Effect of gold-mine related operations on the physical and chemical characteristics of sediment texture

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Abstract

The gold-mining process is unique as it not only has effects on the water quality and related environmental impacts, but also on the physical characteristics of the sediment in the area of the mining activities. The texture of the sediment in streams inside the mining area differs from the sediment texture in streams outside the mining area. The impact on the sediment in the gold-mining area is not uniform but area specific. It became clear that certain sections of the gold-mine environment might be common to most gold mines in South Africa. Internal recirculated waterways/streams which are not diverted into wetland areas, and also do not discharge to the outside boundaries of the mine, normally have fine graded sediment particles (≤63 pm). These streams are also close to the actual gold-mining activities. On the other hand, the sediment texture of the streams which do discharge to the outside boundaries of the gold mine and which, in some instances, also flow through wetland areas, is coarser closer to the mining activities than the texture some distance away. This suggests a deposition of coarse sand in the area closest to the mining activities and that fine sand, as a result of a fairly strong stream velocity, is transported through the wetland areas to the outside boundaries of the mine. Wetland vegetation (e.g. *Typha latifolia and Phragmites australis)* may also act as a physical barrier to the transport of coarse sand. Each section has its own characteristics regarding the metal concentrations in the various grain fractions; however, certain similarities exist. In the sections represented by streams, all metals, except iron, have the highest concentration in the size fractions ≤ 63 μm. The lowest concentrations were found in the coarser fractions, which can possibly be ascribed to the presence of quartz in these fractions.

Introduction

The use of heavy metals for industrial purposes and their subsequent occurrence as trace contaminants have resulted in increased metal loading in the aquatic environment. Natural processes may also contribute some trace elements to the environment but the majority originate from mining and industrial processing (Horowitz and Elrick, 1992). The most concentrated pool of trace metals in aquatic ecosystems occurs in suspended and bed sediments. A wide variety of characteristics affect the way metals bind to sediments, and thus the potential biological availability of sediment-bound metals (Luoma and Davis, 1983). Firstly, concentrations of sediment-bound metals are strongly dependent on the surface area of sedimentary particles. Thus, fine-grained sediments bind metals more efficiently than do coarse-grained, sandy sediments. Secondly, several sedimentary components are involved in metal binding of which the most important include iron and manganese hydrous-oxides, organic material and, to a lesser extent, clays and carbonates (US Geological Survey, 1982).

In the past, information on particle size has been used primarily in the study of sediment transport, and the commonly used methods for determination of particle-size distributions are presumably geared to that purpose (Lai, 1982). During the milling process gold-bearing ore is crushed and sediment of various grain sizes is released, to be deposited either on rock-dumps or slimes dams (Funke, 1990). As a result of normal surface run-off from these man-made structures, the soil in the main effluent streams from gold mines consists of bottom sediments, the texture of which differs from other normal, non-mine streams (Funke, 1990).

The purpose of this paper is two-fold: firstly, to identify different sediment textures which can be related to different areas at a gold mine and, secondly to determine the extent to which the sediment texture can play a role in determining the sediment-trace element concentrations in the surface water within the boundaries of a gold mine's property in South Africa.

Material and methods

For a period of 15 months (March 1992 to July 1993) a study at two South African gold mines situated in the Witwatersrand and Transvaal geological sequences was conducted where core bottom-sediment samples were collected on a monthly basis. A total of 23 localities were sampled on a monthly basis and each of these was, in some way, in direct contact with effluent water pumped from underground or run-off water from both slimes dams and rock-dumps. The sediment samples were collected from 9 similar sections at both mines, selected according to habitat and geographical features, in the streams and impoundments affected by mining activities and outside the mine property. Sediment samples were collected with a stainless steel core sampler to a maximum depth of 30 cm. The core samples were placed in glass beakers and oven-dried at 60°C for 24 h. This drying temperature ensures that no chemical or textural characteristics of clay particles that may occur in the sediment will be altered. From each sediment sample a 80 g subsample was placed in an Endecott mechanical siever with a sieve rack consisting of sieves at

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1 ϕ (phi) intervals [Phi is a factor of the grain sizes in micrometer on a logarithmic basis (Folk and Ward, 1957)]. Sieve grid sizes with mesh ranging from 1.00 ϕ (500 µm) to >4.00 ϕ (<63 µm) were used. Sediment particles in the <63 µm grain size class is the clay component. After sieving, each fraction was weighed to the nearest milligram. By using the formulae proposed by Folk and Ward (1957), a Turbo Pascal computer program determined the average percentage contribution of grain size for each sediment core sample.

Chemical analysis of the different size fractions was done by digesting 1 g of each sample using a mixture of 1:2 v/v concentrated perchloric and nitric acid (*Standard Methods,* 1989). Digestion was performed on a hotplate (200 to 250°C) for at least four hours or until all solutions were clear. The individual solutions containing the digested sediment samples were allowed to cool before being filtered with a vacuum pump through acid-rinsed resistant 0.45 µm paper filter. These filter papers were finally rinsed with distilled water to remove all traces of heavy metals. The samples were accurately made up to 100 mℓ volumetric volumes using doubly distilled water. The contents of Fe, Cu, Ni, Mn, Zn, Cd and Pb were determined using a Varian atomic absorption spectrophotometer (model SpectrAA 875). The detection limit for all samples was 5 $\mu g \cdot g^{-1}$.

Prior to use, all glassware was soaked in a 2% Contrad soap solution (Merck chemicals), rinsed in doubly distilled water, acid rinsed in concentrated HCI for 24 h and rinsed again in doubly distilled water (Giesy and Wiener, 1977).

The Statistical Consultation Service at RAU supervised statistical analyses.

Results and discussion

General physical characteristics of the samples

From the gold mines studied, nine distinct areas were identified (Table 1). Of these, some are mine-specific, but the majority of the areas are representative of the same geographical features at the sites where the samples were taken at both mines. The sampling sites were selected according to the physical features of the environment, which were similar at both mines. Although South African gold mines each have their own specific environmental characteristics (e.g. geology) it was clear from this study that certain aspects of the mining environment are common to the mines in the geological sequences where the project was conducted. This phenomenon was evident since the mines are situated in the Witwatersrand and Transvaal geological sequences. Table 2 is a summary of the physical characteristics of the sediment texture in the different areas of the gold mines. The samples from each section indicate diverse physical characteristics, reflecting the diverse nature of the sampling sites, thereby satisfying an important aim of the study.

Two comparisons were made to determine the influence of mining activities on the sediment texture. The first was to compare the sediment texture of streams inside and outside the mining area. The second was to compare impoundments on the same basis. Impoundments in this paper refer to any water body containing lentic water, as opposed to streams with lotic water. Although natural wetlands are a typical feature in the gold-mining environment, some effluent steams are not diverted into these areas. They are normally internal waterways that do not discharge into streams flowing to the outside boundaries of the mine. The sediment texture dominating these streams (i.e. Section 1 and 2) is fine graded sediment particles ≤ 63 µm) which Horowitz (1991) termed very fine sand and coarse silt, respectively. In contrast to this, the dominant texture of the streams in established wetland areas (Section 7) is fine sand (250 µm to 125 µm). The latter section can be divided into three hydrodynamic subregions (Table 2), where Subregion 7.1 is closest to the mining activities, as opposed to Subregion 7.3, which is furthest away from the mining activities. Of special interest in these subregions is the percentage contribution from the grain size 125 µm, which increases from 26.6% in Subregion 7.1 to 51.4% in Subregion7.3.

By contrast, the percentage of coarse sand (500 µm) decreases over a distance of 1 km from 21.2% (Subsection 7.1) to 10.9% in Subregion 7.3. This suggests a deposition of coarse sand in the area closest to the mining activities and also that the stream velocity is strong enough to transport fine sand through the wetland areas. Wetland vegetation (e.g. *Typha latifolia* and

TABLE 1
DESCRIPTION OF THE DIFFERENT ENVIRONMENTAL SECTIONS AT GOLD MINES IDENTIFIED IN THE PRESENT STUDY

Section	Area description
Section 1[1]	Sediment in the vicinity where underground water is pumped to surface. Effluent water has a high percentage of suspended solids.
Section 2[1]	Sediment in effluent streams transporting water from metallurgic plants to retaining dams.
Section 3[1]	Sediment in area the vicinity of old disused mine-dumps
Section 4	Sediment in retaining dams situated next to active slimes dams.
Section 5	Sediment in pollution control dams
Section 6	Sediment in wetland area where surface run-off forms a distinctive impoundment.
Section 7	Sediment in wetiand area where the water does not form an impoundment, but flows through at a reasonable velocity
Section 8[2]	Sediment in stream outside the mine property.
Section 9[2]	Sediment in impoundment outside the mine property.

1. Can be mine-specific
2. Unaffected areas

TABLE 2
AVERAGE PERCENTAGE CONTRIBUTION OF THE GRAIN SIZE SPECTRA TO THE SEDIMENT TEXTURE OF EACH ENVIRONMENTAL SECTION LISTED IN TABLE 1

Section	Sub-sections	500μm	250μm	125μm	63μm	63μm
1		16.8	15.6	16.0	15.7	35.9
2		0	24.5	25.2	29.0	21.3
3		5.2	7.6	35.2	34.8	17.0
4		1.9	7.7	0	60.3	30.2
5		20.6	18.5	26.3	15.7	18.9
6		2.6	4.7	15.6	27.1	50.0
	7.1	21.2	33.0	26.6	11.6	7.6
7	7.2	14.5	28.4	38.2	12.4	6.5
	7.3	10.9	15.6	47.0	10.5	16.0
8		57.9	26.3	7.0	3.8	5.0
9		19.7	24.5	41.0	0	14.8

Phragmites australis) may also act as a physical barrier to the transportation of coarse sand.

In the stream outside the mining property (Section 8) the grain sizes decrease systematically from a dominance in the coarse-sand size range (57.9%) to the finer particle size ranges of ≤63 μm (Table 2). Statistical analysis performed with the student t-test indicated a significantly lower percentage fine particle ($p < 0.05$) in the stream outside the mine area than the streams inside the mining area. If the former stream is taken as a control for the stream sediment texture the results suggest that the gold-mining process may possibly contribute to increase loading of coarse silt in mine effluent streams.

Some of the impoundments in the gold-mining areas were constructed and are situated in the vicinity of old inactive mine-dumps (Section 3) or active slimes dams and/or rock-dumps (Section 4). The present study had both types of impoundments (Table 2) and the texture in each probably reflects the change that has taken place after 1918 with the introduction of the cyanidation process to recover gold (Funke, 1990). After 1918 gold mines gradually changed to the use of ball mills and the sliming process. Today ore is milled much finer, with about 75% of the particles below 75 μm. In Section 3, 35.2% of the particles in the sediment equals 125 pm (Table 2), which, according to Horowitz (1991), is classified as fine sand. Funke (1990) stated that before 1918, ore was mechanically deposited as sand-dumps, and this dominant grain size in Section 3 (125 μm) may have originated from surface run-off from these old disused sand-dumps. Surface run-off from these old disused mine-dumps is still an ongoing process today.

The change that has taken place in the gold-producing process is also reflected in the impoundments, which are situated next to active slimes dams (Section 4). The grain sizes smaller than 75 μm (i.e. 63 μm and <63 μm) dominate the sediment texture in these impoundments with a percentage contribution of more than 90% (Table 2). The total absence of the grain sizes 125 μm (fine sand), which is still the dominant particle size in Section 3 confirms the statement by Funke (1990) (see previous paragraph).

Section 5 is representative of an impoundment functioning as an emergency facility for any unforeseen increase in the volume of effluent water on the mine. The diverse nature of the different types of effluent, which these impoundments may receive, is reflected in an almost equal distribution between the different grain sizes (Table 2). The percentage of very fine sand (63 μm) and coarse silt (<63 μm) are almost equivalent to the percentage of medium sand (250 μm) and coarse sand (500 μm) (Table 2).

The results of Section 9, which were also taken as a control for the sediment texture in the impoundments in the mining area, revealed that the 250 μm and 125 μm grain sizes are the dominant grain sizes (Table 2). This is slightly coarser than the texture in both Sections 3 and 4. Of special interest is the absence of very fine sand (63 μm) although coarse silt (<63 μm) represents 18.9% of the texture. This is equal to the percentage of coarse silt in Sections 3 and 5 (17.0% and 18.9% respectively) but much lower than the 30.2% of Section 4. This suggests a normal percentage silt of 18 to 30% in the sediment of impoundments in gold-mining areas.

Section 6 is unique to the mining areas as it consists of wetlands that receive normal drainage basin run-off (rain water) as well as surface run-off from slimes dams, rock-dumps and sand-dumps, but with no definite flow in the wetland. This section can therefore be described as a semi-marsh land. Coarse silt is the dominant grain size (50.0%) with percentage contributions decreasing with increasing grain sizes (Table 2). In this section coarse sand contributes only 2.6% of the sediment texture which suggests that the finer particles were transported into this section over the years and because there is no definite flow, these particles were deposited in the wetland and presently dominates the sediment texture in this section. However, if sediment samples ± 1 m below the surface is collected, a different sediment texture, which may represent reference material, may be observed. This aspect of spatial variability should be investigated in future. Attempts were made during the present study to take core samples of 1 m deep but the sediment layer was not deep enough at the majority of sampling sites. A significant comparison of sediment texture at different levels could therefore not be done. Careful selection of sampling sites will contribute to reliable results that could provide more information on this aspect in the stream bottom sediment at gold mines.

Grain size/trace element relations

The concentration of cadmium in all samples was lower than the detection limit, and is excluded from all further discussions. Results from the study clearly illustrate that metals, excluding cadmium, are not homogeneously distributed over the various grain-size fractions and that large differences in total metal concentrations can be observed in the sediment samples from the various sections (Table 3).

Although each section has its own characteristics regarding the metal concentrations in the various grain fractions, certain similarities exist. In the sections represented by streams (i.e. Sections 1, 7 and 8) all metals, except iron, have the highest concentration in the size fractions 63 μm and < 63 μm, with the lowest concentrations in the coarser fractions (Table 3). Solomans and Förstner (1984) and Horowitz and Elrick (1987) described them as particle sizes with natural low metal concentrations. In these sections iron has peak concentrations in the 500 μm size fraction (Table 3) which can be related to the presence of Fe-hydroxides, Fe-oxides and Fe-carbonates which are the predominant accumulative phases for metals in autochthonous

TABLE 3

METAL CONCENTRATIONS (µg·g⁻¹) IN THE GRAIN SIZE SPECTRUMS 500 µm TO < 63 µm IN THE DIFFERENT ENVIRONMENTAL SECTIONS FOUND AT THE GOLD MINES STUDIED, WITH AN INDICATION OF THE AVERAGE CONCENTRATION AND THE PERCENTAGE EACH SIZE FRACTION CONTRIBUTES TO THE SEDIMENT METAL LOAD

Metal	Grain size (µm)	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6	Section 7			Section 8	Section 9	Average	%
								7.1	7.2	7.3				
Fe	500	29 000	-	16 774	119 000	110 000	144 286	52 500	140 000	100 625	20 833	183 055	91 607	31
	250	22 500	1 598	17 895	120 000	92 500	91 667	24 875	66 000	29 333	17 142	194 000	61 591	21
	125	5 938	2 062	15 500	-	73 750	43 333	32 750	73 000	57 500	10 294	98 750	41 287	14
	63	16 667	1 973	23 636	154 000	81 429	30 000	22 200	45 000	62 917	5 900	-	44 372	15
	< 63	15 192	1 445	16 667	117 500	10 882	47 500	17 917	53 750	69 048	7 647	248 642	55 108	19
Cu	500	90	-	250	26	80	60	10	20	35	70	60	70	14
	250	100	100	190	8	80	20	5	5	10	70	55	58	11
	125	240	60	60	-	90	10	20	20	25	113	60	70	13
	63	250	311	130	8	240	50	50	30	85	340	-	149	28
	< 63	300	304	300	15	130	90	123	116	86	458	70	181	34
Ni	500	240	-	170	45	60	190	40	30	60	50	80	97	13
	250	200	105	150	20	50	80	45	20	20	60	70	75	11
	125	500	70	50		50	40	65	20	40	103	80	102	15
	63	560	307	100	25	90	120	125	40	75	290	-	173	25
	< 63	740	234	200	20	522	210	270	105	69	322	70	251	36
Mn	500	220		720	118	220	140	55	140	545	70	295	252	18
	250	150	800	380	85	170	60	60	70	140	90	265	206	15
	125	180	260	150	-	130	100	65	40	190	144	290	155	11
	63	150	563	150	30	290	50	40	80	580	230	-	216	15
	< 63	210	578	350	100	3 261	80	124	267	619	339	337	570	41
Zn	500	100	-	310	31	40	70	15	10	40	60	85	76	5
	250	80	2 350	190	20	40	30	30	10	30	70	70	265	18
	125	160	970	60		40	30	35	10	30	175	80	159	11
	63	180	2 895	110	15	70	60	50	30	70	500	-	398	28
	< 63	260	3 426	240	25	1 109	80	136	93	70	576	80	554	38
Pb	500	20	-	50	28	30	40	15	10	30	30	45	30	18
	250	20	60	40	25	20	20	10	10	20	40	35	27	1
	125	30	20	10	-	20	10	10	10	15	62	40	23	14
	63	20	100	30	20	30	20	10	10	35	80	-	36	22
	< 63	30	86	40	25	65	30	25	23	32	136	38	48	29

TABLE 4
ACCUMULATIVE METAL CONCENTRATIONS IN GRAIN SIZES 125, 250 AND 500μm COMPARED TO GRAIN SIZES 63 AND <63 μm FOR STREAMS AND IMPOUNDMENTS ON, AND OUTSIDE THE MINES' PROPERTIES

Metal	Grain size μm	Stream							
		Section 1	Section 2	Section 7 7.1	7.2	7.3	Average ± SE	% 1,2 &7	Section 8
Fe	125 - 500	57438	3660	110 125	279 000	187 458	127536 ±48525	68	48 269 (78)
	63 & <63	31859	3418	40 117	98 750	131 965	61222 ±23518	32	13 547 (22)
Cu	125 - 500	430	160	35	45	70	129±63	28	253 (24)
	63 & <63	550	615	173	146	171	331±103	72	798 (76)
Ni	125 - 500	1140	175	150	70	120	331±203	40	213 (26)
	63 & <63	1300	541	395	145	144	505±202	60	612 (74)
Mn	125 - 500	550	1060	180	250	875	583±171	48	304 (35)
	63 & <63	360	1114	164	347	1199	637±215	52	569 (65)
Zn	125 - 500	340	3320	80	30	100	774±639	35	305 (28)
	63 & <63	440	6321	186	123	140	1442±1221	65	1076 (72)
Pb	125 - 500	70	80	35	30	65	56±10	43	132 (38)
	63 & <63	50	186	35	33	67	74±28	57	216(62)

( ) = %

TABLE 5
ACCUMULATIVE METAL CONCENTRATIONS IN GRAIN SIZES 125, 250 AND 500μm COMPARED TO GRAIN SIZES 63 AND <63 μm FOR IMPOUNDMENTS ON, AND OUTSIDE THE MINES' PROPERTIES

	Impoundment							
Metal	Grain size μm	Section 3	Section 4	Section 5	Section 6	Average ± SE	% 3-6	Section 9
Fe	125 - 500	50 169	339 000	276 250	279 286	236176 ±63663	66	475 805 (66)
	63 &<63	40 303	271 000	92 311	77 500	120279 ±57418	34	248 642 34
Cu	125 - 500	500	34	250	90	218±104	48	175 (71)
	63 & <63	430	23	370	140	241±96	52	70 (29)
Ni	125 - 500	370	65	160	310	226±70	41	230 (77)
	63 & <63	300	45	612	330	322±116	59	70 (23)
Mn	125 - 500	1 250	203	520	300	568±236	35	850 (73)
	63 & <63	500	130	3551	130	1076±829	65	337 (27)
Zn	125 - 500	560	51	120	130	215±116	34	235 (75)
	63 & <63	350	40	1179	140	427±259	66	80 (25)
Pb	125 - 500	100	53	70	70	73±10	53	120 (76)
	63 & <63	70	45	95	50	65±11	47	38 (24)

( ) = %

fractions (Jones and Bowser, 1978; Förstner, 1982). The sections in the vicinity of mine-dumps (Sections 3 and 4) have peak concentrations for manganese, zinc and lead in the coarse grain fractions. This was confirmed by the accumulative values but the opposite was found for manganese and zinc in Section 5 (Table 5). The crushed ore, which may contain elevated levels of heavy minerals (Luoma, 1982; Solomans and Förstner, 1984), is deposited on rock-dumps and sand-dumps and may contribute to peak metal concentrations in these size fractions. If individual differences are ignored and the average concentrations of the metals in the different size fractions are determined, the influence of grain size is clearly seen. Figures 1 (a-f) plot the combined percentage that each metal represents, in the different size fractions, for all sections. It illustrates that all metals, except

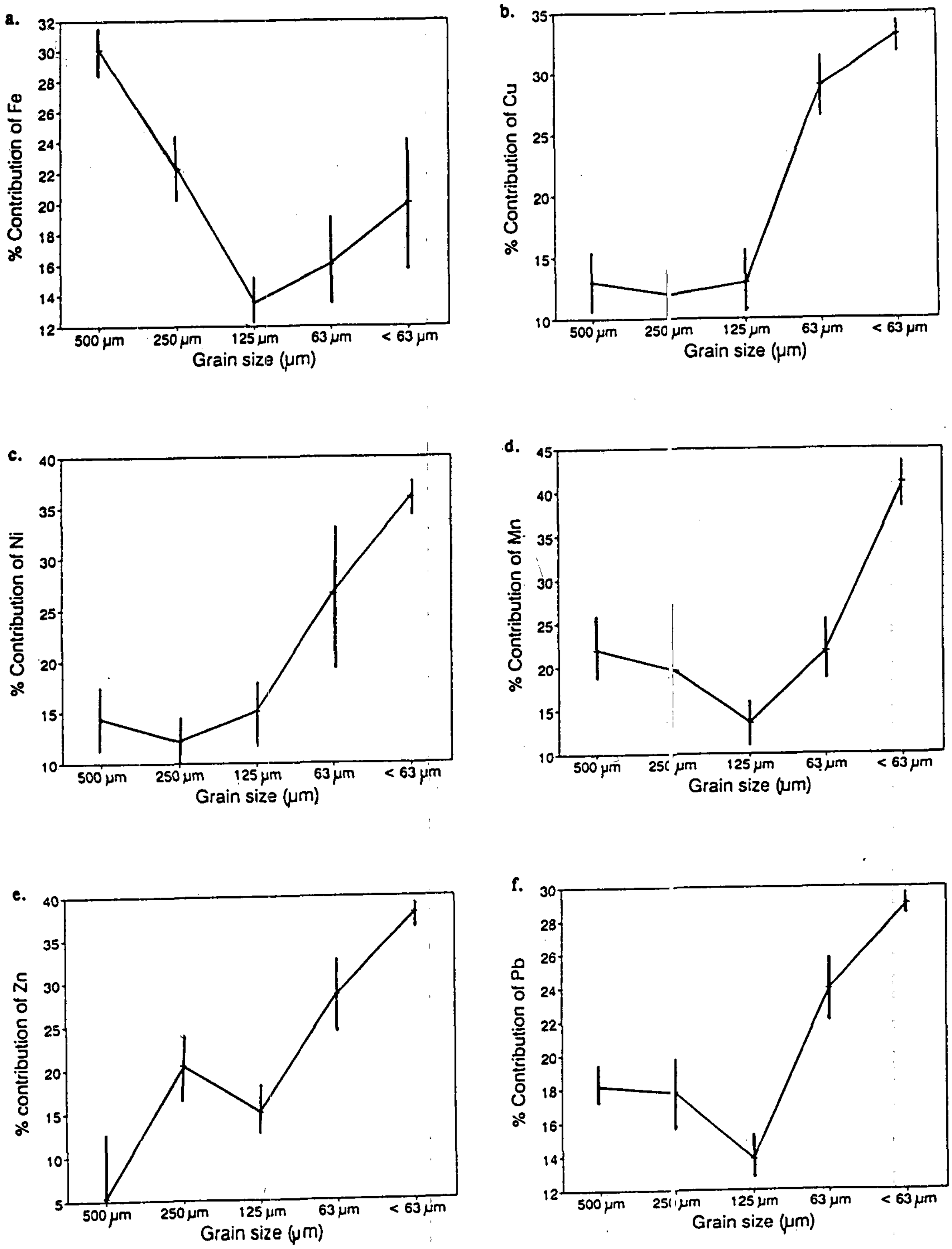

Figure 1

The percentage contribution selected metals represent in the different grain size fractions with regard to their concentrations in sediment core samples at South African gold mines iron, have peak concentrations in the < 63 µm size fraction. Despite the concentration variations within each of the fractions, the 63 µm and < 63 µm grain sizes contain a significantly higher concentration of copper ($p = 0.03$) and nickel ($p = 0.04$) than the 500 µm fraction (Figure 1 b, c; Table 3). The averages calculated for accumulative metal concentrations further support this finding except for lead in the affected impoundments. The same phenomenon was observed in the unaffected stream outside the mine property while the contrary was found in the unaffected impoundment (Tables 4 and 5). The general trend of higher metal concentrations in the ≤63 µm size fractions observed during the present study correlates with the results obtained from limnic sediments of lakes across the world. This phenomenon is of particular importance since metal fractions may be released upon relatively small changes in water conductivity, pH and salinity (Förstner, 1982). At the sites on the mine properties investigated there is, therefore, a possibility that with changes in the chemical condition of the water, for instance a decrease in pH, metals such as Cu, Zn, Mn, and Ni could be released into the water and become bio-available to some extent.

Furthermore, the copper concentrations in the latter two size fractions are also significantly higher than the 250 µm ($p = 0.04$) and 125 µm ($p = 0.01$) fractions (Fig. 1 b). Although the concentrations of nickel (Fig. 1 c), manganese (Fig. 1 d) and zinc (Fig. 1 e) also increase with decreasing grain size, the deviations within each section mean that the concentrations are not significantly different. Abnormally high concentrations of zinc are found in all size fractions of Section 2, which receives effluent water from metallurgical plants (Table 3). High manganese concentrations in the < 63 µm grain size of Section 5 and in the 250 µm size fraction of Section 2 indicate the diverse nature of metal behaviour in the different sections of a gold mine (Table 3). Iron is the only metal for which the concentration in the coarser size fractions (250 µm to 500 µm) exceeds the concentration in the finer fractions (63 µm and < 63 µm) (Fig. 1 a). The lowest iron concentration ($p = 0.02$) is found in the 125 µm grain size, which can probably be related to the presence of quartz in this specific size fraction. It is important to take note of the fact that other minerals than quarts can also be part of these particles (Fig. la).

Conclusions

The gold-mining process is unique as it not only has effects on the water quality and related environmental impacts, but also on the physical characteristics of the sediment in the area of the mining activities. The impact on the sediment texture is not uniform but area-specific. The study areas at both mines are characterised by the presence of slimes dams, wetlands, streams and/or impoundments that developed or were constructed mainly because of the employment of similar and specific mining procedures. The procedures have specific impacts on the aquatic environment.

The high metal concentrations in the fine-graded sediment particles may be related to surface area. As a result of the importance of surface reactions to inorganic-sediment interactions, fine-grained sediments are the main sites for transport and collection of heavy metals. In addition, fine-grained particles can also be viewed as mechanical substrates upon which inorganic constituents can concentrate; as such, surface area is extremely significant and increases with decreasing grain size. It should be borne in mind that inorganic substances could concentrate on larger substrata, including coarse sand. However, higher concentrations are more commonly associated with fine-grained material. The trace elements copper, nickel, manganese, zinc and lead tend to concentrate on coarse silt particles rather than on coarse sand. This fraction (<63 µm) is the closest equivalent to the material carried in suspension (Horowitz, 1982), which is the most important transport mode of sediment. The pollution potential in areas receiving effluent water increases during elevated rates of flow. The increased energy in the water may bring the silt particles into suspension and will transport them in that state until the total load exceeds the available energy. The suspended material therefore gradually settles on the bottom where it will be partially incorporated into the bottom sediment of that area. A certain percentage of those deposits will remain intact despite of any subsequent increased rate of flow due to specific cohesion characteristics of particles (Förstner and Wittmann, 1981). Therefore, increased metal concentrations in the sediment may result in the area receiving suspended material, despite the fact that the specific area may not have any mining activities. This confirms the statement by various sedimentologists that sediment acts as a sink for heavy metals in the environment.

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References

FOLK RL and WARD WC (1957) Brazos River Bar: A study in the significance of grain size parameters. *J. Sad. Petrol.* **27** 3-26.

FÖRSTNER U (1982) Accumulative phases for heavy metals in limnic sediments. *Hydrobiol.* **91** 269-284.

FÖRSTNER U and WITTMANN GTW (1981) *Metal Pollution in the Aquatic Environment* (2nd edn.). Springer-Verlag, New York.

FUNKE JW (1990) The Water Requirements and Pollution Potential of South African Gold and Uranium Mines. Water Research Commission Report No. KV 91/90, Pretoria, South Africa.

GIESY JP and WIENER JG (1977) Frequency distribution of trace metals in five freshwater fishes. *Trans. Am. Fish. Soc.* **106** 393-403.

HOROWITZ AJ (1982) A review of physical and chemical partitioning of inorganic constituents in sediments. In: Bradford L and Horowitz AJ (eds.) *The Role of Sediments in the Chemistry of Aquatic Systems - Proc. of the Sediment Chemistry Workshop*, February 8-12, 1982. US Geological Survey Circular No 969, Department of the Interior, Federal Centre, Denver.

HOROWITZ AJ (1 991) *A Primer on Sediment-trace Element Geochemistry.* Lewis Publishers, Michigan.

HOROWITZ AJ and ELRICK KA (1987) The relation of stream sediment surface area, grain size and composition to trace element chemistry. *Appl. Geochem.* **2** 437-451.

HOROWITZ AJ and ELRICK KA (1992) Effect of Mining-related Activities on the Sediment Trace Element Geochemistry of Lake Coeur D'alene, Idaho, USA - Part 1: Surface Elements. US Geological Survey Open-File Report No. 921109, Doraville, Georgia.

JONES B and BOWSER C (1978) The mineralogy and related chemistry of lake sediments. In: Lerman A (ed.) *Lakes - Chemistry, Geology and Physics.* Springer-Verlag, New York.

LAI T (1982) Concepts and methods for characterising the physical properties of sediments. In: Bradford L and Horowitz AJ (eds.) *The Role of Sediments in the Chemistry of Aquatic Systems - Proc. of the*

Sediment Chemistry Workshop, February 8-12, 1982. U.S. Geological Survey Circular No 969, Department of the Interior, Federal Centre, Denver.

LUOMA SN and DAVIS JA (1983) Modelling trace metals partitioning in oxidised estuarine sediments. *Mar. Chem.* **12** 159-181.

LUOMA SN (1982) Bioavailability of sediment-bound metals. In: Bradford L and Horowitz AJ (eds.) *The Role of Sediments in the Chemistry of Aquatic Systems - Proc. of the Sediment Chemistry Workshop*, February 8-12, 1982. US Geological Survey Circular No. 969, Department of the Interior, Federal Centre, Denver.

SOLOMANS W and FÖRSTNER U (1984) *Metal in the Hydro Cycle.* Springer-Verlag, New York.

STANDARD METHODS (1989) *Standard Methods for the Examination of Water and Waste Water* (17th edn.) American Public Health Association. Port City Press, Maryland, USA.

US GEOLOGICAL SURVEY (1982) *The Role of Sediments in the Chemistry of Aquatic Systems: Proc. of the Sediment Chemistry Workshop*, February 8-12, 1982 (Eds.: Bradford L and Horowitz AJ). Circular no 969, Department of the Interior Federal Centre, Denver.