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Review

Environmental Impacts of Gold Mining—With Special Reference to South Africa

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Abstract: Gold mining has serious negative environmental impacts, especially due to pollution emanating from tailings storage facilities (TSFs, tailings dams, slimes dams). The most important forms of pollution from TSFs are acid mine drainage (AMD) and high levels of potentially toxic elements (PTEs). AMD arises from the high levels of pyrite in the mining ores, which become oxidised in the TSFs where the pyrite is exposed to atmospheric oxygen. The sulphate produced from oxidation of the sulphide in the pyrite dissolves in water to form sulphuric acid, a very strong acid. pH levels in the extremely low range of 3–4 are common. At such low pH the mobilities of numerous metallic PTEs present in gold mine tailings become extremely high, causing them to move into the environment in AMD. AMD acidifies soils to very low pH levels at which the mobility and plant-availability of metallic PTEs are very high, causing toxicities. Very disconcerting is that AMD and PTE pollution is in some cases continueing unabated at high rates even more than 70 years after a mine has been abandoned. Rehabilitation of TSFs to contain AMD and PTEs within them is very expensive and there seems to be reluctance to fully commit to their rehabilitation. Rehabilitation of TSFs is also extremely difficult. There does not yet seem to be any guidelines for their effective rehabilitation.

Keywords: gold mining; pyrite; acid mine drainage; potentially toxic elements

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1. Introduction

Mining has different steps. The main operation is the excavation of the relevant geological material from the earth. This material can be an ore (e.g., in the case of gold mining) or a commodity (e.g., in the case of coal mining).

Where an ore is mined, a large amount of other geological material has to be removed from the earth to get to the ore. This material is disposed of on land in the form of waste rock dumps. The ore is processed by crushing/grinding and chemical extraction of the relevant high value commodity, e.g., gold. During this step large amounts of very fine (silt size) material with potentially highly hazardous chemical properties are produced, which are then disposed of in the form of large mounds, some being even 30 m or higher, called tailings storage facilities (TSFs), slimes dams or tailings dams. The final step should be securing of the mining spoil materials, like waste rock dumps and slimes dams, against causing negative environmental impacts, especially pollution with toxic levels of heavy metals. Although this is supposed to be part and parcel of any mining operation, it is often not done [1], because of the extremely high costs involved [2]. This is an important point of discussion in this paper.

Excessive levels of potentially toxic elements (PTEs) in soil and water are hazardous to the environment and/or human health. Some review papers deal with cationic heavy metal PTEs [3–5]. Some deal with pollution by anions (e.g., [6]), while some deal with both (e.g., [7]). PTEs affect human health due to accumulation in plants and animals which serve as food for them [8]. Various industries are the main sources of heavy metal pollution in developed countries [9]. In less developed countries mining activities, especially gold mining and open-cast coal mining, are often by far the largest sources of heavy metal pollution [8]. In South Africa these two are by far the largest sources of soil and water pollution, particularly PTE pollution, in the country. This is very serious because they are both concentrated in the largest staple food production areas of the country. This paper deals only with the impacts of gold mining activities in South Africa.

Studies on the environmental impacts of gold mining in South Africa often concentrate on areas close to TSFs, while impacts have been found over large areas and at significant distances from these, even up to several kilometres [10,11]. Continued pollution from TSFs has been found up to more than half a century after they have been abandoned [2,10,11]. These are other important points of discussion in this paper.

2. Extent of Gold Mining in South Africa and Its Contribution to Waste Production and Environmental Problems

For very long South Africa used to be the main gold producing country in the world. Although its share has dwindled lately, it is still a major role player globally. Almost all the mining is densely concentrated in three main areas. The biggest is the Witwatersrand goldfields in an east-west strip in the south of Gauteng Province, south of Johannesburg, South Africa's largest city and the economic heartland of the country [2]. It is the world's largest gold resource and has contributed more than a third of all gold that has ever been produced globally [1]. A second is the Free State goldfields in the northwest of Free State Province in the vicinity of main towns like Welkom, Virginia and Odendaalsrus. The third is in North West Province in the vicinity of the towns Klerksdorp, Stilfontein and Orkney. Gold mining in the Witwatersrand started in 1886 and in the other two areas mainly after World War II thanks to improved deep mining technologies.

Mining is a huge producer of waste, for example contributing 87.7% of the 533.6 million tons of waste produced in South Africa in 1998 [10]. Gold mining is a major contributor to this and is considered to be the largest single source of waste pollution in South Africa [1].

According to [1] there are 270 tailings storage facilities (TSFs), also known as tailings dams or slimes dams, in the Witwatersrand Basin alone. These cover a total area of 18,000 ha [2,12]. Similar situations, at somewhat smaller scale, prevail in the other two areas. These are just the areas physically occupied by the TSFs. The off-site impacts of TSFs are much larger and more serious than their occupation of land. According to [1] most TSFs are unlined and pose serious threats to groundwater and surface water quality. The latter is especially serious in densely populated areas, like the Witwatersrand [13]. It furthermore also leads to pollution of sediments [11,13] and soil [10].

Pollution is in the form of acid mine drainage (AMD), salinisation and elevated levels of potentially toxic elements (PTEs), mainly heavy metals, but also including a metalloid like arsenic [10,11]. In addition to the above a TSF can impact a much larger area due to redistribution of material from it by wind and water erosion.

An important question is for how long environmental pollution from a gold mine TSF can continue after the mine has been closed or abandoned. According to [14] TSFs of older than 20 years make no significant contribution to pollution of aquatic systems "since they are often depleted in sulphur bearing minerals in the oxidised zone". From various reported findings in the publications quoted thus far, it is evident that this can not be accepted as a general situation. Ref. [10], for example, found serious continued pollution in the form of AMD and elevated levels of various PTEs from the tailings dams of the New Machavie mine near Potchefstroom in Northwest Province 60 years after is had been abandoned in 1940. In 2012, 72 years after it was abandoned, Ref. [11] still found continued pollution from it. Ref. [2] also pointed out that pollution can in some cases continue for more than 50 years after a TSF has been abandoned.

Ref. [11] found major differences between different cases, depending upon the amount of acid forming minerals and PTE levels still present in the tailings at a specific time. He concluded that even if there is no active pollution taking place at a specific time one can not become complacent if there are still minerals present that could lead to pollution if the situation changes, for example due to pH changes [2].

Confining the impacts of gold mining to the smallest possible areas is very important within the South African context. Ref. [12] pointed out that the Witwatersrand goldfield is in an area with high potential agricultural, urban and industrial land. The Free State goldfield in the northwestern Free State and the one in Northwest Province are in the region where more than 75% of the country's white maize, by far its most important staple food, is produced [15]. In a country with very limited arable land, and especially very little high potential agricultural land, this assumes even greater significance.

According to the Environmental Protection Agency (EPA) of the United States of America mine residues generally consist of high volume, low toxicity wastes [12]. However, although there are big differences between different cases, gold mining in South Africa can be described as generally producing high volume, high toxicity wastes.

3. Physical Properties of Gold Mine Tailings

Gold mine tailings have very unfavourable physical properties, which aggravate their pollution potential and hamper the reclamation of TSFs [16,17]. The tailings consist mainly of material that has been ground to fine sand and silt grain size [18], predominantly silt size [19]. They contain extremely little or no secondary clay minerals. They consequently have low water storage capacities, leading to much leaching from them [18]. It also causes them to be a cohesionless fine single-grained material, making them very vulnerable to wind and water erosion [19]). Other poor physical conditions of tailings materials caused by the grain size and lack of structure are crusting (surface sealing) and very high bulk densities, often in the order of 1800–1900 kg/m^3 [16]. These are in agreement with what is found in soils in regard to relationships between particle size and crusting and compaction [20,21] and hard-setting [22]. This causes rehabilitation of TSFs by means of establishing vegetative covers to be extremely difficult [16,17].

4. Some Key Chemical Properties of Gold Mine Tailings

Since tailings consist almost exclusively from fine sand and silt size material, with virtually no secondary clay minerals, it means that they have extremely low cation exchange capacities (CECs) and can retain virtually no plant nutrient elements which are cationic. Since the vast majority of plant nutrients are cationic, including both most macro nutrients and most micro nutrients, it means that the TSFs are extremely infertile [16,17]. It also means that they are not able to retain applied plant nutrients against leaching, making rehabilitation by means of establishing grass covers extremely difficult [16,17], as will be discussed later. This is exacerbated by the fact that the tailings contain no organic matter. It also means that toxic levels of PTEs can not be sequestrated within the tailings, causing strong leaching of them into the environment.

The vast majority of gold mine tailings are acidic, usually very strongly acidic [2,10–12]. This is the source of acid mine drainage. The level of acidity depends on the amount of sulphide minerals, mainly pyrite, in the tailings (e.g., [11]). As long as these minerals are present in the oxidised zone of a TSF, acidity will be produced [2,11]. This acidity also dissolves PTEs, rendering them mobile and leading to environmental pollution by them (e.g., [10,11]. The latter depends also on the concentrations of different PTEs in the tailings.

5. Acid Mine Drainage (AMD)

Uncontrolled acid mine drainage as a result of poor management of TSFs is the single most important negative impact that gold mining has on the environment [1,2,10,12]. In South Africa acid mine drainage, mainly from gold mine TSFs/tailings dams/slime dams, "remains one of the country's most serious environmental and socio-economic issues" [1]. The acidity forms when pyrite, which is abundant in the gold-bearing ores, is oxidised where it comes into contact with oxygen from the atmosphere in the oxidised zone of a

TSF [10,11,18]. The oxydation goes through a number of steps [10,11,18], summarised as follows by [11]:

$$\underset{\text{Pyrite}}{4FeS_2} + \underset{\text{Oxygen}}{15O_2} + \underset{\text{Water}}{14H_2O} \rightarrow \underset{\text{Iron mineral}}{4Fe(OH)_3} + \underset{\text{Sulphuric acid}}{8H_2SO_4} \quad (1)$$

Not all the oxidation steps are geochemical reactions. Some, which speeds up the oxidation, are driven by microbes, specifically Acidithiobacillus thiooxidans, which oxidises sulphide, and Acidithiobacillus ferrooxidans, which oxidises ferrous iron (the form in which iron is in geological materials) [10,11]. On the left in the above equation pyrite is ferrous sulphide and on the right are ferric oxide and sulphate. In other words, both the iron and sulphur components of pyrite have been oxidised.

Acid mine drainage develops when water (rain) percolates through the zone of oxidised pyrites in a TSF, forming sulphuric acid, a very strong acid, which then drains out of the TSF into the surrounding environment [23].

Main concerns regarding negative impacts of AMD seem to centre around its impacts on the quality of water sources for irrigation and human consumption (e.g., [1]). These include both groundwater sources and surface water sources, like small streams, rivers, wetlands and dams. The impacts of AMD on soils are, however, also very important to keep in mind [10–12]. This is especially important in view of the fact that the mines are in areas with scarce valuable agricultural land, as was earlier indicated.

In order to understand environmental pollution by AMD, it is important to understand source-pathway-receptor principles, adapted by the author as follows from definitions and explanations by [11,13]:

- Source: An entity containing pollutants which can be discharged into the environment, e.g., a TSF.
- Pathway: The route via which a pollutant is distributed from the source. This can be water, e.g., a stream, which carries it, or soil, which acts as the pathway through which the pollutant moves.
- Receptor: This is the entity which is the end point which is becoming polluted and affected negatively by it. This can be soil, which can receive a pollutant directly from a source or via a stream or via irrigation with polluted water, etc. Or it can be a stream which receives a pollutant via soil through which the pollutant moves to the stream. Very important receptors, because of the potential impacts when they are polluted, include wetlands and storage dams.

It can be seen that an entity like a soil or a stream can be either a pathway or a receptor.

Refs. [11,13] indicate plants as the ultimate receptor of pollution and being affected by it. This would be due to them growing on polluted soil or being irrigated with polluted water. The ultimate receptors will be animals which consume such plants and humans who consume such animals and plants and in this way human health is impacted by it [8]. Or it can be animals and humans consuming polluted water [2]. Some PTEs are highly toxic to humans, but are not toxic to plants or have low toxicity for them. Thus, an element like As, for example, may have a serious hidden health hazard for humans because a crop may accumulate very high concentrations of it without showing any signs of toxicity [24].

In the study of the impacts of AMD on soils it is important that not only surface soil layers should be studied, but also subsurface layers within the root zone, especially in sandy soils [10,11]. Refs. [25,26] pointed out out that massive lateral subsurface flow of water occurs in soils, especially in sandy soils. Thus, water which which infiltrates at a higher elevation follows a subsurface flow path to where the water eventually flows out into, for example, a river. Two clearcut cases of pollution of streams via a subsoil pathway were found for other pollutants from a different type of source in a study in which the author was involved [25,27,28].

At the New Machavie gold mine near Potchefstroom, [11] found in 2012, 72 years after the mine had been abandoned, that the pH in all the tailings dams was still extremely low, ranging between 2.5–3.9 in the oxidised zones and between 3.8–4.0 in the unoxidised zones. Similar values were also reported for the New Machavie TSFs by [29]. It is quite unexpected to see such low pH values for unoxidised zones. Modelling for two cases at the eastern side of the Witwatersrand basin by [13] showed that big differences can be found between different cases. In one case it was predicted that the pH of the tailings would return to neutral within 10 years. In the other case it would still be below 3.5 after 25 years and barely above 4 after 50 years.

The pH of the topsoil of a "very contaminated" soil near the main tailings dam at the New Machavie gold mine was 6.6, which is close to that of natural soils in the area [11]. The pH of the subsoil was 4.6, showing that it had been highly acidified by AMD from the tailings dam. Similarly the pH of the subsoil close to a smaller tailings dam was only 4.2. These again confirm the importance of lateral subsoil movement of water as a pollution pathway.

An important finding in relation to the pathways of AMD was that the pH of the subsoil directly under the latter tailings dam was 7.2, i.e., unaffected by AMD. This can be explained as follows: In the Witwatersrand goldfield many tailings dams have been reworked to extract additional gold and uranium with new technologies. It was found that the soil under them had become very densely compacted [19]. Thus, infiltration of acid water into the soil beneath tailings dams is prevented or severely limited. Consequently, soil directly beneath the TSF was not acidified by AMD.

Ref. [10] studied a 930 m transect from the main TSF at New Machavie to the Kromdraai Spruit (a small river). The transect ran through an area where the soil was covered by a thin layer of tailings material which was redistributed from the TSF by wind and water erosion, covering the whole length of the transect from the TSF to the river. It should be noted that this scenario differs from the soil near the same TSF which was studied by [11], which had no tailings cover. Samples were collected at 28 sampling points at equal distances from the river to the paddocked tailings, with five test pits (28–23) being in paddocked tailings. From Test Pit 28 to 16 the tailings material was underlain by sandy colluvial soil and from Test Pit 15 to 1 (next to the river) by clayey alluvium. The tailings (in the TSF and redistributed from it) had an average pH of 3.4, closely corresponding with the pH range for the tailings in the TSFs. This indicates that strongly acidic tailings material was redistributed by wind and water erosion from the TSFs. This means that the tailings dams at New Machavie cover only 30.5 ha, but potentially hazardous tailings material has been redistributed over an area of 110 ha due to wind and water erosion [10]. This should not only be seen relative to this specific mine, but in the wider context of concern about the vulnerability of gold mining TSFs in general to wind and water erosion by others, like [12].

The pH of the sandy colluvial topsoil under the redistributed tailings was strongly acidic, with a pH range of 3.3–4.7 [10]. The pH of the subsoil ranged between 3.1 and 6.3, being mainly on the strongly acidic side. The pH of the alluvial topsoil was between 3.2–7.7, but mainly below 4.5, i.e., strongly acidic, while the pH of the subsoil ranged from 3.9–8.0, but generally above 7.0. Considering that the natural pH of these soils is about neutral (pH 7) [11], this shows that even a thin layer of highly acidic redistributed tailings can have a strong acidifying effect on the underlying soil, in the case of the relatively poorly buffered sandy soil even into the subsoil. This is another variation of AMD impact, which also has serious negative implications, especially for plant growth and crop production.

The main and most serious pollution impact of AMD is due to its effect on the solubility, mobility and availability of PTEs [10,16,18].

6. Environmental Pollution by Potentially Toxic Elements Emanating from Gold Mine TSFs

Although acid mine drainage seems to be the main concern of environmentalists regarding the environmental impact of gold mining, pollution of the environment by toxic levels (to plants, wildlife, domestic livestock, fish, humans, etc.) of various potentially toxic elements (PTEs) in gold mine ores and TSFs is probably the most serious form of pollution by gold mining.

South African gold mine ores and TSFs contain significant amounts of a wide range of PTEs [11–13,16–18]. According to general literature trace elements which are geochemically associated with sulphide minerals, such as pyrite, include *inter alia* Cd, Cu, Ag, Au, Zn, Hg, Pb, As, Sb, Se, Tl and Mo [10]. According to [13], who studied a number of gold mine tailings in the eastern part of the Witwatersrand basin, gold mine tailings contain varying quantities of As, Co, Cu, Cr, Ni, Pb, U and Zn. The relative concentrations of different elements differ between tailings at different mines, depending on their concentrations in the type of ore that was mined. Relative concentrations in tailings from the five sites studied by [13] in the eastern Witwatersrand area were basically identical. The Cr concentration in the tailings was very high, that of As high, those of Ni, Pb and Zn significant and those of Co and Cu low. In tailings of materials from the Black Reef formation the pattern was quite different from the above. As, Co and Ni concentrations were very high, the Pb concentration high, the Cu and Zn concentrations significant and the Cr concentration low [10,13]. Major differences in PTE concentrations can thus be expected for tailings from different geological materials, with different impacts according to the most polluting PTEs present in each.

The mobility of a PTE describes its ease of movement, i.e., how easily it is distributed. This includes the rate at which it is transported in AMD from TSFs into the environment and how freely it is redistributed in the environment, especially in soils. The mobility factor (MF) is defined as the ratio between the so-called extractable concentration and the total concentration of an element expressed as a percentage, i.e.,

$$\text{MF} = (\text{Extractable concentration} \div \text{Total concentration}) \times 100\%$$

The extractable concentration of a metallic PTE is determined by extraction with a 1M NH_4NO_3 solution [10]. The total concentration is usually determined by means of XRF.

Ref. [11] gives graphs of Kabata-Pendias which depict the relationships between soil pH and the mobilities of several PTEs. In all cases these show that above a certain soil pH the mobility of any specific PTE in sandy soils remains at the same low level. Below that pH the graphs indicate that the mobility of the PTE increases linearly with decreasing soil pH until a high to very high mobility is reached at a very low soil pH. According to these the pH at which the changeover happens, is about 5.2 for Cu and Cr and about 6.7 for Co, Mn, Ni and Zn. High to very high mobilities are reached at pH levels below 3.2 for Cu and Cr and below 3.8 for Co, Mn, Ni and Zn. The latter are within the pH ranges found in AMD affected soils by [10,13] and others. These are also in the pH ranges found in the oxidised zones of gold mine tailings dams [10,13]. This means that toxic levels of PTEs can currently be reached due to the effect of AMD. In contrast [10] found that the mobilities of metallic PTEs like Co, Cu, Ni and Zn in soils remained low at all pH levels down to a pH of about 4.5 below which there were sharp increases in the mobilities of these elements. For zinc it remained below about 5% above pH 4.5, rising to above 70% at pH 3.5. He found similar patterns for gold mine tailings, but here the increase occurred at a pH below about 3.5. For zinc it remained below about 10% above pH 3.5, rising to above 80% at pH 2.7.

The very high acidity (very low pH) of AMD is the key factor causing very high solubility and very high bioavailability of metallic PTEs, which the vast majority of PTEs are, and therefore environmental pollution by them. There is a close correlation between bioavailability and mobility, since both are functions of the extractable concentration. The difference is that bioavailability is an absolute value while mobility is a ratio. The relationship between pH and bioavailability of metallic micro-nutrients in soils is common knowledge, as for example discussed in [30]. The pattern is that their bioavailability decreases with increasing pH, leading to micro-nutrient deficiencies in crops [25]. On the other hand the availability of micro-nutrients like Mn and Cu becomes so high at very low pH levels that they become toxic. Ref. [31] discussed this type of relationship for heavy metals. The patterns are similar to those for mobility.

The opposite to the high mobility and bioavalability caused by the increase of PTE concentrations together with high acidity caused by AMD in the gold mining scenarios, is commonly found in countries such as those in Western Europe and Great Britain in the vicinity of sites of mining and processing of metal ores. Large increases in pH to high levels reduce the mobility and bioavailability of PTEs to very low, safe limits. In case studies in Poland [9,32] found increases in total heavy metal PTE concentrations of up to 20-fold over a period of 20 years in soils near metal ore mines and processing plants. However, the pH of the soils were in the process increased from the original about 5.5 to a very high 8.0, reducing the mobility and bioavailability of the elements to extremely low levels. The fields actually became safe for food crop production.

Arsenic is very different from the PTEs discussed above. It is a metalloid and is present in the form of the large anions arsenate ($AsO_4{}^{-3}$) and arsenite ($AsO_3{}^{-3}$) [11]. Its behaviour in soils is thus very similar to the orthophosphate ion ($PO_4{}^{-3}$) [10,33]. It is well-known that phosphate is in strongly acidic soils fixed very strongly into forms that are not available to plants [10,15] and the same will thus be the case with As. When the pH of strongly acidic soils is increased by means of liming, the plant-availability of phosphate is increased greatly. Similarly liming of gold mine tailings, to reduce the impact of AMD on bioavailability of metallic PTEs, will increase the mobility of As, and thus its pollution hazard [10]. In studies at a number of gold mines As was found to be the main pollutant.

When the bioavailable concentration of a PTE exceeds a threshold value, it becomes toxic and can be described as a pollutant. I.e., it currently has negative/harmful effects. It is, however, difficult to determine threshold values, especially for animals and human health, since complex pathways are followed from the soil via plants and animals to humans. Ref. [10] lists the guideline values for 1M NH_4NO_3 extractable levels for several PTEs, obtained from German literature. Concentrations in excess of these decrease soil productivity and soil quality. Some of these are listed in Table 1.

Table 1. Guideline 1M NH_4NO_3 extractable threshold values for soils ($mg \cdot L^{-1}$) (Extracted from [10]).

As	Co	Cr	Cu	Ni	Pb	Zn
1	5	1	2	1	2	10

In Table 2 the frequency (percentage of samples) and the range of ratios by which some elements have exceeded the 1M NH_4NO_3 extractable threshold guidelines in tailings and soil in the study by [10] at the New Machavie gold mine, which had been abandoned 60 years before, are given.

Table 2. Frequency (percentage of samples) and ratio of exceedence of 1M NH_4NO_3 extractable guidelines at New Machavie gold mine (Extracted from [10]).

Unit	Frequency (% of Samples) and Ratio of Exceedence of Guidelines					
	Co	Cr	Cu	Ni	Pb	Zn
Tailings	(63%) 1–23	(47%) 1–36	(33%) 1–4	(70%) 1–37	(3%) 3	(20%) 1–6
Colluvial topsoil	(50%) 2–4	(33%) 1–4	(25%) 1–2	(75%) 1–8	(17%) 1–3	(17%) 1–2
Colluvial subsoil with high ferric oxide content	(28%) 1–2	(14%) 1–6	(7%) 1	(64%) 1–3	(6%) 1	-

Important aspects to note in Table 2 include:

- In some samples the NH_4NO_3 extractable Co concentrations in the tailings were up to 23 times as high as the upper threshold guideline value, 36 times in the case of Cr and 37 times in the case of Ni.
- Pollution of the soil by PTEs emanating from the tailings, in some cases severe.
- The absence of As from the table. This is because As concentrations in all samples were below the detection limit. This is ascribed to the fact NH_4NO_3 can extract cationic elements, but not those present as large anions, like arsenate, phosphate or molybdate.

Because the above is mainly related to soil productivity and soil health—and crop performance, there is a trend to rather use guidelines based on total element concentrations. Different countries have different sets of guidelines, with many similarities, but also with some big differences. The author has extracted som of these from [10] (Table 3).

Table 3. Guidelines for maximum permissible total element concentrations ($mg \cdot kg^{-1}$) in soils from different countries (Extracted and adapted from [10]).

Element	Maximum Permissible Total Element Concentrations ($mg \cdot kg^{-1}$)			
	South Africa	Australia/New Zealand	Germany	Dutch-A *
As	2	20	-	20
Co	20	-	-	20
Cr	80	50	100	100
Cu	100	60	60	50
Ni	15	60	50	50
Pb	56	300	100	50
Zn	185	200	200	200

* The Dutch ABC system has a three tier approach. The A tier value indicates the concentration below which soil or water is "probably not contaminated".

It is important to keep in mind that the threshold values in Tables 1 and 3 are valid for the different PTEs irrespective of their source of origin, which can be some type of mining or some type of industry or some other source. Only those PTEs which have been identified as elements of concern in the South African gold mining industry are included in these tables. That is why a potentially very highly toxic element like cadmium (Cd), for example, does not feature in these tables.

Comparison of the results found at the New Machavie gold mine 60 years after being abandoned with the Dutch-A guidelines shows interesting patterns, especially when compared with Table 2 (Table 4).

Table 4. Frequency (percentage of samples) and ratio by which concentrations of different PTEs exceed the Dutch-A guideline values (Adapted from [10]).

Unit	Frequency (% of Samples) and Ratio of Exceedence of Dutch-A Guidelines					
	As	Co	Cr	Cu	Ni	Zn
Tailings	(97%) 1.1–16.5	(37%) 1.2–4	(100%) 1–5.2	(23%) 1.1.4	(53%) 1–4	(3%) 1
Colluvial topsoil	(82%) 0–4.6	(64%) 0–3.5	(91%) 1.5–4.1	(55%) 0–1.7	(73%) 0–3.1	(0%) -
Ferric oxide rich colluvial subsoil	(60%) 1.1–1.5	(47%) 1.1–5.3	(100%) 1.4–2.1	(27%) 2.1–2.6	(100%) 0–4.5	(0%) -

Noteworthy points in Table 4 include

- The presence of As and its high level of pollution.
- The absence of Pb because no samples had values above the guideline value.

- The very high percentages of soil samples which were above the guideline value for several PTEs, in the case of Cr and Ni especially in the subsoil.
- The low level of contamination with Zn, especially in the soil.
- The exceedence ratios are much lower than for the 1M NH_4NO_3 extractions.

Ref. [10] compared results according to the Dutch-B screening method and 1M NH_4NO_3 extraction for identification of "trace elements of concern" at the New Machavie gold mine (Table 5). Based on total concentrations the former reflects potential future toxicities, while the latter reflects current toxicities.

Table 5. Identification of trace elements of concern according to Dutch-B screening and 1M NH_4NO_3 extraction (Extracted and adapted from [10]).

Unit	Trace Elements of Concern According to Dutch-B Screening	Trace Lements of Concern According to NH_4NO_3 Extraction
Tailings	As > > Cr > >Ni	Ni > Co > > Cr > Cu > Zn > Pb
Colluvial topsoil	Cr > > As > Ni	Ni > > Co > > Cr > Cu > Pb > Zn
Ferric oxide rich subsoil	Cr > > Cu = Ni	Ni > > Co > > Cr > Cu > Pb

The geoaccumulation index [Igeo] for sediments and soils is used by some as an indicator of the worst-case scenario in terms of the potential future contamination impact of a TSF [11]. This is based on assuming that the total PTE concentration will become bioavailable should environmental conditions change to facilitate this. An Igeo ≥ 0 means that potential future contamination is a possible factor to consider at a given locality. Thus, the potential contaminating substrate, soils and underlying geology of drainage systems must be critically evaluated when assessing environmental impacts and making recommendations for the prevention of contamination as well as the mitigation and rehabilitation of affected areas. Ref. [11] determined both (i) current contamination, as indicated by the amount of a PTE presently in an available/mobile form in a TSF, and (ii) potential future contamination, as indicated by the total amount of a PTE presently in a TSF. This seems to be the appropriate approach to adopt.

Ref. [11] found that all eight PTEs which he studied at a number of gold mines in Northwest Province had current contamination impacts, with the order of magnitude of their impacts being, for tailings, soils and stream sediments together

$$As > Co > Zn > Cu > Ni > Cr > Pb$$

Five of these showed potential future contamination impacts, in the order

$$As > Zn > Cu > Co, Ni$$

Ref. [34] evaluated the human health risk posed by heavy metals in tailings and soils from the Witwatersrand gold mining area. They determined the concentrations of Cr, Ni, As, Zn, Cu, Pb, Hg and Cd. The concentrations of Cr, Ni and As were above the permissible levels. These are also the three PTEs which were found to be the elements of concern in the tailings and topsoil according to the Dutch-B criteria at the long abandoned New Machavie gold mine in a different region (refer to Table 4). Ref. [34] found that their results revealed a significant health risk to adults and a very serious risk for children.

Ref. [13] applied the geochemical load index for the assessment of future pollution potential (worst-case scenario) to seven sites where TSFs had been removed during reworking of the TSFs. Three sites classified as moderately to highly polluted, three as highly polluted and one as excessively polluted. The latter reflects a 100-fold exceedance over the background value.

These cases serve to illustrate the seriousness of environmental pollution by PTEs from gold mining TSFs in South Africa.

Comparison with Some Information from Elsewhere

The author found it difficult to find detailed scientific data on the environmental impacts of PTEs from gold mining elsewhere. In China, presently the world's largest gold producer, the PTE about which there is great concern is mercury (Hg) [35]. This is not from ore but is added in the gold extraction process. In a case study in Russia the concentrations of 12 PTEs were determined [36]. The ore contained significant amounts of sulphide minerals, like pyrite and chalcopyrite, producing AMD (pH 3.6). Right at the foot of the studied dump the levels of Cu, As, Pb and Hg were excessive. Away from the dump the levels of all PTEs, including the mentioned four, dropped to low levels even at the closest site (50 m). At a distance of 750 m the levels of all PTEs dropped to extremely low levels. These findings are in contrast to those of [11] in South Africa who found high PTE levels even up to several kilometres away from a slimes dam. In a case study in Kenya the levels of mainly Hg, Pb and As were above acceptable levels [37]. As seems to be the PTE most commonly causing concern in South Africa and elsewhere. Pb was of major concern elsewhere, but not in South Africa. Cr, one of the main elements of concern in South Africa, did not feature elsewhere. It was not even determined in the Russian study. Hg does not feature in the South African studies, because cyanide is instead used in the extraction process. Cyanide is a potentially highly toxic substance, but it is not a PTE. Extensive use of cyanide in the extraction process is of great concern in gold mining in China [35].

7. Combating the Negative Environmental Impacts of Gold Mining in South Africa

From the previous discussions it is clear that the negative environmental impacts from gold mining activities, especially TSFs, are of very large scope and extremely severe. The impact from a TSF is often not of short duration, but can continue at a very high rate for as long as even more than half a century.

A root core of the problem is that people earlier did not anticipate or realise how large and severe off-site environmental harm from gold mining would be. Very importantly they obviously could not and did not foresee that an environmental impact would persist for so long. Even more importantly they could not and did not foresee that environmental impacts could in some cases continue unbated at a very high rate even for numerous decades after a mine had been abandoned or closed. Consequently no or inadequate measures were taken to avoid or strongly limit the environmental impacts.

It seems as if up to a few decades ago there was in general little awareness regarding environmental issues. The gold mining industry was not unique in this regard. There was no legislation which controlled pollution from tailings dams. From the side of the gold mining industry itself the concerns were regarding the engineering aspects of the construction of tailings dams, like the slope angles of their sides, thickness of retaining walls, etc., not regarding pollution from them. In South Africa each mine had its own methods until 1968, when the industry published a set of guidelines, which could be used by all [12]. This was not always followed strictly, leading, for example, to the Merriespruit disaster in 1994, when a tailings dam collapsed, spreading tailings material over a distance of 2 km into a residential area, which was only 320 m from it [12]. Several people were killed or injured and much damage was caused. The residential area existed before the tailings dam was constructed close to it.

Ref. [16] lists 11 acts (government laws) according to which gold mining companies can now be held accountable for environmental damage done. These are all relatively new acts. The oldest one was promulgated only in 1983, with nine of them having been promulgated in 1998 or later. According to [12] the first act of this kind in the world was in fact enacted only in 1980 in Canada when pollution from gold mining posed a threat to Lake Erie. South Africa is renowned for having excellent policies and good laws, but poor strategies to implement them and capabilities to enforce them. When looking at the findings of [1], it seems as if this is also the case in regard to the environmental impacts of gold mining. The biggest controversies are about the mines which were abandoned or closed before these acts were in place, especially those which were abandoned or closed long before.

Two aspects need to be addressed in regard to environmental pollution by gold mining activities:

1. Containment of potential pollutants within the source (TSF) to prevent any new or further pollution of the environment, especially AMD and PTEs. This is, of course, the most critical, primary step [12].
2. Eliminating or strong reduction of pollution where it has already occurred.

Two major factors militate against eliminating or curbing environmental pollution by gold mining activities, namely

1. It, especially containment of pollutants within TSFs, is extremely expensive [12]. Ref. [12] concluded that: "It is obvious that these rehabilitation costs cannot be afforded either by the South African government or by the mining industry. It is also questionable if the predicted costs for Australia and North America will ever be spent. Thus, rehabilitation (including treatment of contaminated soils and groundwater) of large scale polluted sites is uneconomical and this should only be applied at highly contaminated sites or areas determined by a risk assessment as high risk areas". This seems to be a very defeatist outlook, implying that the environment cannot be safeguarded against pollution by the gold mining industry. It also does not seem to be sensitive to the economic consequences for crop farmers whose fields are being or have been polluted and other affected communities. In a country with scarce arable land this also can have consequences in terms of ensuring food security. Gold mining is such an important factor in the South African economy [12] that it cannot be afforded to restrain them by enforcing expensive measures to combat negative environmental impacts arising from it.
2. Because of the properties and characteristics of the material in gold mining TSFs, it is extremely difficult to rehabilitate them, as was pointed out earlier [16,17].

8. Technologies for Rehabilitation of Gold Mining TSFs

8.1. Reworking of Tailings Dams

Reworking of tailings dams started in the 1970s in the Witwatersrand area and by about 1990 a total of 77 TSFs had already been reworked [12]. Reworking of the tailings dams is actually not done as a rehabilitation technology. Old existing tailings dams are seen as assets which still contain a lot of gold and uranium, which is extracted from them by improved new technologies [12,13,19]. The reworked tailings are deposited as new TSFs at other sites. During the reworking process 70–75% of the pyrite is also extracted from the reworked material [19]. Thus, the potential of the reworked TSFs for production of AMD and release of PTEs is much smaller. It still exists, however. PTEs are not extracted and the potential for future pollution remains [12].

The sites where the original TSFs were before reworking are seen as land which can be used beneficially [13]. Studies at several sites by [12,13], however, found that the footprints of these sites are still contaminated. According to [12] a major factor contributing to this is that the tailings materials are not removed completely. The remaining tailings constitute serious sources of potential pollution. Unfortunately, there are no guidelines for rehabilitation of these footprints and consequently it is done on a basis of "best practice technology without entertaining excessive costs" [12]. Various options can be considered for remediation, depending on their relative costs. Ref. [12] discusses the following *inter alia* as possibilities

1. Removal of the contaminated layer, i.e., the layer which can be a source of pollution. The author has the following question: The source of pollution has been removed at this site, but it must be deposited somewhere else. Is it not just simply going to be a source of pollution where it has been deposited?

2. Paddocking of the remaining tailings material, an option also mentioned by [13]. Ref. [12] rejects this option. According to him it will have negative impacts at the site, because it will be concentrating more water there, leading to more leaching of pollutants into the soil and groundwater below it. He actually recommends that paddocks should be removed where they had already been made.
3. Capping (surface sealing) of the footprint if costs are not prohibitive. Even if it would be cost effective, the author has two concerns about this:
    (a) Large bare areas in the vicinity of urban areas will not be aesthetically acceptable. Keep in mind that there is always a whole cluster of tailings dams together.
    (b) Excessive runoff from the sealed areas can lead to local flooding and stream-bank erosion, similar to the impacts described by [38]. This is aggravated by the fact that rainfall in the areas where South Africa's gold mines are, is in the form of heavy thunderstorms.
4. Immobilising PTEs within the contaminated tailings and topsoil. Ref. [12] suggests four possible ways for achieving this:
    (a) Liming the acidic tailings and topsoil to a pH where the mobility of cationic PTEs is low. Ref. [12] suggests liming of the tailings/soil from a pH of 4 to pH 7. He states that for a silty clay loam soil this would require 10 tons of lime per hectare plus annual maintenance applications. The author wishes to point out that there are at least two flaws in this reasoning. Firstly, many soils in this area have much lower clay contents and would require much less lime. It has already been mentioned that tailings have almost no clay minerals and would, therefore, require little lime to raise their pH. Secondly, it is clear from earlier discussions that metallic PTEs (i.e., the vast majority of PTEs) become immobile at pH levels much lower than 7. Liming to a pH of 5.5 would be adequate. Thus, much less than 10 tons of lime per hectare should be adequate, making it an economically viable proposition.
    (b) Application of clays with high cation capacities or organic matter to adsorb large quantities of metallic PTEs. This will reduce their leaching, also because the clay has higher water retention capacities. Note by the author: When there is any intention to use the footprint areas for growing plants, it must be kept in mind that these adsorbed cations are plant-available and can thus still be toxic.
    (c) Application of sesquioxides (ferric and/or Al oxides or hydroxides) in order to immobilise oxy-anionic PTEs. The only real one in this category is As, as has been shown earlier. The author wishes to point out that this will be effective only at the very low pH levels prevailing in unlimed tailings and AMD polluted soils. Sesquioxides are amphoteric, meaning that above a certain (very low) pH they are negatively charged and below it positively charged. Large anions, like arsenate and arsenite (and phosphate and molybdate) are strongly sorbed to these positive charges at very low pH and are so rendered immobile and unavailable to absorption by plants. Of course, at these low pH levels the metallic PTEs are highly mobile. This is the conundrum facing those who want to lower the mobility and plant-availability of PTEs: The conditions required to achieve this for metallic PTEs are directly opposite to what is required for As.
    (d) Finally, ref. [12] lists application of hydroxides, carbonates or phosphate containing minerals. Notes by the author: Hydroxides and carbonates are liming materials and are covered under Point a above. It is well-known that very high phosphate levels seriously lower plant-availability of metallic trace elements, especially at relatively high pH. This is reviewed by *inter alia* [7,25].

8.2. Rehabilitation of Gold Mining TSFs (Tailings Dams, Slimes Dams) by Means of Establishing a Dense Vegetative Cover

Mines in South Africa are presently by law obliged to rehabilitate land, such as TSFs, to a post-closure land use in accordance with their environmental management plan (EMP) [16]. The post-closure land use is supposed to be self-sustainable, entailing the establishment of a dense vegetation cover on the TSFs which do not need further maintenance [12,16]. When the rehabilitation plan is not correctly designed and/or properly implemented the site will stay barren [16]. From experience in the agricultural field this means that to be effective a dense stable basal grass cover must be established [16,20]. The objectives with the vegetative cover are (i) to stabilise and protect a TSF against wind and water erosion and (ii) to reduce the amount of leachate by removing large quantities of water by means of transpiration [12].

Because of the unfavourable properties of tailings materials, mentioned earlier, establishment of a dense grass cover is extremely difficult [12,16]. Results with rehabilitation efforts are more often than not very disappointing. The author ascribes this to the fact that these efforts concentrate only on ameliorating the poor chemical properties (such as very low pH), low plant nutrient contents and toxic levels of PTEs [12,16].

Although soil physical problems are mentioned as characteristics of tailings, these very seldom, if ever, receive attention when efforts are made to overcome problems with vegetative cover establishment. The researchers are then surprised by the lack of success. The author has found the same is the case when efforts are made to achieve revegetation of bare soil areas. The main reason is soil crusting (surface sealing) [20,25]. Severe crusting is also a characteristic of gold mining tailings. Ref. [16] was surprised by the poor seed germination which he obtained in a study with rock flour amelioration to improve the fertility of tailings. Poor germination in a crusted soil/material is due to poor gas exchange through the crust and thus inadequate oxygen levels in the soil/material below the crust [20]. A further reason for lack of recovery of bare crusted soils is because the mechanical resistance of a crust is very high and seedlings of small-seeded plants, like grasses, are unable to break through the crust. Thus, seedling emergence is very poor. Likewise crusted soil areas which have been barren, with no recovery, for even up to more than 40–50 years, have been found [20].

Thus, measures to overcome soil crusting by creating stable structure in the surface area is essential for establishing a dense grass cover. Ref. [17] studied the ability of a wide range of ameliorants to create stable aggregates (structural units) in gold mine tailings. According to his criteria he obtained at the best no effect, but in most cases negative results. He considered an increase in relatively large aggregates and decrease in small aggregates as a positive result and the converse as being negative. In reality, stable small (crumb) aggregates are usually seen as the best type of structure in soils [25,39]. In unpublished experiments the author achieved great success with producing stable aggregates in fine sandy tailings material with pH 3.8 from a gold mine TSF from the Witwatersrand area with application of a soil conditioner (also including a growth stimulant, super water absorbent material and fertiliser) which was developed and produced in a European country. Pot experiments with then showed 3.5 times as much top growth and 3.5 times as much root growth where the soil conditioner had been applied than in untreated controls. According to reports the company subsequently stabilised gold mining TSFs in Australia successfully with application of the product.

Because of the inherent unfavourable conditions of gold mine tailings for establishing a vegetative cover a special approach is followed to create a more conducive situation for plant establishment, as discussed very well by [17]. According to him rehabilitation of mine tailings facilities in South Africa is "heavily reliant" on the application of topsoil for the construction of store and release covers on these. By promoting a better grass cover, this brings about better stability of a TSF and reduce erosion.

Ref. [17] quotes an Australian publication which pointed out that although a soil cover is effective to stabilise TSFs, the soil which is used in that way is a non-renewable resource which is essential for long-term food security. The author wishes to add that this is even more so in the case of South Africa, with its scarcity of arable land. Ref. [17] thus stresses that: "As such, topsoil should not be considered as the go-to method for rehabilitation of mine tailings due to the value thereof and the potential to permanently lose the production capacity of the area from which the soil is stripped. Topsoil can also be permanently degraded when placed on chemically aggressive mine tailings without the proper use of break layers." He also points out that stripping and placing of topsoil is one of the most expensive technologies for the rehabilitation of TSFs, making it less attractive for mining companies to fund. This is why he studied alternatives for stabilising TSFs for bringing about creation of stable structural units within the TSFs.

Despite all the problems, ref. [19] believe that gold mining TSFs can be converted into valuable assets which can, for example, be used for small-scale vegetable production. They do point out that special management is required, however.

9. Reclamation of Off-Site Areas Polluted by Gold Mining Pollutants

Only reclamation of soil polluted by pollutants emanating from gold mine tailings TSFs will be discussed here. The emphasis will be on reclamation of agricultural land, both rangeland and cultivated areas. Reclamation of soils is technically much easier than rehabilitation of TSFs, although practical implementation of these may in some cases be difficult. Where a layer of tailings has been deposited on soil, instead of the soil just being polluted by AMD and PTEs carried in it, different approaches are required.

It is straightforward what needs to be done to overcome the acidification of soil by AMD: The soil must be limed to an acceptable pH level. Although it is usually recommended that soil should be limed from the acidified pH level of 3–4 to a pH (Water) of 6.5–7.0, it is not necessary to lime it to that level. The aim should just be to lime it to the lowest pH at which metal PTEs reach low mobility/plant-availability and plant-availability of essential plant nutrients is optimal. This is at pH (Water) of 5.5–6.0 in regard to both low mobility of metal PTEs (Aucamp, 2000) and optimal availability of essential plant nutrients [15,25]. This will mean much lower liming costs. Keep in mind that pH (KCl), which is often used in South Africa, is 1 pH unit lower than pH water. Thus, the aim should be for a pH (KCl) of 4.5–5.0, especially in sandy soils. In experiments in the 1960s the author showed this very clearly. The results were published in Afrikaans at the time, but they are summarised by [7,25].

Amelioration of subsoil acidity is a big practical problem, since lime does not move in the soil [7]. Since AMD causes pollution of subsoils also, this is a problem in soils polluted by leachates from gold mining TSFs. This means that deep incorporation of lime will be required. The much higher amounts of lime to be applied and the high costs of deep incorporation, will thus make this liming process quite expensive. However, there is no other choice if effective amelioration is to be achieved.

Refs [11,23] compared the risk after treatment for eight possible reclamation strategies, including doing nothing. The latter has a very high risk, as could be expected. The only one giving a very low risk is complete removal of the top 30–50 cm of polluted soil, which is impossible unless it is just a very small patch. Both paddocking (containing runoff) and minimising infiltration by means of surface sealing were extremely inefficient, ending up in high risk. Amelioration of soil was not perfect, but gave the lowest risk end result of all methods, except the basically impossible total removal of polluted soil.

Arsenic is a special case, as has been indicated before, ameliorating polluted soil to reduce the mobility and plant-availability of metallic PTEs to safe levels increases the mobility and plant-availability of As. And it has been shown that As is the dominant polluting PTE from gold mine tailings. A potential technology to reduce As levels in soils is by growing plant species which are known hyperaccumulators of As at highly contaminated spots [11]. These are then mowed or harvested and incinerated to reduce the amount of material that has to be disposed of.

Ref. [10] studied an area where tailings had been deposited over the soil due to wind and water erosion. Close to the Kromdraai Spruit (small river) the clayey alluvial topsoil had not yet been polluted. The pollution hazard for the river was in the highly polluted tailings overburden. In this case he thus recommended that the tailings over this specific area had to be removed by bulldozer and stockpiled in a berm about 100 m from the river.

A grass cover should then be established on the berm and on the exposed alluvial soil to inhibit erosion.

10. Concluding Remarks

It is clear that gold mining has very serious negative environmental implications. It is disconcerting that it is found that pollution from gold mine TSFs can in some cases continue unabated at high rates for even up to more than half a century. There seems to be lack of real concern among involved parties about the environmental degradation caused by gold mining and lack of real commitment to curtail it. There appears to be poor understanding of the basic scientific knowledge required to come up with effective solutions for containing pollutants within TSFs. The main problem appears to be poor understanding of the role of poor soil physical conditions, especially crusting (surface sealing). The author believes that it is essential that well-trained soil scientists should, together with experts from other fields, be part of all teams working on solutions to curb the environmental degradation from gold mining TSFs. Protecting the environment against degradation from gold mining waste should form part and parcel of gold mining operations.

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