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The environmental impact of gold mines: pollution by heavy metals

Research article

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Abstract: The gold mining plant of Oman was studied to assess the contribution of gold mining on the degree of heavy metals into different environmental media. Samples were collected from the gold mining plant area in tailings, stream waters, soils and crop plants. The collected samples were analyzed for 13 heavy metals including vanadium (V), chromium (Cr), manganese (Mn), nickel (Ni), copper (Cu), cadmium (Cd), cobalt (Co), lead (Pb), zinc (Zn), aluminium (Al), strontium (Sr), iron (Fe) and barium (Ba). The water in the acid evaporation pond showed a high concentration of Fe as well as residual quantities of Zn, V, and Al, whereas water from the citizens well showed concentrations of Al above those of Omani and WHO standards. The desert plant species growing closed to the gold pit indicated high concentrations of heavy metals (Mn, Al, Ni, Fe, Cr, and V), while the similar plant species used as a control indicated lesser concentrations of all heavy metals. The surface water (blue) indicated very high concentrations of copper and significant concentrations of Mn, Ni, Al, Fe, Zn, lead, Co and Cd. The results revealed that some of the toxic metals absorbed by plants indicated significant metal immobilization.

Keywords: Environment • Gold mining • Heavy metals • Pollution • Tailings • Soil • Water

1. Introduction

Mining has been identified as one of the human activities which may impact negatively on the quality of the environment [1]. It causes the destruction of natural ecosystems through removal of soil and vegetation and burial beneath waste disposal sites [2]. In principle, mining waste can be divided into two categories: (i) mine tailings, generated when processing the ore, and (ii) waste rock produced when uncovering the ore body. Many processing methods for minerals involve grinding of rock and ores, recovery of the desired fraction and disposal of the wastes, often as slurry, to a tailings or retention pond. More than 99% of the original material may finally become tailings when low-quality ores are utilized [3].

Impacts of mining range from physical/habitat destruction with accompanying the loss of bio-diversity resources to the accumulation of pollutants in different media of the environment [4]. Therefore, the mining sites are a permanent toxicological problem for the surrounding ecosystems and human health [5]. Like any productive activity, the exploitation of mineral resources produces negative impacts upon the three elements in the environment: water, atmosphere and soil [6].

The mining sites are often contaminated with several kinds of heavy metals that come primarily from the processing

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of ores and disposal of tailings and wastewaters around mines [1, 7] These heavy metals can be released into the environmental media especially water, sediment and soil [5, 8–10] According to certain changes in the physical and chemical properties in the Lithosphere, heavy metals in tailings can be transported to, dispersed to, and accumulated in plants and animals, and can then be passed up the food chain to human beings as a final consumer [11]. In addition, the tailings contain many heavy metals, some of which are toxic contaminants in the soil that may cause adverse effect on the ecosystem around the metal mines [11–13]. Therefore, contamination of soils, sediments, water and biota by heavy metals is a primary concern in the mining sites because of their toxicity, persistence, and accumulation in food chains [1].

Heavy metals associated with mining are of particular interest for a number of reasons. Firstly, they show a tendency to accumulate in sediments and soils and have a long persistence time (are not biodegradable). Secondly, they are ubiquitous in sediments and soils arising from both natural and anthropogenic sources with pathways including inheritance from the parent rocks, application of water as well as local and long-range atmospheric and fluvial deposition of emissions from dust and mining [4]. These metals can then enter the food chain via uptake by plants and animals including man [4, 14–16].

Although many heavy metals at low concentrations have an essential role as nutrients for plants, animals and human health, some if present at higher quantities and in certain forms may also be toxic and can cause harm to life [17–20]. Copper (Cu) and zinc (Zn) provide clear examples, both being essential for normal metabolism and both can be toxic in high concentrations [21]. When the quantities of Cu and Zn in the body increase they become toxic, which can result in damaged and malfunctioning human organs. Heavy metals like Arsenic (As), lead (Pb), and cadmium (Cd) are believed to cause cancer, neural and metabolic disorders and other diseases [4, 16]. Arsenic is considered one of the most important contaminants of drinking water in the world as it causes cancer of the skin, lungs, urinary bladder and kidney. Lead is another metal of great concern as it can cause brain, liver and kidney damage in children and nerve damage in adults, while long term exposure to cadmium can cause kidney failure, liver, bone and blood damage [5].

Heavy metals cause oxidative stress in plants [22–25]. Metal stress was reported to affect photosynthesis, chlorophyll fluorescence and stomatal resistance [26]. For instance, copper inhibits photosynthesis and reproductive processes; lead reduces chlorophyll production, while arsenic interferes with metabolic processes. Consequently, plant growth is reduced or impossible [5]. A number of case histories related to health problems due to excess concentration of heavy metals were documented and reported from different parts of the world [4, 27–33].

One of the most important environmental problems linked to metal mining activities is acid mine drainage (AMD), which is produced by oxidation of pyrite and other metallic sulphides [34–36]. The genesis of the acid drainage and the main physical, chemical and biological factors which are involved in this process were widely studied by many investigators [37, 38].

Being a precious metal which is found in small quantities, gold mining operations tend to cover wide areas, and thus can inflict environmental damage over a geographically wide area. The mining process sometimes is complex and results in the release of highly toxic pollutants. Gold mining tends to have huge negative impacts on the environment from digging out a huge pit, to disposing of the left over chemicals and tailing. The environmental impacts of gold mining are particularly severe because of the chemical processes often used to extract gold. At the present time, the cyanide leaching technique is used in extracting gold. This process is particularly damaging the environment, infringes the principle of sustainable development, consumes large quantities of water and energy, contributes to global warming, emits hydrogen cyanide and creates a morass of hazardous waste. Land, water, and air pollution are all a byproduct of gold mining through the cyanide heap-leaching method. Open pits can also lead to the destruction of villages and relocation of communities. Gold mining disturbs the landscape, the water table, the geological stability and the surrounding ecosystems because the large amounts of ore have to be removed to get small amounts of gold. Gold mining disturbs underground water and pollutes water systems. Gold mining creates mountains of toxic waste because of the nature and quantities of chemicals used in processing gold. It also produces noise pollution, which is caused by blasting and the movement of large vehicles.

In both underground and opencast mines, exposure to dust is a major problem. This dust can be toxic and radioactive. This is a true problem for workers, but can also be a dangerous problem for communities located near mines, especially in areas where roads are unpaved. Therefore, opencast mining can have a damaging impact on the ordinary activities of people living in rural areas.

Land pollution is the contamination of land by solid and hazardous wastes. This is really dangerous to the land and the people around. These toxic waste storage places cause problems to the local environment as well as the local citizens. Birth defects, sickness, and even death have all been observed in people surrounding these toxic waste storage facilities.

Air pollution occurs when more pollutants are emitted into the atmosphere that can be safely absorbed and diluted by

natural processes. This is seen in cases when the locations of the digging sites are in remote areas and the machines, the waste removal trucks, and the workers travel back and forth to complete the job. By making all of these trips and with some of the trucks that are used the emissions are massive. All the CO_2 that are entering the air causes acid rain and holes in the atmosphere, which is a contributor to the global warming.
Open cast mining has a very direct effect on the water table in the area of the mine. As soon as the pit goes below the line of the water table, the water table around the pit has to be lowered otherwise the pit would be flooded. The water around the pit is pumped out for kilometres, meaning that wells dry up and ecosystems linked to the water table (like wetlands and rivers) are seriously disturbed. Cyanide used to extract gold can pollute the rivers and can kill fish and other lives. Other waste products can also have bad effects on water quality. The air around a gold mine can also easily be polluted. Dust from open mine pits can blow around into the community. Both the mental health of workers and those living near mines will be badly affected. In this work, the gold plant in Oman was studied to see the contribution of gold mining to the accumulation of heavy metals in different environmental media.

2. Processing plant

At the processing plant, gold is extracted from the ore by cyanide leaching method where piles of crushed ore are soaked with cyanide solution. The ore processing consists of the following stages:

- Crushing and grinding of the ore.
- Addition of the process water to form slurry.
- Addition of lime to the ore, and cyanide solution to the slurry, to leach the gold into solution.
- Addition of carbon to adsorb dissolved metals and to remove them from the slurry.
- Stripping the metals from the carbon by acid washing and circulation of a caustic cyanide solution.
- Precipitation of the gold by electro-winning.
- Smelting of metal products into bars of dore bullion.
- Pumping of the barren slurry (tailings) to the tailings storage facility.

The above stages can be described under three main steps:

1. Grinding and size classification to reduce the ore down to a fine particle size.
2. Leaching and adsorption to extract the precious metals from the rock.
3. Recovery of gold to produce dore bullion bars.

Fig. 1 shows the gold plant under investigation. The plant is divided into 4 main areas: (1) crushing, (2) grinding and sizing, (3) leaching, adsorption and filtration, and (4) elution and gold room.

2.1. Crushing

The ore is stockpiled and the process begins by feeding the ore into a hopper with a loader. The ore is then drawn via a variable speed hydraulically driven belt feeder and delivered to the crusher. Crushing is carried out in a jaw crusher. Crushed ore is conveyed directly into the ball mill.

2.2. Grinding and sizing

In this area, grinding and size classification will be carried out in order to reduce the ore down to a fine particle size. The ore is conveyed directly from the jaw crusher into the ball mill. This ball mill has a larger proportion of steel balls to assist in the grinding process. Water from the process water tank is also added inside the ball mill to assist in the grinding process inside it. At the end of the day, the grinding process inside the ball mill will reduce the ore to slurry that has a very fine particle size. The outlet discharge of the mill is then pumped to the cyclones. The cycle underflow gravity flows back to the mill for further grinding and the cyclone overflow gravitates over the trash screen and into the leaching and adsorption area. It should be noted that fine particle size is required for gold liberation so the cyanide will be able to see the gold in the leaching process.

2.3. Leaching, adsorption and filtration

This area consists of two leaching tanks and six adsorption tanks. Sodium cyanide and caustic soda are added into the first and second leaching tank. The tanks provide sufficient retention time to allow the gold to be dissolved by the cyanide solution. The slurry then moves through six carbon adsorption tanks. The primary objective of the carbon is to remove (adsorb) the gold from the slurry solution leaving the leaching tanks. Carbon will be fed into the circuit in the opposite direction to the slurry flow, moving from the last adsorption tank to the first. This is because the gold moves towards the surface of carbon via a diffusive process. Therefore, the fresh carbon is fed through the last adsorption tank to scalp the gold that

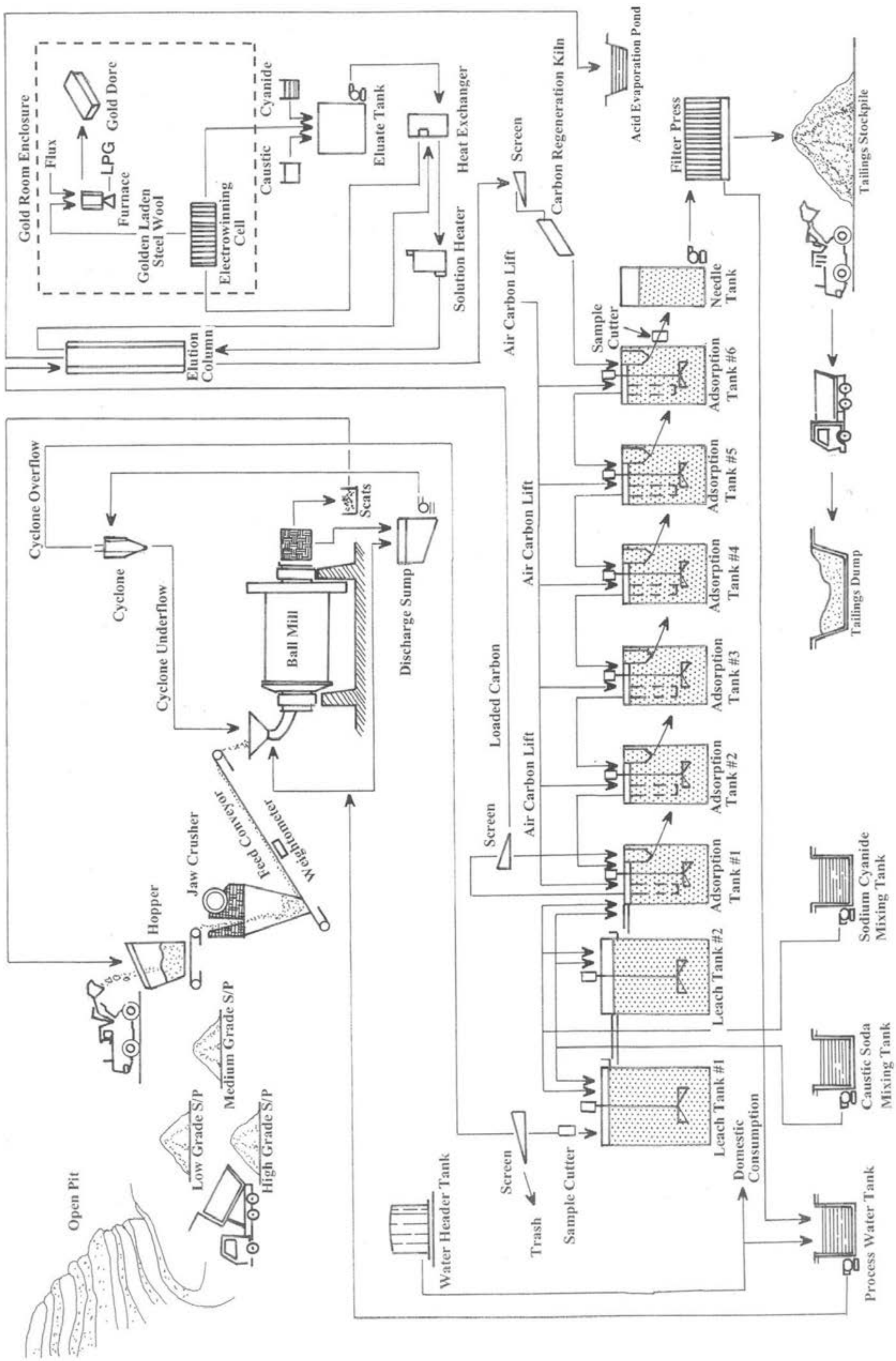

Figure 1. Flow chart of gold mining plant.

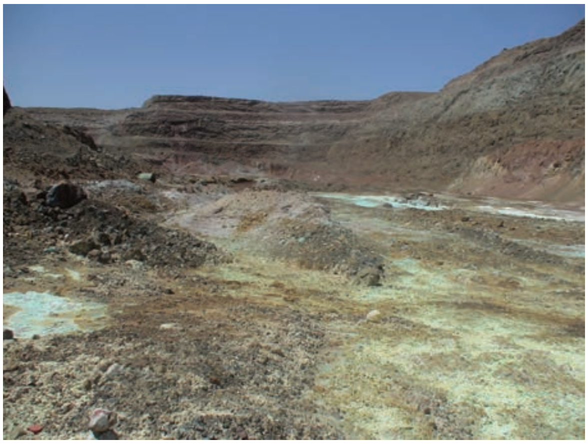

Figure 2. Photograph shows the open pit.

Figure 3. Photograph shows the jaw crusher.

has not been removed in the previous adsorption tanks. The carbon will be eventually removed from the circuit at the first adsorption tank for stripping (i.e., loaded carbon). By the time the slurry reaches the final adsorption tank, most of its gold has been removed by the carbon (i.e., the barren slurry). The barren slurry then passes out the final adsorption tank to the tailings filter needle tank. Slurry from the tailings filter needle tank is pumped into the filter press and is dewatered. The filter cake is dropped from the filter press onto the ground where it is removed by front end loader, loaded onto trucks and dumped into the tails dam. The filtrate gravity flows to the process water tank.

2.4. Elution and gold room

Carbon loaded with gold (i.e., loaded carbon) is then air-lifted from the first adsorption tank. It is pumped to the elution circuit where the gold is washed off with super-heated water. The washed solution (called pregnant eluate) is passed to the electrowinning circuit. The remaining barren carbon is reactivated by acid washing and returned back to the last adsorption tank.

Real photographs of the open pit, the jaw crusher, and the ball mill are shown in Fig. 2, 3 and 4 respectively.

Figure 4. Photograph shows the ball mill.

3. Materials and methods

3.1. 3.1. Study site

The plant is located in Wilayet Yanqol in Adaherh region of the Sultanate of Oman. The plant production is almost 20 kg of gold per month. The pit is a mountainous terrain and raw soil is cut terraced to the bottom of the pit until it reached the ground water table. Samples were collected from the different sampling areas as indicated in Table 1.

Table 1. Sampling location.

Seq.	Location
1.	Raw feed soil
2.	Soil open pit
3.	Blue surface water at bottom of terraced pit
4.	acid evaporation pond
5.	Water from citizens well 500-1000 m north of mine (used for irrigation)
6.	Crop plants
7.	Plants from vegetation close to mine and control away from mine

3.2. Samples and reagents

Deionised ultrapure water (18 ohm-SG water, Germany) was used to dilute standards and samples. Analytical Grade 37% HCl (Aldrich) and 70% nitric acid, (Sigma-Aldrich). ICP multi standards (1 and 2) were used to generate a calibration curve to quantify the samples. Microwave oven digestion has proved to be a suitable technique to digest samples with complex matrices [39] and was therefore used for digesting, soil samples and ashed plant samples. The soil sample, solid tailings and ashed plant samples were digested in teflon bombs using method EPA 3050B in a microwave oven (ETHOSEL, Milestone Microwave Stystem USA) with the following program; 8 min in phase one and 4 min in phase two at 200°C. The digested samples were filtered using Whatman filter paper and transferred to 100 ml volumetric flasks. The samples were analysed using a PerkinElmer Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES). Six reagent blanks were analysed with the samples but did not show any significant contamination.

Plant samples were air dried, ground using a mortar and pestle and sieved (100 um). The sieved sample was then ashed in a muffle furnace at 500°C and acid digested using ultrapure hydrochloric acid (37%) and nitric acid (70%) in equal ratio in a microwave oven in two phases.

4. Results and discussion

The trace elements considered for this study were vanadium (V), chromium (Cr), manganese (Mn), nickel (Ni), copper (Cu), cadmium (Cd), cobalt (Co), lead (Pb), zinc (Zn), aluminium (Al), strontium (Sr), iron (Fe) and barium (Ba). The feed soil of the gold plant was analysed for their metal concentrations which indicated high concentrations of copper (0.32%), manganese (0.29%), aluminum (10.8%), iron (1.4%) and lesser concentrations of zinc, nickel, chromium, vanadium, lead and cobalt (Table 2). Mineralized rocks which contain significant amounts of pyrite and other sulphide minerals can cause pyrite oxidation and the generation of acid solutions where heavy metals could become highly mobile when scarce rainfall occurs in this arid region.

Table 3 shows the result of the analysis of the soil and water in an open pit from where the light blue coloured surface water was collected. The soil indicated appreciably high copper concentrations (4.4%). Cadmium, lead, molybdenum and cobalt were showed marginally higher concentrations in the soil from the open pit when compared to the metal concentrations of the feed soil. The surface water from the bottom of the pit was light blue in colour. The blue colour was due to the high concentration

Table 2. Concentrations of heavy metals in soil samples.

Parameter	Raw ore used as gold plant feed soil (mg/kg)
Cu	3240
Mn	2865
Sr	680
Al	108476
Zn	964
Fe	14108
Ni	282
Cr	486
V	290
Cd	5.33
Pb	96.82
Mo	4.54
Co	101.2
B	316.1
Ba	118.5
Li	30.63
K	13970
Pb	n.d
Na	2410
Mg	51571
Ca	58882
S	24106

of copper (1170 mg/L). In addition there were appreciably high residual concentrations of manganese, aluminium, zinc, iron, nickel, cadmium, lead, and cobalt. Heavy metal pollution could be caused when such metals as cobalt, copper, cadmium, lead, and zinc contained in mine tailings come in contact with scarce rainfall water. Metals are leached out and carried downstream as water washes over the tailings. Although the metals can become mobile in neutral pH conditions, leaching is particularly accelerated in the low pH conditions which for example are created in the dissolution of some metals.

Table 4 shows the analysis results of similar vegetation. Plants taken from close to the gold pit and a control plant collected close to the citizens water well about 1000 metres, north of the mine. Analysis of the desert plant close to the gold pit indicated an alarming increase in almost all trace elements (Fe, Mn, Al, Zn, Cu, Ni, Cr, V, Co, Ba) and a decrease in the lead and molybdenum concentrations when compared to the control desert plant. The boron concentrations in this plant however showed an appreciable decrease (1.77% to 0.07%), when compared to the control. Despite the plants collected being of the same genus, the metal immobilization capabilities depend very much on the availability of metal concentrations in the soil as it is growing explaining the differences in metal concentrations. Lead concentrations of 80 mg Kg^{-1} were observed in the tailings and also high levels of lead were observed in the plants growing in close proximity to the gold mining area. The plant control taken downstream had lesser

Table 3. Concentrations of heavy metals in the soil and water in the open pit.

Parameter	Soil from bottom of open pit	Blue surface water (mg/L)
Cu	44156	1170
Mn	1780.2	23.7
Sr	409.6	8.04
Al	14525	76.6
Zn	605.4	21.1
Fe	9351	31.0
Ni	58.34	3.05
Cr	241.7	0.105
V	123.7	0.129
Cd	10.79	0.790
Pb	168.2	1.56
Mo	13.0	0.023
Co	493.5	23.7
B	192	1.25
Ba	48.5	0.026
Li	n.d	0.117
K	1522.5	3.77
Pb	n.d	n.d
Na	13287	246
Mg	64935	828
Ca	11988	245
S	151448	2780

n.d – not detected: < 0.01 mg/L

Table 4. Concentrations of heavy metals in crop plant.

Parameter	Plant close to the open pit (mg/kg)	Control plant (mg/kg)
Cu	119.7	35.1
Mn	433.6	233.2
Sr	7277	5102
Al	14834	1646
Zn	757.7	26.1
Fe	1349.4	129.3
Ni	92.2	56.0
Cr	105.6	6.2
V	60.8	18.9
Cd	n.d	n.d
Pb	30.4	41.4
Mo	11.6	34.1
Co	9.2	n.d
B	727.7	17793
Ba	255.9	66.6
Li	6.0	3.2
K	120352	35672
Pb	12535	1110
Na	5658	3986
Mg	88964	27302
Ca	277889	334794
S	10396	304888

concentrations of heavy metals than the ones in close proximity. This indicates that there could be translocation of these metals in metal rich soils from roots to the other parts in the plants. In an environment where there is less fodder the presence of toxic elements in soils could be ingested by livestock grazing in the vicinity of the mining area and subsequently to the humans suggesting a potential contamination of the food chain which could give rise to environmental and health problems.

There is every possibility that toxic trace elements in the soil could enter the water table following rain and surface water. Some of these toxic metals such as lead (Pb) was present at high concentrations not only in the soil but also in the plants of the surroundings and acid evaporation ponds. Despite the excessive phytotoxicity evidenced in soils analyzed containing high levels of metals, posing a risk for the surrounding area [40] and its scarce water resources the water from the Citizens Well about 500–1000 m north downstream of the mine conformed to the Omani Standards for Drinking Water and the WHO standards for drinking water.

Table 5 indicates the analysis results of the water sample obtained from the citizen's well located about 500–1000 m, north of the gold Plant. The water is used only for agriculture.

Depending on the changes in their physical-chemical states, the metal contaminants could cause soil substrate and groundwater pollution. Furthermore, heavy metals in tailings could be transported to, dispersed to, and accumulated in plants and animals, and then passed through the food chain to human beings.

The analysis of water from the acid evaporation pond (Table 6) indicates that the mining process has taken sufficient precautions to prevent environmental pollution. But soil samples taken from around the acid evaporation pond and the slurry sample taken from the tailing dump and analyzed for some specific heavy metals (lead, cadmium, zinc and copper) indicates otherwise with toxic concentrations of lead, cadmium, that any spill over from the acid evaporation pond could solubilise the heavy metals and be transported downstream during the scarce rainy seaon and translocated through plants to the human food chain.

5. Conclusions

The highest potential threat for the environment is mostly represented by mineralized rocks exposed in waste dumps and open pits. The water chemistry observed in the area, clearly show that these materials, have a high capability for acid drainage generation and release of toxic or harmful elements (Pb, Cd, Co, Cr, Cu, Ni). Moreover, the acid, high-metal waters can cause contamination in the scarce local groundwater through the solubilisation of toxic metals.

Although the analysis done on the well water from the vicinity did not conform to the Omani and WHO Standards

Table 5. Analysis of citizen's well water.

Parameter	Value
Colour	< 5 Hazen Units
Odour	None
pH	7.6
Electrical Conductivity	822 uScm-1
Total Dissolved Solids (TDS)	427 mg/L
Total Hardness as $CaCO_3$	310 mg/L
Calcium Hardness	100 mg/L
Magnesium Hardness	210 mg/L
Total Alkalinity	190 mg/L
Carbonate Alkalinity	0
Hydroxide Alkalinity	0
Turbidity	1.92 NTU
Cations	
Sodium	61.8 mg/L
Potassium	2.9 mg/L
Calcium (Ca)	40.0 mg/L
Magnesium (Mg)	50.9 mg/L
Copper (Cu)	0.028 mg/L
Manganese (Mn)	n. d
Strontium (Sr)	1.87 mg/L
Al	0.128 mg/L
Zinc (Zn)	0.387 mg/L
Iron (Fe)	0.02 mg/L
Nickel (Ni)	n. d
Chromium (Cr)	n. d
V	0.127 mg/L
Cadmium (Cd)	n. d
Lead (Pb)	0.565 mg/L
Mo	0.037 mg/L
Co	n.d
B	0.315 mg/L
Ba	0.062
Li	n.d
K	3.82 mg/L
P	0.5657 mg/L
Na	1617 mg/L
Mg	61.47 mg/L
Ca	50.27 mg/L
S	75.7 mg/L
Anions	
Fluoride (F)	0.16 mg/L
Chloride (Cl)	88.29 mg/L
Bromide (Br)	0.37 mg/L
Nitrate (NO_3)	19.14 mg/L
Sulphate (SO_4)	80.52 mg/L
Chemical Oxygen Demand*	< 1.6 mg/L

*Minimum Detectable limit – 1.6 mg/L
n.d. – not detected: 0.1 mg/L

for drinking water because of a high concentration of Aluminum, these threats to the local water chemistry must be carefully considered in the future plans.

Tailings are also a potentially harmful material, because of the high metal and cyanide contents. However, their confinement to a restricted site should mitigate their environmental impact but spill over could pose environmental

Table 6. Analysis of water from acid evaporation pond, soil sample and slurry sample from tailings stockpile.

Parameter	Water from acid evaporation pond (mg/L)
Cu	0.023
Mn	n.d
Sr	1.96
Al	0.195
Zn	0.269
Fe	60.032
Ni	n.d
Cr	n.d
V	0.117
Cd	n.d
Pb	0.030
Mo	0.044
Co	n.d
B	0.443
Ba	0.062
Li	n.d
K	4.20
Pb	0.112
Na	75.7
Mg	66.5
Ca	54.8
S	48.5

n.d. – not detected: < 0.01 mg/L

problems. Finally, the presence of livestock grazing nearby the mining area suggests a potential contamination of the food chain. The absence of any data on amounts of toxic elements in soils and local vegetation makes this risk unquantifiable.

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