02	<0.01	<0.1	0.5	<0.01	0.01	<0.01	<0.01	<0.01	<0.05	<0.01	<0.01	29	<0.02	0	<0.01
28350	98	40	<0.5	0.04	0.04	<0.01	<0.1	0.2	0	0.01	<0.01	<0.01	<0.01	<0.05	<0.01	<0.01	33	<0.2	0	<0.01
28563	100	5	0.8	0.04	0.01	0.01	<0.1	0.1	0	0.01	<0.01	0.01	<0.01	<0.05	<0.01	<0.01	18	<0.2	<0.01	0.01
61076	88		<0.5	0.1	0.01	<0.01	<0.1	0.2	<0.01	0.02	<0.01	<0.01	<0.01	<0.05	<0.01	<0.01	31	<0.2	0	0.04
61082	107		1	0.03	<0.01	<0.01	<0.1	0.1	0	<0.01	<0.01	<0.01	<0.01	<0.05	<0.01	<0.01	16	<0.2	0	0.02
62377	80	40	0.9	12	1.5	<0.01	0.2	0.2	0	0.04	<0.01	0.01	<0.01	<0.05	<0.01	<0.01	35	<0.2	<0.01	0.6
62377	80	30	<0.5	12	1.9	<0.01	<0.1	0.2	<0.01	0.04	<0.01	<0.01	<0.01	<0.05	<0.01	0.01	34	<0.02	<0.01	0.8
63400	5	15	17	0.05	0.2	<0.01	<0.1	0.3	0	0.05	<0.01	<0.01	0.01	<0.05	<0.01	<0.01	32	<0.2	0	0.2
63400	5	30	77	0.03	0.8	<0.01	0.4	0.3	0	0.03	<0.01	0.01	<0.01	<0.05	<0.01	<0.01	29	<0.2	0	0.6
79273	12	10	<0.5	0.2	0.2	<0.01	0.3	0.1	0	0.02	<0.01	<0.01	<0.01	<0.05	<0.01	0.02	49	<0.2	<0.01	<0.01
81270	82	10.45	<0.5	0.9	0.4	<0.01	<0.1	0.1	<0.01	0.05	<0.01	<0.01	<0.01	<0.05	<0.01	0.06	25	<0.2	<0.01	<0.01
81637	14		1.2	0.01	<0.01	0.01	<0.1	0.1	<0.01	0.06	<0.01	<0.01	0.01	<0.05	<0.01	<0.01	16	<0.2	<0.01	0.03
82824	79	30	3.5	0.2	0.3	<0.01	<0.1	0.1	<0.01	<0.01	<0.01	0.01	<0.01	<0.05	<0.01	0.01	16	<0.2	<0.01	0.5
82824	79	20	4.3	0.03	0.2	<0.01	<0.1	0.1	<0.01	0.01	<0.01	<0.01	0.06	<0.05	<0.01	0.01	17	<0.2	<0.01	0.6
200572		30	<0.5	1.6	0.3	0.01	<0.1	0.2	<0.01	0.05	<0.01	0.01	<0.01	<0.05	<0.01	0.01	26	<0.2	0	<0.01
200572		80	<0.5	1.6	0.3	<0.01	<0.1	0.2	<0.01	0.03	<0.01	<0.01	<0.01	<0.05	<0.01	0.03	26	<0.2	<0.01	<0.01
200573		15	0.5	0.04	0.01	<0.01	<0.1	0.2	<0.01	0.05	<0.01	<0.01	<0.01	<0.05	<0.01	0.02	30	<0.2	0	0.02
200573		30	0.8	0.03	0.01	<0.01	<0.1	0.3	<0.01	0.01	<0.01	<0.01	<0.01	<0.05	<0.01	0.01	30	<0.2	0	0.01
NYS			2.1	<0.01	<0.01	<0.01	<0.1	0.2	0	0.03	0.01	<0.01	<0.01	<0.05	0.06	0.02	18	<0.2	<0.01	1.7

Namibia Guideline Values for Drinking Water	NO_3	Fe(II)	Mn	Mo	NO_2	F	As	B	Cd	Cr	Cu	Hg	Pb	Se	SiO_2	U	V	Zn
Group A: excellent quality	10	0.1	0.1	0.05		1.5	0.1	0.5	0.01	0.1	0.5	0	0.1	0.02		1	0.3	1
Group B: acceptable quality	20	1	1	0.1		2	0.3	2	0.02	0.2	1	0	0.1	0.05		4	0.5	5
Group C: low health risk	40	2	2	0.2		3	0.6	4	0.04	0.4	2	0	0.2	0.1		8	1	10
Group D: high health risk, or unsuitable for human consumption	40	2	2	0.2		3	0.6	4	0.04	0.4	2	0	0.2	0.1		8	1	10
Standard for effluent water (maximum allowable levels)						1	0.5			0.5	1		1					5