Removal of barriers to the introduction of cleaner artisanal gold mining and extraction technologies in the Kadoma-Chakari area, Zimbabwe.

Part A: Environmental Assessment

Final Report

BRGM/RC-53320-FR
September, 2004

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Executive summary

Introduction

In response to a request from the Government of Zimbabwe and in the framework of the general project entitled 'Removal of barriers to the introduction of cleaner artisanal gold mining and extraction technologies', a contract was signed in September 2003 between the United Nations Industrial Development Organisation (UNIDO) and BRGM, in order to carry out the environmental and health assessment in the Kadoma-Chakari area. This area is characterised by the presence of thousands of artisanal gold miners using mercury for gold recovery.

The ultimate aim of the project is to replace mercury amalgamation practice in this area by alternative technologies, while improving the income and the health of the people using mercury. It includes a more efficient Hg and gold recovery process, increasing knowledge and awareness and provides policy advice on the regulation of artisanal gold mining.

The fieldwork of the environmental assessment of the artisanal gold mining activity in the Kadoma-Chakari area, selected by UNIDO, was carried out by a joint French (BRGM) and Zimbabwean team in November 2003 just before the rainy season and completed in April 2004 during the health assessment survey.

Two fieldwork reports have already been submitted to UNIDO:

- The first one, entitled “Removal of barriers to the introduction of cleaner artisanal gold mining and extraction technologies in Kadoma-Chakari area. Zimbabwe. Fieldwork report 1. BRGM/RC-52796-FR”, dated December 2003, concerns the environmental assessment carried out in November 2003.
- The second one, entitled “Health Assessment of small-scale miners in a mercury contaminated area (Kadoma area. Zimbabwe)” describes the health survey carried out in April 2004. During this second mission, some additional work was accomplished for the environmental study.

The final results of the project are given in two separate reports:

- This Final Report (Part A) deals with the environmental survey. It summarises the fieldwork carried out during the missions of November 2003 and April 2004, the organisation, the planning and the methodology used for site selection and sampling. The chemical analysis results are provided site-by-site, followed by the interpretation, the evaluation of exposure to Hg and the recommendations.
- The Final Report of the health survey (Part B) was completed in November 2004 by the health team. It summarises the fieldwork carried out in April 2004 and presents all the specimen analyses and statistical results, with recommendations to improve the health conditions and reduce hazard relative to the professional use of mercury.

Site selection

On the basis of the sociological survey, the environmental assessment started by a preliminary survey north of the town of Kadoma to describe the gold mining and milling processes implemented by miners and millers and the extent of the milling sites. The final objective was to select milling sites for the environmental and health survey. Following the advice of the Kadoma Mine Department, the study was extended south of Kadoma. Ten milling sites were selected north and south of Kadoma. The detailed study was completed taking into account the size of the milling centre, the equipment available for gold processing and its technical status, quality and maintenance, the number of millers and miners involved, the quantity of mercury used, the presence of villages near the milling centre, and also the presence of watercourses with a regional or national impact. According to these parameters, two groups of milling centres could be determined: the first being representative of gold processing north of Kadoma and the second representative of the south.

Ore processing and use of mercury

Amalgamation: After extraction by miners, the ore is crushed in custom milling center with, most of the time, wet stamp mill (with two to four stamps) in batch of 1 to 5 tons. Jaw-crushers and ball mills are only used in some of the newly equipped mill center. The pulp produced by the stamp mill through a 48 or 65 mesh screen and composed of around 20% solids is sent onto a copper-amalgam plate (copper-plate) coated with a film of mercury.

The quantity of mercury used in the process varies from one place to another, but it is said that at least 150 g m^{-2} (3 teaspoons of 45 g each) of mercury are used for this operation. At the end of the process, when all the batch of ore is crushed, the copper-plate is scoured with sand or tailings to remove any remaining amalgam. The resulting bright metallic copper is then rinsed with clean water and washed with a 2 to 3% solution of cyanide (if available). The millers can use solid Na-cyanide tablets to clean up the plate by hand without glove or mask protection. Following this procedure, the amalgam with fine sand particles is collected by hand and then squeezed in a cloth to remove unused mercury that will be recycled in the next process.

In the milling centre newly equipped with a jaw-crusher and a ball mill, but also in some of the well-maintained milling centres equipped with a stamp mill, the copper-plate is replaced by a bowl-concentrator (also called Zimbabwean centrifuge, ABJ bowl or “speedy bowl“) where mercury is added at the beginning of the process at a rate of 25 to 30 g of Hg per ton of ore. At the end of the process the heavy concentrate is collected at the bottom of the bowl.

Some millers provide the miners with amalgamation barrels, but in many cases, the miners complete the amalgamation by hand, adding up to 800 g of mercury in plastic trays. The final separation between the amalgam and heavy minerals is accomplished by panning. The amalgam is then squeezed in a cloth to remove unused mercury.

After the copper-plate or the bowl-concentrator, the tailings are evacuated by open channel or pipes to a settling pond, for clarification and drying. Most of the time, the water is collected and recycled in the crushing process. Once dry, the tailings are loaded onto truck and transported to concrete tanks for cyanidation, to recover the remaining gold.

Roasting: The amalgam is roasted always in the same open places in the milling centre or back home by the miners. Except at Even Milling Centre and New Plus, miners, they burn amalgam on a wood fire without further protection. They do not use a retort or any home-made torch. At low temperatures, the roasting process remains incomplete resulting in around 20% of residual mercury remaining in the gold beads.

Cyanidation: The rest of the gold contained in the dried tailings, is recovered by vat-cyanidation. The tailings are leached with Na-cyanide solution for an average of six to ten days in concrete tanks. The solution that percolates through the tailings is recovered at the bottom of the tanks where a filtering process (layer of sand) is set up. The gold-cyanide solution is analysed for gold content using a $SnCl_2$ colorimetric method. The solution passes through a few columns lined with activated charcoal to remove the gold from the cyanide solution. After this process, the concentration of the cyanide solution is adjusted and then re-used in the vats.

Gold extraction from the charcoal is never performed in the milling centre. The millers send the activated charcoal to other companies that carry out the elution process.

The final tailings of vat-leaching with residual cyanide are generally dumped in outlying parts of the milling site, but also close to the village, as in the case of Amber Rose. It can be also used as track construction materials (Tix village).

A general flow sheet summarises the main artisanal gold processing.

Sampling and methodology

In each selected site the sampling locations were determined according to the technical organisation and composition of the processing equipment, the geomorphology, the local drainage, the landscape and the proximity of the village. The objective was to check the source of Hg contamination, its pathways and the level of Hg in the potential identified targets.

For the environmental survey, a total of 49 soil samples, 39 stream sediment samples, 12 dust samples, 56 tailings samples and seven water samples was collected on the ten selected sites. Fifty-two fish samples were collected from six sites, in the southern zone only. Air monitoring was carried out on the three most important sites situated in the southern zone. All the solid samples were analysed at BRGM laboratories using a LUMEX RA915$^+$ and 33 duplicate samples of soil, dust and tailings were analysed in the IMR laboratory in Harare using conventional CV-AAS. Fish samples were analysed at the University of Bordeaux (LEESA) in France.

Results

The environmental assessment confirms that miners and panners use large quantities of Hg in the selected area. The estimation of the quantity of mercury annually consumed in the Kadoma-Chakari area is difficult according to the lack of available and official data. It ranges from 1.2 and 17.5 tons of mercury taking into account a range of 100 000 to 700 000 tons of processed ore and 50% of Hg recycling. Amalgamation and amalgam roasting processes were observed in all sites. Most of the time, these operations are carried out without any precaution to protect human health. If some precautions do indeed exist, such as the amalgam roasting room at New Plus and a shelter for amalgamation at Even Milling Centre, the survey shows that they are not efficient. At New Plus, the dispersion of Hg in the air during roasting operations is only shifted several meters further away by the exhaust pipe, but the risk to humans remains the same. At Even Milling Centre, Hg concentrations continue to be high in the soil near the shelter provided for amalgamation.

Fish analysis

Total mercury concentrations were measured in 52 fish samples, from six different species, collected in the Muzvezve River during the sampling campaign in November 2003. This river is roughly 250 km long and flows into Lake Kariba on the Zambezi River, which constitutes the boundary between Zambia and Zimbabwe in the north-western part of the country. Fish were captured in six sites along the Muzvezve River. Sampling sites were determined according to the location of the milling centres (official gold mining sites) and panning areas (illicit gold mining sites). Mercury determinations in the dorsal muscle of the fish revealed mercury accumulation for some fish with concentrations two to four times in excess of the WHO safety limit (0.5 µg g^{-1} on a fresh weight basis or 2.5 µg g^{-1} on a dry weight basis). Average mercury concentration in the 52 samples collected was 0.41 ± 0.46 µg g^{-1} fresh weight. Differences among species can depend on the diet of the species, with comparatively high levels in the carnivorous fish (1.05 ± 0.44 µg g^{-1} Hg fresh weight,) and lower levels in the omnivorous species (0.12 ± 0.09 µg g^{-1} Hg fresh weight), except for one omnivorous species that had a mercury concentration of 0.88 ± 0.25 µg g^{-1} fresh weight. No sizeable fish was collected. If the results of the small-sized samples are representative of the area, it is very likely that most of the fish eaten by the local population along the Muzvezve River is contaminated with mercury.

Hg hot spot

Two types of “hot spots” are identified, both defined as sites containing high Hg concentrations relative to the local contamination in soils and sediments.

The first one, called a single-source hot spot, corresponds to a well-delimited pollution source and is associated with a specific technique used in gold processing, such as amalgamation, roasting… There is no hot spot with an unknown source. The area concerned is small – a few hundred square meters – but the consequence in terms of human exposure is potentially very important for the population of miners.

The second one, called a multi-source hot spot, corresponds to a wider area characterised by several but associated single-source Hot Spots. The concerned area is much more extensive than in the previous case, and the associated pollution can affect a regional level, spreading far through the mining and milling area with environmental consequences in a radius exceeding the tens of kilometer scale. The contamination is more diffuse and may affect the whole population living in the area and the aquatic environment at a regional scale.

Single-source hot spot: Three main single-source hot spot are found:

- **Copper-plate areas** are the most contaminated spots as observed in the surrounding soils within a radius of 10 to 20 m and also in the tailings such as at Tix, New Plus, Etena, Summit and Glasgow mills. Contamination of soils does not seem to disperse very far from these emission sources. In contaminated places, the Hg values in the soils are ten to four hundred times the local background that is 0.02 to 0.12 mg kg^{-1}. The air monitoring carried out at Tix mill shows a Hg concentration sixty times higher (108 µg m^{-3}) than the local background (1.7 µg m^{-3}) during the operations on the copper-plate. By comparison, at Amber Rose, where a bowl-concentrator is operated, the Hg concentration in the air reaches 67 µg m^{-3} that is forty times the local background. At Tix, the loss of Hg in these areas follows two pathways;
  - · first, the tailings, which flow on the copper-plate throughout the process, and
  - · second, the air, mainly at the end of the process, when the miners are scraping and washing the copper-plate.

  It is also in this area that the concentration of workers (miners and millers) is the most important during the process.
- The second single-source Hot Spot corresponds to:
  - · the free amalgamation sites,
  - · the bowl-concentrator surrounding area in the mill centre, where miners are up-grading manually the amalgam mixed with tailings, and
  - · amalgamation sites such as in the villages (Tix) or on the bank of a reservoir (Claw Dam) or river (small stream or Muzvezve River) where miners and panners use pans to concentrate the gold particles and plastic basins to amalgamate the gold.

  At Even Milling Centre, which is one of the better and cleaner milling centres, the Hg concentration in soil (23.55 mg kg^{-1}) is more than one hundred fifty times the local background 5 metres away from the amalgamation shelter. The dust collected within a radius of 3 m on the concrete floor around the workers, who perform amalgamation under the shelter, reaches 74.60 mg kg^{-1} that is five hundred times the background.

  At the Claw Dam bank, downstream from Tix village, the Hg concentration in sediments can reach 8 to 10 mg kg^{-1} that is twenty times the local background at the sites of digging, panning and amalgamation activities. These kinds of sites are favourable environments to generate methylmercury (MeHg). These sites are also known as fishing spots, where fish with high Hg levels were collected.
- The third single-source hot spot corresponds to the free roasting sites or roasting rooms. High concentrations of Hg were measured during the air monitoring within a

radius of 1 to 3 meters around the free roasting sites located in the middle of the village, such as at Tix. The Hg concentration reaches nine to eighty times the local background of air (0.2 µg m^{-3} outside the copper-plate area). Even when a specific room is built, with specific equipment including an air extractor, to roast the customers' amalgam, the risk is still present, as at New Plus, where the dust collected on the concrete floor close to the exhaust pipe reaches 50.5 mg kg^{-1} Hg.

Multi-source hot spot: Among the sites studied, the multi-source hot spots can be located:

- At Tix, which is the most important, including the mill, the village, and the area surrounding the mining and amalgamation activities on the Claw Dam banks. This area is characterised by a group of scattered single-source hot spots, such as four copper-plates, many but not well located roasting areas at the entrance to the mill, in the village itself, and many amalgamation areas along the Claw Dam bank. Moreover, the same types of activities have been observed during the environmental assessment in other villages close to Tix, such as Mhisi and May Flower. Artisanal activity has been in progress for many years. Several tens of thousands of people are exposed directly or indirectly to this multi-source hot spot.
- At Amber Rose, contamination is less important than in Tix. But the contaminated tailings are dumped very close to the village and often spread out on the tracks in the village. Tailings may also contaminate the sediments in the tributaries of the Muzvezve River. Roasting locations may also contribute to the local contamination of the environment by their emissions.
- All along the Muzvezve River, where panners use Hg over a distance of at least 7 km corresponding to the studied zone. This distance is certainly longer than that, but an inventory of the panning areas upstream and downstream from the zone visited is necessary to ascertain the actual extent. Results of Hg concentration in carnivorous fishes, which are good bioindicators of the contamination, show the Hg contamination reached the living aquatic environment.
- The Etena area, in the northern zone can be classified as a multi-source hot spot according to the Hg concentrations found in the tailings close to the stamp mill, but also in the soils near the many amalgamation and roasting sites in the village.

Evaluation of exposure

Direct exposures to Hg contamination have been observed for miners and millers men and sometime women who are working close to the copper-plate. Exposure to mercury occurs by skin contact, vapour inhalation, and particle ingestion.

Amalgamation and roasting areas are also the sites of direct exposure through the same way. Young men who are frequently involved in the amalgamation process are affected.

Passive exposure may be suspected because this artisanal activity is performed in villages and along the riverbanks. Children and women are frequently present in the proximity of this activity.

The following table summarises the exposure pathways and related risks.

Sources	Exposure route	Professional exposure	Non professional exposure	Observations
Copper plate	Skin contact	***	0	Most of the milling centre
	Inhalation	***	*	
	Dust ingestion	**	*	
Free amalgamation sites	Skin contact	**	0	All milling centre, villages, the Claw Dam bank and the Muzvezve River
	Inhalation	**	*	
	Dust ingestion	**	**	
Amalgam roasting sites	Inhalation	***	*	Mainly at free roasting sites in milling centres and villages, but also at organised roasting rooms in milling centre.
	Dust ingestion	*	** (children)	
Fish consumption		** ?	** ?	Depending of the diet
Drinking water		?	?	Local contamination with Hg cyanide ?

*Summary of the exposure pathways and the related risks (probability of occurrence: ***high, **moderate, *possible, 0 none).*

Recommendations

The extension of the mining activity in the Kadoma-Chakari area, its economical importance and the amount of ore processed have reached semi-industrial levels. This situation justifies an adapted action plan to develop alternative technologies and the progressive ban of mercury in the mining process in the area.

Recommendations contain first urgent actions to reduce significantly the exposure of workers and their family to mercury. They concern the ore processing technologies, practices and actions to rehabilitate and preserve the environment.

Medium- to long- term actions aim at improve the management of the artisanal mining activity and reduce the environmental impacts.

The support and the management of these short-medium and long-term actions require the creation of a Task Force involving all the key stakeholders at the local, regional, national and international level.

Acknowledgements

This work benefited from the efficient support of Noba Ernest Allai, organisation UNIDO representative for Zimbabwe and Zambia. He facilitated contact and formalities with the local authorities, and gave all facilities to D. Shoko to take part in the organisation and the successful realisation of the two field work projects.

Special thanks go to Dr. Oliver Maponga, Chairman of the Institute of Mining Research, who gave us advice and scientific and technical assistance during the whole project and, in particular, allowed Spencer G.T. Kahwai to participate in the project and to facilitate considerably the two field work missions.

Many thanks are owed to the Kadoma Mine Department for assistance during field work, and also for the site selection.

We are grateful to Dr Christian Leveque, (CNRS, Meudon, France) who determined the species and food regimes of the fish collected during the study in Zimbabwe.

The authors greatly appreciated the contribution and the motivation of the Zimbabwean Team, who made possible the success of work in the Kadoma-Chakari area and also in Harare.

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1. Introduction

In response to a request from the Government of Zimbabwe and in the framework of the general project entitled "Removal of barriers to the introduction of cleaner artisanal gold mining and extraction technologies", a contract was signed in September 2003 between the United Nations Industrial Development Organisation (UNIDO) and the BRGM, in order to carry out the environmental and health assessment in the Kadoma-Chakari area. This area is characterised by the presence of thousands of artisanal gold miners using mercury for the gold recovery.

The ultimate aim of the project is to replace mercury amalgamation practice in this area by alternative technologies, while improving the income and the health of the people using mercury. It includes a more efficient Hg and gold recovery process, an increasing knowledge and awareness and provides policy advice on the regulation of artisanal gold mining.

In accordance with the decision taken during a meeting with UNIDO in November 2003 in Vienna (Austria), the study has been divided in two field steps. The first one was completed in November 2003 in order to carry out the environmental survey before the rainy season, and the second, focussing on the health assessment, was conducted in April 2004 at the end of the rainy season.

Two fieldwork reports have been submitted to UNIDO:

- The first one entitled “Removal of barriers to the introduction of cleaner artisanal gold mining and extraction technologies in Kadoma-Chakari area. Zimbabwe. Fieldwork report 1. BRGM/RC-52796-FR”, dated December 2003, describes the environmental assessment carried out in November 2003.
- The second one, entitled “Health Assessment of small-scale miners in a mercury contaminated area (Kadoma area. Zimbabwe)” describes the health survey carried out in April 2004. During this second mission, some additional work was accomplished for the environmental study.

The final results of the project are given in two separate reports:

- This Final Report (Part A) deals with the environmental survey. After the presentation of the project team, it summarises the fieldwork carried out during the November 2003 and April 2004 missions, the organisation and planning, the methodology used for site selection and the sampling. The chemical analysis results are given site by site, followed by interpretation and recommendations.
- The health survey Final Report (Part B) was completed in November 2004 by the health team (Boese-O’Reilly, 2004). It summarises the fieldwork carried out in April 2004 and presents all the specimen analysis and statistical results, with recommendations to improve health and reduce hazard relative to the use of mercury.

2. Organisation and schedule

The fieldwork completed in November 2003 is described in detail in the Field Work Report BRGM/RC-52796-FR dated December 2003.

Complementary data given hereafter synthesise the entire organisation and schedule of the work accomplished between November 2003 and August 2004, including the field work carried out in April 2004.

2.1. PROJECT TEAM

2.1.1. Main team

The project team was composed of two groups, the first for the environmental survey and the second for the health survey. These two groups received a considerable and necessary assistance from local people (illus. 1).

Environmental assessment		
Name	**Organisation**	**Activity in the project**
Dr. Pierre Billaud	BRGM Orléans	Project manager
Dr. Valérie Laperche		Geochemist
Dr. Régine Maury-Brachet Prof. Alain Boudou	LEESA CNRS, University of BORDEAUX	Aquatic Ecology and Ecotoxicology
Health Assessment		
Dr. Stephan Boese-O'Reilly	Institute of Forensic Medicine, Ludwig-Maximilians University, Munich	Leader of the health survey. Paediatrician, master of public health, Environmental medicine
Dr. Felicitas Dahlmann		Physician
Beate Lettmeier		Pharmacist. On site mercury analyses
Local team for the environmental and the health assessment		
Dr. Dennis Shoko	UNIDO	National Expert
Spencer G. T. Kahwai	Institute of mining research. University of Zimbabwe	Analytical Chemist (+ field works)
Dr. Edwin Muguti		Medical Expert
Tapuwa Mwanjira	Kadoma hospital	Nurses to assist the medical examinations
Vigilance Parirenyatrwa	Kadoma hospital	
Joan Marembo	Kadoma hospital	
Felicitas Navahya		Translator
Ezequiel Maponga	IMR	Driver

Illustration 1 - Composition of the main project team.

The two teams benefited, in the organisation of field work and also during the full time of the missions, from the efficient assistance of D. Shoko, UNIDO National Expert of the Global Mercury Project in Zimbabwe.

Moreover, Dr. O. Maponga, Chairman of the Institute of Mining Research of the University of Zimbabwe (IMR), granted us the scientific, technical and administrative support of the Institute and also permitted Spencer G. T. Kahwai, chief of the chemistry laboratory, to participate in all the fieldwork.

Prof. Alain Boudou (Univ. Bordeaux, LEESA) provided fish sampling kits and analysis facilities.

The assistance of Dr. L. Christian Leveque (CNRS, Meudon, France) determined the species and food regimes of the collected fishes.

2.1.2. Local workers

Local workers were hired on each surveyed site to help in the sediment, soil, and tailing sampling and in the panning operations (see fieldwork report, Billaud and Laperche, 2003).

2.2. EQUIPMENT

The list and origin of the equipment used for the environmental assessment is given in the Field Report (Billaud and Laperche, 2003). Equipment used for the health assessment is listed in the Field Report dated June 2004 from the Institute of Forensic Medicine.

2.2.1. Schedule

According to the briefing meeting held at the UNIDO headquarters in Vienna in November 2003, the field work was divided into two periods due to the availability of the health team and the imminence of the rainy season, during which it would have been difficult to carry out the sampling and health survey.

The first fieldwork was completed in November 2003 just before the rainy season and concerned the environmental survey. The second mission, corresponding to the health survey, was scheduled and carried out in April 2004 at the end of the rainy season.

The schedule of the project is summed up in illustration 2.

Global Mercury Project : Kadoma - Chakari area. Schedule as of 31.08.04																																																
Tasks	**2003**								**2004**																																							
	Nov				**Dec**				**Jan**				**Feb**				**Mar**				**Apri**				**May**				**June**				**July**				**Aug**				**Sep**				**Oct**			
Environmental assessment																																																
Main field works			▨	▨																																												
Field work report						▨	▨	▨																																								
Chemical analyses									▨	▨	▨	▨	▨	▨	▨	▨										▨	▨	▨	▨																			
Additional site sampling																					▨	▨	▨																									
Fish analyses and interpretation																					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																
Final report																																									▨	▨	▨	▨				
Health assessment																																																
Field works																					▨	▨	▨																									
Field work report																												▨	▨	▨																		
Analyses (Hair, blood, Urine)																																							▨	▨	▨	▨	▨	▨				
Final report																																													▨	▨	▨	▨

Illustration 2 - Project schedule as of October 2004.

3. Generalities and methodology

3.1. GENERAL CONTEXT – AREA SELECTION

The Kadoma – Chakari area, which was selected by UNIDO, is located roughly 150 km west south west of Harare (illus. 3). Kadoma, the most important city of the area, can be easily reached from Harare by the wide blacktop road going to Bulawayo. The area is covered by the topo-sheet No.1829B2 and 1829B4 at 1:50,000 scale.

Illustration 3 - Situation of the Kadoma – Chakari area.

The short preliminary survey carried out during the first days of the field mission in November 2003 allowed us to sketch in a rough map of the area (illus. 4) showing two main zones:

- The northern zone, with the mining town of Chakari in the north and the town of Kadoma in the south, has a fairly flat relief and no major river between Chakari and Kadoma. Consequently, no major panning activity was found. The main activities are farming, with big cotton, maize… producers, large-scale cattle breeding with extensive farms, and mines. The industrial activity is centred on gold mining and processing by local and international companies and numerous self-employed miners and millers scattered throughout the area. The gold deposits are vein and shear-zone types within the Archaean volcanic-sedimentary belt. The self-employed miners extract the ore from laterite and semi-weathered rocks and use mercury for gold amalgamation in the milling centres or in their own villages. The roasting of the amalgam is done essentially near the milling centre, but also in the villages.

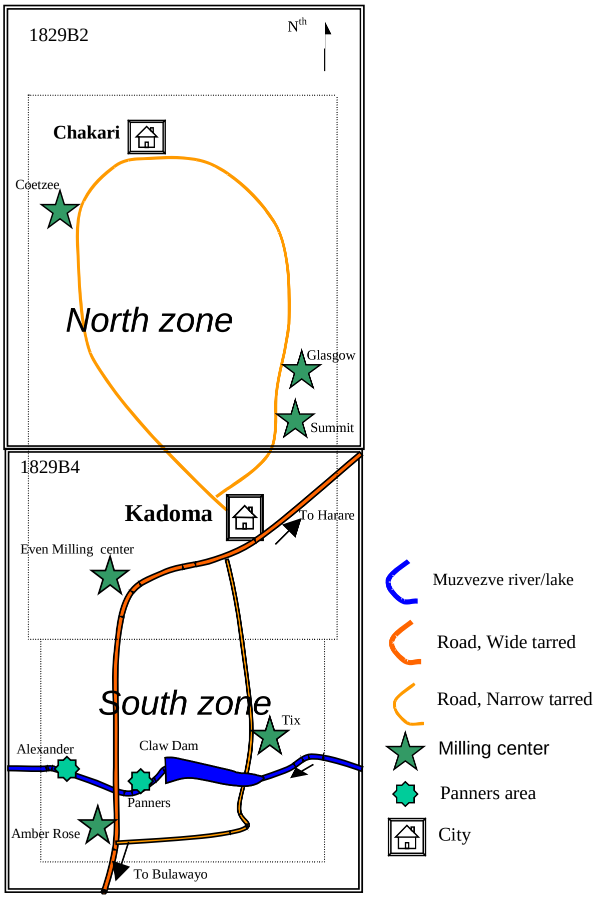


Illustration 4 - General map of the Kadoma – Chakari area showing the localisation of the north and south zones.

- The southern zone is somewhat hilly and crossed by a major river, the Muzvezve (pronounced Mujeje), flowing to the west-north-west for roughly 250 km, to the Lake Kariba on the Zambezi River, which forms the boundary between Zambia and Zimbabwe in the north-western part of the country. In this zone, all the streams are tributaries of the Muzvezve River. The area is covered by forest and bush. The main activities are small farms and gold mining. Self-employed and small-scale gold-mining miners and millers work in the area, and panners are found along the whole length of the Muzvezve River. Gold is mined from semi-weathered Archaean volcanic-sedimentary units, resembling those in the northern zone, but it is also panned from alluvial deposits and sometimes from old tailings. Miners and millers are mainly grouped in villages installed close to the milling centres.

3.2. GOLD PROCESSING IN THE KADOMA-CHAKARI AREA

The main preliminary data about the artisanal gold mining and processing in the Kadoma-Charkari area can be found in the UNIDO report dated October 2003 (Veiga and Shoko, 2003). Following the first fieldwork carried out in November 2003, additional information is given in the fieldwork report No.1 (Billaud and Laperche, 2003). Other general information is presented in a more recent document of UNIDO available on the GMP website (Shoko and Veiga, 2004; Hinton and Veiga, 2004).

Three kinds of artisanal gold processing are conducted in the area. The main one, which concerns stockpiles of 1 to 5 tons of ore, takes place in custom milling centre using a copper-amalgam plate or bowl-concentrator for the amalgamation process. It is carried out by miners or groups of miners who are renting the services of millers. The second one, which concerns only a small quantity of ore, less than one ton, involves hand crushing with a hammer and a grinder, followed by panning and amalgamation in buckets or plastic trays. It concerns isolated miners or women and children of miners. The last one is performed by panners in the riverbed, where gold is collected though a sluice, then panned, followed by amalgamation in pan or bucket. For all of these processes, roasting is the last operation.

More than 20,000 individuals are engaged in artisanal mining in this area. These are roughly comprised of 3,000 to 5,000 miners, 1,000 to 2,000 millers located in the recorded 70 milling centres and 15,000 to 20,000 panners.

3.2.1. Main artisanal gold processing

The main artisanal gold processing is summarised in the general flow sheet shown in illustration 5.

a) Crushing and grinding

After extraction, the ore is sent to the custom milling centre by the miners, where the work is carried out by batches of 1 to 5 metric tons of ore. Two kinds of equipment are found. The most frequent one, which is also the oldest, the least expensive but also the least efficient, is the wet stamp mill (with two to four stamps) having a capacity of 0.2 to 1.5 metric tons/hour. The second equipment, more recent (2002) operating only on one site (Even Milling Centre), is composed of a jaw-crusher followed by a ball mill. The crushing capacity is 0.7 to 2 metric tons/hour. The objective of crushing is to free the gold from its gangue. With the stamp mills, the ore is never ground finely enough to free the gold or to expose it at the surface of the grain. With this level of crushing, only 30% of the gold is extracted and recovered by the miners.

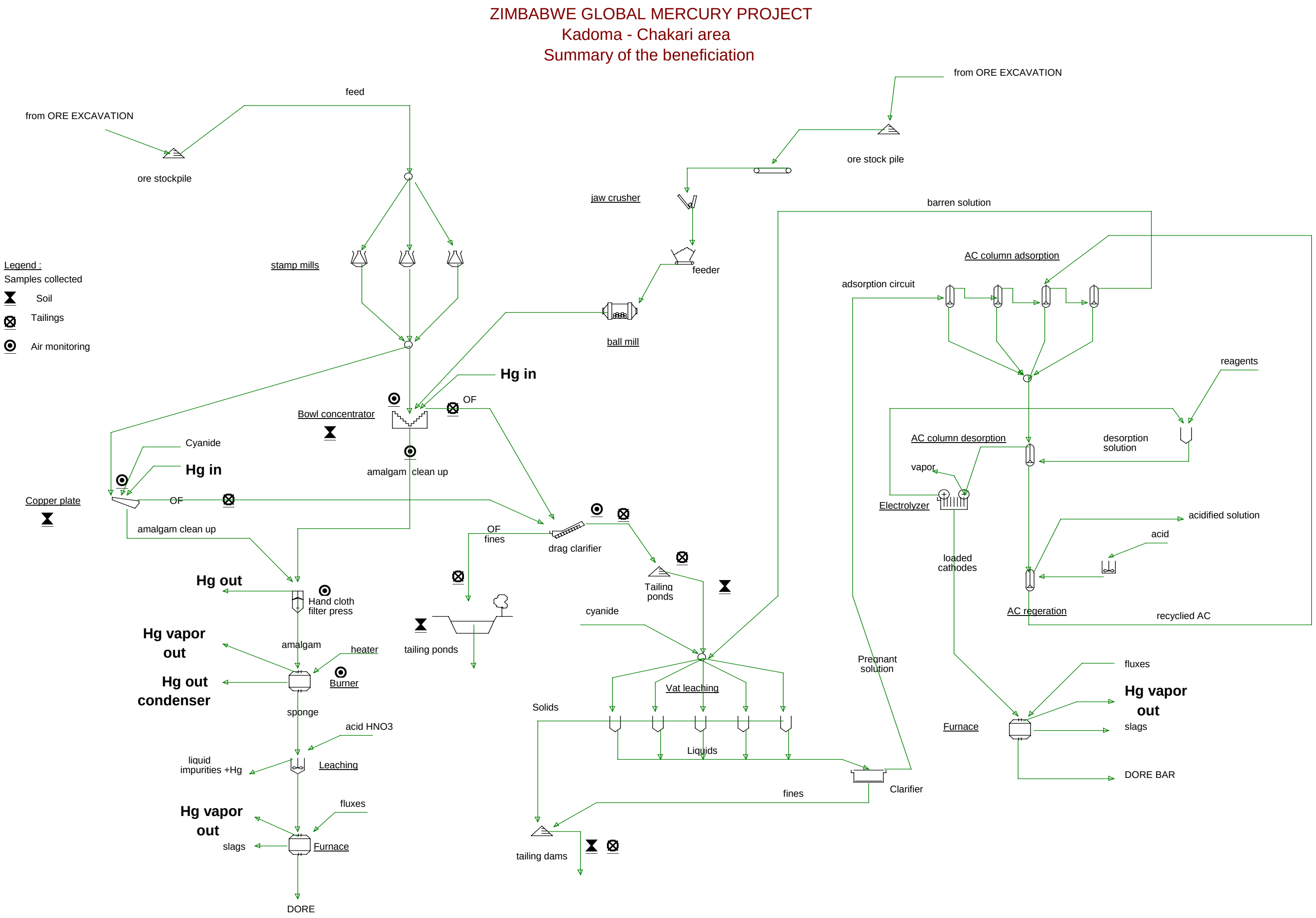


Illustration 5 - General flow sheet of artisanal gold processing in the Kadoma-Chakari area.

The remaining gold is collected by the millers through a cyanidation process. Depending on the quantity of the stockpile and the hardness of the ore but also on the technical status of the stamp mill (quartz takes more time than laterite), the crushing operation for one batch takes between a few hours to one day.

b) Amalgamation / mineral concentration

Most of the time, the pulp coming from the stamp mill through a 48 or 65 mesh screen (not always well maintained) and composed of around 20% solids is sent directly to a copper-plate covered with a film of mercury. In the milling centre newly equipped with a jaw-crusher and ball mill, but also in some of the well-maintained milling centres equipped with a stamp mill, the copper-plate is replaced by a bowl-concentrator (also called Zimbabwean centrifuge, ABJ bowl or “speedy bowl“) where mercury is added at the beginning of the process.

The copper-plate consists of a sheet of pure annealed copper. At the beginning of the process, the plate is coated with as much mercury as the plate will adsorb. The quantity of mercury used varies from one place to another, but it is said that at least 150 g m^2 (3 teaspoons of 45 g each) of mercury are used for this operation. This mercury film immediately amalgamates any gold particles that come in contact with it. At the end of the process, when all the ore is crushed, the copper-plate is scoured with sand or tailings to remove any remaining amalgam. The resulting bright metallic copper is then rinsed with clean water and washed with a 2 to 3% solution of cyanide (if available). Most of the time, the millers use solid Na-cyanide tablets to clean the plate by hand with no glove nor mask protection. Following this procedure, amalgam with fine sand particles is collected by hand and then squeezed in a cloth to remove unused mercury. The quantity of water necessary to keep the pulp travelling slowly down the copper-plate depends on the slope of the plate (10%), on the fineness of the crushing, as well as on the nature of the gold (coarse or fine).

Illustration 6 shows some part of this process.

With bowl-concentrators, the pulp flows directly into the bowl composed of a 120° cone containing horizontal ribs (riffles) welded along the inside wall. Rotational forces allow separate heavy from light particles. The light particles are carried away by the water flowing out of the upper part of the bowl, while the heavy materials are concentrated at the bottom of the bowl with amalgam. At the beginning of the process, the miners add roughly 150 g of Hg directly into the cone (3 teaspoons) to amalgamate the gold particles. Mercury consumption appears to be roughly 25 to 30 g t^{-1} of ore in the bowl-concentrator (Amber-Rose mill). Clean up is accomplished by stopping the rotation of the bowl, opening the drain at the bottom, and flushing out the concentrate (illus. 7). About 30 kg of heavy concentrate is produced from a batch of 15 to 20 metric tons of ore. Some millers provide the miners with amalgamation barrels, but in many cases, the miners finish the amalgamation by hand, adding up to 800 g of mercury in plastic trays. The final separation between the amalgam and heavy minerals is accomplished by panning. The amalgam is then squeezed in a cloth to remove unused mercury.

A: Stamp mill and copper plate

B: Copper plate at the end of the process

C: Amalgam recovery on the copper plate

D: Copper plate cleaning by hand
with sand and cyanide tablets

E: Amalgam recovery in a piece of cloth

F: Amalgam after squeezing to remove
unused mercury

Illustration 6 - A to F Amalgamation process at Summit mill.

After the copper-plate or the bowl-concentrator, the tailings are evacuated by open channel or pipes to a settling pond, for clarification and drying. Most of the time, the water is collected and recycled in the crushing process. Once dry, the tailings are loaded onto a truck and transported to concrete tanks for cyanidation, to recover the remaining gold.

At New Plus, a sluice box has been installed just after the copper-plate in order to increase the gold and amalgam recovery by the miners before sending the tailings to the settling pond.

a) General view of the bowl-concentrator b) Remaining amalgam droplets in the riffles

Illustration 7 - Etena Mill - Empty bowl-concentrator with amalgam droplets in the riffles at the end of the concentration process.

c) Roasting

Following this process, the miners carry away their amalgams for the roasting operations, these take place in the same open places in the milling centre or back home. In all the sites visited, except at Even Milling centre and New Plus, miners burn amalgam on a wood fire without further protection. They do not use a retort or any home-made torch. At low temperatures, the roasting process remains incomplete resulting in around 20% of residual mercury remaining in the gold beads.

d) Cyanidation

To recover the rest of the gold in the dried tailings, which can contain 70% of the total gold content of the crude ore, the millers apply vat-cyanidation. The milling centres have between five and ten concrete tanks for cyanidation. The tailings are leached with Na-cyanide solution for an average of six to ten days. The solution percolates through the tailings and is recovered at the bottom of the tanks, where a filtering process (layer of sand) is set up. The gold-cyanide solution is analysed for gold content using an $SnCl_2$ colorimetric method. The solution passes through a few columns lined with activated charcoal to remove the gold from the cyanide solution. After this process, the concentration of the cyanide solution is adjusted and then re-used in the vats.

Gold extraction from the charcoal is never performed in the milling centre. The millers send the activated charcoal to other companies that carry out the elution process. One of them is installed in Kwe-Kwe, approximately 50 km from the mining area.

The final tailings of vat-leaching with residual cyanide are generally dumped in outlying parts of the milling site, but also close to the village, as in the case of Amber Rose. It can be also used as track construction materials (Tix village).

e) Remarks

Despite the poor efficiency of the stamp mill, most of the miners prefer milling centres with stamp mills over those with ball mills because they think the ball mill is holding back some parts of the gold. Moreover, they can see all the process steps and they clean the stamp mill by hand at the end of the process. The cleaning of the ball mill is done only after grinding several stockpiles of different origins and from different miners. Nevertheless, it is well known that the gold recovery is better with the ball mill, and the grinding capacity is between 0.7 and 2 $t\ h^{-1}$, instead of 0.2 to 1.5 $t\ h^{-1}$ for the stamp mills.

3.2.2. Individual artisanal gold processing

Another kind of gold processing is carried out by isolated miners, women and children, but on a small quantity of ore (a few hundreds of kg). The ore is crushed with a hammer directly on the extraction site then carried out in bags to the processing place, which is generally close to their houses in the village (a few meters away) (illus. 8). There, the ore is reduced to powder in a small iron grinder before panning. At the end of the panning process, some mercury is added to the heavy material in the pan or bowl and mixed by hand to facilitate amalgamation. The panning process is carried out completely in order to separate the amalgam from the tailings. Amalgam is then squeezed in a cloth to remove unused mercury before being roasted as described above.

3.2.3. Mercury consumption in the Kadoma-Chakari area

The assessment of the mercury consumption in the Chakari-Kadoma area is a difficult exercise because no official statistics are available about the mercury market. No measurement of the mercury recycling, no information concerning the tonnage of ore processed in the different milling center or of gold produced by the miners and by the millers exist. Moreover people are not ready to give clear information about the mercury and gold market.

a) Ore grinding at Tix village
b) Panning and amalgamation at Tix
c) Small artisanal sluice box at Etena
d) Amalgam roasting at Tix village
e) Detail of the amalgam roasting on a wood fire showing the sponge-like gold “doré”

Illustration 8 - Individual artisanal gold processing in different villages.

Data that can be used are coming from discussions with miners, millers, agents of the Kadoma Mine Department and from O. Maponga and also from the literature.

They can be summarised as follows:

- 70 mill sites with 1 to 4 stamp mills (including a few ball mills) have been inventoried by the Kadoma Mine Department. That represents around 140 stamp mills, considering an average of 2 stamp mills per milling site.
- An estimation of 12 working hours per day (including breakdowns, stand by periods for ore supplying, cleaning and maintenance periods…) for 280 working days per year. So we can estimate 470,400 working hours for all the 140 stamp mills and for one year in this area.
- As said previously (§ 3.2.1.) the capacity of one stamp mill ranges from 0.2 to 1.5 t h^{-1}. So, the annual quantity of ore crushed and ground ranges from 94,000 to 705,600 tons.
- The quantity of mercury used on the copper plate is roughly 150 g for one batch of ore ranging from 3 to 5 tons. That is 30 to 50 g of mercury per ton of ore.
- The mercury consumption in the bowl concentrator ranges from 25 to 30 g ton^{-1} of ore.
- The mercury recycling is estimated at 50%.

Finally the annual quantity of mercury used in this area can range:

- from 94,000 x 25 / 2 = 1,175,000 g of Hg rounded up to 1.2 t;
- to a maximum of 705,600 x 50 / 2 = 17,640,000 g of Hg rounded up to 17.5 t.

3.3. SITE SELECTION AND SAMPLING LOCATION

The strategy for site selection and sampling location was chosen in line with the risk assessment approach as explained in the field work report and summarised as follows:

- Where are the main sources of mercury pollution in the artisanal gold mining of the Kadoma-Chakari area, presuming that the visited and studied sites are representative of this activity in this area?
- What are the main pollution vectors (pathways) that are likely to transfer the mercury towards a target?
- What are the main target(s) exposed to the direct or indirect effects of the known pollutant?

This analysis enabled us to classify the sites we visited according to their specific features and their ability to represent the main local and regional risks arising from the artisanal mining activity in this area.

3.3.1. Milling site selection

The site selection was done during the preliminary survey, at the beginning of the first field work program in November 2003. It is described in detail in Field Work Report No.1 (Billaud and Laperche, 2003).

The following sites were selected (illus. 4):

- in the northern zone: Summit, Glasgow, Coetzee, Even Milling Centre, and Lilly;
- in the southern zone: Tix, Amber Rose, and a few panning sites along the Muzvezve River downstream Claw Dam.

During field work in April 2004, some additional sampling focussed on Lilly and Etena mill in the northern zone and on New Plus mill in the southern zone.

3.3.2. Sampling locations

In each selected area, the sampling locations were determined individually on each site according to the technical organisation and composition of the processing equipment, the geomorphology, the local drainage, the landscape and the proximity of the village. The objective was to check the sources of the Hg pollution, its pathways and the level of Hg in the potential targets that had been identified (surface or groundwater, plants, animals or humans). It is important to note that the number of samples collected is sufficient to provide information on the level, pathway as well as an indication of the extension of mercury pollution. Nevertheless, the number of samples is insufficient to allow us to draw up detailed maps of the pollution for each selected area. However, a comparison of the mercury level in the different types of milling centres and associated villages is possible and particularly interesting for making recommendations concerning the reduction or elimination of Hg pollution.

The geographical co-ordinates of the samples were collected with a portable Global Positioning System GPS (Datum number: Zimbabwe ARC1950) and recorded in an “Excel” database with all the other information, such as sample number, sample description, sample location, chemical analysis results… (app. 1). The list of the collected samples is given in illustration 9.

Sample type	Code	Quantity	Number: from / to
Soil	SO	49	1 to 47*
Superficial layer**	SL	12	1 to 12
Stream sediment	SE	39	1 to 39
Tailings	TA	56	1 to 56
Drinking water	WA	7	1 to 7

* Sample SO35 is composed of SO351, SO352 and SO35b.

** The superficial layer corresponds to the fine particles (< 2 mm) deposited on the soil and collected with a paintbrush. It contains dust.

Illustration 9 - List of collected samples.

Illustration 10 gives, site by site, the detail of the collected samples.

Site	Sample quantity				
	SO	**SL**	**SE**	**TA**	**WA**
Summit mill	6	2		6	
Glasgow mill	9	1		6	
Coetzee mill	5	1		6	
Lilly mill				4	1
Even Milling Centre	8	1		6	
Tix mill	12	2	14	14	4
Muzvezve River: Alexander farm			6		
Muzvezve River: downstream Claw Dam			11		
Amber Rose mill	7	3	9	11	2
New Plus mine		1		1	
Etena	1	1		1	
Total	**48**	**12**	**40**	**55**	**7**

Illustration 10 - List of collected samples site by site.

Only drinking water used in the miners' villages or on the milling sites was collected. The samples were taken from the tap of the water tanks used by the inhabitants.

At Tix mill and village, the drinking water is pumped on the bank of Claw Dam and transported by a 2-km-long pipe. One sample was collected near the pumping raft and another at the tap of the water tank in the village.

At the pumping area, miners dig a lot of small pits for ore extraction. This place is also very close (some tens of meters) to the point where the small watercourse flowing from Tix village and mill reaches Claw Dam. At Amber Rose mill the drinking water stored in a tank comes from a borehole drilled outside the milling centre. At Lilly village, the drinking water comes from a borehole installed close to the tailing dumps in the middle of the processing area.

3.3.3. Selected sites for air monitoring

Three sites were selected for air monitoring:

- Tix and Amber Rose mills in the southern zone were selected for air monitoring because they both have villages close by and use different amalgamation processes. Whereas amalgamation is carried out on copper-plate at Tix mill, bowl-concentrators are used at Amber Rose mill. Both sites have four stamp mills, drag clarifiers and a cyanidation process.
- Even Milling Centre in the northern zone was selected for air monitoring because it is new and well organised. In addition to the ball mill and bowl-concentrator, the biggest improvement in this centre compared to the others is the well-organised burning room. The person in charge of roasting uses a torch, and the amalgam is placed inside an air extractor during roasting. The exhaust air flows out through a pipe to the forest area just behind the roasting room. It is a custom amalgam burning site where roasting is done by batch for each miner successively.

3.3.4. Fish sampling locations

a) Generalities

Fish are exposed to mercury present in the aquatic system, either through fresh water, via the respiratory exposure, or through their diet (Snodgrass *et al.,* 2000), and are therefore good indicators of mercury contamination in the environment. Besides, they constitute a substantial proportion of the protein ration for people living along the rivers, and consequently represent for them a source of exposure to mercury. Additionally there exists a direct exposure concerning people directly involved in the extraction of gold combined with this metal. Mercury contamination levels in the water column of rivers and lakes are generally very low (ng L^{-1}), and mercury is mainly present in inorganic form (HgII). The trophic route of exposure, via ingestion of metal accumulated in prey, represents a more important pathway of contamination for most fish species than direct water exposure (Boudou and Ribeyre, 1997; Mason *et al.,* 1995; Wiener *et al.,* 2002).

The resulting biomagnifications (cumulative trophic transfers of the methylated form of mercury, MMHg: monomethylmercury – CH_3HgX, between prey and predators) can lead to extremely high mercury concentrations particularly in the different organs of carnivorous species. Most notable accumulations are met in muscle tissue (Bloom, 1992; Boudou and Ribeyre, 1997). To become part of the biomagnification process, the elemental form Hg° used for amalgamation has to be oxidized in the atmosphere and/or in the water (HgII) and then methylated by bacteria (SRB: sulphur-reducing bacteria). This process occurs mainly under hypoxic/anoxic conditions (Morel *et al.,* 1998; Rudd, 1995) (illus. 11).

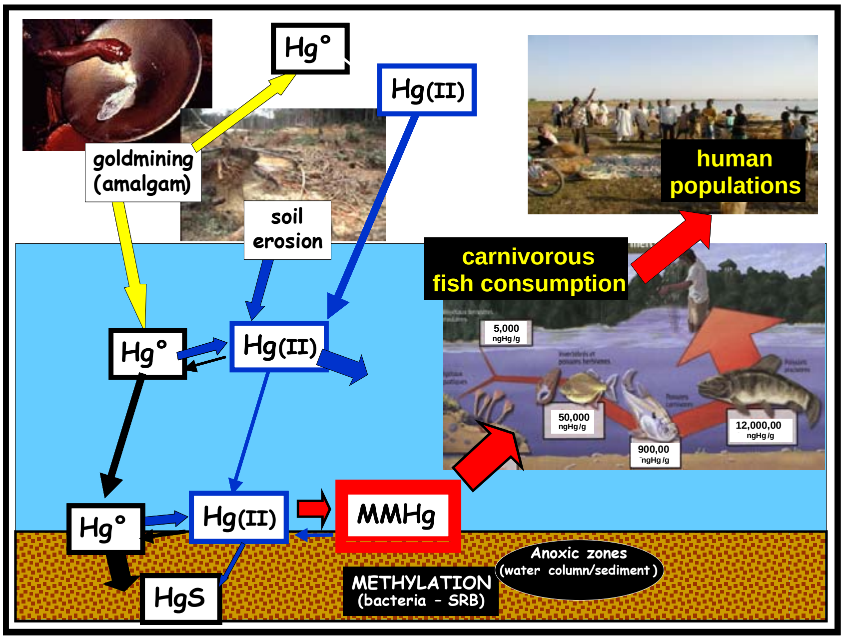


Illustration 11 - Main biogeochemical steps entailed in gold mining activities using amalgamation procedures and human population exposure, via the ingestion of carnivorous fish species, at the top of the aquatic food chain (from Boudou 2004).

b) Site selection

The survey conducted in November 2003 in Zimbabwe focused on the evaluation of contamination levels of the artisanal gold mining sites along the Muzvezve River in the south zone of the Kadoma-Chakari area (illus. 12).

The Muzvevze River was chosen for the fish study for the following reasons:

- The river is still running at the end of the dry season, while most of its tributaries are completely dried up;
- The river crosses an area characterised by many artisanal gold mines and custom milling centres of different sizes. Among them, two interesting custom milling centres are operated and studied in the present environmental and health assessment: Tix, located upstream (18°2689 S and 29°5623 E), and Amber Rose, located downstream (18°2756 S and 29°4913 E) from Claw Dam. Both custom milling centres use mercury for gold amalgamation and produce tailings in close proximity to small watercourses that are tributaries of the Muzvezve River. These tributaries were dry in November 2003.

Collection took place in six different spots located along the Muzvezve River:

- Upstream from Claw Dam (fishing points 4 and 5, illus. 12) close to the Tix mine. Point 5 is upstream from the Claw Dam reservoir next to the Mupfuti River, a tributary of the Muzvezve River. The fishermen caught fish with a bamboo fishing rod. Point 4 is downstream along the dried-up stream coming from Tix mine at the beginning of the Claw Dam reservoir. Fish were caught at night with a net, the use of small-mesh nets being normally forbidden.
- Downstream from the Claw Dam reservoir (fishing points 1 and 2, illus. 12). The water level in the river was low. At some places, it was possible to cross the river on foot. These fishing points are situated between the two main milling centres studied in the environmental assessment. In alluvial mining surroundings, fish live in ponds resulting from alluvial digging by panners. Water is almost completely drained off by hand with a plastic basket to catch fish.
- Eight km downstream from Claw Dam (fishing points 3 and 6, illus. 12). Point 3 was just downstream from the small dam on the Alexander farm. Panners used the same technique as described above to catch fish. Point 6 is the reservoir of Alexander farm. This site is directly connected to the gold mining activities because it is located downstream from Amber Rose mill. Mr. Alexander went fishing for us using nets and was able to catch six fish, although of the same species. After sampling, the fishes were given back to his farmers.

Fish from Points 4 and 6 were caught with a net in “deep“ water (reservoirs of the Claw and Alexander dams) and fish from Points 1, 2, 3 and 5 were caught in shallow water. Villagers fishing at the Point 5 told us that they were not involved in mining activities and that they were fishing to make some extra money.

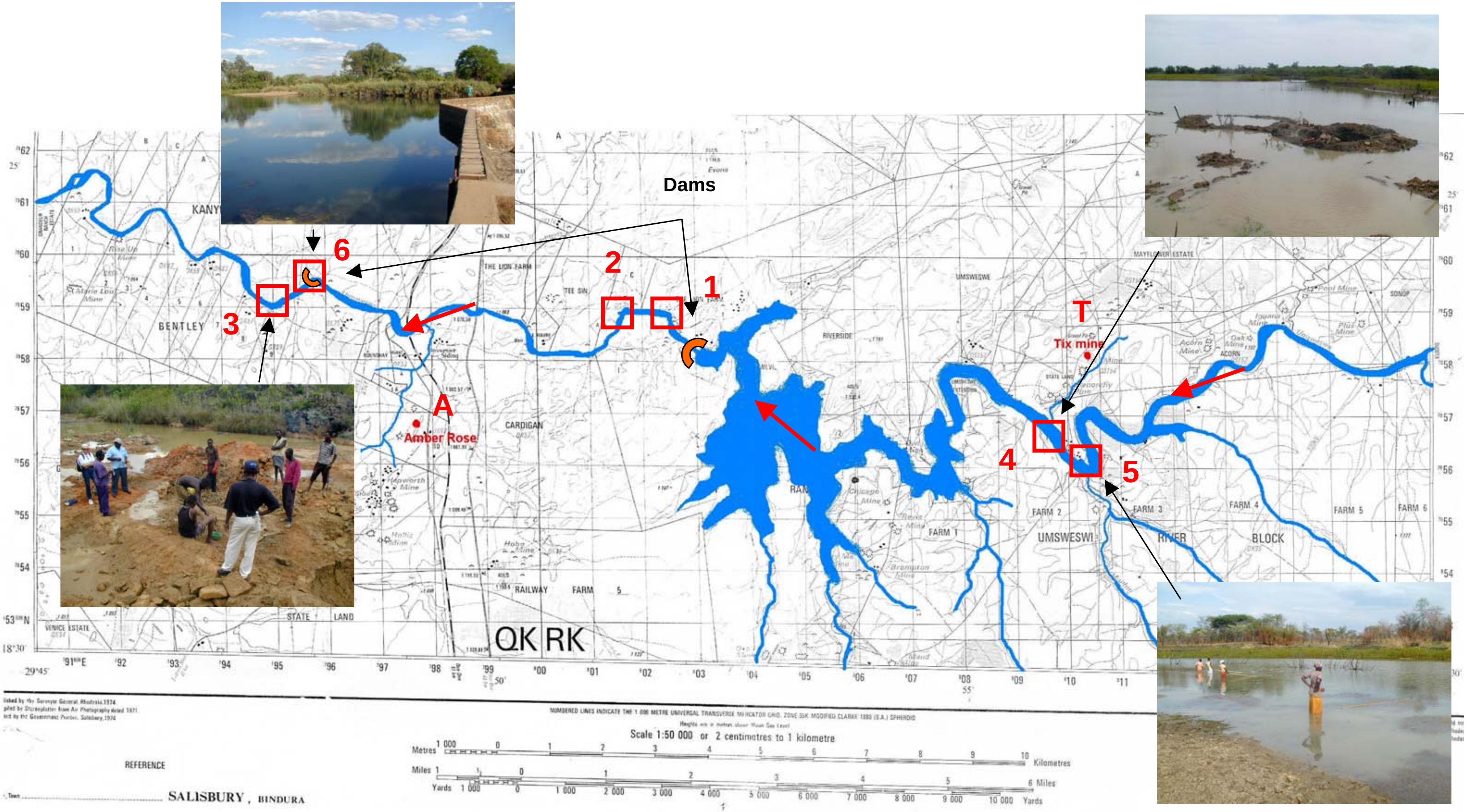


Illustration 12 - The six fishing points on the Muzvezve River, Amber Rose mill (A) and Tix mill (T).

3.4. SAMPLING: METHODOLOGY

3.4.1. Superficial layer, soil, tailings, sediment and water

Superficial layer (SL): Very fine particles deposited essentially by the wind at the surface of the soil, or concrete are equivalent of dust. They are found in the village houses, on the tracks in the village, in the milling centre building and close to the milling equipment (stamp mill, copper-plate, bowl-concentrator, panning area, roasting site…). This material, which contains only particles less than 2 mm in size, is collected with paintbrush at random sampling points (three to five) over an area of 2 to a maximum of 10 square meters (m^2), in order to obtain a composite sample.

Soil (SO): The topsoil from 0 to 3 cm deep. For each sampling point, the soil was collected at several points (three to five) over a surface of 2 to 10 m^2 using a small trowel and dry-sieved in the field to pass 2 mm, also in order to obtain a composite sample. The sample was divided up to obtain sub-samples of smaller size than the bulk sample without reducing the size of the individual particles.

Tailings (TA): The crushed or ground rocks that are sent to the settling ponds after the amalgamation process and then dumped after cyanidation. Tailings were collected all along the process in order to analyse mercury dispersion site by site:

- just after the copper-plate or bowl-concentrator,
- at different points all along the channel to the pond (if available),
- within the active pond (wet sample),
- within dry ponds from which the tailings will be sent to the cyanidation tanks,
- on the dumps of cyanided tailings.

For each sample, the tailings were collected with a small travel at several points (three to five) over an area of 1 to 4 m^2 in order to obtain a composite sample.

Small trenches 5 to 10 cm long were dug along the slope of the dump, also to collect a composite sample.

For some sites, tailings were panned just after the amalgamation process, allowing the collection of the heavy particles and the analysis of the Hg content, which corresponds to that lost during the amalgamation process. This operation was always done on the same quantity of tailings of three 7 litre pans. Moreover, the coarse fraction of tailings and slime were collected separately for chemical analyses just after the drag-clarifier.

Stream sediment (SE): stream sediment samples were collected:

- on the northern bank of Claw Dam close to Tix mill,
- over 7 km all along the Muzvezve River downstream from Claw Dam during the dry season, so in the middle of the riverbed,

- in small Muzvezve River tributaries at the Tix and Amber Rose mills during the dry season.

For each sample, the sediments were collected with a small trowel at several points (three to five) over an area of 1 to 4 m². The dry sediments were sieved to pass 2 mm.

Packing: The solid samples were collected and stored in new, clean and double-capped 150 mL plastic bottles imported from France. The numbering was marked on the double-cap, on the cap and on the bottle itself, to avoid losing the number (erasing) during the transit operations. For some of them, a duplicate was made for chemical analysis in the IMR laboratory at Harare. The same type of bottles were used for the water samples, but sealed with a paraffin wax film (Parafilm)®.

3.4.2. Fish sampling conditions and procedures

a) General condition

The collection of fish samples close to the Muzvezve River met with many logistical challenges. We were faced with the problem of finding fishermen, miners, panners, or farmers who might help us to catch fish in order to sample only a small piece of flesh from each fish, because no fresh fish markets were available in the selected area. Concerned individuals were informed that the sampling would not alter the quality of the fish and that the animals would be returned to them after sampling only a small quantity of flesh. Some of them also asked for compensation payments for their time lost during fishing and collecting activity instead of gold mining. For panners, who are clearly engaged in unlawful activities, it was difficult to fish during our absence because they frequently have problems with the police officers, who regularly chase them away from the riverbank. Our presence on the site allowed them to carry out this activity. All the fish sampled were paid for and returned to the owner after sampling.

Despite these time-consuming steps, fifty-two (52) specimens were collected along the Muzvezve River in November 2003.

b) Sampling procedures

Before sampling fish flesh, standard length (from the nose to the base of the caudal fin) and body weight were measured, and a picture was taken of each individual fish. Then, a small piece of dorsal muscle (1.5 x 1.5 cm) was removed and kept in 30-mL plastic bottles filled with a formalin solution (10% in deionised water). Caps were sealed with Parafilm®. It was not always possible to reach our goal of five fish per species except for Tillapia zilli, which is the species most often caught by the panners and miners. For this latter species, individuals of differing weights and sizes were sampled, thereby allowing us to investigate relationships between size and mercury contamination.

The samples of fish flesh were collected directly on the spot in front of the owner.

3.5. ANALYSIS OF SOLID SAMPLES

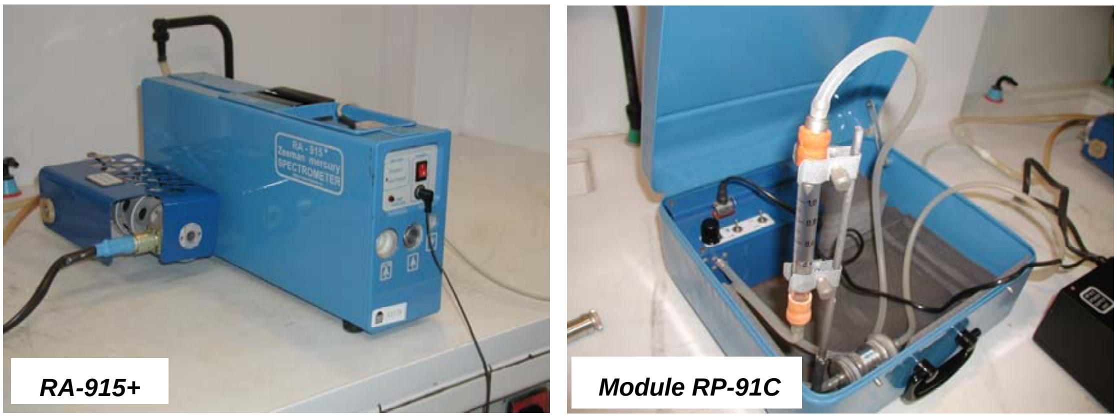
The LUMEX RA-915+ analyser equipped with the RP 91C attachment (illus. 13) is intended for measuring mercury in solid samples. The RA-915$^+$ analyser operation is based on differential Zeeman atomic absorption spectrometry using high-frequency modulation of polarised light.

A radiation source (mercury lamp) is placed in a permanent magnetic field. The mercury resonance line, $\lambda = 254$ nm, is split into three polarised Zeeman components (π, σ- and σ+).

When radiation propagates along the direction of the magnetic field, a photodetector detects only the radiation of the σ- component, one of those falling within the absorption line profile, another one lying outside.

When no mercury vapour is present in the analytical cell, the radiation intensities of both σ components are equal.

When absorbing atoms appear in the cell, the difference between the intensities of the σ components increases with increasing mercury vapour concentration. The principle of the RP-91C attachment is based on the thermal destruction (at 800°C) of a sample matrix and the reduction of the bound mercury in the sample followed by a volatilisation and a determination of the amount of elemental mercury formed by the RA 915$^+$ analyser.



RA-915+

Module RP-91C

Illustration 13 - The LUMEX RA-915$^+$ analyser equipped with the RP 91C attachment.

The detection limit is 0.01 mg kg^{-1}. For high concentrations (between 0.5 mg kg^{-1} up to 1,000 mg kg^{-1}) a specific single-path cell is used in place of the multiple-path cell. After stabilisation (about 40 minutes) of the equipment (lamp of the RA 915$^+$ and pyrolisis attachment), a calibration curve was obtained with five points. During mercury determination, the calibration curve was checked, and the apparatus drift followed every ten-sample determination, by analysing reference materials (NIST 8407 and LGC 6156). A sample (20 mg to 300 mg) is placed in a quartz spoon and inserted in the oven (800°C). Signal acquisition is automatically ensured by monitoring software on a laptop linked to the LUMEX RA915$^+$. The RA-915$^+$ analyser does not differentiate between mercury forms; it yields a total mercury concentration.

3.6. AIR MONITORING

3.6.1. Operating principle

The LUMEX RA-915$^+$ analyser without the oven is also intended for measuring the mercury vapour concentration of ambient air, both in stationary and continuous mode (without a pre-concentration step in the absorption trap). Currently, there is no generally available methodology for measuring low levels of mercury in ambient air. The mercury values for air analysis given in this report are not certified as they are for solid samples. But they make it possible to make comparison between the different steps of the process. The RA-915$^+$ analyser (Lumex) requires an external mercury supply, such as a gas cylinder, for calibration.

After switch-on, it takes about 20 min. to stabilise the light source. When the measurement mode is started, a zero adjustment is first carried out automatically. Then the analyser measures and indicates continuously the measured mercury concentration of the gas as both a numerical value and a graphic chart.

According to the constructor, the detection limit is 2 ng m^{-3} and the flow rate is 20 L mn^{-1}. Concentrations less than three times the limit of detection cannot be considered significantly different. The multi-path cell should not be operated for too long in rooms with high mercury vapour concentrations (higher than 10,000 ng m^{-3}).

3.6.2. Problems

The RA-915$^+$ analyser is relatively simple to use but it is not always easy to operate on a mining site, essentially because of the quality of the power supply and of the high level of mercury concentration measured in this study.

a) Internal battery and main power supply

When fully charged, the battery allows the analyser to operate continuously for approximately 3.5 hours. The analyser needs to warm up for at least 20 minutes. This means that unless the analyser is switched off between two monitoring rounds, air cannot be monitored continuously for more than 3 hours.

It was not always possible to use the main power supply on the site due to its instability. As a result, most of the time it was only possible to monitor for 1 to 1½ hrs. per day. It would be necessary to bring a generator or to connect the LUMEX to the car battery.

b) High mercury concentration

The RA-915$^+$ analyser has a multi-path cell, which should not be operated for a long time in places with a high concentration of mercury vapour (higher than 10,000 ng m^{-3}). In fact, the mercury concentration frequently exceeded 10,000 ng m^{-3}. In order to avoid contamination of the multi-path cell, the intake hose of the Lumex was withdrawn each time the mercury concentration stayed above 10,000 ng m^{-3} for more than 1 or 2 minutes.

At Even Milling Centre, the efficiency of the air extractor was checked in the closed roasting room. Momentarily, the mercury concentration was too high, and the multi-path cell became contaminated. A complete clean up was done (replacement of the dust filter and cleaning of the cell). For lack of time, it was not possible to return to the Even Milling Centre for another monitoring operation.

In cases like this, a single-path cell is needed to allow analyses of mercury concentrations as high as 200,000 ng m^{-3}.

3.6.3. Air monitoring at the custom milling centres

The air monitoring operations did not cover entire sites. Monitoring was mainly carried out in the areas where we saw workers using mercury.

The objective was to cover each step of the process from ore crushing to amalgam recovery. This was not always possible, because crushing could sometimes last more than one day depending on the quantity of the ore pile and the hardness of the ore (as mentioned before, quartz requires more time than laterite).

At the Tix mill, the monitoring could be performed all along the process, from ore crushing to amalgam recovery on the copper-plate, including cleaning the copper-plate, and applying of a fresh coat of mercury. The measurements were made during the following phases:

- pulp running on the copper-plate;
- scraping off the mercury by hand with a rubber scraper;
- collecting the amalgam, also with the hand;
- scouring with sand and lye to remove any coating or oxidation;
- scrubbing fine sand containing mercury onto the plate (as much mercury as the plate will adsorb).

At Amber Rose mill, the process involves a bowl-concentrator installed a few meters away from the stamp mill (~3 m). Some mercury is added inside the bowl, but no additional mercury is handled during the concentration process. Here, the monitoring is conducted around the stamp mills:

- on the top of the bowl-concentrator located a few meters away from the stamp mill;
- forty cm above the bowl;

- on top of the coarse tailings stockpile (after the bowl);
- on top of the slime pond (fine tailings);
- close to the cyanidation tanks;
- close to the office buildings.

At Even Milling Centre:

- in the roasting room.

3.6.4. Air monitoring in the villages

The two villages are quite different. Tix village consists of about a hundred houses built in a disorganised manner, and the first one to the north is at least 300 m away from the mills. The villagers are not farmers; they all work as miners all around the village and near or on the Claw Dam bank. They are also frequently at the Tix mill for the ore crushing and amalgamation process. At Amber Rose, the village is smaller (less than 30 houses) and situated on the milling site between the mill and the cyanidation tank, to the north, and the cyanided tailings, in the south. The tracks in the village are frequently covered with cyanided tailings.

At Tix village, some of the villagers crush, pan and roast their amalgam next to their houses. No roasting activity, however, was observed at Amber Rose village during the survey.

Based on these two different contexts, the air monitoring was performed as follows:

- in Amber Rose in two places:
  - · inside the village,
  - · at the entrance of the milling site;
- in Tix village in four different places:
  - · in a public place (bar) in the middle of the village,
  - · at the southern extremity of the village, opposite the stamp mill,
  - · next to a roasting place in activity,
  - · next to a mercury storage place.

3.7. ANALYSIS

3.7.1. Tailings, soils and sediments

All the samples collected in Zimbabwe and brought back to France were analysed with the Lumex device in the BRGM laboratory at Orléans, France.

All samples were sieved at 2 mm in the field. These samples were dried at 40 °C for a couple of days then, after homogenisation, each sample was separated into two sub-samples. The first sub-samples were directly analysed with the Lumex. The second sub-samples were ground to less than 100 µm, to be analysed with the Lumex.

The level of mercury is highly variable in the different samples. In order to avoid any contamination by a high-mercury sample on a-low mercury sample, uncontaminated mercury sand was analysed to control the absence of memory effect between two determinations.

During mercury determination, the calibration curve was checked and the apparatus drift followed every twenty sample determinations by analysing reference materials.

Fourteen samples (10 % of all the samples taken) were selected and sent to a control laboratory (Chemex ALS, Canada). The analyses of the Chemex ALS laboratory were done by CV-AAS (see app. 1).

The quality control done for the Lumex analyses vs. Standard References Materials (SRM) on the solid samples, and the quality control for the water samples and for the fish are given in the appendix 2 followed with interlaboratory comparisons.

4. Results

4.1. SOIL, SEDIMENT, TAILINGS AND WATER BY SELECTED AREA

4.1.1. Southern zone

a) Tix mill

At Tix, the custom milling centre and the village of miners and millers are very close to each other (less than one kilometer), but separated by a small watercourse that flows southwards to the Claw Dam reservoir, approximately 2 km away (illus. 14). The sampling was performed in the milling centre and in the village and, further away, mainly to the south, up to 3 km downstream from Claw Dam and on the bank of Claw Dam.

- **Surrounding area level**

Soil, sediments and tailings

The mining and milling activities in the Tix area are distributed in several spots in the area:

- One kilometer to the north of Tix mill, the village of May Flower is characterised by mining (small pits) and artisanal milling (hand crusher), panning (pit) and roasting activities. One sediment sample (SE33) collected in a small 4 m² area panning pit in the middle of the village shows 41.7 mg kg^{-1} Hg, attesting to the use of Hg for amalgamation by the inhabitants.
- One kilometer to the south of Tix mill, very small sluices are visible in the middle of the village of Mhisi, indicating artisanal (individual) mining, milling and amalgamation activities (illus. 15A). Tailings collected at the sluice box site show 10.83 mg kg^{-1} Hg. Moreover, sediment from the Claw Dam bank situated a few hundred meters from the village yields a value of 3.17 mg kg^{-1} Hg.
- One kilometer to the south-west, a large mining activity (digging) can be seen during the dry season all along the bank of Claw Dam (illus. 15B). During the rainy season all these pits are totally flooded. The sediments collected along the bank are contaminated by Hg (8.29 and 8.31 mg kg^{-1} Hg). If part of the pollution can come from this mining activity visible during the dry season, it is obvious that another part is coming from Tix, which is in the upstream drainage (SE16 with 8.29 mg kg^{-1} Hg). It is also important to note that the Tix drinking water pumping raft is located in this area (illus. 15C).

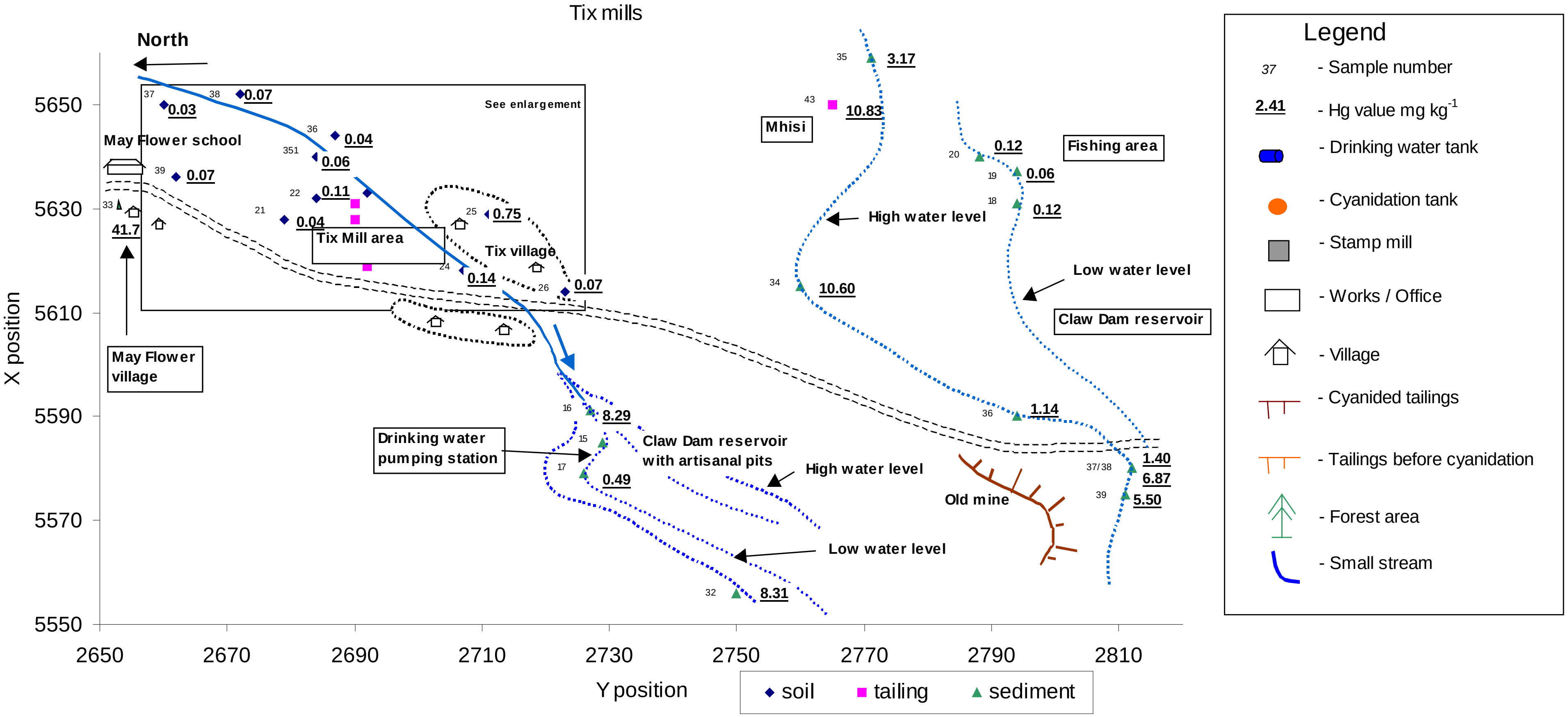


Illustration 14 - Local sketch of the Tix area. Sampling location and Hg results.

A: Mhisi village: Small pit for an artisanal sluice box

B: Numerous digging activities at the Claw Dam bank downstream from Tix mill. Fishing area Point 4

C: Drinking water pumping raft at Claw Dam downstream from Tix mill

D: Gold-processing area at Claw Dam bank downstream from the old Tix mine

E: Fishing area (Point 5) at Claw Dam downstream from Tix mill

Illustration 15 - Example of sample locations on the Tix site.

- Two kilometers towards south, the track runs along the tailing dumps of the old (closed) underground Tix mine. One part of the "waste", mainly low-grade abandoned ore and tailings, are locally reprocessed by individuals (hand crushing with an iron grinder, panning and amalgamation). A large part of these activities are conducted on the Claw Dam banks. Sediment samples (SE36 to SE39) collected here close to the processing areas are polluted by Hg (1.14, 1.40, 6.87 and 5.50 mg kg^{-1} Hg) (illus. 15D). These places are also used for daily fishing activities by miners and millers from Tix.

Water samples

- Water samples were collected in different locations. At the drinking water pumping raft (WA1) at Claw Dam, the Hg concentration is 0.34 µg l^{-1}, a value under the WHO limits of 1 µg l^{-1} (WHO 1993). This value is confirmed by the sample collected at the tap of the water tank (WA2) in the middle of Tix village that shows a concentration of 0.33 µg l^{-1} Hg. Another water sample (WA6) was collected in the small watercourse between the mill and the village. It drains the settling ponds and the tailing dumps of Tix mill and yields one sample with 0.73 µg l^{-1} Hg, confirming the presence of Hg in the tailings. For information purposes, the pregnant cyanided solution (WA7) collected at the bottom of the cyanidation tanks with the authorisation of the millers, shows 741 µg l^{-1} Hg.

This initial local survey indicates that, in Tix area, there is much scattered artisanal gold mining activity that complicates the study of the sources and dispersion of the pollution from Tix mill area itself.

The sediment samples collected in the fishing area along the Claw Dam bank display a low Hg content of 0.12, 0.06 and 0.12 mg kg^{-1}. (illus. 15E) that can probably be considered as geochemical background values for such kind of sediments.

- **Site level**

In Tix mill and Tix village, the solid sampling was carried out in three main locations with the following main results (illus. 16):

- North of the mill, in the soil, the Hg values reach a maximum of 0.07 mg kg^{-1} a few hundred metres from the tailing dumps.
- In Tix village, traces of Hg are found in soil sample SO25, with 0.75 mg kg^{-1} in the middle of the village. In the southern part of the village, the Hg value of soil drops to 0.07 mg kg^{-1}which is probably close to the background value.
- In the milling centre, the tailings and soils are clearly contaminated by Hg at different levels according to the proximity of amalgamation sites (See below).

Two north-south pseudo-sections illustrate the distribution of Hg contents in soils and tailings in the landscape.

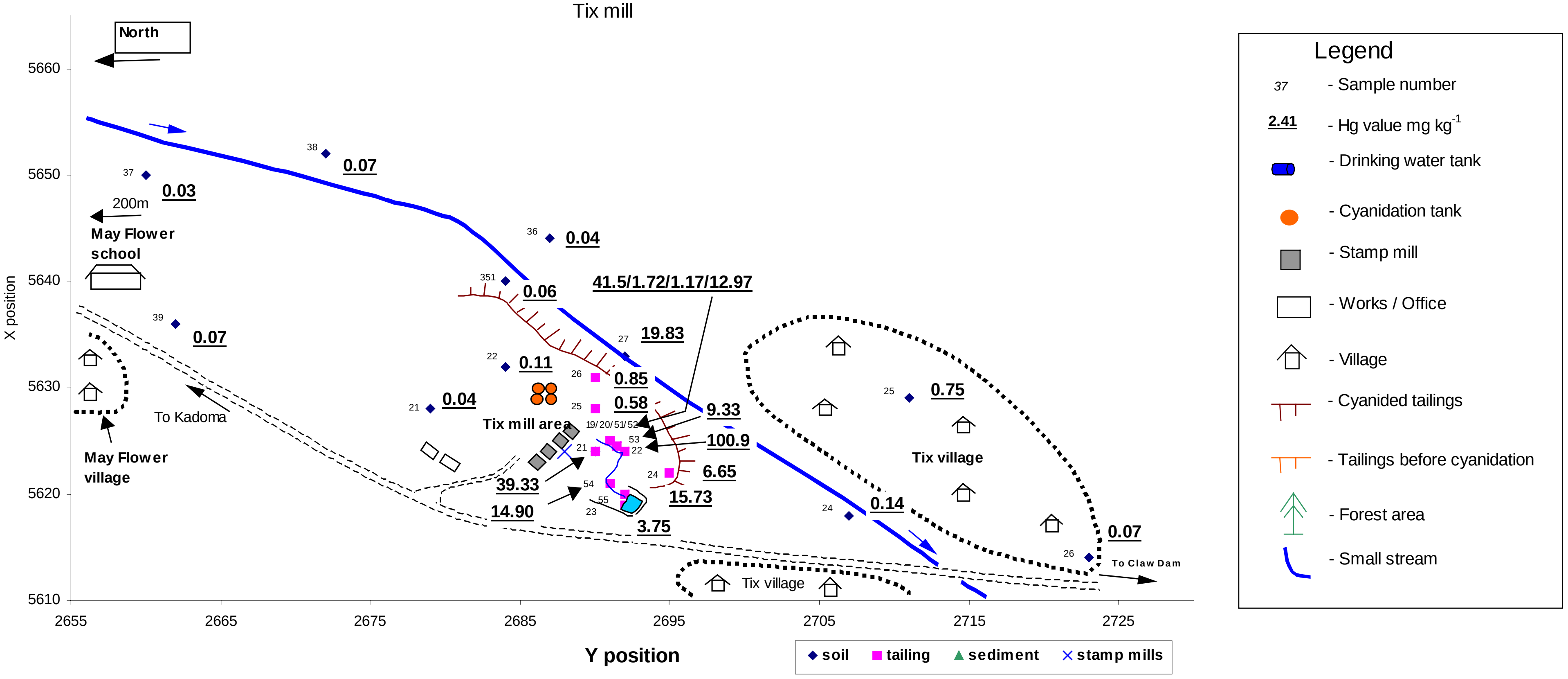


Illustration 16 - Sketch of Tix mill and village. Sampling location and Hg results.

The first pseudo section (illus. 17) displays values in soils:

- Background values in soils are below 0.10 mg kg^{-1} and are observed from one hundred meters to more than one kilometer from the artisanal settlements.
- Close to the bottom of the tailing dump after cyanidation, a soil sample (SO27) shows high values around 19.8 mg kg^{-1} Hg. This area is drained by a small stream flowing to Claw Dam.
- High Hg values (105 mg kg^{-1}) were found at the entrance of the site in SL5, close to the stockpiles, and in SO23 (43.53 mg kg^{-1} Hg) collected a few metres from the copper-plate between two stamp mills.
- Relatively moderate contamination were observed 300 m away from of the tailings, close to the village in SO24 (0.14 mg kg^{-1} Hg) and also in the village in S025 (0.75 mg kg^{-1} Hg).

The second pseudo section (illus. 18) illustrates the dispersion of Hg in the tailing samples with:

- low Hg values (0.85 and 0.58 mg kg^{-1}) in TA26 and TA25 collected on the dumps after the cyanidation process,
- High Hg content in TA21 (39.33 mg kg^{-1}) collected after the copper-plate.
- High Hg contents along the small channel (200 m long) carrying the tailings from the drag clarifier to the tailing pond. Fifteen metres from the drag clarifier, TA22 presents a very high anomaly (100.9 mg kg^{-1} Hg), which is confirmed, 100 m downstream, by TA54 (14.9 mg kg^{-1} Hg), and then by TA 55 (15.73 mg kg^{-1} Hg) at the inflow of the pond. The Hg grade varies according to the grain size of the samples (from slime to coarse sand) but also according to the position of the sampling point in the channel (in the middle of the flow or in small deposit area in the curve of the channel) (illus. 19). The slime (TA52) contains more Hg (12.97 mg kg^{-1} Hg) than the coarse sand (TA20, TA51), with respectively 0.72 and 0.17 mg kg^{-1} Hg.
- There are moderate Hg contents in the dry tailings (TA23 and TA24), ready to be collected for vat-cyanidation, with 3.75 and 6.65 mg kg^{-1} Hg.

Remarks: The gold processing activity is artisanal and discontinuous, carried out in batches by a succession of miners on different qualities of ores. Thus there is a significant variation in the quantity and quality of tailings even during a single day of work. The quantity of mercury used on the copper-plate in each batch of processed ore is not known, or is recorded anywhere.

Consequently, the Hg contents in tailings may vary tremendously, hour after hour, throughout the process. It is therefore not possible to give a true picture of the Hg contents in the tailings without a systematic sampling of the ponds and dumps in addition to several months monitoring of the tailing flow, to analyse also the seasonal variation (outside temperature and rainfall).

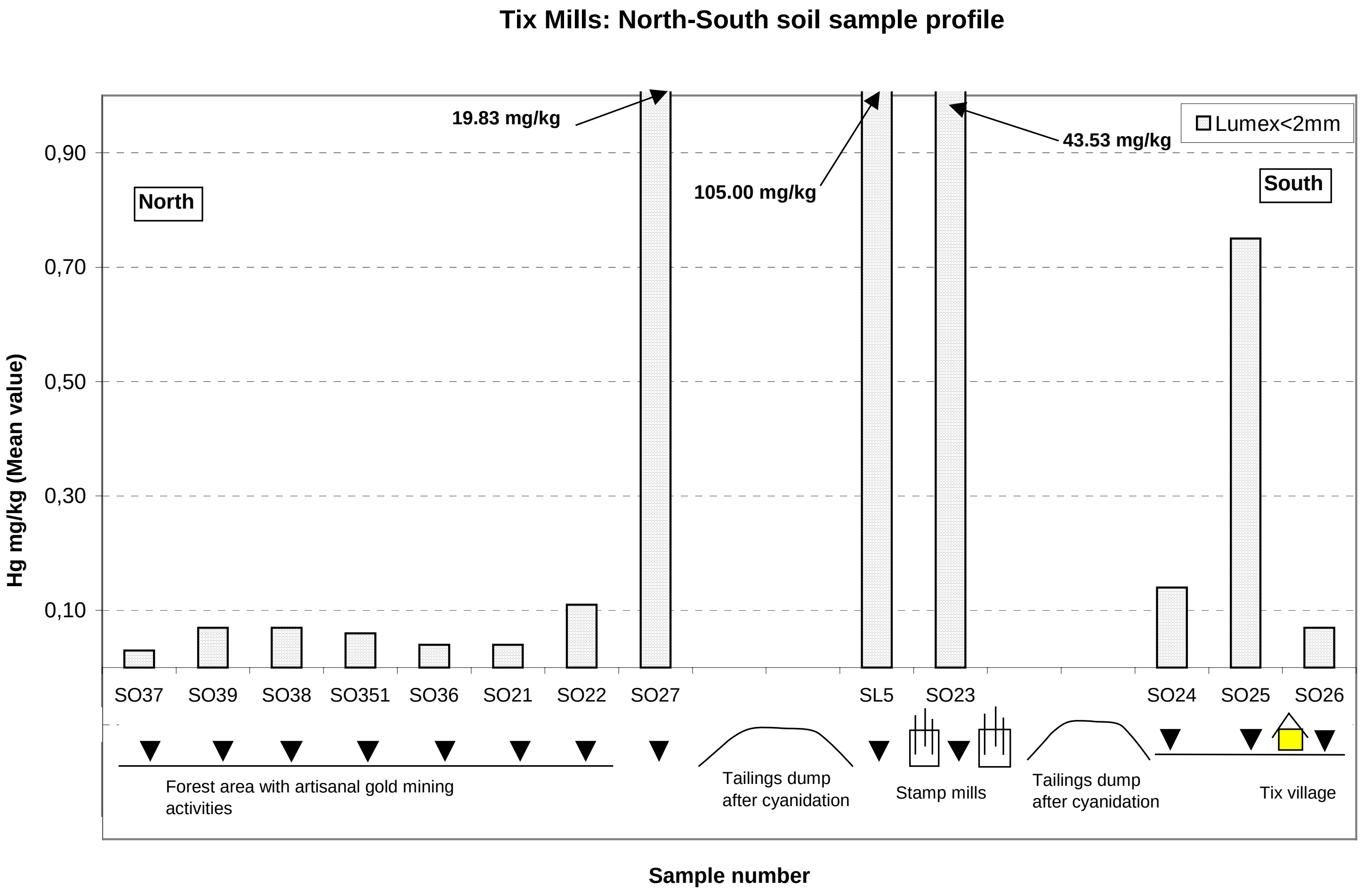


Illustration 17 - Hg distribution in soil samples following the process at Tix mill.

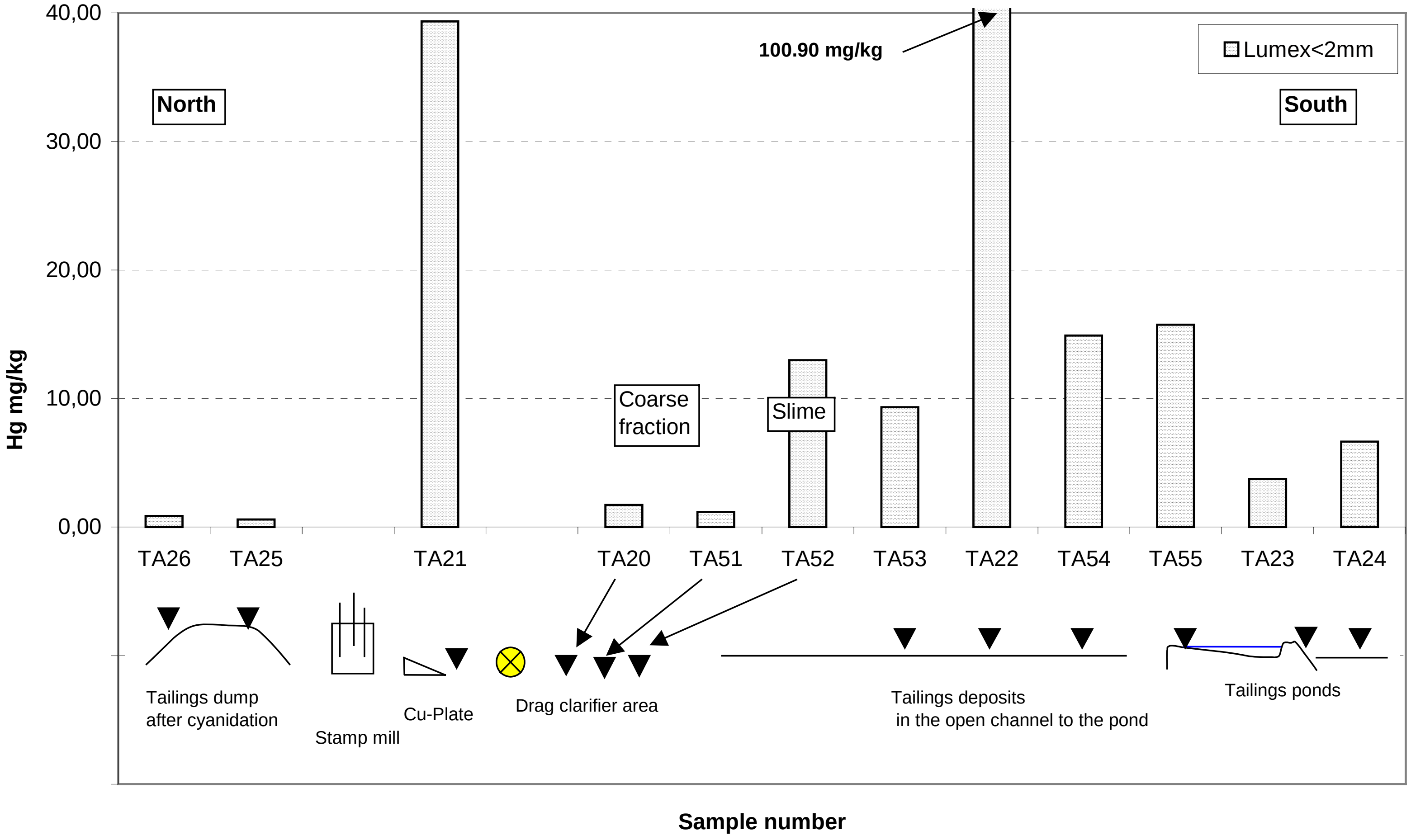


Illustration 18 - Hg distribution in various tailings samples at Tix mill.

The analytical results on tailings clearly shows the dispersion of Hg in tailings throughout the process, giving us the possibility to identify the “Hot Spots” and to locate the source of contamination.

Illustration 19 - Tailings “channel” at Tix mill.

b) Amber Rose mill

At Amber Rose mill, the village of miners and millers is surrounded by tailings and all the village tracks are covered with tailings (illus. 20). The sampling was detailed in the milling centre for soils, sediments, tailings, in the village and in the surrounding area, mainly in the small streams draining the site.

- **Surrounding area level**

Sediments were collected in two small streams:

- The first one, around 700 m south of Amber Rose, runs across the road. It is characterised by sediments that look like fine-grained tailings. The bottom sediments (SE29), brown to reddish, are covered over by 2 cm of white sediments (SE28). They both contain Hg, with 27.7 and 23.15 mg kg^{-1} respectively, attesting that they come from tailing dumps located somewhere in the upstream drainage. Lack of time did not allow us to check this upstream part.

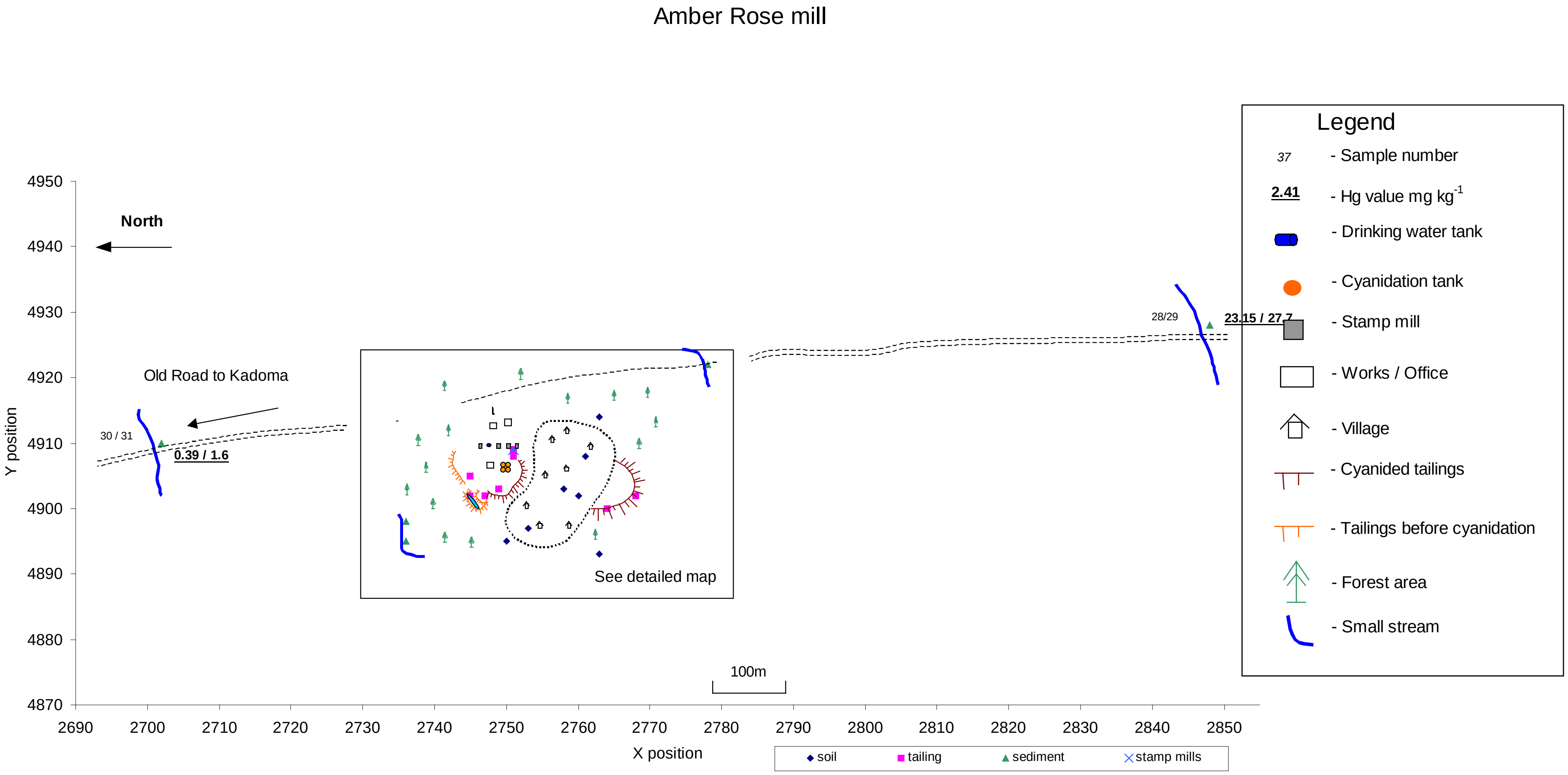


Illustration 20 - Surrounding area of Amber Rose: sampling location.

- The second one, around 500 m north of Amber Rose, crosses the road. It is also characterised by the presence of transported tailings, brown to reddish, at the bottom (SE31) and white in the upper part (SE30). The Hg content is slightly lower than that above, with 1.6 and 0.39 mg kg^{-1} Hg respectively. It is also difficult to certify that these tailings (sediments) come from the Amber Rose mill because the drainage network is not well indicated on the available maps, but also because other small milling centres are visible along the road.

These two sediment samplings indicate that tailings can be found as sediments in the drainage structures. The tailings are not systematically stored in tailing dumps. A lot of them are transported far from the milling centre in the watercourse during the rainy season or may be carried off voluntarily by the millers when the dumping is not well organised. Consequently the risk of the dispersion of Hg contained in the tailings is high.

- **Site level**

At the site level of Amber Rose mill and village, the solid sampling was carried out in five places with the following main results (illus. 21):

- In the small watercourse located north of the mill. The sediments collected in two different places (SE25 and SE26) are polluted and contain respectively 4.26 and 1.23 mg kg^{-1} Hg. According to the drainage network, we can certify that this pollution comes from Amber Rose mill, roughly 200 m away.
- In the Amber Rose village, traces of Hg are found in soil samples SO40, SO43, SO44 and SO45 with respectively 0.67, 14.31, 2.11, and 2.08 mg kg^{-1}. These Hg concentrations are associated with the large quantity of tailings that are spread out in the village.
- Roughly 50 to 100 m around the village, in a bush area. Samples SO41, SO42 and SO46 present a low Hg content, between 0.12 and 0.27 mg kg^{-1}.
- In the milling centre, the tailings and soils are clearly contaminated by Hg at different levels depending on the proximity of amalgamation sites.
- In the tailing dumps, stored after cyanidation in the southern part of the village, traces of Hg are found in samples TA39 and TA40 with respectively 1.39 and 2.10 mg kg^{-1} Hg.

Illustration 22 shows the distribution of Hg contents following the process in various media (soils and tailings).

- The Hg values range from 0.40 mg kg^{-1} for TA34 to 6.90 mg kg^{-1} for TA48 in the tailings collected just after the bowl-concentrator (overflow).
- The heavy material from the tailings pan concentrate are contaminated with 30.40 mg kg^{-1} Hg, attesting that part of the mercury used in the bowl-concentrator is lost during the amalgamation process.
- The tailings stored in settling ponds before cyanidation and dumped after cyanidation (TA36, TA38, TA50, TA57, TA37, TA39 and TA40) contain relatively moderate amounts of Hg between 1.04 and 5.30 mg kg^{-1}.

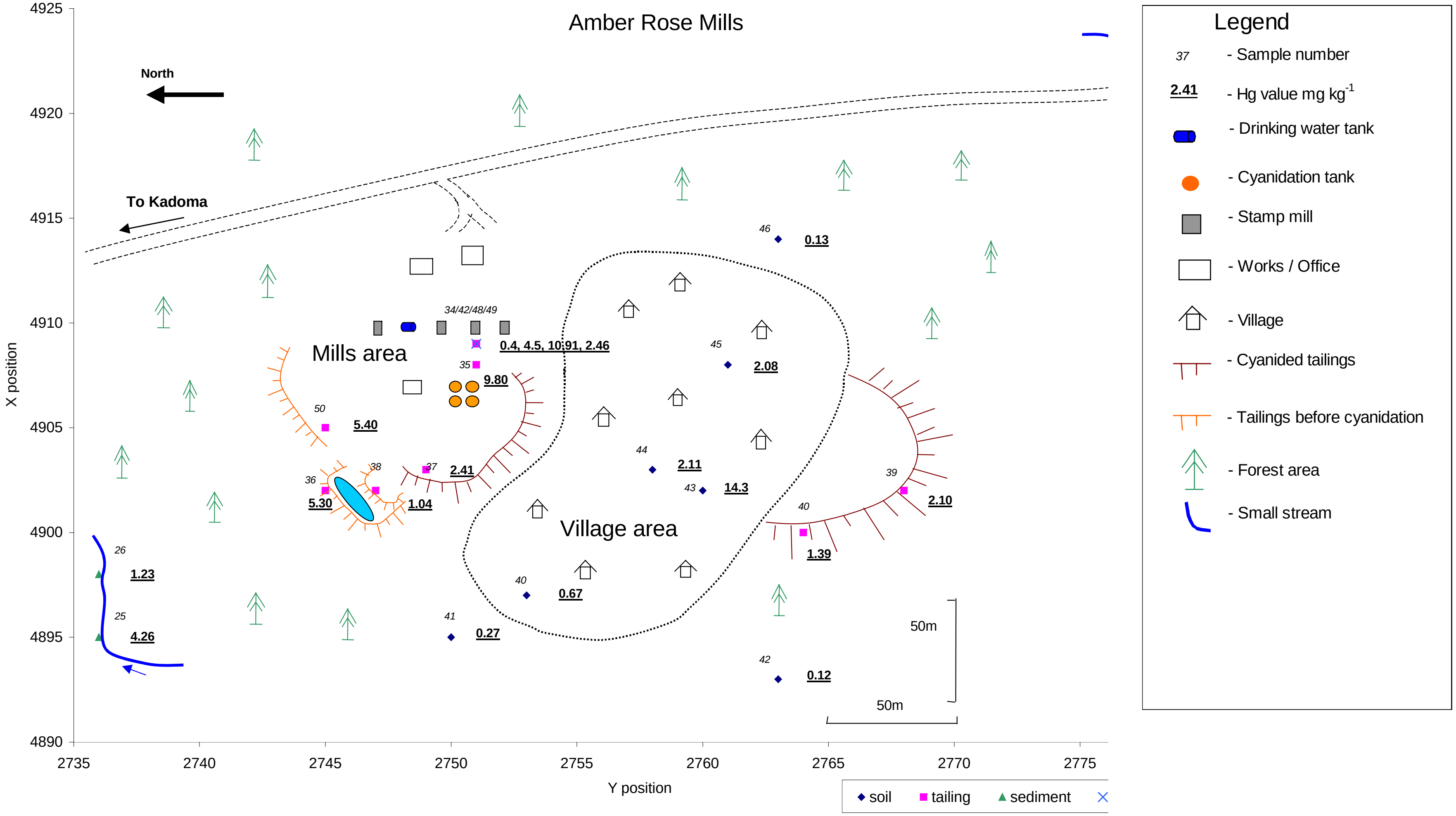


Illustration 21 - Site of Amber Rose: sampling location.

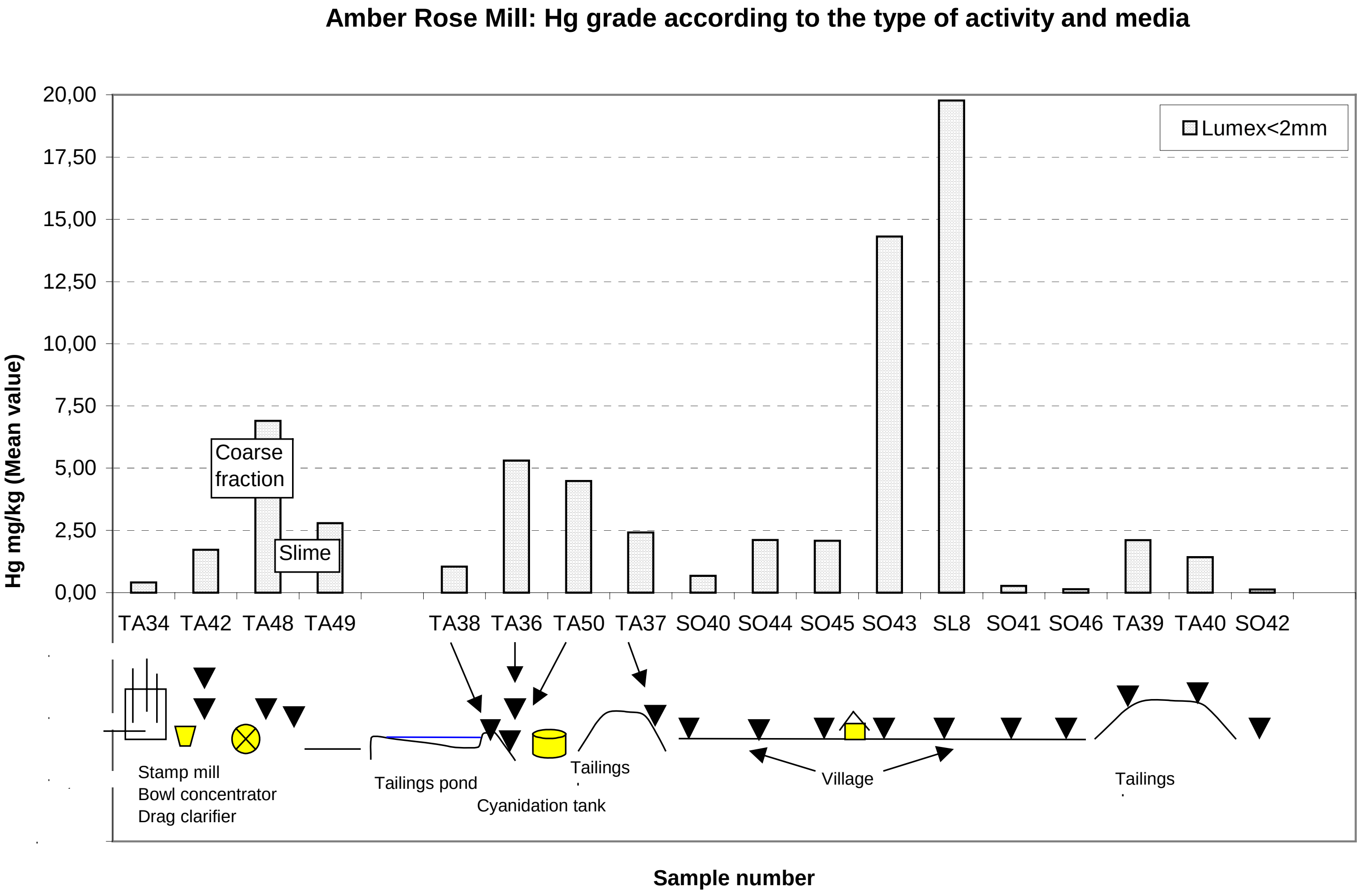


Illustration 22 - Hg content distribution in various samples following the ore process at Amber Rose.

- The soils in the village are significantly above natural backgrounds (<0.1 mg kg^{-1}) and show values below 2.5 mg kg^{-1} Hg. However a sample (SO43) shows clearly an abnormal value of 14.31 mg kg^{-1}. The superficial layer covering the soil and containing mostly the local dust may show abnormal values, like the sample (SL8), collected in the same place, with 19.77 mg kg^{-1} Hg.

- **Water samples**

The drinking water sample (WA3) collected at the bottom of the water tank, installed in the milling centre by the owner, shows a Hg concentration of 0.01 µg l^{-1}. The water comes from a well outside the milling site.

A sample of the pregnant solution (WA5) was collected in the clarifier tank by permission of the owner. The Hg concentration reaches 110.50 µg l^{-1}. After passing through a few column lined with activated charcoal to remove the gold, the solution is regenerated and recycled in the cyanidation tanks (illus. 5).

c) Muzvezve River

Along the Muzvezve River, stream sediment sampling was performed on a 7 km long profile, from Claw Dam (downstream from the Tix site) up to the panning area just after the "Alexander Farm reservoir" and downstream from Amber Rose site. The stream sediments profile (illus. 23) shows that the highest Hg value (0.76 mg kg^{-1}) is found in a mud sample (SE9) collected downstream a panning area. The other samples display low Hg contents, between 0.01 and 0.26 mg kg^{-1}, with a mean at 0.09 mg kg^{-1} that can be considered close to the local natural background.

It is important to note that the Hg concentration in sediments is depleted after Claw Dam (SE3 to SE6), with a mean value of 0.02 mg kg^{-1}. At the other sampling points, the mean value ranges around 0.12 mg kg^{-1} (excluding the SE9). This can be explained by the lack of panning activity (forbidden activity) just below Claw Dam up to the small dam where the pumping station for the Kadoma drinking water is settled.

d) New Plus mill

New Plus mill was not investigated in detail because of its similarity and proximity to Tix mill. The only difference lies in the fact that a roasting room is available for the local customers (illus. 24). If indeed the principle of setting up a roasting room is appreciable, this installation is not safe at all because all the fumes are rejected directly outside the building on the site of the milling plant. People staying in the area are then directly exposed to the smoke and dust rejected by this roasting room. The dust (SL10) collected on the cement covering the soil around the roasting house contains 50.53 mg kg^{-1} Hg (illus. 25).

A sample of tailings (TA41) was collected downstream from the drag clarifier installed after the copper-plate and the sluice. It contains 19.73 mg kg^{-1} Hg, which is in the same range of values as in Tix mill.

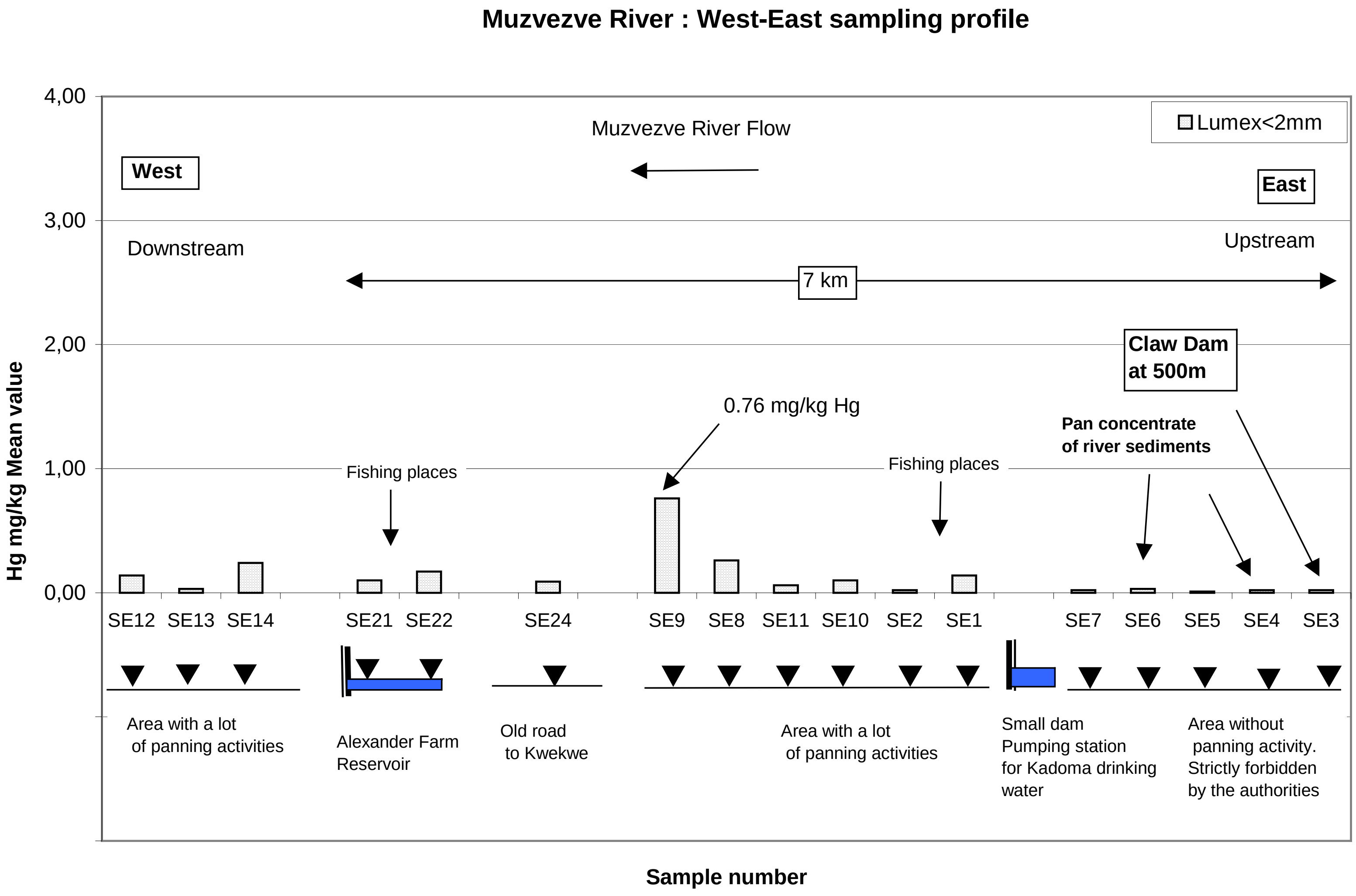


Illustration 23 - Hg content in the Muzvezve River samples.

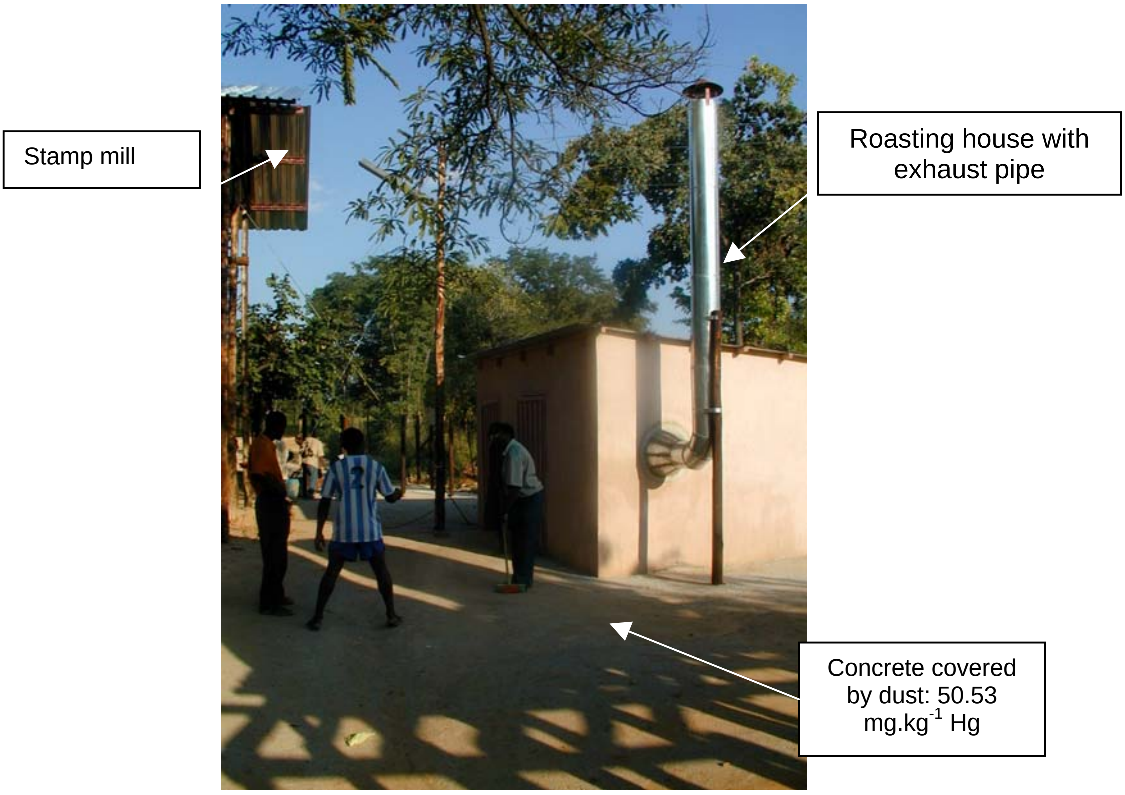


Illustration 24 - New Plus Mill. Dust sampling on the concrete floor around the roasting house with an exhaust pipe.

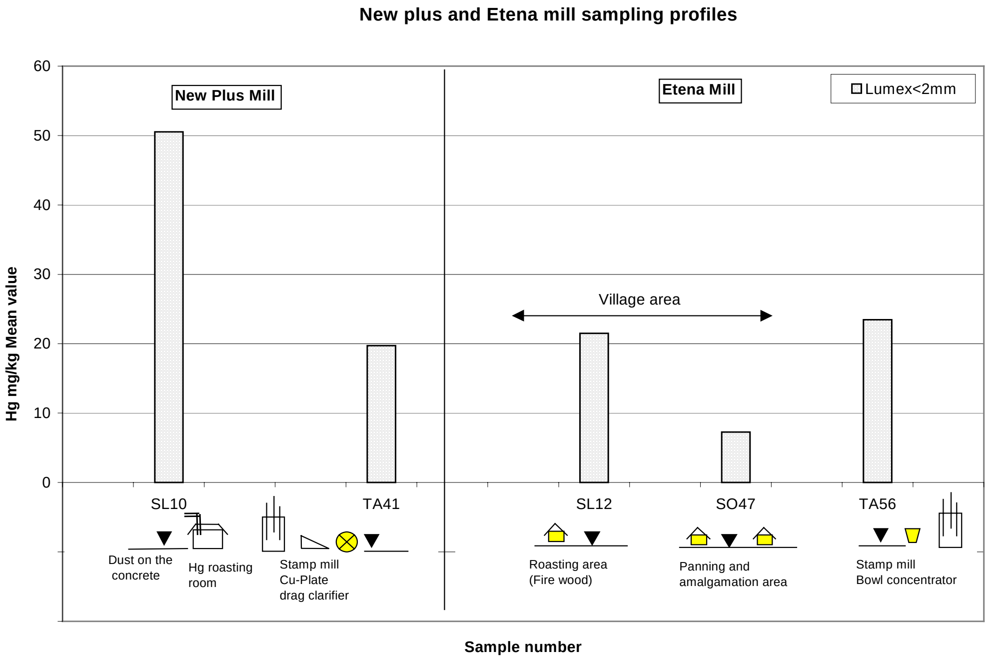


Illustration 25 - Hg content in New Plus and Etena samples.

4.1.2. Northern zone

a) Summit mill

As in the other sites of the northern zone, the workers of the custom milling centre live two to three hundred meters away from the processing plant. Illustration 26 summarizes the distribution of Hg contents in the various samples collected at that site.

- The tailings collected downstream from the copper-plate (TA2) and at the inflow of the settling pond (TA3) contain 7.02 and 14.45 mg kg^{-1} Hg respectively. This shows some contamination of the process residues after the copper-plate. The presence of Hg is confirmed with 32.97 mg kg^{-1} in the a heavy mineral concentrate sample of tailings TA4.
- The tailings collected on the tailing dump after cyanidation (TA6) still contain traces of Hg (2.46 mg kg^{-1}), with consequently a slight pollution of the soils close to the tailing dumps (SO4 with 1.21 mg kg^{-1} Hg).
- A few hundred meters from the dumps, the Hg contents in cultivated soils (SO5 and SO6) are low (0.05 and 0.2 mg kg^{-1} Hg).
- Soil samples (SO01, SO02, SO03) collected between the mill and the village (200 m) present traces of Hg, respectively 0.97, 0.11 and 0.33 mg kg^{-1}. The superficial layer collected in the village SL02 shows some traces of Hg, with 3.96 mg kg^{-1}.

b) Glasgow Mill

Results are displayed on the illustration 27.

- The tailings collected downstream from the copper-plate (TA7) and at the inflow of the settling pond (TA9) contain respectively 2.42 and 11.60 mg kg^{-1} Hg, attesting to the contamination of processing residues from the copper-plate. Moreover, the slime part of the tailings is particularly polluted with 30.67 mg kg^{-1} Hg. These Hg contaminations are confirmed in the crushing and amalgamation area in soil sample (SO11) and in the superficial layer (SL3) collected near the stamp mill and the copper-plate. These two samples show, respectively, 21.93 and 28.8 mg kg^{-1} Hg.
- The tailings collected on the dump after cyanidation (TA11 and TA12) still contain Hg, respectively 1.35 and 1.10 mg kg^{-1}.
- Soil samples SO12 to SO15, collected close to the tailings dumps, contain low amounts of Hg (0.05 to 1.14 mg kg^{-1}).
- The soil samples (SO7 and SO8) collected between the mills and the village, 200m away, present some traces of Hg, respectively 0.21 and 0.52 mg kg^{-1}. The soils collected in the village (SO9 and SO10) show traces of Hg with 2.08 and 1.50 mg kg^{-1}.

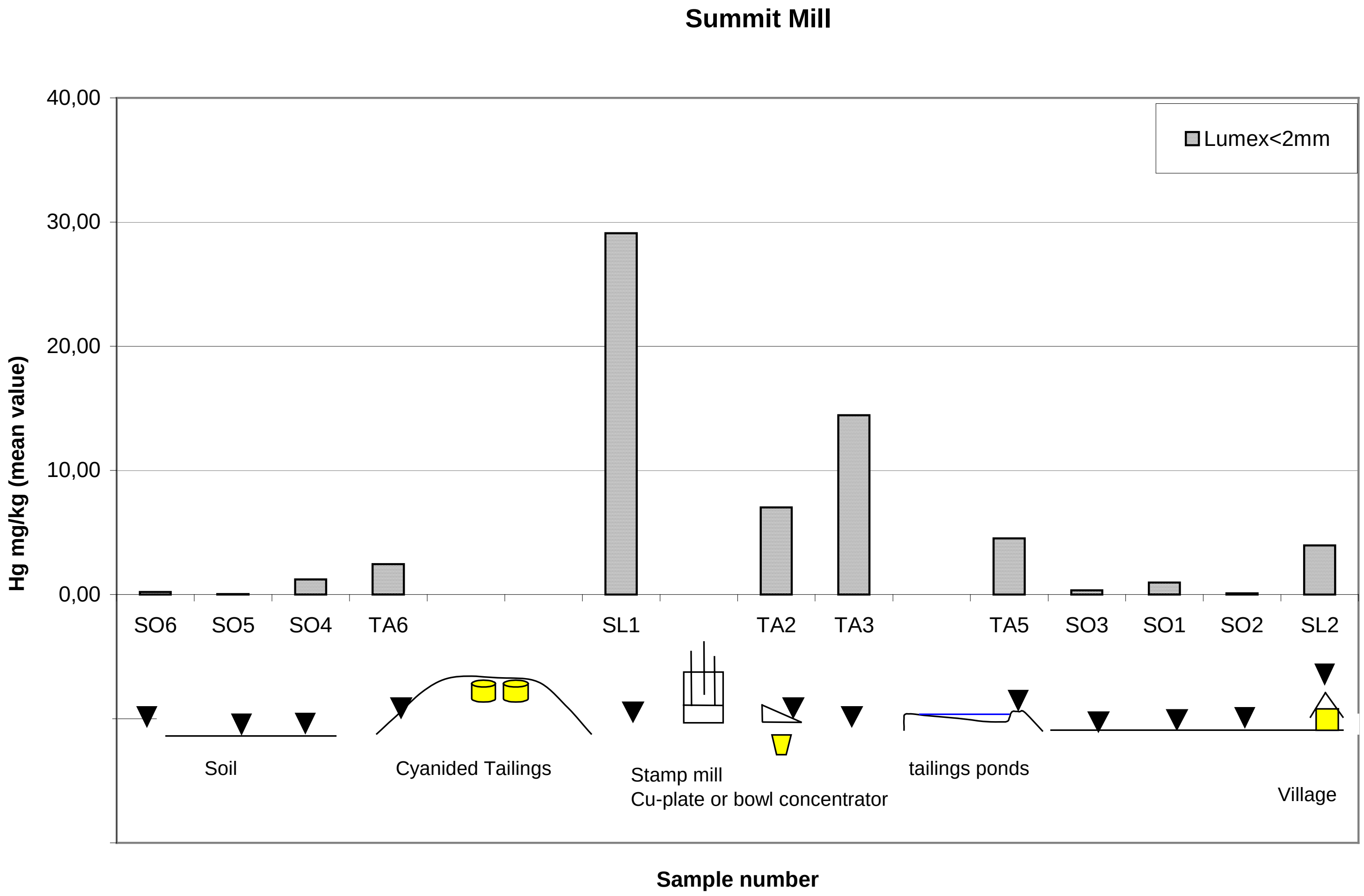


Illustration 26 - Hg distribution in various samples following the process at Summit Mill.

c) Coetzee mill

Results are displayed on the illustration 28.

- As for the other milling centres, the heavy mineral part of the tailings (TA13) that has been concentrated by panning contains high Hg concentrations (69.03 mg kg^{-1}).
- The tailings collected downstream from the copper-plate (TA14) and at the inflow of the settling pond (TA15) located 50 m away from the copper-plate, contain respectively 2.31 and 2.34 mg kg^{-1} Hg, attesting some moderate contamination of the residues during the amalgamation process. The dried tailings of the ponds (TA16) confirms that point, with 5.73 mg kg^{-1} Hg.
- The tailings collected on the dumps after cyanidation, TA17 and TA18, contain also some traces of Hg with respectively 4.07 and 1.53 mg kg^{-1}.
- Two soil samples collected on the edge of a small stream coming from the tailing dump are also anomalous. SO19 collected 150 m from the tailings shows 1.10 mg kg^{-1}, and SO20 collected at 200 m contains 2.64 mg kg^{-1} Hg. The soil sample collected in the cultivated area 50 m from the tailings presents 0.22 mg kg^{-1} Hg, which is close to the background level.
- Soil samples (SO16 and SO17) collected respectively in the village and in a forest area, these two points being nearly 200 m away from the copper-plate, present low Hg values, respectively 0.13 and 0.21 mg kg^{-1}. This is confirmed by sample SL4 that contains 0.36 mg kg^{-1} Hg.

d) Lilly mill

Lilly mill was not studied in detail, but four samples were collected during the main steps of the process in order to compare this site with the other ones located in the northern zone. The process in Lilly is slightly different because of the presence of both a copper-plate and a bowl-concentrator. Moreover, and unlike the other sites, the stamp mill, the copper-plate and the bowl-concentrator are installed in a closed building. The poor ventilation of this place can induce a strong concentration of Hg in the atmosphere that is breathed (illus. 29A and B). It must be verified by an air monitoring.

- **Tailing samples**

The tailings (TA44) collected in the building downstream from the bowl-concentrator shows an Hg content of 3.89 mg kg^{-1}. The tailings TA45 collected outside, in the tailings channel 10 m away from the building, presents some traces (0.77 mg kg^{-1}) (illus. 30 and 31A). This observation is confirmed by TA46 collected 5 meters downstream, with 1.44 mg kg^{-1} Hg. In the settling pond 80 m downstream, the concentration of Hg increases, with 12.27 mg kg^{-1} on a wet sample (illus. 31B).

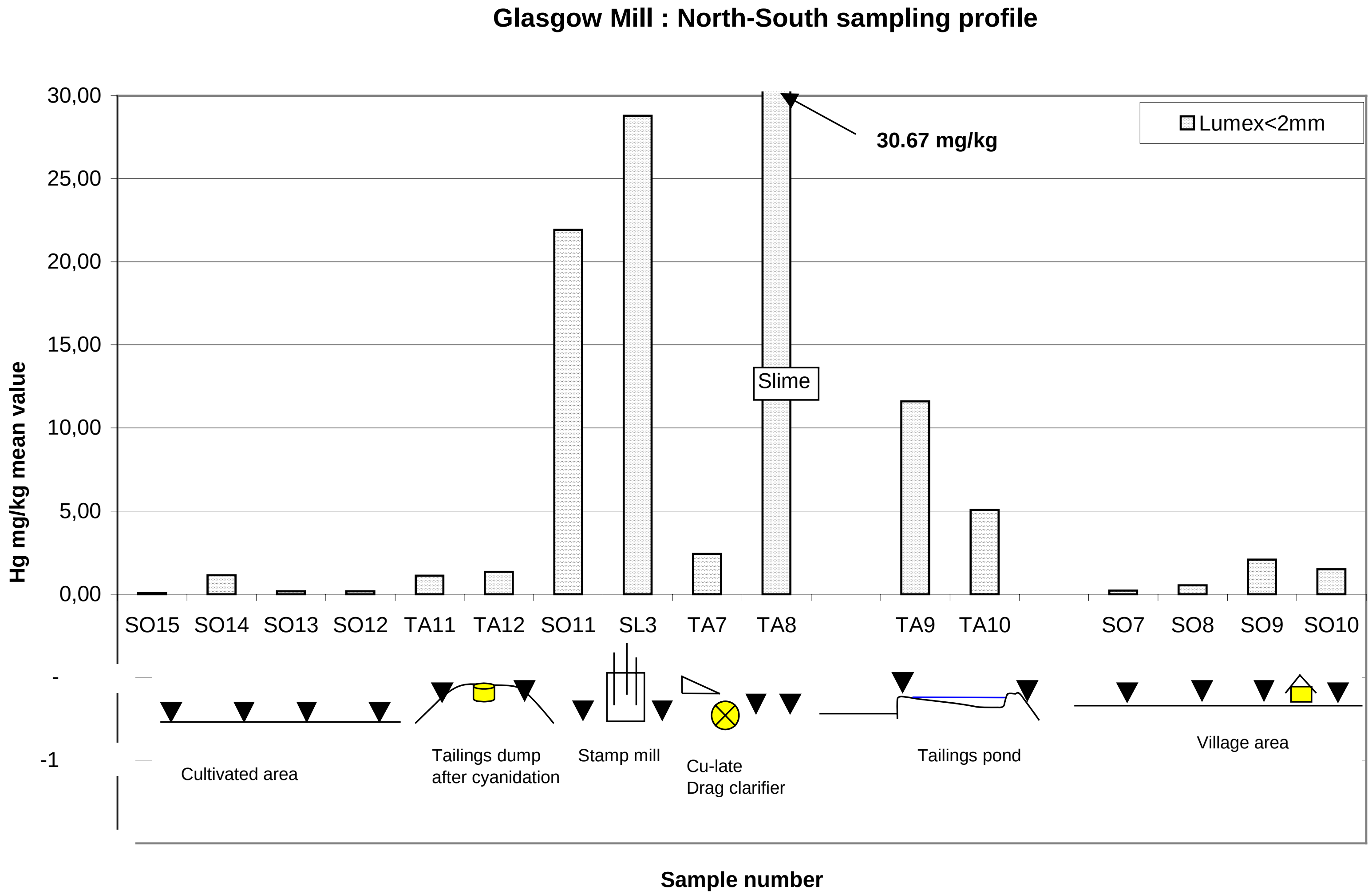


Illustration 27 - Hg distribution in various samples following the process at Glasgow site.

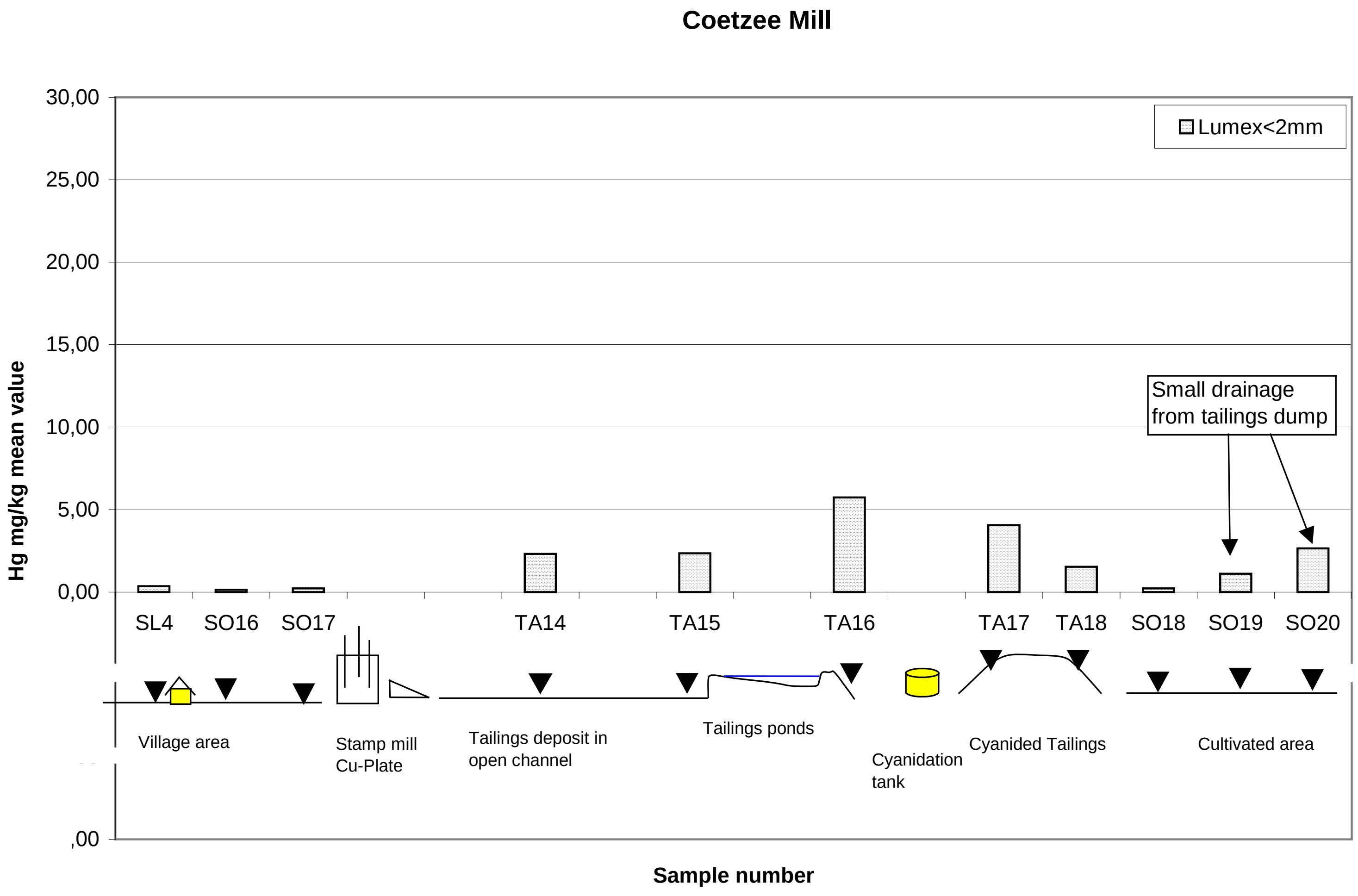


Illustration 28 - Hg distribution in various samples following the process at Coetzee site.

A: Bowl-concentrator B: Copper-plate

Illustration 29 - Bowl-concentrator and copper-plate in a closed building at Lilly mill.

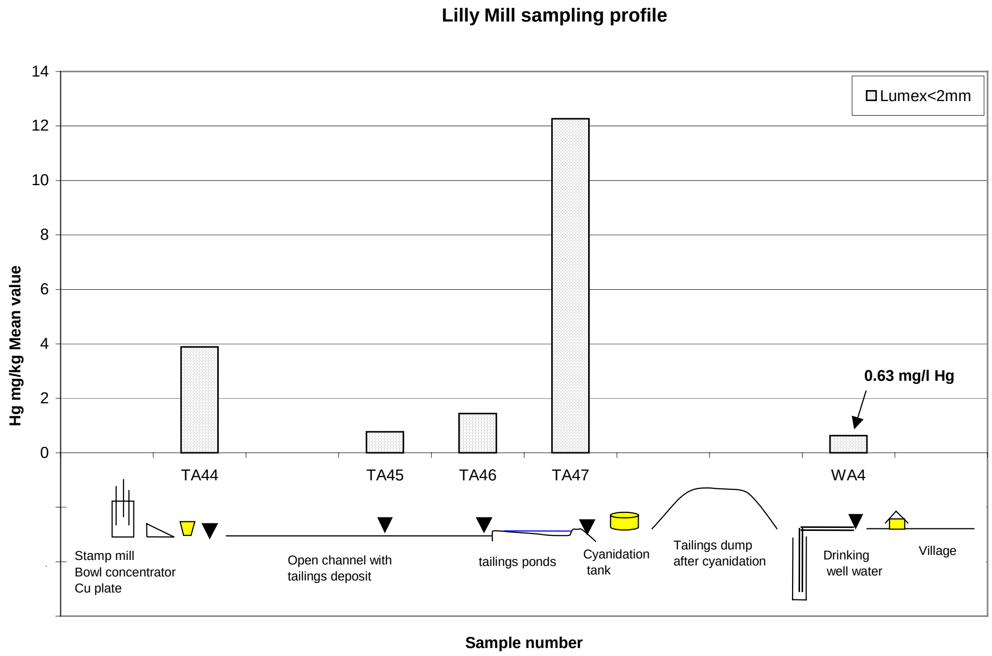


Illustration 30 – Hg contents in samples collected at Lilly mill.

A: Channel to the settling pond (TA45 and TA 46)

B: Settling pond (TA47) with 12.27 mg.kg^{-1} Hg

Illustration 31 - Tailings sample location at Lilly mill.

- **Water samples**

The drinking water (WA4) collected at a tap in the village shows 0.63 mg l^{-1} Hg. This water is pumped in a well dug by the mill owner, situated roughly 50 m from the cyanided tailing dumps (illus. 32A and B).

A: A well dug for drinking water, with cyanided tailings in the background

B: Drinking water at a tap in the village

Illustration 32 - Drinking water installation at Lilly mill.

e) Even Milling Centre

Even Milling Centre was studied more in detail because it was recently installed with modern equipment and is the only milling centre equipped with a jaw-crusher and a ball-mill followed with bowl-concentrator. Moreover, a roasting room was built for the local customers and also an open shelter with a concrete floor for panning and final amalgamation by the miners.

The Hg content distribution is displayed on illustration 33.

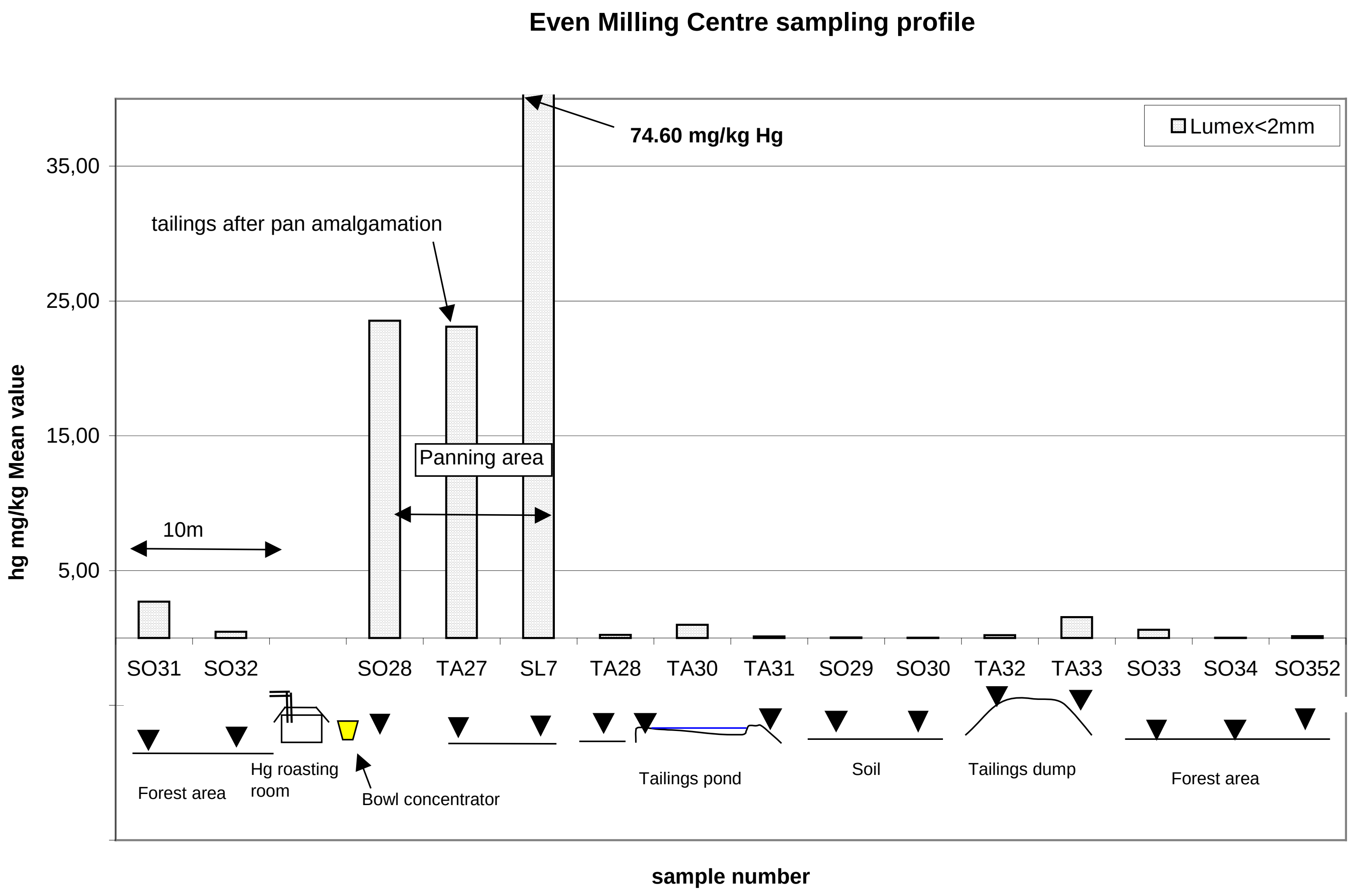


Illustration 33 - Hg contents in the samples of Even Milling Centre.

- The soil sample collected a few meters from the shelter (SO28), where the miners use mercury, presents a relatively high Hg value of 23.55 mg kg^{-1}. This result is confirmed on the fine fraction (< 100 µm) of the same sample that shows, after grinding, 41.43 mg kg^{-1}. High Hg contents are found in the dust (SL7) collected by cleaning the concrete floor under the shelter with 74.60 mg kg^{-1}. The same sample yields 985.40 mg kg^{-1} Hg on the < 100 µm fraction (illus. 34). The tailings (TA27) downstream from the amalgamation in a plastic basin also show a high Hg value of 23.10 mg kg^{-1} (61.75 mg kg^{-1} on the < 100 µm fraction). This area is the most contaminated area of the milling centre.
- The soil samples near the roasting room (10 m away) (SO31 and SO32), show respectively 2.71 and 0.47 mg kg^{-1} Hg (illus. 35).
- The tailings show only a few Hg traces in the channel to the settling pond (TA28), in the pond itself (TA 30 and TA31) and also in the tailing dump after cyanidation (TA32 and TA33), with low to moderate Hg values between 0.12 and 1.55 mg kg^{-1}.
- A soil sample (SO33), which is composed of in-situ soil and tailings transported by a small watercourse, was collected beyond the boundaries of the site. It presents some traces of Hg (0.62 mg kg^{-1}). Soil samples SO29 and SO30 close to the tailing ponds (a few meters away) and those collected outside the site (SO34 and SO352), roughly 50 and 150 m from the tailings, contain a very low Hg level (between 0.02 and 0.13 mg kg^{-1}). These values can be taken as representative of the background level.

At this site, the hot spot is located in and near the shelter for amalgamation. As the milling centre is recent, the Hg dispersion remains relatively restricted to the shelter place and the surrounding soil. Nevertheless, precautions must be taken, mainly at the amalgamation site, which seems to be the more polluted of the two, presenting the maximum risk for humans.

Illustration 34 - Dust collection by miners on the concrete floor of the shelter for amalgamation at Even Milling Centre.

Illustration 35 - Roasting room at Even Milling Centre.

f) Etena

Etena milling centre was investigated only summarily at the end of the second field work (April, 2004), to collect additional data in the northern zone and also to visit this site, described as highly polluted. In the village, many hand crushing sites with an iron grinder, small sluice or “james-tables”, panning and amalgamation areas and also open roasting places are visible.

The illustration 36 shows relatively high Hg concentration in the dust (SL12) collected around a roasting area, with 21.50 mg kg^{-1} (illus. 36A), and in the soil sample SO47 collected in the panning and amalgamation area showing 7.27 mg kg^{-1} (illus. 36B).

At the custom milling centre, tailings TA56 collected in the overflow of the bowl-concentrator shows 23.47 mg kg^{-1}, which is confirmed in the second analysis carried out on the ground sample < 100 µm (43.20 mg kg^{-1}).

A: Roasting area (21.50 mg kg^{-1} Hg)

B: Crushing, panning and amalgamation area (7.27 mg kg^{-1} Hg)

Illustration 36 - Sampling location at Etena village.

Despite the small number of sample collected in Etena, the disorganisation of the artisanal activity and the chemical analyses indicate that this site is highly contaminated and can be considered as an important hot spot.

4.1.3. Main outcomes on solid samples

- **Background values for soils and sediments**

At each site we observed a rapid decline in Hg concentration outside the milling centre in the cultivated and forest areas. This decrease is visible within the first 10 metres and was verified more than 300 m away from the milling installations. The local background values range from 0.02 mg kg^{-1} at Even Milling Centre to 0.22 mg kg^{-1} at Coetzee mill. These values are in the range of those published by INERIS (2003), which are 0.03 to 0.15 mg kg^{-1} as a medium value generally found and are comparable to 0.09 mg kg^{-1} given by G. Sposito (1989) (illus. 37).

Downstream from Claw Dam, six stream sediment samples collected in a protected area where panning is strictly forbidden for security reasons, and also without any milling activity close by, show a Hg concentration between 0.01 and 0.03 mg kg^{-1}. These values can be used as Hg background values for sediments in this area, that stay in the range of the reference value of 0.2 mg kg^{-1} (illus. 37).

- **Soils at the processing sites**

The soils collected close to the copper-plate are systematically contaminated. The highest Hg concentration is found at Tix mill, with 43.53 mg kg^{-1}. In the other places, the Hg content ranges between 7.27 mg kg^{-1} (Etena) and 21.93 mg kg^{-1} (Glasgow). It was not possible to collect soil samples systematically on all the sites visited due to the presence of large amounts of tailings dumped all around the equipment. The value of 23.55 mg kg^{-1} recorded at Even Milling Centre does not indicate a contamination associated with the main process of amalgamation by the bowl-concentrator but rather a contamination due to the presence of miners performing an additional amalgamation in pans and plastic basins under the shelter. Globally it seems that the Hg pollution is more important around the copper-plate than around the bowl-concentrator.

- **Tailings**

As the tailing sampling was conducted over a short period of time, the results obtained are indicative of the quality of the process but can not be used to determine a quantitative balance of Hg in the process. In order to obtain such a balance, the tailings will need to be monitored during the different steps over at least several weeks.

All the tailings collected during the different steps of the process, from the copper-plate or bowl-concentrator to the settling ponds no more than 300 m away, contain medium to high Hg concentration: 0.12 mg kg^{-1} at Even Milling Centre to 39.33 mg kg^{-1} at Tix mill.

Synthesis of the chemical analyses on tailings, sediment, soil and water samples. Min – Max values in mg kg^{-1} otherwise specified

Sample Type	Summit	Glasgow	Coetzee	Lilly	Etena	Even	Tix	Amber	New plus	Muzvezve	Reference / Background
TA: Copper-plate/bowl-concentrator to settling ponds	7.02 – 14.45	2.42 – 11.60	2.31 – 2.34	0.77 – 3.89	23.47	0.12 – 1.55	14.9 – 100.9	0.4 – 6.9	19.73		
TA: Settling ponds			5.73	1.44			3.75 – 6.65	1.04 – 5.30			
TA: Dumps	2.46	1.10 – 1.35	1.53 – 4.05				0.58 – 0.85	1.39 – 2.10			
TA: Pan concentrates	32.97	2.42	69.03				41.5	30.40			
TA: Slime		30.67					12.97				
TA: Coarse fraction							0.17 – 0.72				
TA: In stream								0.39 – 27.7			
SO: Close to copper-plate		21.93			7.27	23.55 (2)	43.53				0.03 – 0.15 (5) 0.09 (6)
SO: Background ?	0.05 – 0.2	0.05 – 1.14	0.13 – 0.22			0.02 – 0.13		0.12 – 0.27			
SO: Roasting area						0.47 – 2.71 (3)			50.53 (13)		
SO: Village	0.11 – 0.97	1.50 - 2.08					0.07 – 0.75	0.67 – 14.31			
SL: Village	3.96				21.50 (1)			19.77			
SL: Copper-plate		28.8				74.60 (14)	105				
SE: Claw Dam							0.06 – 0.12 (15) 0.49 – 8.29 (16) 1.14 – 10.60 (17)				<0.4 (5) 0.7 PEL (US) 0.3 LEL (Canada) 2 SEL (Canada)
SE: Small drainage			1.10 – 2.64					1.23 – 4.26 (4)			
SE: Muzvezve										0.01 – 0.03 0.01 – 0.76	
WA: Drinking water **µg l^{-1}**				0.63 µg l^{-1}			0.33 – 0.34 µg l^{-1}	0.01 µg l^{-1}			1 (7) 1 (8) 0.5 (9)
WA: Surface water **µg l^{-1}**							0.73 µg l^{-1}				0.0005 – 0.015 (10) 0.002 – 0.012 (11) 0.00001 – 0.006 (12)

1. Roasting area in the village. 2. Close to the shelter for amalgamation. 3. Soil in the forest area near the roasting room. 4. Tailings in small stream. 5. INERIS (France) 2003
6. G. Sposito The chemistry of soils. 1989 7. UNEP 1994 International Drinking Water Guidelines 8. EU Limit values. 1992 Council Directive 76/464/EEC.
9. EU Guide values. 1992 Council Directive 76/464/EEC 10. INERIS (France) 2003 for groundwater (mean values). 11. INERIS (France) 2003 for lakes (Mean values).
12. INERIS (France) 2003 for rivers (Mean values). 13. Dust on the concrete close to the roasting room. 14. On the concrete under the amalgamation shelter.
15. Low water level (dry season). 16. Low water level. Digging area (dry season). 17. High water level (rainy season)
PEL : Probable Effect Level; LEL : Low Effect Level; SEL : Strong Effect Level

Illustration 37 - Synthesis of the chemical analyses on TA, SO, SE, SL and WA.

The lowest values are found first in Even Milling Centre (0.12 mg kg^{-1}) and at Amber Rose (0.40 mg kg^{-1}). They are both using bowl-concentrator and are well managed.

The highest values are located in Tix mill (39.33 mg kg^{-1}) and in New Plus (19.73 mg kg^{-1}), where the copper-plate technology is used, confirming the fact that the loss of Hg is higher with a copper-plate than with a bowl-concentrator.

After vat-cyanidation, the dumped tailings display an Hg concentration between 0.58 to 4.05 mg kg^{-1}. The lowest value is found at Tix mill and the highest at Coetzee mill. It is important to note that parts of these tailings containing Hg are used to cover the soil of the tracks, even in the villages (Amber Rose, Tix).

The fine particles of tailings (slime) present a higher Hg concentration than in the coarse fraction, with 12.97 mg kg^{-1} as opposed to 0.17 to 0.72 mg kg^{-1} at Tix mill. The slime from Glasgow shows 30.67 mg kg^{-1} Hg. The mercury lost during the amalgamation process is associated with the fine particles in the tailings.

The Hg grade of the tailings from the stamp mill to the settling ponds seems showing a random distribution. For example, at Tix, the Hg concentration in tailings at the inflow of the pond is higher than for the tailings downstream from the copper plate. This can be explained by the following phenomenon:

- The channel through which the tailings flow between the copper-plate and the settling pond is neither straight nor constant in slope. Consequently, the heavy particles of the tailings including Hg droplets, are liable to be deposited in some preferential spots all along the channel, thereby creating areas with high Hg contents.
- Each stamp mill of a milling centre works simultaneously on different type of ore, originating from different locations. Each miner does not use the same quantity of Hg, depending on the gold content and also on its professional habits. So the Hg grade of the tailings is always changing hours after hours.

- **Sediments**

In the Muzvezve River, the Hg concentration ranges from 0.01 to 0.26 mg kg^{-1}, with a moderate peak of 0.76 mg kg^{-1}. Panners use Hg at some spots but contamination remains moderate. Tailings with moderate Hg contents (1.23 to 4.26 mg kg^{-1}) were found in small tributaries of the Muzvezve River in the Amber Rose area. It can be a fortuitous or voluntary action of the millers to let the tailings flow into the downstream drainage. The important runoff of the Muzvezve River may dilute the contamination in the riverbed.

At Claw Dam reservoir, which is the main fishing place, all samples show contaminated levels ranging from 1.40 to 10.60 mg kg^{-1}, caused by the nearby milling centre, ancient mining activity and the numerous isolated panning and amalgamation areas on the banks of the reservoir.

In conclusion, most of the small watercourses running close to the tailing dumps that were sampled show moderate to high Hg contamination from 1 to 10 mg kg^{-1}.

- **Superficial layers and dust samples**

All the samples of the superficial layer or dust collected in the milling centre close to the amalgamation process with copper-plate show very high Hg concentrations ranging from 28.8 mg kg^{-1} at Glasgow to 105 mg kg^{-1} at Tix. At Even Milling Centre, 74.6 mg kg^{-1} Hg are found in the dust collected on the floor of the shelter used for amalgamation by individual miners. The dust collected on the concrete floor around the roasting room at New Plus mill is highly contaminated too (50.53 mg kg^{-1}).

The village of Amber Rose presents locally high Hg concentrations (up to 20 mg kg^{-1}). Mostly because contaminated tailings are used to consolidate tracks and to fill up holes in the soil. Local soil or dust may be contaminated too by isolated spots of amalgam roasting. The same conclusions can be proposed for Summit village.

We were not authorized to enter in the house of miners to collect and analyse domestic dust.

4.1.4. Drinking water

The lowest value of 0.01 µg l^{-1} is found at Amber Rose, where the water comes from a well situated outside the milling area.

Conversely, the highest value of 0.63 µg l^{-1} is found at Lilly mill, where the water is pumped from a dug well situated close to the tailings dump.

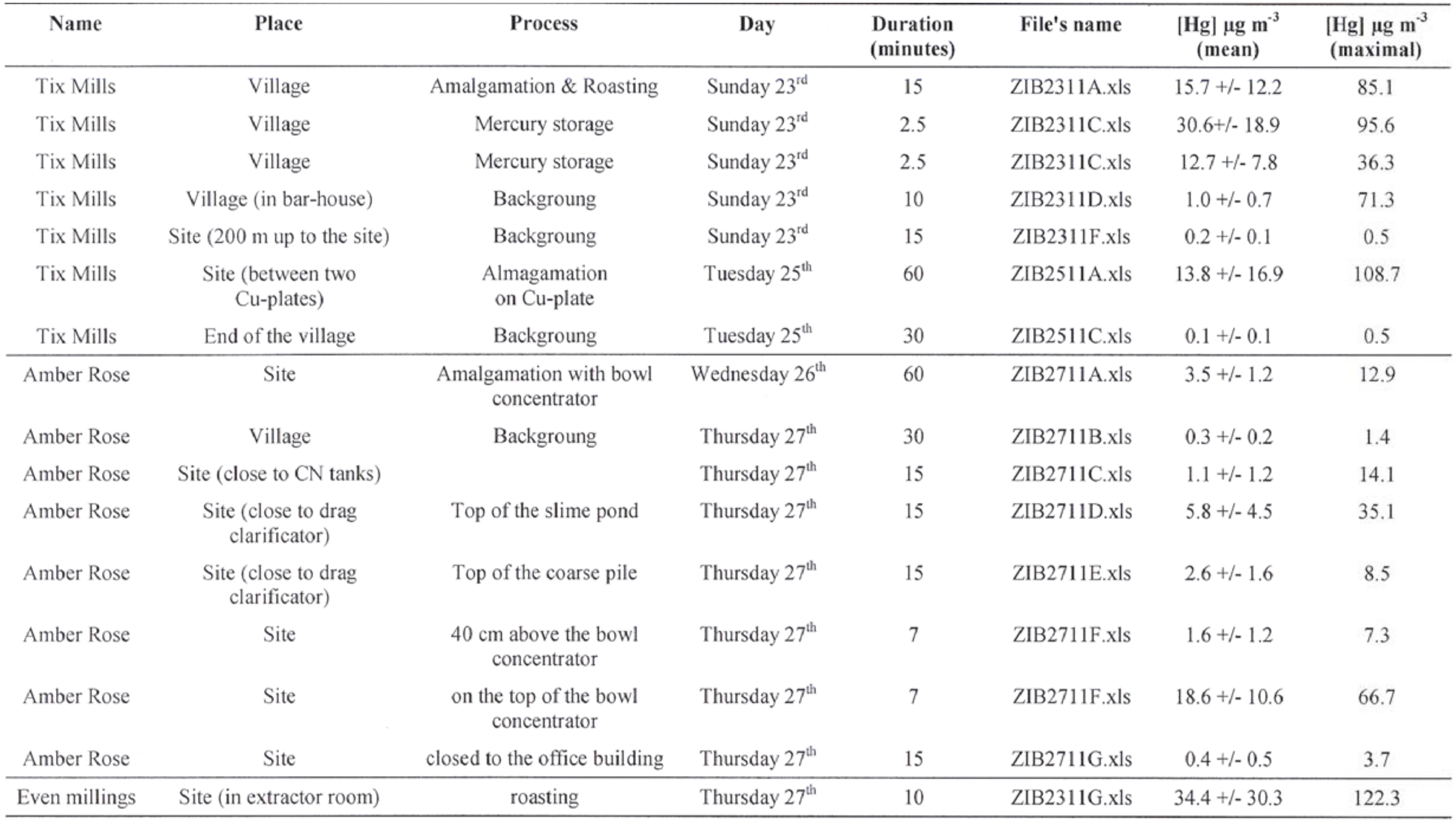
At Tix, the drinking water reaches 0.33 µg l^{-1} Hg. It is pumped at Claw Dam in a place characterised by the inflow of the small stream coming from the village and the mill and also by the presence of many digging places and possibly panning and amalgamation spots.

These last two examples demonstrate the direct relation between milling activity and the dispersion of mercury in the surface and groundwater, and consequently the risk for human beings.

4.2. AIR MONITORING

The list of the different analyses performed in November 2003 are presented in illustration 38. The preliminary results were already presented in Field Work Report No.1 (Billaud and Laperche, 2003).

The monitoring sequences were performed to estimate the air quality breathed by the population under different typical situations. For this, the intake hose of the RA-915^{+} analyser was installed approximately at nose height of the persons involved in the mining activities.



Name	Place	Process	Day	Duration (minutes)	File's name	[Hg] µg m^{-3} (mean)	[Hg] µg m^{-3} (maximal)
Tix Mills	Village	Amalgamation & Roasting	Sunday 23rd	15	ZIB2311A.xls	15.7 +/- 12.2	85.1
Tix Mills	Village	Mercury storage	Sunday 23rd	2.5	ZIB2311C.xls	30.6+/- 18.9	95.6
Tix Mills	Village	Mercury storage	Sunday 23rd	2.5	ZIB2311C.xls	12.7 +/- 7.8	36.3
Tix Mills	Village (in bar-house)	Backgroung	Sunday 23rd	10	ZIB2311D.xls	1.0 +/- 0.7	71.3
Tix Mills	Site (200 m up to the site)	Backgroung	Sunday 23rd	15	ZIB2311F.xls	0.2 +/- 0.1	0.5
Tix Mills	Site (between two Cu-plates)	Almagamation on Cu-plate	Tuesday 25th	60	ZIB2511A.xls	13.8 +/- 16.9	108.7
Tix Mills	End of the village	Backgroung	Tuesday 25th	30	ZIB2511C.xls	0.1 +/- 0.1	0.5
Amber Rose	Site	Amalgamation with bowl concentrator	Wednesday 26th	60	ZIB2711A.xls	3.5 +/- 1.2	12.9
Amber Rose	Village	Backgroung	Thursday 27th	30	ZIB2711B.xls	0.3 +/- 0.2	1.4
Amber Rose	Site (close to CN tanks)		Thursday 27th	15	ZIB2711C.xls	1.1 +/- 1.2	14.1
Amber Rose	Site (close to drag clarificator)	Top of the slime pond	Thursday 27th	15	ZIB2711D.xls	5.8 +/- 4.5	35.1
Amber Rose	Site (close to drag clarificator)	Top of the coarse pile	Thursday 27th	15	ZIB2711E.xls	2.6 +/- 1.6	8.5
Amber Rose	Site	40 cm above the bowl concentrator	Thursday 27th	7	ZIB2711F.xls	1.6 +/- 1.2	7.3
Amber Rose	Site	on the top of the bowl concentrator	Thursday 27th	7	ZIB2711F.xls	18.6 +/- 10.6	66.7
Amber Rose	Site	closed to the office building	Thursday 27th	15	ZIB2711G.xls	0.4 +/- 0.5	3.7
Even millings	Site (in extractor room)	roasting	Thursday 27th	10	ZIB2311G.xls	34.4 +/- 30.3	122.3

Illustration 38 – List of the different air monitoring carried out in November 2003.

For background air monitoring in open (spaces) the intake hose of the RA 915^+ analyser was held approximately 1-1.2 m above the ground.

Comment: the monitoring were performed with the LUMEX $RA915^+$ under field conditions. *At this stage, there is no existing validation of this device for air monitoring in the literature or performed by BRGM. Thus Hg air concentrations are consistent for comparison site by site, but absolute Hg concentration values have to be considered as indicative values.*

4.2.1. Tix site

a) Tix mill – amalgamation on a copper-plate

At Tix mill, two amalgamation operations were monitored. In the first operation, the miners were working slower than usual (~40 min) to take time to explain the process to us, so each step could have been analysed in detail. During the second operation, we did not interfere so that the whole process took about half the time of the first operation. Consequently the measures taken during the second operation are more representative of the real conditions.

The mercury concentrations measured are given for each processing step, but they should be considered cautiously (illus. 39 et 40). Four copper-plates were working simultaneously, but not at the same processing step. The RA 915^+ unit was installed between two copper-plates. Mercury was present everywhere.

	Mercury in µg m^{-3}				
	M	σ	Q_{50}	min	max
First amalgamation	11.8	16.8	3.9	-0.6	87.9
1: Pulp running on the copper-plate	23.3	14.7	14.7	1.2	83.9
2: Scraping amalgam with rubber scraper	15.5	18.4	9.0	-0.5	66.9
3: Opening of the amalgam container	23.6	16.2	19.7	1.3	87.9
4: Cleaning with sand	5.1	7.5	2.4	-0.5	42.5
5: Water running on the copper-plate	2.4	1.9	2.2	-0.5	12.5
6: Cleaning with gravel	8.7	9.6	5.1	-0.7	54.9
Second amalgamation	18.1	20.3	10.6	-0.4	107.7
7: From phases 2 to 3	21.6	25.1	10.0	-0.4	107.7
8: From phases 4 to 5	15.5	15.3	10.8	-0.4	90.2

The mercury concentration statistics (µg m^{-3}) were calculated separately for the different phases of the process using the copper-plate: average value (m), median (Q_{50}), standard deviation (σ), minimum (min) and maximum (max). Two amalgamations were performed: the first from phase 1 to 6 and the second amalgamation from phase 7 and 8. The intake hose of the RA- 915^+ analyser was positioned on the top of the copper-plate except during the phase 3 where it was held below the copper-plate.

Illustration 39 - Mercury monitoring in air at Tix mill.

The values are higher for the second amalgamation because no interruption was observed during the process. The mercury concentration is lower when the pulp is running and when the copper-plate is covered with sand. Under these conditions, mercury is not in direct contact with the air.

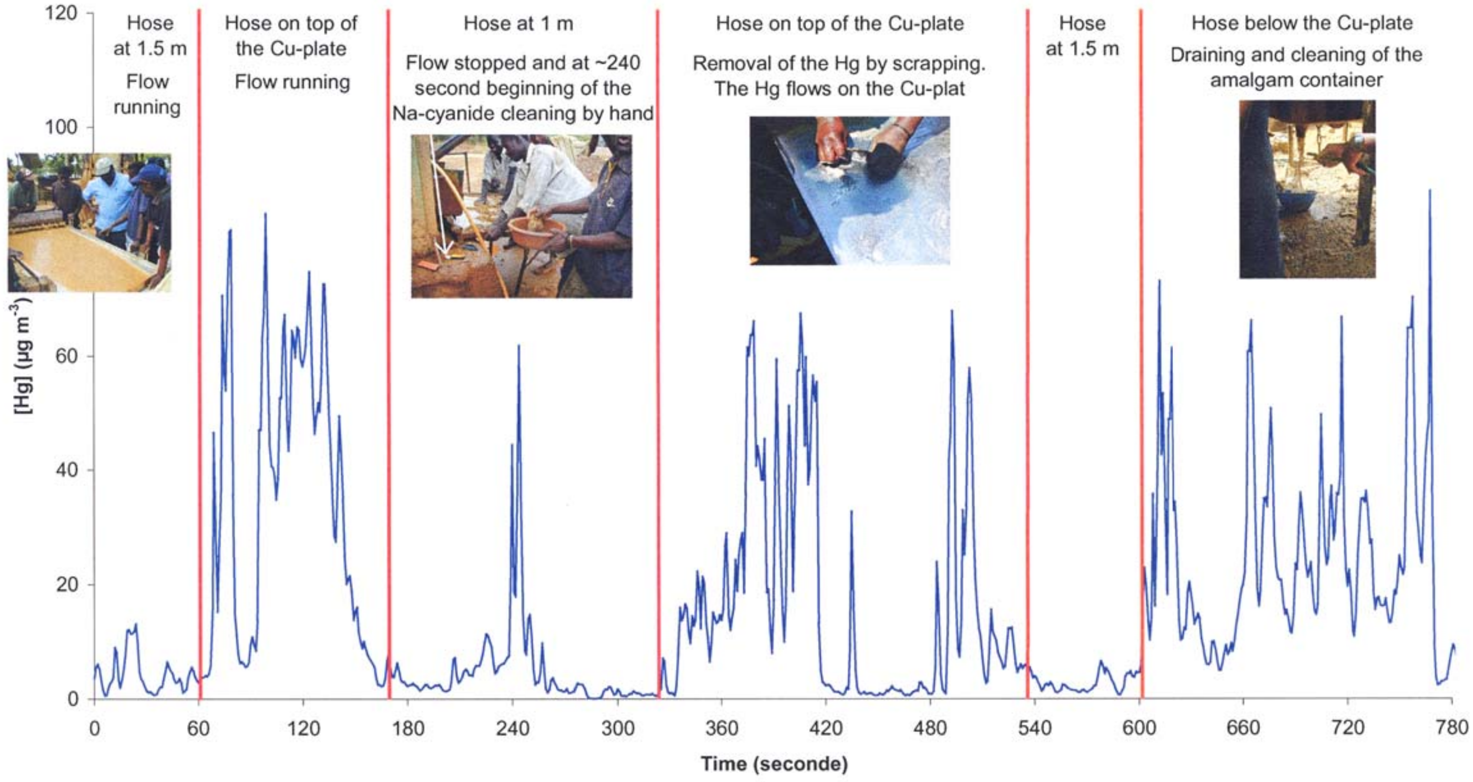


Illustration 40 - Monitoring on the copper-plate at Tix mill (ZI2511A.xls).

During the second amalgamation, the miners (two to four individuals) were very active around the copper-plate. Sometimes, when they were scraping the amalgam, we observed liquid mercury flowing on the copper-plate.

The average mercury concentration around the copper-plates is 18.1 ± 20.3 µg m^{-3}, with a maximum of 107.7 µg m^{-3}. Two meters from the copper-plate, the mercury concentration decreases to 1.7 ± 1.5 µg m^{-3}, with a maximum of 5.5 µg m^{-3}.

During the one-hour monitoring session at Tix mill, mercury condensation was observed on the metal unit of the RA 915^{+} analyser. We even could collect a few Hg droplets on the instrument and on the metal box (illus. 41A and B).

A: Mercury droplets on the LUMEX B: Mercury droplets on the metal box

Illustration 41 - Deposit of mercury droplets during the air monitoring of the copper-plate at Tix mill.

b) Tix village

Three background air monitoring sessions were conducted inside the village and in its vicinity. The first one took place on Sunday, November 23rd, 2003, 150 m from the stamp mill and at 800 m, in the north western part of the village. The stamp mills were not working, and no miners were working in the area. The average mercury concentration measured at this time was 0.2 ± 0.1 µg m^{-3}, with a maximum of 0.43 µg m^{-3}. We measured the same concentration on a working day at the end of the village (~1000 m down from the stamp mills) (illus. 42 and 43).

	Mercury in µg m^{-3}				
	m	σ	Q_{50}	min	max
Background 800 m (north) up to the village	0.2	0.1	0.1	0.0	0.4
Background in the village (meeting room)	1.0	0.7	0.9	0.0	7.5
Background at the south part of the village	0.1	0.1	0.1	0.0	0.5
Roasting operation in the village	9.9	12.0	5.8	-1.8	78.2

The mercury concentration statistics (µg m^{-3}) were calculated separately for the different monitoring operations inside and in the vicinity of the village. Average value (m), median (Q_{50}), standard deviation (σ), minimum (min) and maximum (max).

Illustration 42 - Mercury monitoring in air at Tix village.

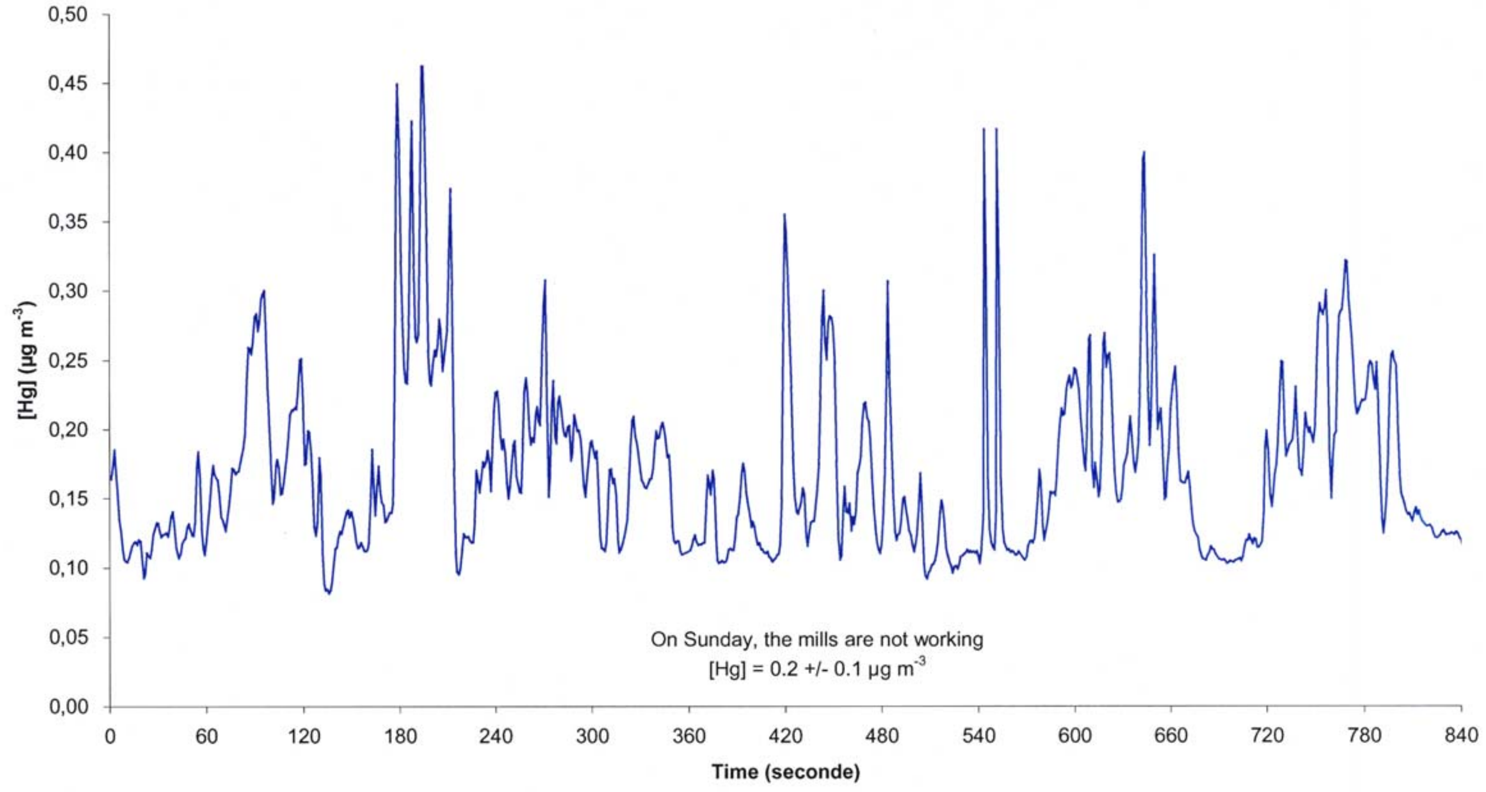


Illustration 43 - Monitoring in an open area 200 m from Tix mill (ZIB2311F).

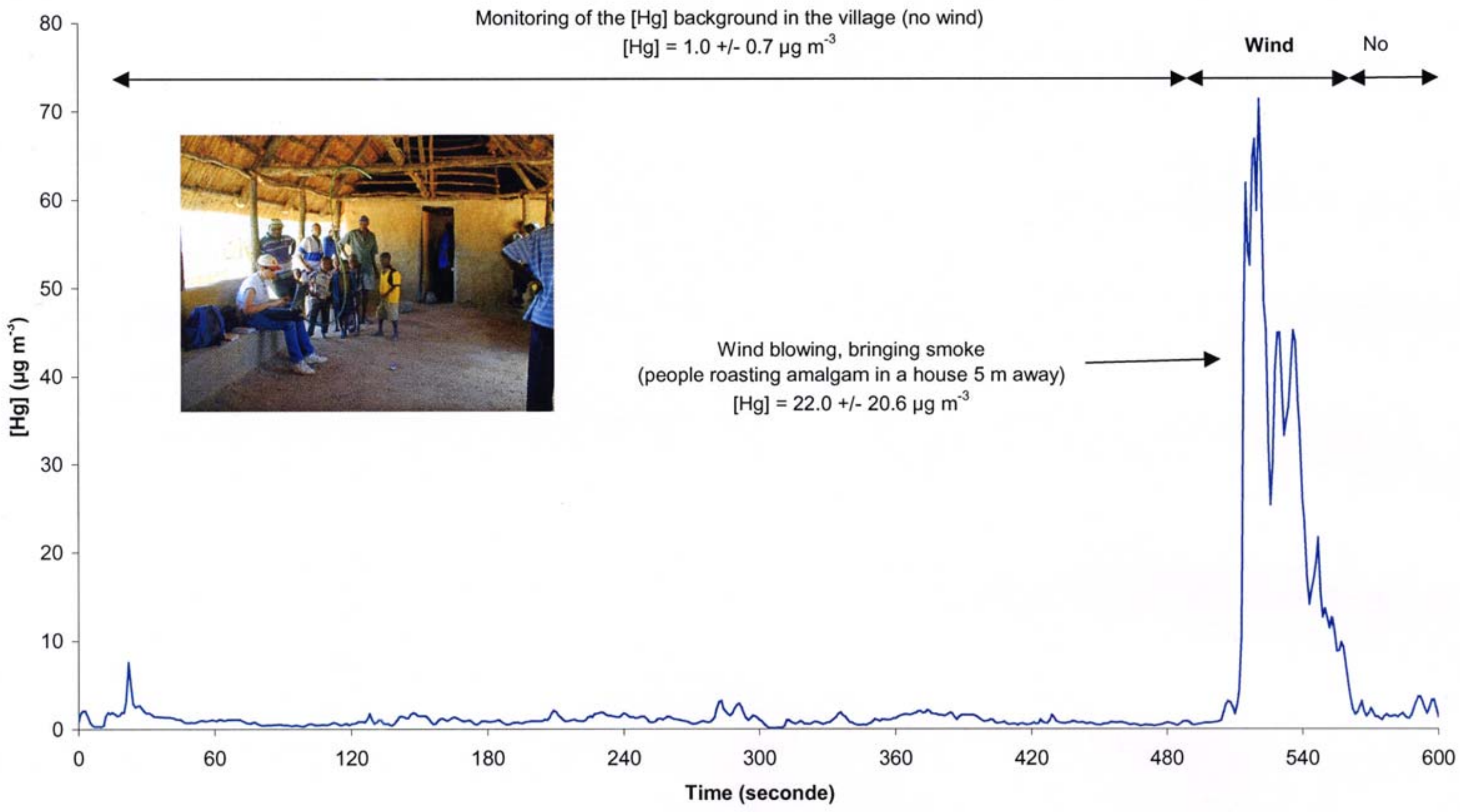


Illustration 44 - Monitoring in the bar house in the village close to Tix mill (ZIB2311D.xls).

The third measurement was conducted in the middle of the village, in a meeting-room (bar). The walls were less than 1 m high, with a 1 m open space between the walls and the roof. The intake hose of the RA 915^+ analyser was suspended from a wooden beam to analyse the air the people in the room were breathing.

The average mercury concentration was 1.0 ± 0.7 µg m^{-3}, with a maximum of 7.5 µg m^{-3} (illus. 44). Suddenly, the mercury concentration increased abruptly to reach a maximum of 78 µg m^{-3}, as a result of a villager roasting an amalgam in his kitchen, close to the meeting-room.

4.2.2. Amber Rose site

a) Amber Rose mill

Air monitoring was carried out on the top of two bowl-concentrators, one with a cover and one without.

No difference was observed in the mercury concentration for these two conditions. The average mercury concentration, at the top of the bowl-concentrator is 15.6 ± 10.6 µg m^{-3}, with a maximum of 66.7 µg m^{-3}. At 0.4 m above or 1 m away, the mercury concentration decreases to 1.6 ± 1.5 µg m^{-3}, with a maximum between 7.3 to 8.9 µg m^{-3} (illus. 45).

	Mercury in µg m^{-3}				
	m	σ	Q_{50}	min	max
On top of the bowl-concentrator	15.6	10.6	16.2	0.2	66.7
0.4 m above the bowl-concentrator	1.6	1.2	1.3	0.2	7.3
1 m from the bowl-concentrator	1.7	1.8	1.1	0.0	8.9
Top of the slime pond (fine tailings)	5.7	4.5	4.4	0.0	35.1
Top of the coarse tailings stockpile	2.2	1.6	1.7	-0.1	8.1
Between the CN tanks and the C columns	1.1	1.2	0.9	0.0	14.1

The mercury concentration statistics (µg m^{-3}) were calculated separately for the different monitoring events on the site. Average value (m), median (Q_{50}), standard deviation (σ), minimum (min) and maximum (max).

Illustration 45 - Mercury monitoring in air at Amber Rose mill.

The mercury concentration increases around the slime pond and the coarse stockpile to decrease again 20 m away from the bowl-concentrator between the carbon (C) columns and the cyanide (CN) tanks (illus. 46).

b) Amber Rose village

At an equal distance from the stamp mills, we held two background monitoring sessions; one at the sites entrance and one inside the village.

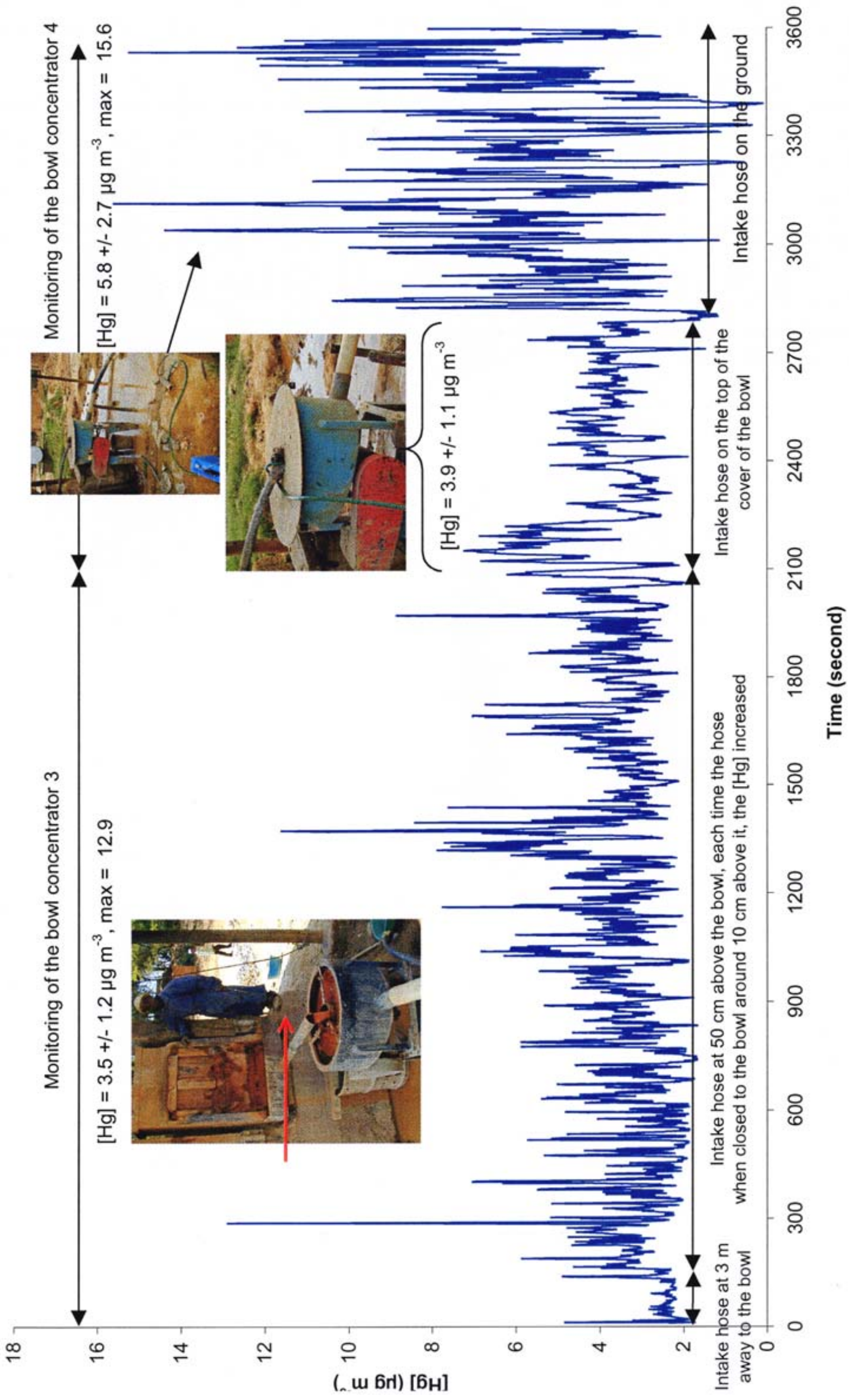


Illustration 46 - Air monitoring at Amber Rose mill (ZIB2711A.xls).

The mercury concentrations are lower than in the mill area (illus. 47). The average mercury concentration inside the village is 0.2 ± 0.2 µg m^{-3}, with a maximum of 1.3 µg m^{-3}. At the site entrance, the average is 0.4 ± 0.5 µg m^{-3}, with a maximum of 3.6 µg m^{-3}. We did not see anybody crushing or roasting inside the village at the time of our visit. The manager of the milling centre told us that the miners burn amalgams on wood fires in the milling centre in an open area under trees near the stamp mill.

	Mercury in µg m^{-3}				
	M	σ	Q_{50}	min	max
Inside the village	0.2	0.2	0.1	-0.1	1.3
Entrance to the site	0.4	0.5	0.2	-0.1	3.6

The mercury concentration statistics (µg m^{-3}) were calculated separately for the monitoring operations inside and around the village. Average value (m), median (Q_{50}), standard deviation (σ), minimum (min) and maximum (max).

Illustration 47 - Mercury monitoring at air Amber Rose village.

4.2.3. Even Milling Centre

The monitoring sessions were conducted inside the roasting room during a burning event (illus. 48). The intake hose of the RA 915$^+$ analyser was installed on the shoulder of the person in charge of the roasting, almost 0.4 m from the extractor opening. The mercury concentration in the room was low: 0.8 ± 0.6 µg m^{-3}.

The mercury concentration increased sharply to reach a maximum of 122 µg m^{-3} when we put the intake hose close to the extractor opening. *We could not do any additional monitoring because there was too much mercury in the air and the instrument was saturated and needed to be cleaned.*

	Mercury in µg m^{-3}				
	M	σ	Q_{50}	min	max
Inside the roasting room	0.8	0.6	0.7	-0.3	3.6
Close to the extractor	34.4	30.3	27.3	-5.1	122.3

The mercury concentration statistics (µg m^{-3}) were calculated separately for the monitoring sessions inside the roasting room. Average value (m), median (Q_{50}), standard deviation (σ), minimum (min) and maximum (max).

Illustration 48 - Mercury monitoring of air at Even Milling Centre.

4.2.4. Main outcomes for air monitoring

A few individuals were involved with the use of the copper-plate. However, the miners were continuously close to the copper-plate. During the process with the bowl-concentrator, nobody was close to the bowl; the closest person was the miner filling the stamp, 3 m away from the bowl.

In the villages, the average mercury concentrations in the air were below 0.4 and 1.0 µg m^{-3} for outdoor and indoor conditions, respectively. When the villagers were roasting at home, the mercury concentrations could reach 10 µg m^{-3} but only for less than 10 min. This time exposure is very short compared to WHO guideline; exposure limit for workers exposed to mercury is 25 µg m^{-3} average air concentration for an 8 hour shift (WHO, 1994).

There was an important difference between the sites using copper-plates and the sites using bowl concentrators.

If the average mercury concentrations in air were similar in both processes (~20 µg m^{-3}), the bowl concentrator seemed to be safer to use because nobody needed to be close to the concentrator during the process. The miners were breathing high mercury contents "only" when they were flushing the concentrate at the end of the process. Unfortunately, no flushing was performed during the afternoon we were monitoring air quality at Amber Rose. Miners using bowl concentrators were exposed to high mercury concentration maybe once or a few times per day.

When miners used copper-plates, they were continuously breathing high mercury concentrations (scrapping, scrubbing and rinsing with solution Na-cyanide solution).

Time exposure of the miners ranges from a few hours to a day and the average mercury concentration was ~20 µg m^{-3}. These values are close to the WHO (1994) exposure limit for workers (25 µg m^{-3} average air concentration for an 8 hour shift). We do not know how often the miners come to the site to grind and amalgam their ores.

At Even Milling Centre, the air monitoring data from inside the roasting room indicated a good efficiency of the air extractor. The person in charge of the roasting was exposed to average air concentrations lower than 0.8 µg m^{-3}. This person was involved in roasting activities for a few hours a day and 5 or 6 days a week. This average mercury concentration exposure was low compared to WHO limits (1994).

It must be pointed out that no air monitoring was done inside the house of the villagers because they did not allow us to come inside. They let us sample around their house and in their garden only.

4.3. FISH SAMPLES

4.3.1. Fish characterisation

Six different species were collected, with a total of 52 individuals: Tillapia zilli, Tillapia rendali, Oreochromis macrochir, Laboe cylindricus, Brycinus imberi and Micropterus salmonides (illus. 49 and 50).

Sampling point	1	2	3	4	5	6	TOTAL
Number of species	1	3	4	1	1	1	6
Number of fish	10	11	5	10	10	6	52

Illustration 49 - Balance of the sampled fish species and numbers, from the six sampling points.

Tillapia zilli
Tillapia rendali

Laboe cylindricus
Oreochromis macrochir

Micropterus salmonides
Brycinus imberi

Illustration 50 - Photographs of the six different species caught in the Muzvezve River.

4.3.2. Global biometric characteristics and mercury contamination levels in fish

Mean biometric data (total body weight, standard length and mercury concentrations measured in the dorsal muscle) are shown in illustration 51 for the six sampling points and the different species. Biometric data and mercury concentrations measured in the 52 individual fish are given in appendix 3.

Family	Genus	Species	Food regime	Sampling point	Standard length (cm)	Body weight (g, fw)	[Hg] µg g^{-1} (fw)	N
Characiformes	Brycinus	Brycinus imberi	Omnivorous carnivorous	5	13 ± 0	59 ± 10	0.88 ± 0.07	10
Cypriniformes	Cyprinidae	Labeo cylindricus	Omnivorous herbivorous	2	12 ± 1	43 ± 13	0.19 ± 0.01	4
Cypriniformes	Cyprinidae	Labeo cylindricus	Omnivorous herbivorous	3	14	50	0.26	1
Gnathostomes	Centrachidae	Micropterus salmonides	Only Carnivorous	2	14 ± 1	55 ± 7	0.83 ± 0.18	2
Gnathostomes	Centrachidae	Micropterus salmonides	Only Carnivorous	6	18 ± 1	112 ± 19	1.13 ± 0.20	6
Perciforme	Cichlidae	Oreochromis macrochir	Omnivorous herbivorous	3	12	50	0.19	1
Perciforme	Cichlidae	Oreochromis macrochir	Omnivorous herbivorous	4	16 ± 0	129 ± 17	0.04	10
Perciforme	Cichlidae	Tilapia zillii	Omnivorous herbivorous	1	8 ± 1	33 ± 5	0.07 ± 0.01	6
Perciforme	Cichlidae	Tilapia zillii	Omnivorous herbivorous	2	15 ± 5	118 ± 119	0.15 ± 0.03	5
Perciforme	Cichlidae	Tilapia zillii	Omnivorous herbivorous	3	10 ± 2	30 ± 10	0.31 ± 0.04	2
Perciforme	Cichlidae	Tilapia rendali	Omnivorous herbivorous	3	11.8	40	0.36	1

Data are means ± standard error and N = number of fish.

Illustration 51 - Mean biometric data (standard length and body weight), mercury concentrations (wet weight) in the dorsal muscle and diet for the fish species collected in the six sampling points.

Only one or two species were found per sampling location except at spot n° 2, where three species were caught (illus. 52).

Genus	Species	Sampling spot	N
Cyprinidae	Labeo cylindricus	2	4
		3	1
Centrachidae	Micropterus salmonides	2	2
		6	6
Cichlidae	Oreochromis macrochir	3	1
		4	10
Cichlidae	Tilapia zillii	1	6
		2	5

Illustration 52 - Fish species common to the sampling points.

The fish caught were very small, with only one fish among the 52 longer than 20 cm. Size differences emerged between fishes of the same species collected at different sampling points, probably due to differences in age and/or nutritional intake. Thus, marked differences appeared in Tilapia zillii between body weights with 32.5 ± 5.0 g fresh weight value at sampling spot 1 and 330.0 g fresh weight value for a big specimen at sampling spot 2, the other fishes being all in the same range at that site: 65.0 ± 12.9 g fresh weight.

Mercury contamination levels in different fishes ranged from low to high; however, average concentration for the 52 fishes collected was 0.41 ± 0.46 µg g^{-1} on a fresh weight basis. Assuming that a value of 5 is attributed to the fresh weight / dry weight ratio, we can consider that safety standard defined by the WHO is 0.50 µg g^{-1} on a fresh weight basis or 2.50 µg g^{-1} on a dry weight basis (WHO, 1990).

Thus, mean concentrations for species at specific sampling locations ranged from 0.04 ± 0.002 µg g^{-1} fresh weight for Oreochromis macrochir (n = 10), at sampling point 4, to 1.13 ± 0.49 µg g^{-1} fresh weight for Micropterus salmonides (n = 6) at sampling point 6 (illus. 53).

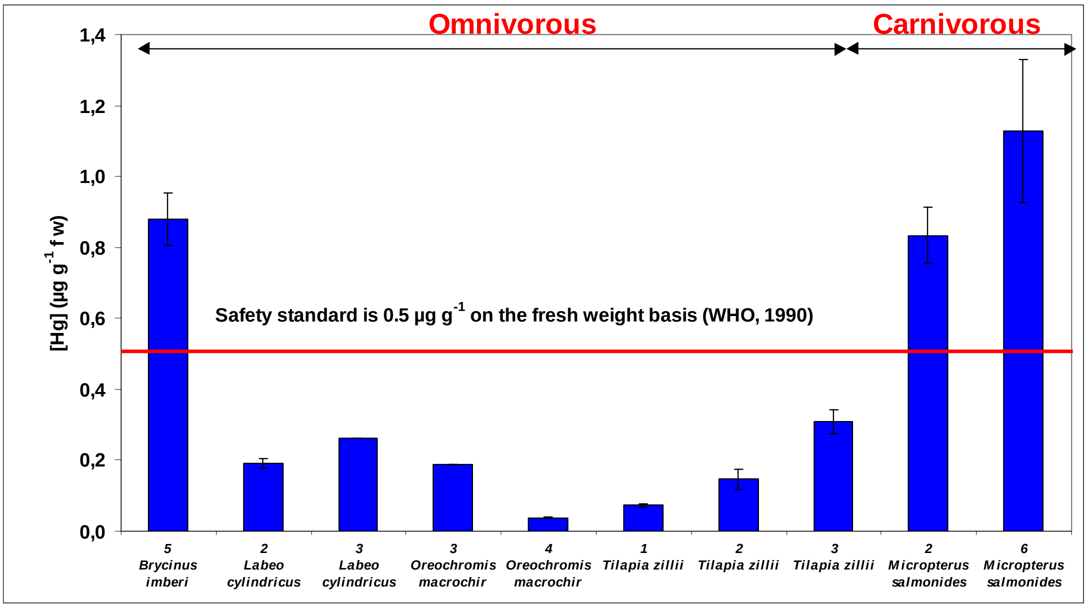


Illustration 53 - Average mercury concentrations in the muscle of all the fish species collected.

4.3.3. Mercury contamination levels according to the trophic level of fish and to the sampling sites

Data from sampling point 2 downstream from Claw Dam (illus. 54) revealed differences between fish species according to their food regime. The average concentration for the carnivorous species (Micropterus salmonides) was 0.83 ± 0.11 µg g^{-1} fresh weight. This is six to seven times higher than the concentration determined for the omnivorous species. One of them has a high value of 2.00 µg g^{-1}.

These results support the hypothesis that mercury concentrations measured in fish muscle in contaminated areas vary depending on the diet of the species and its position along the trophic chain as already reported in literature (Durrieu *et al.,* 2004; Roulet and Maury-Brachet, 2001; Veiga *et al.,* 1999; Wiener *et al.,* 2002).

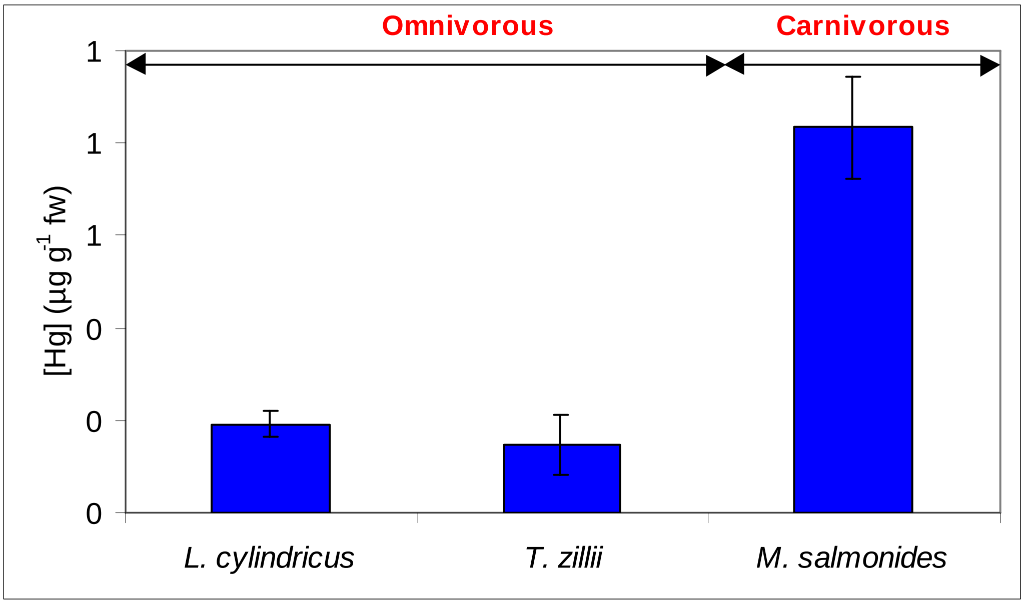


Illustration 54 - Mercury concentrations in the muscle of the 3 fish species collected from the sampling spot 2.

The highest mean Hg concentrations (average of 1.05 µg g^{-1}) were found in predaceous Micropterus salmonides followed by the omnivorous species Brycinus imberi, Tilapia rendali, Labeo cylindricus, Tilapia zillii and Oreochromis macrochir (0.88, 0.36, 0.21, 0.12, 0.05 µg g^{-1}, respectively). The high Hg level (0.88 µg g^{-1}) shown by omnivorous species Brycinus imberi might possibly be due to the local environment (shallow water and close proximity to numerous mines, or panning areas (illus. 12) and to the fact that its diet is closer to a carnivorous fish regime than the other omnivorous fish which are more herbivorous (app. 4).

Relationships between fish body weights and Hg concentrations in the muscle do not show differences for each species collected (illus. 55). These relationships are established from a small number of samples, and therefore cannot be considered as representative. Bioaccumulation levels appeared independent of the fish weight in relation probably with the small number of samples that do not allow to define a reliable statistical relationship. But mercury concentrations in fish seemed to depend more on their diet than on where they were fished. Thus, in Illustration 56, two distinct populations can be identified according to diet in this study. This comment is not confirmed for the omnivorous species Brycinus imberi considered as similar to carnivorous, as already mentioned above (app. 4).

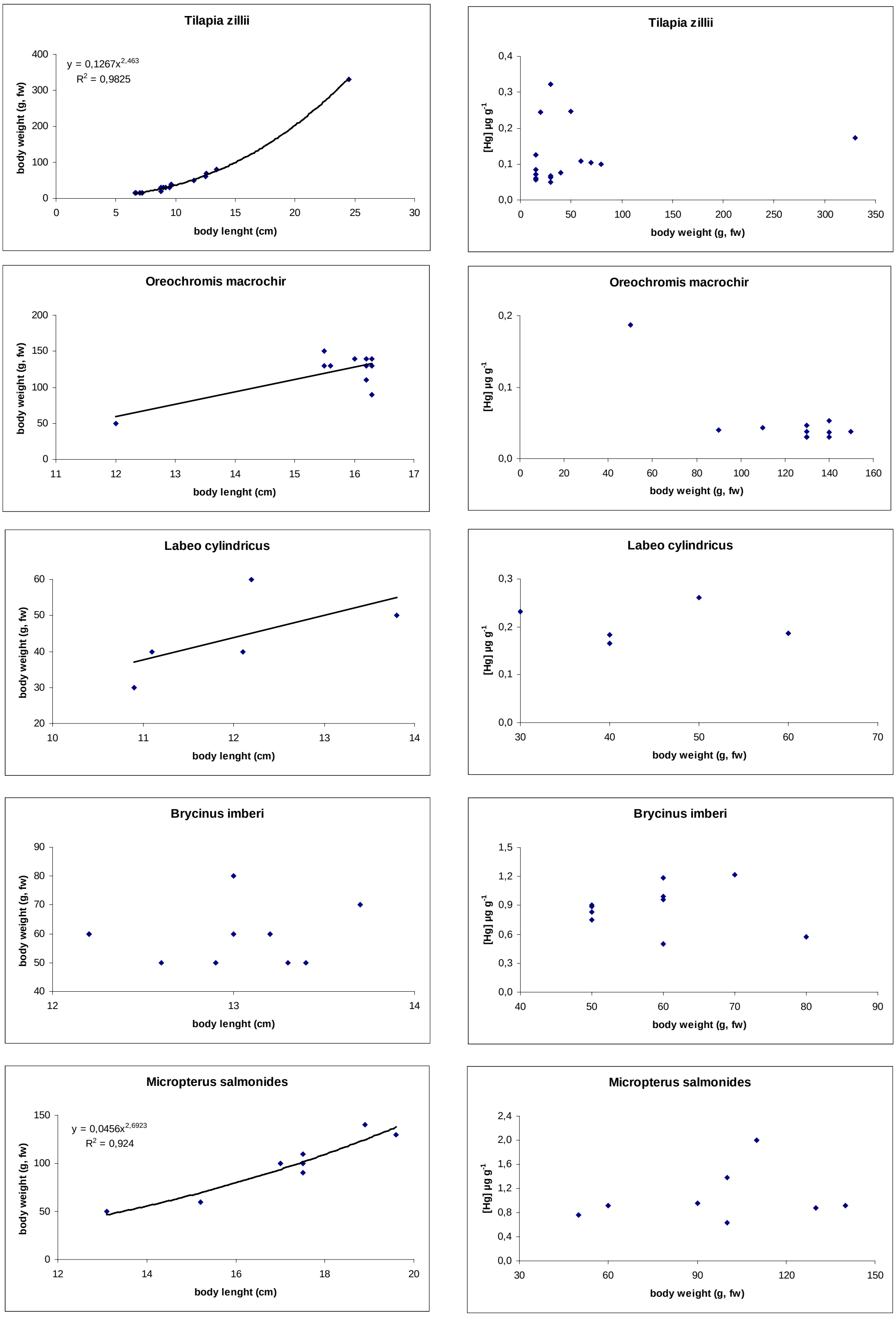


Illustration 55 - Relationships between fish body weight and standard length and between fish body weight and mercury concentration in muscle (fresh weight) of all the species.

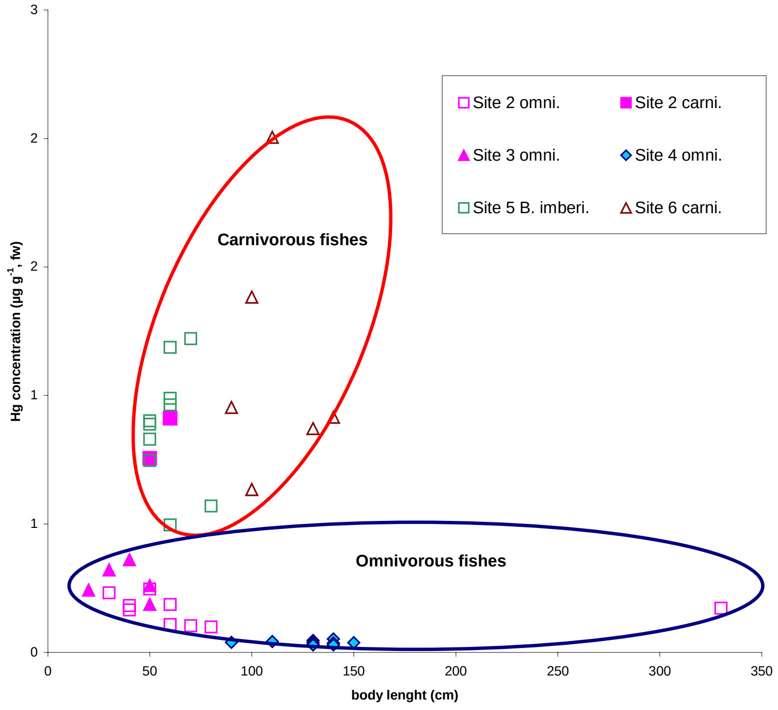


Illustration 56 - Mercury concentrations in the muscle of all fish species collected from the six sampling spots, relationships between fish body weight and mercury concentrations in muscle.

However, numerous earlier field studies conducted in European countries and North-America/Canada had shown a significant positive correlation between Hg concentrations in fish muscle and biometric criteria (body weight or standard length), suggesting an increase in bioaccumulation as a function of the age of the fish. More recent studies performed in Amazonia (South America: Brazil and French Guiana) reported inconsistent results (no positive or negative correlation) between bio-accumulation and fish species, food regime or developmental stages (alevins/adults) (Roulet *et al.,* 1999; Frery *et al*., 2001; Durrieu *et al*., 2004).

4.3.4. Comparison between mercury concentrations in fish muscle in this study (Zimbabwe) and in other artisanal gold mining sites

Mercury concentrations in fish muscle and biometric criteria (standard length and body weight) are shown in illustration 57 for carnivorous species collected in Sudan, Zimbabwe and Lao PDR, during the UNIDO surveys (2003/2004). Results point towards a high contamination levels in fish in Zimbabwe, with mean Hg concentrations ten times greater than in Sudan for fish of similar size.

Fish caught in the Mekong River and its tributary (Nam Ou) in Lao PDR were also less contaminated despite the fact that the body weight of fish in Lao PDR is

14 times bigger than the fish in Zimbabwe. However, the quantities of mercury used in artisanal gold mining areas in Zimbabwe are much higher compared to those used in Lao PDR and Sudan, with about 1 kg of Hg used per milling centre and per day in Zimbabwe and 1 kg of Hg used per village per year only in Lao PDR.

Country	Family	Genus	Species	Food regime	Standard length (cm)	Body weight (g g^{-1})	[Hg] (µg g^{-1})	N
Sudan	Alestiidae	Hydrocinus	Forskalii	Carnivorous	21.3 ± 1.5	116.4 ± 21.4	0.139 ± 0.015	5
Sudan	Centroponidae	Lates	Niloticus	Carnivorous	14.1 ± 0.7	55.7 ± 8.7	0.142 ± 0.010	6
Sudan	Mornyridae	Marcusenius	Senegalensis	Carnivorous	21.0 ± 1.0	105.0 ± 7.0	0.021 ± 0.005	2
Sudan	Mornyridae	Mormyrus	Nicoticus	Carnivorous	24.0 ± 1.0	122.0 ± 16.0	0.020 ± 0.001	2
Sudan	Schilbeidae	Schilbe	Intermedius	Carnivorous	15.6 ± 1.1	47.2 ± 10.1	0.081 ± 0.014	5
Sudan	Schilbeidae	Schilbe	Intermedius	Carnivorous	23.4 ± 0.7	133.5 ± 3.6	0.108 ± 0.017	4
Zimbabwe	Centrachidae	Micropterus	Salmonides	Carnivorous	14.15 ± 1.49	55.0 ± 7.1	0.834 ± 0.110	2
Zimbabwe	Centrachidae	Micropterus	Salmonides	Carnivorous	18.00 ± 1.01	111.67 ± 19.41	1.127 ± 0.494	6
Lao PDR			Kop	Carnivorous	38	400	0.220	1
Lao PDR			Oad	Carnivorous	53	1820	0.038	1
Lao PDR			Dang Deng	Carnivorous	45.5	610	0.120	1
Lao PDR			Kop	Carnivorous	48.5	680	0.489	1
Lao PDR			Sangoa	Carnivorous	70	3280	0.242	1
Lao PDR			Kheung	Carnivorous	23	160	0.065	1
Lao PDR			Sangoa	Carnivorous	52.5	970	0.139	1

Illustration 57 - Comparison between mercury concentrations in carnivorous fish collected during UNIDO missions in Sudan, Zimbabwe and Lao PDR.

In a similar UNIDO study, in an artisanal gold mining area in Ghana (Babut *et al.,* 2003), no relationship was established either between fish tissue mercury concentration and fish size. Contamination levels of fish muscle ranged between 0.02 and 0.15 µg g^{-1} fresh weight, and are comparable to Lao PDR results but lower than Zimbabwe results.

Data from several rivers in French Guiana (Durrieu *et al.,* 2004) show higher contamination levels, with mercury concentrations in the muscle of carnivorous/ piscivorous species reaching maximal values close to 3 µg g^{-1} fresh weight, with almost all piscivorous fishes exceeding the WHO safety limit (0.5 µg g^{-1}, wet weight).

Other studies conducted in gold mining areas in Colombia, Tanzania, France and Brazil showed, on the other hand, a wide range of mercury contamination levels in fish muscle (Alho and Viera, 1997; Bidone *et al.,* 1997; Castilhos *et al.,* 1998; Fréry *et al.,* 1999; Ikingura and Akagi, 1996; Malm, 1998; Olivero and Solano, 1998 and Olivero *et al.,* 1998) varying between less than 0.01 µg g^{-1} fresh weight in some species in Colombia (Olivero and Solano, 1998) to more than 16 µg g^{-1} in soga species in Tanzania (Ikingura and Akagi, 1996).

4.3.5. Conclusion

The range of sample size per species being too limited and consequently specific to one range of weight and age, the results can not be interpreted as in term of Hg bioaccumulation factor per species.

One third of the fish (18/52) exceeded the WHO safety limit of 0.5 µg g^{-1} fresh weight. The average Hg concentration was 0.41 ± 0.46 µg g^{-1}. The average concentration for carnivorous species was 1.05 ± 0.44 µg g^{-1}, but a young specimen reached

2 µg g^{-1} despite its light weight (110 g), whereas the oldest fishes could weigh up to 10,000 g. One omnivorous species (Brycinus imberi) exceeded the WHO safety limit, but, on the one hand, all the fish of this species were caught at the same point characterised by high contamination levels and it had a particular diet composed predominantly of animal prey rather than vegetal.

If the results of the small-sized samples are representative of the area, it is very likely that *most of the fish consumed by the local population along the Muzvezve River is significantly contaminated by mercury and above WHO safety standard* (*i.e.* Hg > 0.5 µg g^{-1} fresh weight).

5. Evaluation of exposure to Hg

During this study, two types of “hot spots” were identified, both defined as sites containing high Hg concentrations relative to the local contamination in soils and sediments.

The first one, called a single-source hot spot, corresponds to a well-delimited pollution source and is associated with a specific technique used in gold processing, such as amalgamation, roasting… In our case, there is no hot spot with an unknown source. The area concerned is small – a few hundred square meters – but the consequence in terms of human exposure is potentially very important for the population of miners.

The second one, called a multi-source hot spot, corresponds to a wider area characterised, in most cases, by several but associated single-source Hot Spots. The concerned area is much more extensive than in the previous case, and the associated pollution can affect a regional level, spreading far through the mining and milling area with environmental consequences in a radius exceeding the tens of kilometer scale. The contamination is more diffuse and may affect the whole population living in the area and the aquatic environment at a regional scale.

5.1. SINGLE-SOURCE HOT SPOTS

The illustration 58 summarises the main contamination sources of Hg in the gold processing system and the potential routes of exposure.

Three main single-source hot-spot are found:

- Copper-plate areas, are the most contaminated spots as observed in the tailings such as at Tix, New Plus, Etena, Summit and Glasgow mills, but also in the surrounding soils within a radius of 10 to 20 m. Contamination of soils does not seem to disperse very far from these emission sources. In contaminated places, the Hg values in the soils are ten to four hundred times the local background that is 0.02 to 0.12 mg kg^{-1}. This is confirmed by the high Hg content in the dust or superficial layers collected in Tix and Glasgow mills. The air monitoring carried out at Tix mill shows a Hg concentration sixty times higher than the local background (1.7 µg m^{-3}) during the operations on the copper-plate. By comparison, at Amber Rose, where a bowl-concentrator is operated, the Hg concentration in the air reaches 67 µg m^{-3} that is forty times the local background. At Tix, the loss of Hg in these areas follows two pathways;
  - · first, the tailings, which flow on the copper-plate throughout the process, and
  - · second, the air, mainly at the end of the process, when the miners are scraping and washing the copper-plate.

  It is also in this area that the concentration of workers (miners and millers) is the most important during the process.

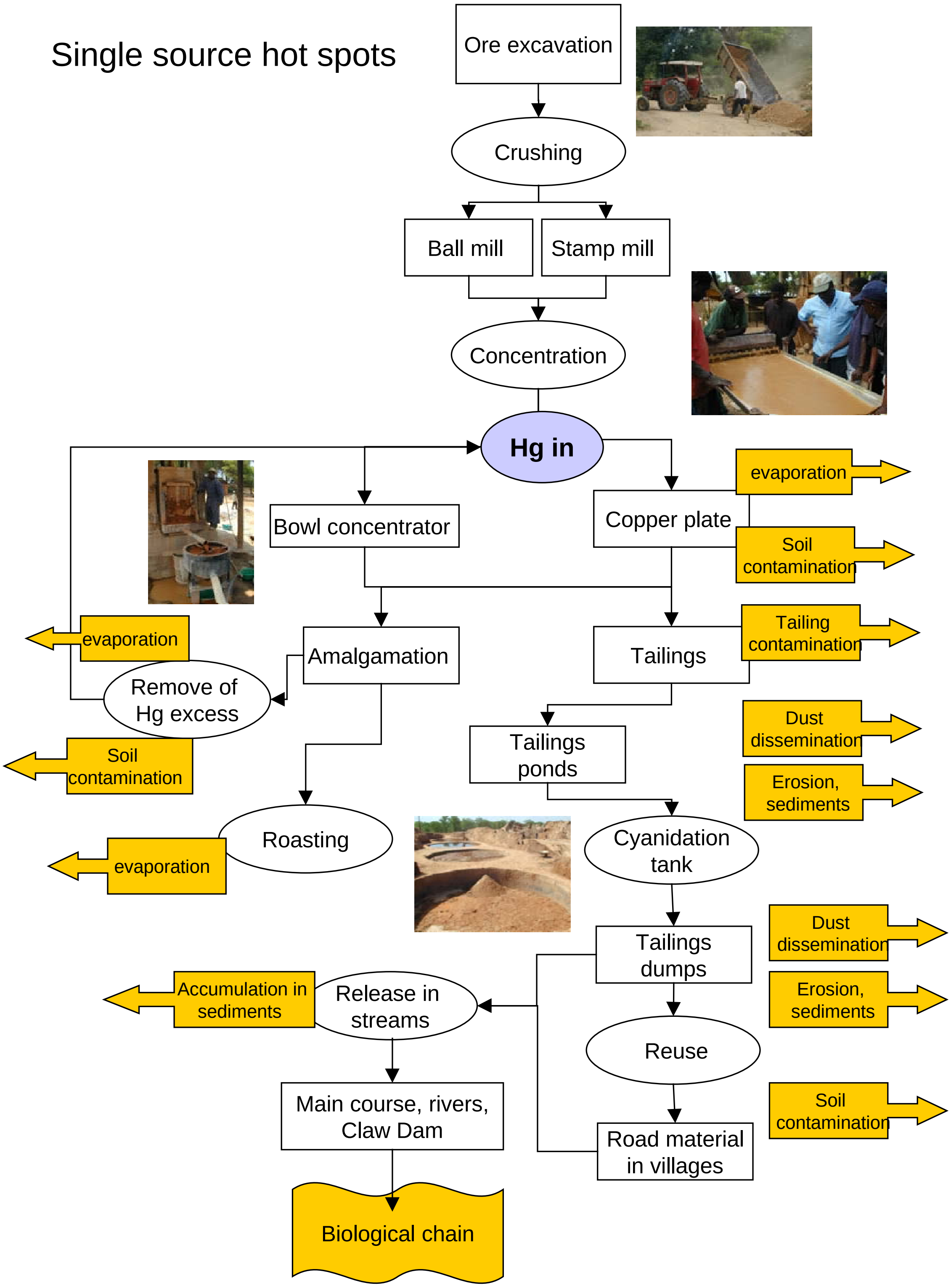


Illustration 58 - Main contamination sources and route to Hg exposure.

- The second single-source hot spot corresponds to:
  - · the free amalgamation sites that are widely distributed along the drainage but also close to the water tank in the milling center,
  - · the bowl-concentrator surrounding area in the mill centre, where miners are up-grading manually the amalgam mixed with tailings collected at the bottom of the bowl-concentrator (Even Milling Centre), and
  - · amalgamation sites such as in the villages (Tix) or on the bank of a reservoir (Claw Dam) or river (small stream or Muzvezve River) where miners and panners use pans to concentrate the gold particles and plastic basins to amalgamate the gold.

  At Even Milling Centre, which is one of the better and cleaner milling centres, the Hg concentration in soil (23.55 mg kg^{-1}) is more than one hundred fifty times the local background 5 meters away from the amalgamation shelter. The dust collected within a radius of 3 m on the concrete floor around the workers, who perform amalgamation under the shelter, reaches 74.60 mg kg^{-1} that is five hundred times the background.

  At the Claw Dam bank, downstream from Tix village, the Hg concentration in sediments can reach 8 to 10 mg kg^{-1} that is twenty times the local background at the sites of digging, panning and amalgamation activities. These kinds of sites are favourable environments to generate methylmercury (MeHg). These sites are also known as fishing spots, where fish with high Hg levels were collected.

- The third single-source hot spot corresponds to the free roasting sites or roasting rooms. High concentrations of Hg were measured during the air monitoring within a radius of 1 to 3 meters around the free roasting sites located in the middle of the village, such as at Tix. The Hg concentration reaches nine to eighty times the local background of air (0.2 µg m^{-3} outside the copper-plate area). Even when a specific room is built, with specific equipment including an air extractor, to roast the customers' amalgam, the risk is still present, as at New Plus, where the dust collected on the concrete floor close to the exhaust pipe reaches 50.53 mg kg^{-1} Hg. This place is located at the entrance of the mill where many workers are walking around or waiting.

5.2. MULTI-SOURCE HOT SPOTS

Among the sites studied, the multi-source hot spots can be located:

- At Tix, which is the most important, including the mill, the village, and the area surrounding the mining and amalgamation activities on the Claw Dam banks. This area is characterised by a group of scattered single-source Hot Spots, such as four copper-plates, many but not well located roasting areas at the entrance to the mill, in the village itself, and many amalgamation areas along the Claw Dam bank. Moreover, the same types of activities have been observed during the environmental assessment in other villages close to Tix, such as Mhisi and May Flower. Artisanal activity has been in progress for many years. Several tens of thousands of people are exposed directly or indirectly to this multi-source hot spot.

- At Amber Rose, contamination is less important than in Tix. But the contaminated tailings are dumped very close to the village and often spread out on the tracks in the village. Tailings may also contaminate the sediments in the tributaries of the Muzvezve River. Roasting locations may also contribute to the local contamination of the environment by their emissions.
- All along the Muzvezve River, where panners use Hg over a distance of at least 7 km corresponding to the studied zone. This distance is certainly longer than that, but an inventory of the panning areas upstream and downstream from the zone visited is necessary to ascertain the actual extent. Results of Hg concentration in carnivorous fishes, which are good bioindicators of the contamination, show the Hg contamination reached the living aquatic environment.
- The Etena area, in the northern zone can be classified as a multi-source Hot Spot according to the Hg concentrations found in the tailings close to the stamp mill, but also in the soils near the many amalgamation and roasting sites in the village.

5.3. EVALUATION OF EXPOSURE

Direct and passive exposures to mercury have been observed. Illustration 59 summarises the main exposure routes and their probability of occurrence.

- **Exposure for miners and millers**

People using or working close to the copper-plate are the most exposed. Large amounts of mercury are used in that process. People are in close contact with mercury and work in strongly contaminated environment. Most of the time, young men are working there, but we have also seen women, as in New Plus mill. Exposure to mercury can occur under several conditions:

- skin contact, when they clean up the copper plate, refill the plate with mercury, etc;
- inhalation, it was estimated that people breath during occupation, an atmosphere around 20 µg/m^3 of vaporized mercury with peak contents of probably several hundreds of micrograms per cubic meter; the amalgam recovery step is the most dangerous;
- inhalation of mercury vapours can be coupled with cyanide vapours, as people use cyanide solution or tablets during the cleaning phase of the copper-plate;
- dust ingestion and inhalation. Tailings and slimes are contaminated after the copper-plate step and the process generates dust.

The amalgamation areas are scattered both in the milling center and in the villages and near the riverbanks. The miners complete manually the amalgamation process on the material collected on the copper-plates or at the bottom of the bowl-concentrator.

Sources	**Exposure route**	**Professional exposure**	**Non professional exposure**	**Observations**
Copper plate	Skin contact	***	0	Most of the milling centre
	inhalation	***	*	
	Dust ingestion	**	*	
Free amalgamation sites	Skin contact	**	0	All milling centre, villages, the Claw Dam bank and the Muzvezve River
	inhalation	**	*	
	Dust ingestion	**	**	
Amalgam roasting sites	Inhalation	***	*	Mainly at free roasting sites in milling centres and villages, but also at organised roasting rooms in milling centre.
	Dust ingestion	*	** (children)	
Fish consumption		** ?	** ?	Depending on the diet
Drinking water		?	?	Local contamination with Hg cyanide ?

*Illustration 59 - Summary of the exposure pathways and the related risks (probability of occurrence: ***high, **moderate, *possible, 0 none).*

During this process, exposure to mercury can occur under several conditions:

- skin contact when completing the panning process;
- inhalation when roasting, as the process is performed outdoor on limited amounts of mercury, it seems that exposure is less important than for people working artisanal plants (copper plants, bowl concentrator…);
- dust ingestion, as contaminated tailings are dispersed in various places.

- **Passive exposure**

As part of the artisanal mining process is performed in villages and riverbanks, passive exposure may be suspected. Children and women are frequently present and take part in the activity. Sites like New Plus are characteristic of that situation, mainly around the roasting room.

Dust ingestion (particularly for children) and inhalation are the most probable routes of exposure for non miners.

- **Additional mercury intake**

We demonstrated that a significant part of the fishes are contaminated, Hg concentrations are above WHO safety standards. The sociological survey ordered by UNIDO and performed in the same area does not allow us to evaluate the daily intake of mercury by food consumption. However our field observations show that local people consume fishes from Claw Dam, the Muzvezve local and its tributaries. We do not know if local fishing represents the main source of proteins, but this intake should be taken into consideration in the risk analysis.

The analyses of the tailings samples after cyanidation show also some contamination. Hg may be complexed with cyanides and may contaminate the surface water or even the groundwater, particularly during the rainy season. This point should be verified in a further step, because strong contamination of tailings dumps may create severe local contamination for the aquatic life and the quality of drinking water.

6. Recommendations

6.1. GENERALITIES

The artisanal gold processing in the Kadoma region involves thousands of people with different educational levels, scattered over a very wide area. The outcomes of the environmental assessment clearly demonstrated the important use of mercury in the area generates high level risks for human health and the environment. This is in agreement with the outcomes of the health assessment (see Boese-O'Reilly *et al.,* 2004).

The extension of the mining activity in the Kadoma-Chakari area, its economical importance and the amount of ore processed have reached semi-industrial levels. This situation justifies an adapted action plan to develop alternative technologies and the progressive ban of mercury in the mining process in the area.

The improvement of the life quality and the acquisition of the best available techniques for gold mining and processing require time, training and financing. The implementation of a real Environmental Management Plan (EMP) is necessary. Three levels of actions can be proposed: urgent actions to reduce the immediate or direct risks to human health, complementary data acquisition and medium- to long-term actions to improve life quality, including proper management of natural resources. All these proposed actions have the following objectives:

- To reduce on a short term basis the high levels of exposure for workers.
- To implement cleaner technologies.
- To increase the knowledge and awareness amongst artisanal miners and millers.
- To assess the extent of Hg pollution in the single-source and multi-source hot spots.
- To rehabilitate the polluted sites (soil cleaning, tailing containment…).
- To analyse the consequences of the urgent actions.
- To improve life quality.
- To improve the management of the mining resources.

6.2. URGENT ACTIONS

Urgent actions have to be taken in the single-source hot spots to reduce significantly the exposure of workers to mercury. Action should focus on (1) the copper-plate equipment, (2) the amalgamation areas and (3) the roasting sites. Several actions are suggested, although these are not exhaustive:

6.2.1. Actions on ore processing technologies and practices

Replacement of the copper-plates by alternative equipment that could be in a first step a bowl-concentrator. Discussion with local authorities should be initiated to demonstrate the dangerousness of the copper-plate process.

Action should be taken by the local authorities to reduce the exposure of workers who are the most exposed around the copper-plates (use of gloves and masks…), education on safe procedures for these workers.

An awareness raising campaign should be urgently organised for the miners and millers to show them the impact on health of their professional occupation. This would allow initiating a process in order to modify local practices and adopt safe procedures for workers and their families.

Amalgam roasting operations should be performed in a specific room per milling site, equipped with an air extractor and air filter to recover most of the mercury dispersed in the air during this operation. The location of this room should be selected in an appropriate place allowing the control of the environment and avoiding new contamination of the surrounding soils,

Exhaust pipes of the present roasting rooms should be adapted to improve the recovery of mercury and avoid its dissemination in the environment (*i.e.* at Even Milling Centre and New Plus mill).

Roasting operations should be prohibited in villages. Free roasting places for independent miners (using small amounts of Hg) should be settled.

6.2.2. Actions to rehabilitate and preserve the environment

The drinking-water pumping raft of Tix should be removed to an another site, away from the gold mining and local processing area. Another solution is to dig a well after checking the groundwater quality.

The stability of the cyanided tailing dumps and the effluent released from these dumps should be controlled, particularly during the rainy season,

An awareness raising campaign should be initiated about the contamination of local fishes from the Muzvezve River. The communication should insist on the dangerousness to consume local carnivorous fishes. Similar communication actions were implemented successfully in Brazil.

6.3. MEDIUM- TO LONG-TERM ACTIONS

6.3.1. Improvement in the management of the artisanal mining activity

A regional strategy should be designed with regional and national authorities to improve the management of the artisanal gold mining activity, with the objectives of creating employment and stabilising the population involved in this activity. This may require changes in the policy and legislation dealing with mining activities, to promote the use of alternative technologies, to control the flux of mercury, and the artisanal mining activity.

Policy action should focus in the area of Kadoma on the reduction of mercury use by the use of alternative technologies that are adequate with the ore volumes that are processed. The implementation of Transportable Demonstration Units (TDUs) proposed by the Global Mercury Project Team should represent the core of that action.

Develop awareness raising campaigns for the miners and millers on good practices and mitigation of risks in the use of Hg. Training sessions on the best available techniques in artisanal gold mining and processing should be proposed.

Promotion campaigns on the use of retorts should be adapted for individual miners that use small amounts of mercury.

6.3.2. Reduction of environmental impacts

This environmental assessment provided preliminary information at the regional scale. However, it was demonstrated that significant contamination was observed in various components of the environment (tailings, soils, sediments) and the aquatic life is already affected. The evaluation of the contamination shows that people may be exposed (at least passively) on a long-term basis because their close environment is contaminated. A regional strategy has to be defined to decrease the release of Hg to the environment.

A regional policy should be designed and implemented to improve the recycling of mercury from the shops to the miners. It is improbable that independent miners using small amounts of mercury could be forced to change their process. An adapted policy on the Hg market should be implemented to control the import of Hg, and improve the recycling of Hg. An experiment of free Hg replacement could be tested in the Kadoma region in order to check if such kind of policy could decrease the Hg release to the environment.

A regional environmental management plan (EMP) should be designed with the collaboration of national and local institutions (Associations or representatives of artisanal miners and millers, local and national authorities…) to define a strategy of remediation and monitoring actions, define priorities of action at regional scale. The EMP should focus on the monitoring of Hg concentration in soils, sediments and tailings in the identified single-source hot spots.

An exhaustive inventory of the mining, milling and panning areas should be carried out at a national level. Results should be summarised in a national database, not only for the Kadoma-Chakari area but also for all the states of Zimbabwe.

Analytical facilities for Hg control in solids and fishes (LUMEX…) should be implemented in Kadoma to ensure the effectiveness of the EMP.

A monitoring strategy of professional exposure should be implemented in close co-ordination with the health authorities.

6.3.3. Support and management of these actions

The support and the management of these short-medium and long-term actions require the creation of a Task Force involving all the key stakeholders such as the following:

- Associations or representatives of artisanal miners and millers,
- Local authorities (Mine, Environment, Health…),
- A UNIDO representative and national expert,
- National authorities (all the involved governmental organisations),
- Local and international universities and institutes involved in this subject,
- NGOs.

7. Conclusion

The fieldwork of the environmental assessment of the artisanal gold mining activity in the Kadoma-Chakari area, selected by UNIDO, was carried out in November 2003 just before the rainy season and completed in April 2004 during the health assessment survey. The team was composed of a BRGM staff, the UNIDO National expert of the Global Mercury project and the Chief of the chemical Laboratory of IMR (Institute of Mining Reseach) of the University of Zimbabwe.

On the basis of the outcomes of the previous sociological survey, the environmental assessment started on sites located at the North of Kadoma. Following the advice of the Kadoma Mine Department, the study was extended to the South of Kadoma. Ten milling sites were then selected north and south of Kadoma. The site selection was based on the following criteria: the size of the milling centre, the type of ore processing, the population involved in the activity, the quantity of mercury used, the presence of a village near the milling centre, and also the presence of environmental targets (rivers, lake…).

The sampling strategy focused on soils, sediments, tailings, dust, air monitoring, and fishes. Air monitoring was carried out on the three most important sites, Tix, Amber and Even Milling center. All the samples, including the fish, were analysed in France and thirty-three duplicate samples of soil, dust and tailings were analysed in the IMR laboratory in Harare.

The environmental assessment confirms that a large quantity of Hg is used by miners and panners in the selected area. Probably between 1.2 to 17.5 tons of mercury are used and released to the environment annually. The range is very wide according to the difficulties to get information about the quantity of processed ore and the mercury market and recycling in this area. The Mercury is used for amalgamation on all sites. Most of the time these operations are carried out without any precaution to protect the workers. If some precautions do exist, this survey shows that they are neither sufficient nor satisfactory.

Hot spots, corresponding to sites containing high concentrations of Hg relative to the local background levels in soils and sediments are identified and classified as single-source or as multi-source hot spots.

The single-source hot spots correspond to a well-delimited pollution source and are associated with specific tools such as copper-plate and technique such as amalgamation or roasting used in gold processing. In the visited sites, all pollution sources are known. The areas concerned are relatively small, a few hundred square meters, but these sites induce a strong exposure to mercury for the local workers.

Multi-source hot spots, on the other hand, correspond to much wider areas characterised by several associated single-source hot spots. The contamination can affect a local level and extend widely throughout the mining and milling area. The environmental impacts can spread out over a distance exceeding tens of kilometers around the emission sources. Potential impact may even affect the neighbouring countries.

The most important single source hot spot is situated around the copper-plate inside the milling centres where the Hg concentration in soil reaches ten to four hundred times the local background. This level of Hg pollution is the consequence of the dispersion of Hg vapour in the air around the copper-plate followed by condensation and impregnation of fine soil particles. Moreover, a substantial quantity of Hg is lost with the tailings downstream from the copper-plate.

Free amalgamation places are also described as single-source hot spot. They are found where water is available for the panning operation, at the milling centre, in the village, on the river or lake banks. If there is indeed little Hg dispersion in the air during the process, a large quantity of Hg is lost with the tailings and consequently reaches the surface water and the biological chain.

A third of single-source hot spots is represented by roasting places. A large quantity of mercury is lost during the open air roasting operations that are carried out by miners at the milling centre and very frequently in the village. Miners, but also women and children may be exposed during that process.

Tix site is characteristic of a multi-source hot spot. It is the most polluted area among all the visited and studied sites. Tix site presents four copper-plates at the milling centre, and numerous amalgamation places and roasting sites scattered in the milling centre, in the village and in the country around. Both semi-industrial and ancient artisanal mining activities induced a strong contamination in the area. Risk is increased because of the dissemination of contamination to the Muzvezve River that supplies water and food at a regional scale and runs to the Zimbabwe border. Abnormal Hg concentrations are found in sediments and fishes collected downstream from the Tix sites. Several tens of thousands of people are directly or indirectly concerned by this multi-source hot spot.

The site of Amber Rose is also classified as a multi-source hot spot. The difference with Tix comes from the lack of copper-plate and the exposed population is lower in Amber Rose than in Tix.

The Muzvezve River itself, downstream from Claw Dam, is also considered as a multi source hot spot because it is the location of amalgamation and roasting sites for many independent miners. Local tributaries may also provide contaminated sediments from Tix and Amber Rose and other milling centres. Aquatic life is affected by mercury contamination. One third of the fish (18/52) display Hg concentrations exceeding the WHO safety limit of 0.5 µg g^{-1} fresh weight. The average Hg concentration is 0.41 µg g^{-1}. For the carnivorous species, it rises up to 1.06 µg g^{-1}, and a young specimen of them displays 2 µg g^{-1} despite its light weight (110 g). If the results of the small-sized samples are representative of the area, it is very likely that most of the fish eaten by the local population along the Muzvezve River are contaminated with mercury.

Direct exposures to Hg contamination have been observed for miners and millers men and sometime women who are working close to the copper-plate. Exposure to mercury occurs by skin contact, vapour inhalation, and particle ingestion.

Amalgamation and roasting areas are also the sites of direct exposure through the same way. Children who are frequently involved in the amalgamation process are affected.

Passive exposure may be suspected because this artisanal activity is performed in villages and along the riverbanks. Young men and women are frequently present in the proximity of this activity.

The extension of the mining activity in the Kadoma-Chakari area, its economical importance and the amount of ore processed have reached semi-industrial levels. This situation justifies an adapted action plan to develop alternative technologies and the progressive ban of mercury in the mining process in the area.

Recommendations contain first urgent actions to reduce significantly the exposure of workers and their family to mercury. They concern the ore processing technologies, practices and actions to rehabilitate and preserve the environment.

Medium- to long- term actions aim at improving the management of the artisanal mining activity and reduce the environmental impacts.

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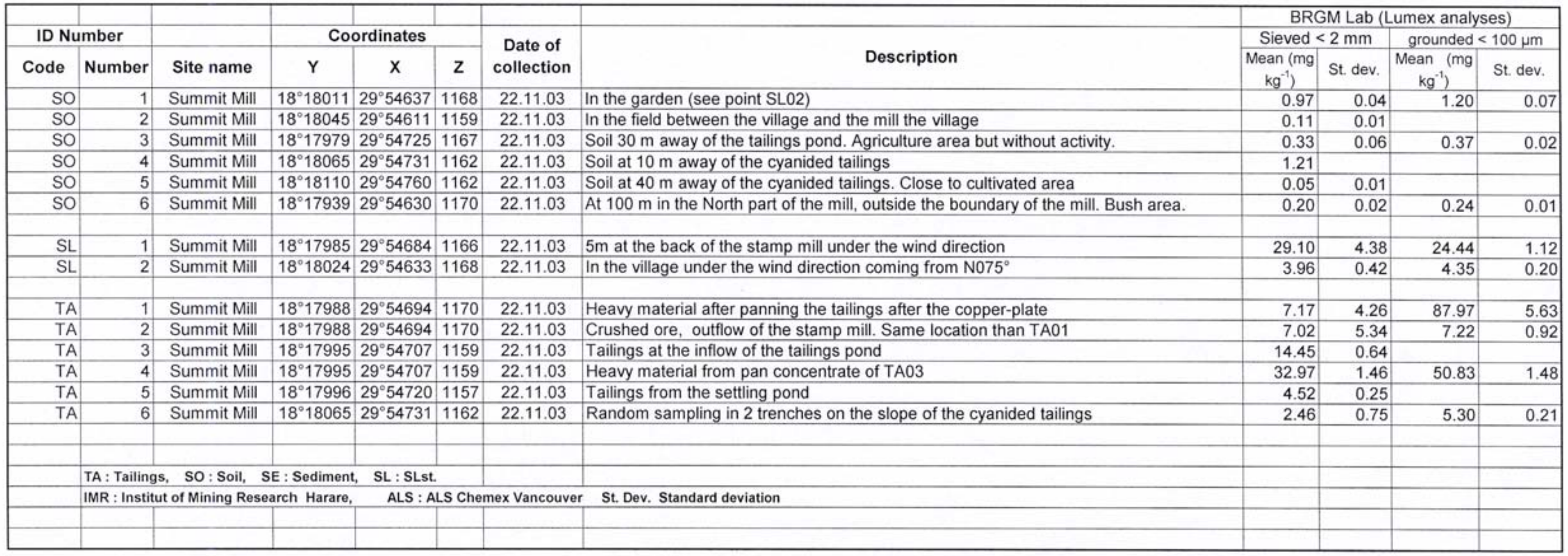
Appendix 1

List of collected samples with results of the chemical analyses



ID Number			Coordinates			Date of collection	Description	BRGM Lab (Lumex analyses)			
								Sieved < 2 mm		grounded < 100 µm	
Code	Number	Site name	Y	X	Z			Mean (mg kg^{-1})	St. dev.	Mean (mg kg^{-1})	St. dev.
SO	1	Summit Mill	18°18011	29°54637	1168	22.11.03	In the garden (see point SL02)	0.97	0.04	1.20	0.07
SO	2	Summit Mill	18°18045	29°54611	1159	22.11.03	In the field between the village and the mill the village	0.11	0.01		
SO	3	Summit Mill	18°17979	29°54725	1167	22.11.03	Soil 30 m away of the tailings pond. Agriculture area but without activity.	0.33	0.06	0.37	0.02
SO	4	Summit Mill	18°18065	29°54731	1162	22.11.03	Soil at 10 m away of the cyanided tailings	1.21			
SO	5	Summit Mill	18°18110	29°54760	1162	22.11.03	Soil at 40 m away of the cyanided tailings. Close to cultivated area	0.05	0.01		
SO	6	Summit Mill	18°17939	29°54630	1170	22.11.03	At 100 m in the North part of the mill, outside the boundary of the mill. Bush area.	0.20	0.02	0.24	0.01
SL	1	Summit Mill	18°17985	29°54684	1166	22.11.03	5m at the back of the stamp mill under the wind direction	29.10	4.38	24.44	1.12
SL	2	Summit Mill	18°18024	29°54633	1168	22.11.03	In the village under the wind direction coming from N075°	3.96	0.42	4.35	0.20
TA	1	Summit Mill	18°17988	29°54694	1170	22.11.03	Heavy material after panning the tailings after the copper-plate	7.17	4.26	87.97	5.63
TA	2	Summit Mill	18°17988	29°54694	1170	22.11.03	Crushed ore, outflow of the stamp mill. Same location than TA01	7.02	5.34	7.22	0.92
TA	3	Summit Mill	18°17995	29°54707	1159	22.11.03	Tailings at the inflow of the tailings pond	14.45	0.64		
TA	4	Summit Mill	18°17995	29°54707	1159	22.11.03	Heavy material from pan concentrate of TA03	32.97	1.46	50.83	1.48
TA	5	Summit Mill	18°17996	29°54720	1157	22.11.03	Tailings from the settling pond	4.52	0.25		
TA	6	Summit Mill	18°18065	29°54731	1162	22.11.03	Random sampling in 2 trenches on the slope of the cyanided tailings	2.46	0.75	5.30	0.21

TA : Tailings, SO : Soil, SE : Sediment, SL : SLst.

IMR : Institut of Mining Research Harare, ALS : ALS Chemex Vancouver St. Dev. Standard deviation

Table 1 - Summit mill: list of the collected samples and chemical analysis results

ID Number		Coordinates			Date of collection	Description	BRGM Lab (Lumex analyses)				IMR Lab	ALS Lab
							Sieved < 2 mm		grounded < 100 µm		< 100 µm	< 100 µm
Code	Number	Y	X	Z			Mean (mg kg^{-1})	St. dev.	Mean (mg kg^{-1})	St. dev.	Mean (mg kg^{-1})	Mean (mg kg^{-1})
SL	3	18°15466	29°53665	1136	22.11.03	Dust around the stamp mill	28.80		569.75	56.66		
SO	7	18°15441	29°53592	1141	22.11.03	Soil between the village and the stamp mill	0.21				0.39	
SO	8	18°15501	29°53578	1142	22.11.03	Soil between the village and the stamp mill	0.52				0.88	
SO	9	18°15416	29°53601	1144	22.11.03	Soil in the village	2.08	0.28	2.18	0.03	1.98	
SO	10	18°15508	29°53645	1145	22.11.03	Soil in the village	1.50		1.12	0.02	1.84	
SO	11	18°15479	29°53691	1137	22.11.03	Soil at 50 m away of the mill	21.93	4.31	17.60	0.30	16.73	
SO	12	18°15389	29°53716	1141	22.11.03	Soil close to the cyanided taillings (cultivated area)	0.16	0.04				
SO	13	18°15353	29°53654	1138	22.11.03	Soil close to the cyanided tailings	0.16					
SO	14	18°15353	29°53645	1139	22.11.03	Soil close to the cyanided tailings	1.14					
SO	15	18°15386	29°53763	1130	22.11.03	Cultivated area at 120 m away of the stamp mill	0.04					
TA	7	18°15448	29°53673	1134	22.11.03	Heavy material from pan concentration of the coarse grain after the drag clarifier.	2.42					
TA	8	18°15448	29°53673	1134	22.11.03	Tailings slime just after the stamp mill	30.67	3.31	31.47	0.35		
TA	9	18°15445	29°53664	1134	22.11.03	Tailings slime just before the tailings pond	11.60					
TA	10	18°15429	29°53647	1132	22.11.03	Dry tailings slime in the tailings pond	5.07	0.43	5.34	0.02	3.53	
TA	11	18°15410	29°53659	1145	22.11.03	Tailings after cyanidation first section	1.10	0.14	0.92	0.02	1.39	
TA	12	18°15371	29°53655	1146	22.11.03	Tailings after cyanidation second section	1.35	0.17	1.67	0.01	1.14	

TA : Tailings, SO : Soil, SE : Sediment, SL : SLst.

IMR : Institut of Mining Research Harare, ALS : ALS Chemex Vancouver St. Dev. Standard deviation

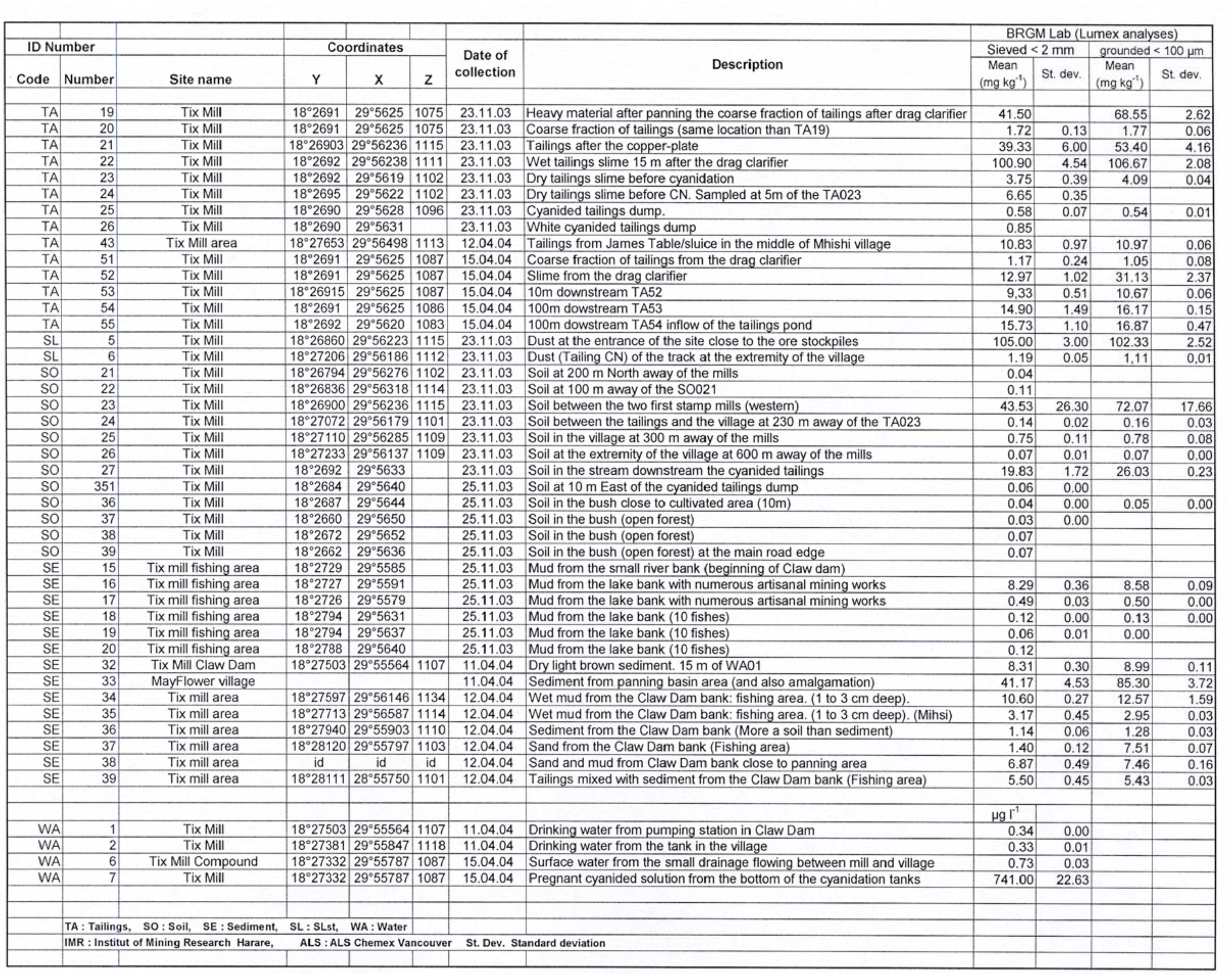
Table 2 - Glasgow mill : List of the collected samples and chemical analysis results

ID Number			Coordinates			Date of collection	Description	BRGM Lab (Lumex analyses)			
								Sieved < 2 mm		grounded < 100 µm	
Code	Number	Site name	Y	X	Z			Mean (mg kg^{-1})	St. dev.	Mean (mg kg^{-1})	St. dev.
SL	4	Coetzee Mill	18°07712	29°47928	1097	22.11.03	Dust in the village close to SO16	0.36	0.10	0.41	0.00
SO	16	Coetzee Mill	18°07688	29°47950	1104	22.11.03	Soil at 160 m away of the stamp mill in the middle of the village	1.013			
SO	17	Coetzee Mill	18°07802	29°47917	1087	22.11.03	Soil at 90 m away of the mill on the other side of the main road to Chakari	0.21			
SO	18	Coetzee Mill	18°07760	29°47825	1088	22.11.03	Cultivated area close to the cyanided taillings	0.22			
SO	19	Coetzee Mill	18°07765	29°47824	1086	22.11.03	Field at 150 m away to the mill sample inside a drainage of cyanided tailings	1.10			
SO	20	Coetzee Mill	18°07774	29°47796	1088	22.11.03	Cultivated area at 200 m away of the mill. Inside a drainage from cyanided tailings	2.64			
TA	13	Coetzee Mill	18°07761	29°47876	1093	22.11.03	Heavy material from pan concentration of the tailings after the copper-plate.	69.03	15.67	3557.50	1291.39
TA	14	Coetzee Mill	18°07761	29°47876	1093	22.11.03	Tailings just after the copper-plate	2.31			
TA	15	Coetzee Mill	18°07765	29°47865	1099	22.11.03	Tailings 20 m after the copper-plate	2.34			
TA	16	Coetzee Mill	18°07773	29°47866	1095	22.11.03	Dry tailings dump before cyanidation	5.73	0.61	6.27	0.05
TA	17	Coetzee Mill	18°07754	29°47840	1092	22.11.03	Cyanided tailings; Upstream the SO19	4.05			
TA	18	Coetzee Mill	18°07729	29°47855	1101	22.11.03	Cyanided tailings	1.53	0.12	1.76	0.02

TA : Tailings, SO : Soil, SE : Sediment, SL : SLst.

IMR : Institut of Mining Research Harare, ALS : ALS Chemex Vancouver St. Dev. Standard deviation

Table 3 – Coetzee mill: List of the collected samples and chemical analysis results



ID Number			Coordinates			Date of collection	Description	BRGM Lab (Lumex analyses)			
								Sieved < 2 mm		grounded < 100 µm	
Code	Number	Site name	Y	X	Z			Mean (mg kg^{-1})	St. dev.	Mean (mg kg^{-1})	St. dev.
TA	19	Tix Mill	18°2691	29°5625	1075	23.11.03	Heavy material after panning the coarse fraction of tailings after drag clarifier	41.50		68.55	2.62
TA	20	Tix Mill	18°2691	29°5625	1075	23.11.03	Coarse fraction of tailings (same location than TA19)	1.72	0.13	1.77	0.06
TA	21	Tix Mill	18°26903	29°56236	1115	23.11.03	Tailings after the copper-plate	39.33	6.00	53.40	4.16
TA	22	Tix Mill	18°2692	29°56238	1111	23.11.03	Wet tailings slime 15 m after the drag clarifier	100.90	4.54	106.67	2.08
TA	23	Tix Mill	18°2692	29°5619	1102	23.11.03	Dry tailings slime before cyanidation	3.75	0.39	4.09	0.04
TA	24	Tix Mill	18°2695	29°5622	1102	23.11.03	Dry tailings slime before CN. Sampled at 5m of the TA023	6.65	0.35		
TA	25	Tix Mill	18°2690	29°5628	1096	23.11.03	Cyanided tailings dump.	0.58	0.07	0.54	0.01
TA	26	Tix Mill	18°2690	29°5631		23.11.03	White cyanided tailings dump	0.85			
TA	43	Tix Mill area	18°27653	29°56498	1113	12.04.04	Tailings from James Table/sluice in the middle of Mhishi village	10.83	0.97	10.97	0.06
TA	51	Tix Mill	18°2691	29°5625	1087	15.04.04	Coarse fraction of tailings from the drag clarifier	1.17	0.24	1.05	0.08
TA	52	Tix Mill	18°2691	29°5625	1087	15.04.04	Slime from the drag clarifier	12.97	1.02	31.13	2.37
TA	53	Tix Mill	18°26915	29°5625	1087	15.04.04	10m downstream TA52	9,33	0.51	10.67	0.06
TA	54	Tix Mill	18°2691	29°5625	1086	15.04.04	100m dowstream TA53	14.90	1.49	16.17	0.15
TA	55	Tix Mill	18°2692	29°5620	1083	15.04.04	100m dowstream TA54 inflow of the tailings pond	15.73	1.10	16.87	0.47
SL	5	Tix Mill	18°26860	29°56223	1115	23.11.03	Dust at the entrance of the site close to the ore stockpiles	105.00	3.00	102.33	2.52
SL	6	Tix Mill	18°27206	29°56186	1112	23.11.03	Dust (Tailing CN) of the track at the extremity of the village	1.19	0.05	1,11	0,01
SO	21	Tix Mill	18°26794	29°56276	1102	23.11.03	Soil at 200 m North away of the mills	0.04			
SO	22	Tix Mill	18°26836	29°56318	1114	23.11.03	Soil at 100 m away of the SO021	0.11			
SO	23	Tix Mill	18°26900	29°56236	1115	23.11.03	Soil between the two first stamp mills (western)	43.53	26.30	72.07	17.66
SO	24	Tix Mill	18°27072	29°56179	1101	23.11.03	Soil between the tailings and the village at 230 m away of the TA023	0.14	0.02	0.16	0.03
SO	25	Tix Mill	18°27110	29°56285	1109	23.11.03	Soil in the village at 300 m away of the mills	0.75	0.11	0.78	0.08
SO	26	Tix Mill	18°27233	29°56137	1109	23.11.03	Soil at the extremity of the village at 600 m away of the mills	0.07	0.01	0.07	0.00
SO	27	Tix Mill	18°2692	29°5633		23.11.03	Soil in the stream downstream the cyanided tailings	19.83	1.72	26.03	0.23
SO	351	Tix Mill	18°2684	29°5640		25.11.03	Soil at 10 m East of the cyanided tailings dump	0.06	0.00		
SO	36	Tix Mill	18°2687	29°5644		25.11.03	Soil in the bush close to cultivated area (10m)	0.04	0.00	0.05	0.00
SO	37	Tix Mill	18°2660	29°5650		25.11.03	Soil in the bush (open forest)	0.03	0.00		
SO	38	Tix Mill	18°2672	29°5652		25.11.03	Soil in the bush (open forest)	0.07			
SO	39	Tix Mill	18°2662	29°5636		25.11.03	Soil in the bush (open forest) at the main road edge	0.07			
SE	15	Tix mill fishing area	18°2729	29°5585		25.11.03	Mud from the small river bank (beginning of Claw dam)				
SE	16	Tix mill fishing area	18°2727	29°5591		25.11.03	Mud from the lake bank with numerous artisanal mining works	8.29	0.36	8.58	0.09
SE	17	Tix mill fishing area	18°2726	29°5579		25.11.03	Mud from the lake bank with numerous artisanal mining works	0.49	0.03	0.50	0.00
SE	18	Tix mill fishing area	18°2794	29°5631		25.11.03	Mud from the lake bank (10 fishes)	0.12	0.00	0.13	0.00
SE	19	Tix mill fishing area	18°2794	29°5637		25.11.03	Mud from the lake bank (10 fishes)	0.06	0.01	0.00	
SE	20	Tix mill fishing area	18°2788	29°5640		25.11.03	Mud from the lake bank (10 fishes)	0.12			
SE	32	Tix Mill Claw Dam	18°27503	29°55564	1107	11.04.04	Dry light brown sediment. 15 m of WA01	8.31	0.30	8.99	0.11
SE	33	MayFlower village				11.04.04	Sediment from panning basin area (and also amalgamation)	41.17	4.53	85.30	3.72
SE	34	Tix mill area	18°27597	29°56146	1134	12.04.04	Wet mud from the Claw Dam bank: fishing area. (1 to 3 cm deep).	10.60	0.27	12.57	1.59
SE	35	Tix mill area	18°27713	29°56587	1114	12.04.04	Wet mud from the Claw Dam bank: fishing area. (1 to 3 cm deep). (Mihsi)	3.17	0.45	2.95	0.03
SE	36	Tix mill area	18°27940	29°55903	1110	12.04.04	Sediment from the Claw Dam bank (More a soil than sediment)	1.14	0.06	1.28	0.03
SE	37	Tix mill area	18°28120	29°55797	1103	12.04.04	Sand from the Claw Dam bank (Fishing area)	1.40	0.12	7.51	0.07
SE	38	Tix mill area	id	id	id	12.04.04	Sand and mud from Claw Dam bank close to panning area	6.87	0.49	7.46	0.16
SE	39	Tix mill area	18°28111	28°55750	1101	12.04.04	Tailings mixed with sediment from the Claw Dam bank (Fishing area)	5.50	0.45	5.43	0.03
								µg l^{-1}			
WA	1	Tix Mill	18°27503	29°55564	1107	11.04.04	Drinking water from pumping station in Claw Dam	0.34	0.00		
WA	2	Tix Mill	18°27381	29°55847	1118	11.04.04	Drinking water from the tank in the village	0.33	0.01		
WA	6	Tix Mill Compound	18°27332	29°55787	1087	15.04.04	Surface water from the small drainage flowing between mill and village	0.73	0.03		
WA	7	Tix Mill	18°27332	29°55787	1087	15.04.04	Pregnant cyanided solution from the bottom of the cyanidation tanks	741.00	22.63		

TA : Tailings, SO : Soil, SE : Sediment, SL : SLst, WA : Water

IMR : Institut of Mining Research Harare, ALS : ALS Chemex Vancouver St. Dev. Standard deviation

Table 4 – Tix mill: List of the collected samples and chemical analysis results

ID Number		Coordinates			Date of collection	Description	BRGM Lab (Lumex analyses)				IMR Lab	ALS Lab
							Sieved < 2 mm		grounded < 100 µm		< 100 µm	< 100 µm
Code	Number	Y	X	Z			Mean (mg kg^{-1})	St. dev.	Mean (mg kg^{-1})	St. dev.	Mean (mg kg^{-1})	Mean (mg kg^{-1})
SL	7	18°2180	29°5062	1087	23.11.03	Dust on the floor (concrete) of the panning area (customer area)	74.60	37.34	985.40	36.20		
SO	28	18°2180	29°5062	1087	23.11.03	Soil between bowl concentrator and shelter for additional amalgamation	23.55	15.63	41.43	0.01		
SO	29	18°2185	29°5058		23.11.03	Soil at 3 m South of the tailings pond	0.04					
SO	30	18°2186	29°5054		23.11.03	Soil at 50 m West of the tailings pond (Pomani vegetation, Open forest area)	0.03	0.00	0.04	0.00		
SO	31	18°21838	29°50701	1121	23.11.03	Soil in the open forest in front (at 2 m away) of the Hg fume extractor	2.71		3.79	0.04		
SO	32	18°21838	29°50703	1114	23.11.03	Soil in the open forest in front (at10 m away) of the Hg fume extractor	0.47		0.56	0.01		
SO	33	?	?		23.11.03	Soil mixed with slime from tailings outside the boundaries of the site. 50m east of SO034	0.62					
SO	34	18°2175	29°5054		23.11.03	Soil in the open forest	0.02	0				
SO	352	18°2167	29°5064		23.11.03	Soil in the open forest close to the mill park	0.13	0				
TA	27	18°2180	29°5062	1087	23.11.03	Tailings after amalgamation in a pan. (Coarse and slime)	23.10		61.75	5.23		
TA	28	18°2185	29°5056	1103	23.11.03	Dry tailings slime after the bowl concentrator	0.23		0.50	0.01		
TA	30	18°2185	29°5058		23.11.03	Wet tailings slime at the inflow of the tailings pond	0.97		4.07	0.24		
TA	31	18°2185	29°5058		23.11.03	Wet tailings slime at the inflow of the tailings pond	0.12	0.05				
TA	32	18°2180	29°5059		23.11.03	Cyanided tailings, random sampling in the tailings dump	0.22	0.03	0.27	0.01		
TA	33	18°2180	29°5059		23.11.03	Cyanided tailings, random sampling in the tailings dump (30m in the North of TA032)	1.55		0.64	0.02		

TA : Tailings, SO : Soil, SE : Sediment, SL : SLst.

IMR : Institut of Mining Research Harare, ALS : ALS Chemex Vancouver St. Dev. Standard deviation

Table 5 – Even Milling centre : List of collected samples and chemical analysis reults

ID Number			Coordinates			Date of collection	Description	BRGM Lab (Lumex analyses)			
								Sieved < 2 mm		grounded < 100 µm	
Code	Number	Site name	Y	X	Z			Mean (mg kg^{-1})	St. dev.	Mean (mg kg^{-1})	St. dev.
SE	3	Muzvezve River downstream Claw Dam	18°26722	29°51905	1080	24.11.03	River sediment < 2 mm	0.02	0.00		
SE	4	Muzvezve River downstream Claw Dam	18°26722	29°51905	1080	24.11.03	Pan concentrate of river sediment < 2 mm	0.02			
SE	5	Muzvezve River downstream Claw Dam	18°26477	29°51708	1082	24.11.03	River sediment < 2 mm	0.01	0.00		
SE	6	Muzvezve River downstream Claw Dam	18°26477	29°51708	1082	24.11.03	Pan concentrate of river sediment < 2 mm	0.03			
SE	7	Muzvezve River downstream Claw Dam	18°26477	29°51708	1082	24.11.03	Radom sampling of mud (same location)	0.02			
SE	1	Muzvezve River downstream Claw Dam	18°26493	29°51302	1088	24.11.03	Mud in the second fishing area (11 fishes)	0.14			
SE	2	Muzvezve River downstream Claw Dam	18°26577	29°51135	1075	24.11.03	Mud in the first fishing area (10 small fishes)	0.08		0.16	0.00
SE	8	Muzvezve River downstream Claw Dam	18°26774	29°51135	1079	24.11.03	River sediment < 2 mm	0.26			
SE	9	Muzvezve River downstream Claw Dam	18°26774	29°51135	1079	24.11.03	Mud in the river bed	0.76		0.87	0.01
SE	10	Muzvezve River downstream Claw Dam	18°26731	29°51163	1080	24.11.03	Mud in the river bed between SO02 and SO08	0.01			
SE	11	Muzvezve River downstream Claw Dam	18°26650	29°51255	1081	24.11.03	Mud in the river bed between SO02 and SO08	0.06			

TA : Tailings, SO : Soil, SE : Sediment, DU : Dust.

IMR : Institut of Mining Research Harare, ALS : ALS Chemex Vancouver St. Dev. Standard deviation

Table 6 – Muzvezve River downstream Claw Dam: list of collected samples and chemical analysis results

ID Number		Coordinates			Date of collection	Description	BRGM Lab (Lumex analyses)				IMR Lab	ALS Lab
							Sieved < 2 mm		grounded < 100 µm		< 100 µm	< 100 µm
Code	Number	Y	X	Z			Mean (mg kg^{-1})	St. dev.	Mean (mg kg^{-1})	St. dev.	Mean (mg kg^{-1})	Mean (mg kg^{-1})
SE	12	18°26341	29°47750	1070	24.11.03	Mud from the river bed downstream Alexander farm dam	0.14		1.19	0.00		
SE	13	18°26341	29°47750	1070	24.11.03	River sediment < 2 mm	0.03	0.02	0.05	0.00		
SE	14	18°26341	29°47750	1070	24.11.03	Pan concentrate of river sediment < 2mm	0.02					
SE	21	18°2615	29°4797		25.11.03	Mud and sand from the bank of the Alexander farm dam.	0.10					
SE	22	18°2615	29°4802		25.11.03	Mud and sand from the bank of the Alexander farm dam.	0.17					
SE	24				26.11.03	Mud from the Muzvezve River bank at the bridge on the road to Alexander farm.	0.09	0.01				

TA : Tailings, SO : Soil, SE : Sediment, DU : Dust.

IMR : Institut of Mining Research Harare, ALS : ALS Chemex Vancouver St. Dev. Standard deviation

Table 7 – Muzvezve River Alexander Dam : List of collected samples and chemical analysis results

ID Number			Coordinates			Date of collection	Description	BRGM Lab (Lumex analyses)			
								Sieved < 2 mm		grounded < 100 µm	
Code	Number	Site name	Y	X	Z			Mean (mg kg^{-1})	St. dev.	Mean (mg kg^{-1})	St. dev.
SL	8	Amber Rose Mill	18°27604	29°49017	1092	26.11.03	Dust on the western part of the village (CFSO43)	19.77	3.85	17.70	0.36
SL	9	Amber Rose Mill	18°27575	29°49033	1089	26.11.03	Dust on the North-eastern part of the village (CFSO44)	2.83	0.46	3.38	0.06
SL	11	Amber Rose Mill				12.04.04	Dust at the amalgame roasting location at the milling centre	9.16	1.00	13.76	1.78
SE	23	Amber Rose Mill	18°27513	29°49087	1072	26.11.03	Sediment (tailings) around the bowl concentrator				
SE	24	Amber Rose Mill	18°26605	29°48885	1088	26.11.03	Sediment in the river	0.44			
SE	25	Amber Rose Mill	18°2736	29°4895		27.11.03	Dry sediment in the river from the western part of the mill (forest area)	6.00	0.10	5.37	0.04
SE	26	Amber Rose Mill	18°2736	29°4898		27.11.03	Dry sediment in the river from the western part of the mill (forest area)	1.35	0.12	1.34	0.02
SE	27	Amber Rose Mill	18°2778	29°4922		27.11.03	Dry sediment from a small drainage along the main road to the mill	0.24	0.04	0.28	0.00
SE	28	Amber Rose Mill	18°2848	29°4928		27.11.03	White fine sediment (tailings ?) of 2 cm thickeness	23.15	16.19	48.24	3.63
SE	29	Amber Rose Mill	18°2848	29°4928		27.11.03	Brown to reddish sediment under SO28	27.70	4.38	23.54	1.26
SE	30	Amber Rose Mill	18°2702	29°4910		27.11.03	White fine sediment (tailings ?) of 3 mm thickeness	0.39	0.06	0.48	0.01
SE	31	Amber Rose Mill	18°2702	29°4910		27.11.03	Brown to reddish sediment under SO30	1.02	0.02	1.12	0.04
SO	40	Amber Rose Mill	18°27530	29°48974	1084	26.11.03	Soil western part of the village	0.67			
SO	41	Amber Rose Mill	18°27500	29°4895	1096	26.11.03	Soil western part of the village	0.27			
SO	42	Amber Rose Mill	18°27631	29°48928	1096	26.11.03	Soil downstream the cyanided tailings	0.12			
SO	43	Amber Rose Mill	18°2760	29°4902	1092	26.11.03	Soil in the western part of the village (CFSL08)	14.31	7.06	12.10	0.28
SO	44	Amber Rose Mill	18°2758	29°4903	1089	26.11.03	Soil in the eastern part of the village (CFSL09)	2.11			
SO	45	Amber Rose Mill	18°2761	29°4908	1103	26.11.03	Soil at the eastern limit of the village	2.08			
SO	46	Amber Rose Mill	18°2763	29°4914	1100	26.11.03	Soil in the forest at the eastern part of the village	0.13			
TA	34	Amber Rose Mill	18°27513	29°49087	1072	26.11.03	Coarse grain tailings after bowl concentrator and drag clarifier	0.40			
TA	35	Amber Rose Mill	18°27513	29°49087	1072	26.11.03	Pan concentrate of tailings after drag clarifier	30.40	3.24	33.47	2.74
TA	36	Amber Rose Mill	18°2745	29°4902		26.11.03	Tailings pond. Wet slime close to the village	5.30			
TA	37	Amber Rose Mill	18°2749	29°4903		26.11.03	Cyanided tailings CN in the village	2.41			
TA	38	Amber Rose Mill	18°2747	29°4902		26.11.03	Tailings before cyanidation	1.04			
TA	39	Amber Rose Mill	18°2768	29°4902		26.11.03	Cyanided tailings CN dry in the southern part of the village	2.10			
TA	40	Amber Rose Mill	18°2764	29°4900		26.11.03	Cyanided tailings CN dry in the southern part of the village	1.42	0.15	1.45	0.02
TA	42	Amber Rose Mill	18°27513	29°49087	1072	12.04.04	Tailings from the outflow of the bowl concentrator	1.72	0.15	4.50	0.14
TA	48	Amber Rose Mill	18°27513	29°49087	1072	15.04.04	Overflow of the bowl concentrator (coarse grain) after the drag clarifier	6.90	0.39	10.91	1.58
TA	49	Amber Rose Mill	18°27513	29°49087	1072	15.04.04	Overflow of the bowl concentrator (slime) inflow of the tailings pond	2.79	0.14	2.46	0.11
TA	50	Amber Rose Mill	18°2745	29°4905	1087	15.04.04	Dry tailings collected in a trailer for cyanidation	4.48	0.39	5.40	0.05
								µg/L			
WA	3	Amber Rose Mill				12.04.04	Drinking water from the water tank installed at the milling center	0.01	0.01		
WA	5	Amber Rose Mill				15.04.04	Pregnant cyanided solution from the bottom of the cyanidation tanks	110.50	3.54		

TA : Tailings, SO : Soil, SE : Sediment, SL : SLs, WA : Water.

IMR : Institut of Mining Research Harare, ALS : ALS Chemex Vancouver St. Dev. Standard deviation

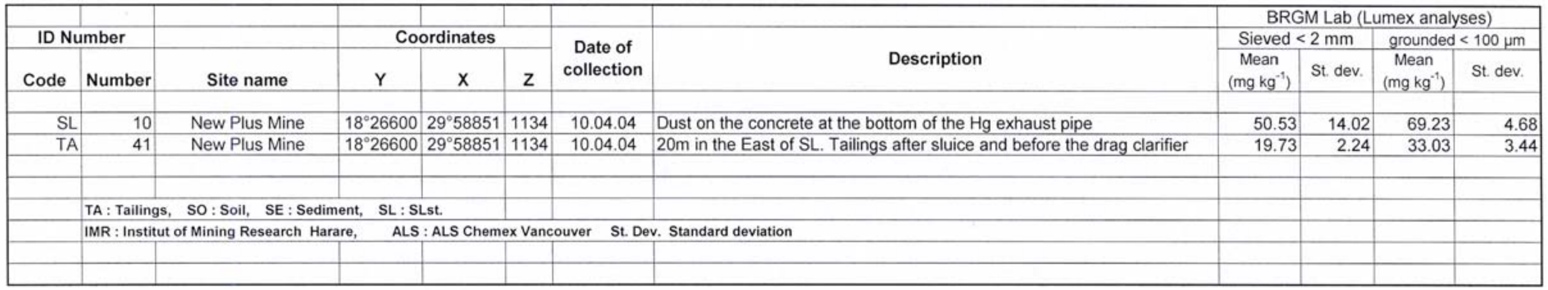
Table 8 – Amber Rose mill: List of collected samples and chemical analysis results

ID Number			Coordinates					BRGM Lab (Lumex analyses)				IMR Lab
								Sieved < 2 mm		grounded < 100 µm		< 100 µm
Code	Number	Site name	Y	X	Z	Date of collection	Description	Mean (mg kg^{-1})	St. dev.	Mean (mg kg^{-1})	St. dev.	Mean (mg kg^{-1})
TA	44	Lilly Mill	18°15099	29°44862	1082	14.04.04	Random sampling on the ground in the stamp mill building	3.89	0.44	9.21	0.28	19.00
TA	45	Lilly Mill			1081	14.04.04	Tailings in the effluent from the stamp mill building (outflow)	0.77	0.08	1.02	0.02	4.00
TA	46	Lilly Mill			1081	14.04.04	Ditto 5 meters downstream TA45	1.44	0.14	1.25	0.03	6.20
TA	47	Lilly Mill			1080	14.04.04	Ditto 80 meters downstream TA46	12.27	1.08	14.43	0.21	26.60
								µg/L				
WA	4	Lilly Mill			1082	14.04.04	Drinking water at the tape in the village	0.63	0.01			

TA : Tailings, SO : Soil, SE : Sediment, SL : SLst.

IMR : Institut of Mining Research Harare, ALS : ALS Chemex Vancouver St. Dev. Standard deviation

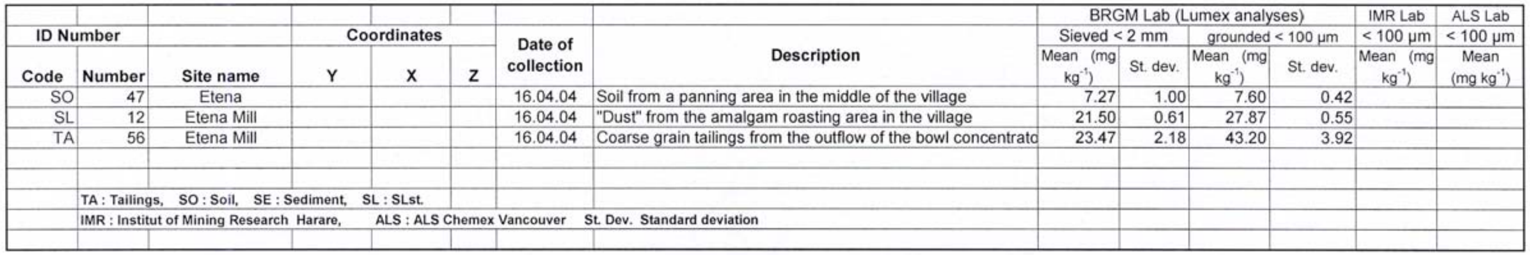
Table 9 – Lilly mill: List of the collected samples and chemical analysis results



ID Number			Coordinates			Date of collection	Description	BRGM Lab (Lumex analyses)			
								Sieved < 2 mm		grounded < 100 µm	
Code	Number	Site name	Y	X	Z			Mean (mg kg^{-1})	St. dev.	Mean (mg kg^{-1})	St. dev.
SL	10	New Plus Mine	18°26600	29°58851	1134	10.04.04	Dust on the concrete at the bottom of the Hg exhaust pipe	50.53	14.02	69.23	4.68
TA	41	New Plus Mine	18°26600	29°58851	1134	10.04.04	20m in the East of SL. Tailings after sluice and before the drag clarifier	19.73	2.24	33.03	3.44

TA : Tailings, SO : Soil, SE : Sediment, SL : SLst.
IMR : Institut of Mining Research Harare, ALS : ALS Chemex Vancouver St. Dev. Standard deviation

Table 10 – New Plus mill: List of the collected samples and chemical analysis results



ID Number			Coordinates			Date of collection	Description	BRGM Lab (Lumex analyses)				IMR Lab	ALS Lab
								Sieved < 2 mm		grounded < 100 µm		< 100 µm	< 100 µm
Code	Number	Site name	Y	X	Z			Mean (mg kg^{-1})	St. dev.	Mean (mg kg^{-1})	St. dev.	Mean (mg kg^{-1})	Mean (mg kg^{-1})
SO	47	Etena				16.04.04	Soil from a panning area in the middle of the village	7.27	1.00	7.60	0.42		
SL	12	Etena Mill				16.04.04	"Dust" from the amalgam roasting area in the village	21.50	0.61	27.87	0.55		
TA	56	Etena Mill				16.04.04	Coarse grain tailings from the outflow of the bowl concentrato	23.47	2.18	43.20	3.92		

TA : Tailings, SO : Soil, SE : Sediment, SL : SLst.
IMR : Institut of Mining Research Harare, ALS : ALS Chemex Vancouver St. Dev. Standard deviation

Table 11 – Etena Mill: List of the collected samples and chemical analysis results

Appendix 2

Quality control

1. QUALITY CONTROL OF LUMEX ANALYSES VS. STANDARD REFERENCES MATERIALS (SRM)

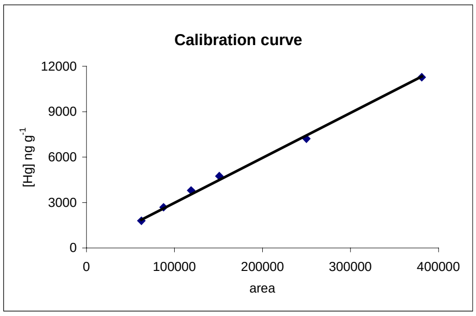
The analyser can be calibrate in two ways:

- calibration by a single standard sample;
- calibration by several standard samples.

We chose the calibration by a single standard sample at 10,100 ng g^{-1}, but we selected several standard samples to check the quality of the calibration curve.

A- To obtain the calibration curve, we weighed a different amount of the single standard sample several times as shown below:

N	Standard	Mass mg	[Hg] ng g^{-1}	Peak area
1	Std__10100	17.8	1798	62500
2	Std__10100	26.7	2697	87700
3	Std__10100	37.6	3798	119000
4	Std__10100	47.0	4747	151000
5	Std__10100	71.5	7222	250000
6	Std__10100	111.7	11282	381000

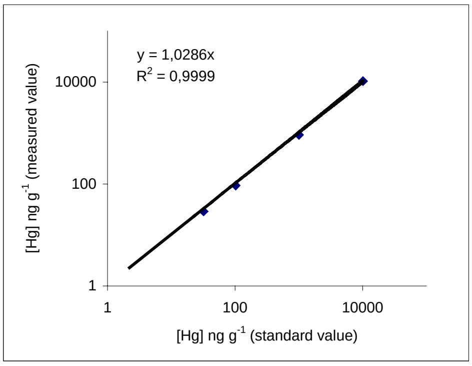


B- Quality control of the calibration curve

We used five samples: a sand without any mercury and four SRM with different mercury concentrations at 32, 102, 1,000 and 10,100 ng g^{-1}.

The results (see illustrations below) showed that the Lumex underestimates the mercury content in the samples by 8 to 10 % for mercury concentrations lower than 1,000 ng g^{-1}. For higher mercury concentrations, the result is correct.

Sample	[Hg] ng g^{-1}	Δ %
sand	2.2	
Std__32	29.0	-10.3
Std__102	93.0	-9.7
Std__1000	922.0	-8.5
Std__10100	10400.0	+2.9



2. WATER

The mercury analyses on water were performed in the BRGM laboratory using as per the European method EN13506 “Determination of mercury by atomic fluorescence spectrometry“.

Samples were first prepared by adding a bromide-bromate mixture. They then were analysed by a system composed of a continuous flow system, a gas-liquid separator and an atomic fluorescence detector. Elemental mercury vapour was generated in the system by reduction with tin chloride (SnCl2). The device used is the atomic fluorescence spectrometer MERLIN from PSA. All reagents were of mercury-free quality.

The accuracy of mercury analyses is frequently checked by inter-laboratory comparisons and by an intra-laboratory control chart. Detection limit is less than 5 ng l^{-1}.

3. FISH

All analyses were performed in the “Laboratoire d’Ecophysiologie et Ecotoxicologie des Systèmes Aquatiques” (LEESA), CNRS, University of Bordeaux, France.

Total Hg concentrations in dorsal fish muscle samples were determined by flameless atomic absorption spectrometry. Analyses were carried out automatically after drying by thermal decomposition at 750°C, under an oxygen flow (AMA 254, Leco-France). Each series of measurements included three standard biological reference materials (TORT-2, lobster hepatopancreas; DORM-2, dogfish muscle; and DOLT-2, dogfish liver, from NRCC-CNRC, Ottawa, Canada) for quality control (illus. 60).

The detection limit (DL) for total Hg was derived as three standard deviations from blank measurement: DL on a dry-weight basis was 1.4 ng g^{-1}. The method precision (relative standard deviation, %RSD) of total Hg determinations, estimated from 5 replicates of fish muscle samples, was 5%.

All dorsal muscle concentrations were reported on a dry-weight basis (40°C over two days).

		TORT-2	**DORM-2**	**DOLT-2**
Total Hg ($\mu g\ g^{-1}$)	Certified value	0.27 ± 0.06	4.64 ± 0.26	2.14 ± 0.28
	Measured value	0.27 ± 0.04	4.78 ± 0.33	2.08 ± 0.12

Illustration 60 - Comparison of measured and certified values of total mercury concentrations using three standard biological reference materials.

4. SOIL, SEDIMENT, TAILINGS AND WATER BY SELECTED AREA

4.1. Inter-laboratory comparison

On the basis of all the chemical analyses carried out at BRGM, at IMR and in the ALS laboratories (app. 1), several comparisons were performed in order to check the quality of the result of the Lumex versus those of the control laboratory (ALS) and then to check the difference between the analyses performed with the Lumex on the < 2 mm fraction as compared to the ground sample < 100 µm. The final objective was to define the best granulometric size to be retained for a preliminary diagnosis of the pollution and to confirm the usefulness of the Lumex as a field tool to detect polluted areas (hot spots).

a) Correlation Lumex - ALS

The samples analysed in the ALS control laboratory are listed in illustration 61. Voluntarily, the samples selected for verification come from different environments: superficial layers, soils, stream sediments and tailings, and they display a wide range of values.

	BRGM LUMEX		**ALS**
Sample	**< 2 mm**	**< 100 µm**	**< 100 µm**
SL5	105	103.33	85.80
SL6	1.19	1.11	2.29
SE16	8.29	8.58	7.68
SE17	0.49	0.50	0.67
SE18	0.12	0.13	0.38
SO24	0.14	0.16	0.22
SO25	0.75	0.78	1.02
SO26	0.07	0.07	0.15
SO36	0.04	0.05	0.10
TA20	1.72	1.77	3.23
TA21	39.33	53.40	24.30
TA22	100.90	106.67	89.20
TA23	3.75	4.09	5.46
TA25	0.58	0.54	0.79

Illustration 61 - List of samples selected for control analyses (in mg kg^{-1}).

The good correlation found between LUMEX < 2 mm and ALS < 100 µm values (illus. 62 and 63) also exists between LUMEX < 100 µm and ALS < 100 µm. Only sample TA21 shows a small difference.

On the 14 samples checked and for a range of values ranging between 0.10 and 120 mg kg^{-1}, it seems that the values obtained with the LUMEX for the < 2 mm fraction is 10% above the values obtained at the ALS laboratory (illus. 64). Nevertheless, due to the small quantity of samples analysed, this observation must be confirmed by conducting more analyses, before it can be generalised.

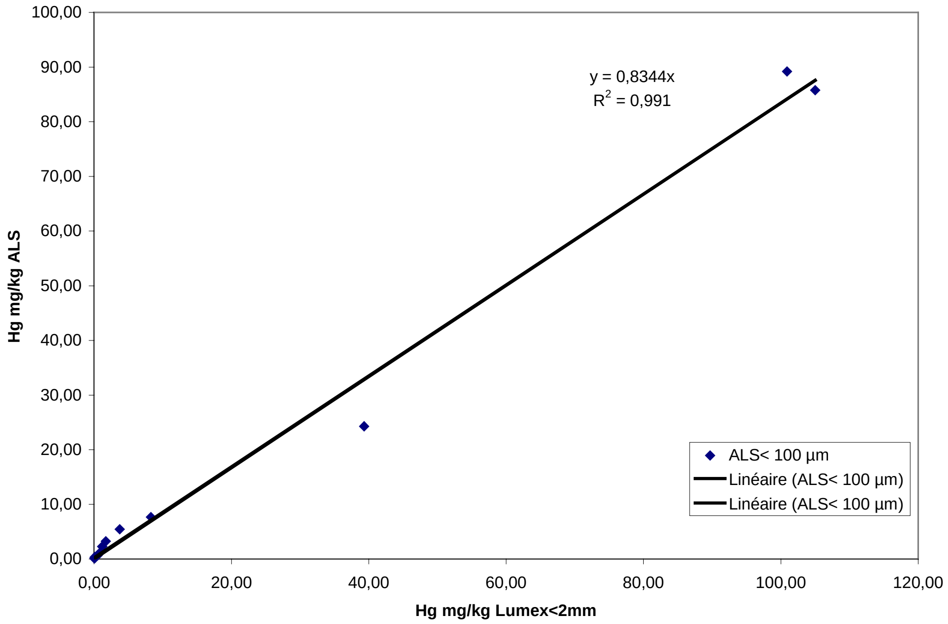


Illustration 62 - Correlation LUMEX < 2 mm versus ALS.

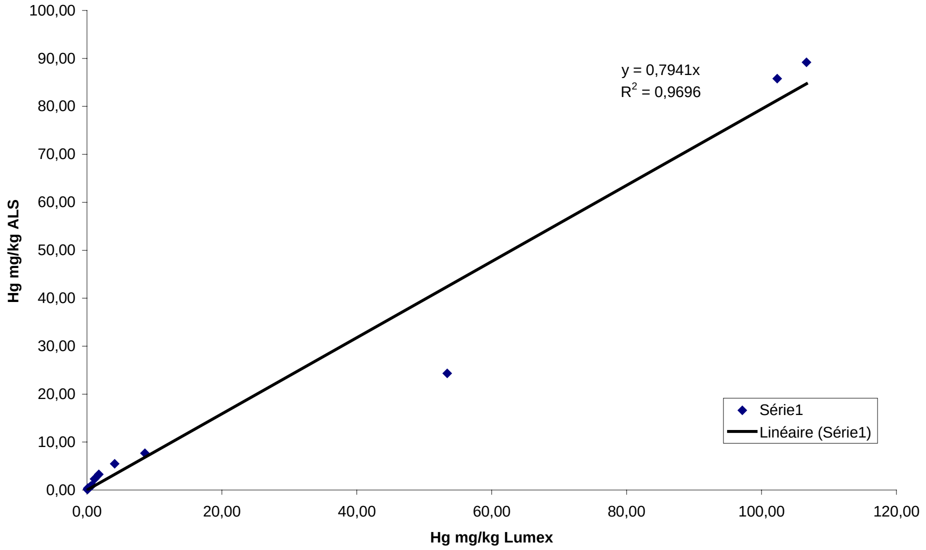


Illustration 63 - Correlation LUMEX < 100 µm versus ALS < 100 µm.

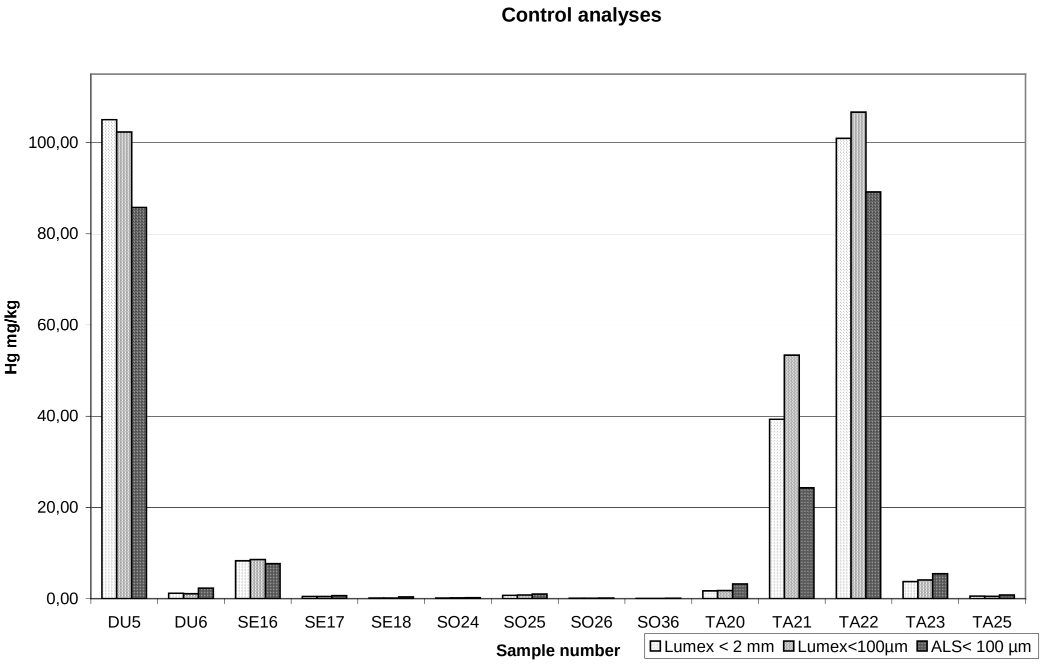
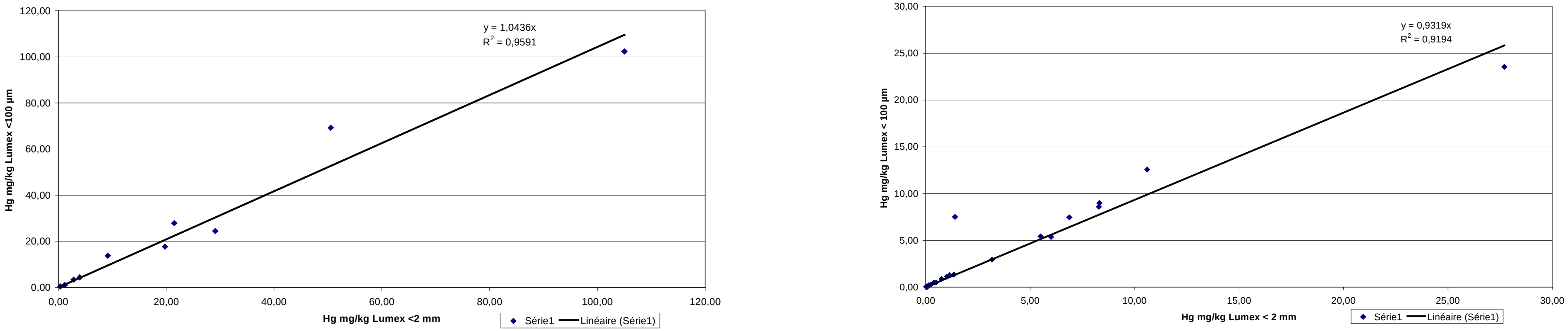


Illustration 64 - Histogram of the control analyses.

b) Correlation LUMEX < 2 mm versus LUMEX < 100 µm

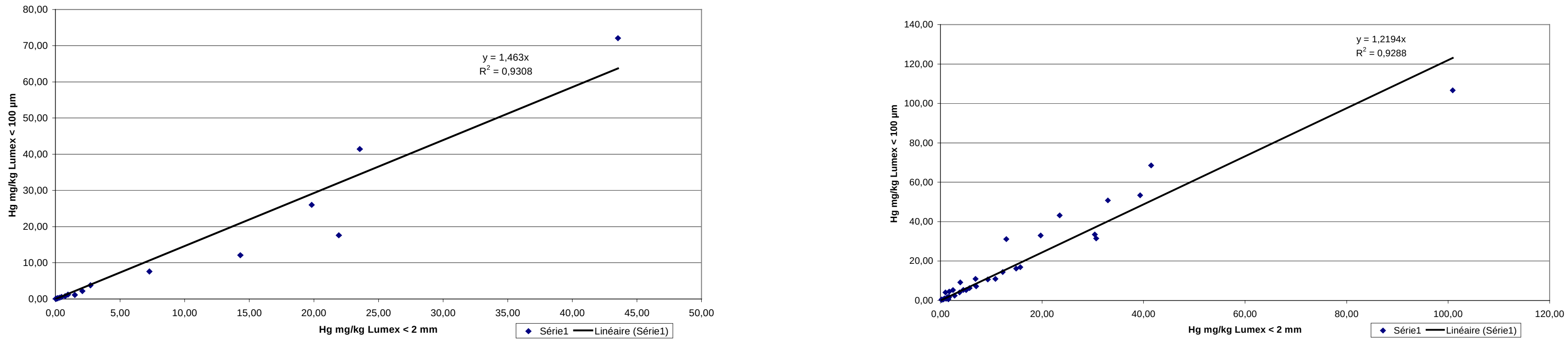
A second and broader control of the LUMEX field analyses was completed on 57 % of the total collected samples. After the analyses of Hg on the < 2 mm fraction, 93 samples were ground < 100 µm and analysed with the LUMEX in the BRGM laboratory (app. 1). Although the population of the superficial samples is limited to 10 samples, the correlation is satisfactory (illus. 65A). We also obtained a good correlation for the 21 stream sediments, for the 18 soils and for the 37 tailings (illus. 65 B, C and D).

Conclusion: The quality control analyses completed first in the ALS lab, and then on the ground sample < 100 µm confirm the validity of the LUMEX analyses done on the < 2 mm fraction. The results obtained with the LUMEX can not be taken as absolute, but good enough to be used as an indicator of Hg pollution. In view of our objective, the LUMEX can be considered to be a good field equipment to establish a preliminary diagnosis on a site polluted by Hg (preliminary survey).



A: Correlation Lumex < 2mm vs. Lumex < 100 µm for 10 dust samples of superficial layer (SL)

B: Correlation Lumex < 2 mm vs. Lumex < 100 µm for 21 stream sediment samples (SE)



C: Correlation Lumex < 2 mm vs. Lumex < 100 µm for 18 soil samples (SO)

D: Correlation Lumex < 2 mm vs. Lumex < 100 µm for 37 tailings samples (TA)

Illustration 65 - Correlation LUMEX < 2 mm vs. LUMEX < 100 µm.

Appendix 3

Biometric data and mercury concentrations (in µg g^{-1} wet weight) in the 52 individual fish

Family	**Genus**	**Species**	**Food regime**	**Standard lenght (cm)**	**Body weight (g, fw)**	**[Hg] µg g^{-1} (g, fw)**	**Sampling spot**
perciforme	cichlidae	Tilapia zillii	Omnivorous	8.80	30	0.050	1
perciforme	cichlidae	Tilapia zillii	Omnivorous	9.60	40	0.076	1
perciforme	cichlidae	Tilapia zillii	Omnivorous	9.20	30	0.064	1
perciforme	cichlidae	Tilapia zillii	Omnivorous	9.00	30	0.067	1
perciforme	cichlidae	Tilapia zillii	Omnivorous	6.60	<	0.083	1
perciforme	cichlidae	Tilapia zillii	Omnivorous	6.70	<	0.071	1
perciforme	cichlidae	Tilapia zillii	Omnivorous	7.20	<	0.061	1
perciforme	cichlidae	Tilapia zillii	Omnivorous	7.00	<	0.070	1
perciforme	cichlidae	Tilapia zillii	Omnivorous	7.00	<	0.056	1
perciforme	cichlidae	Tilapia zillii	Omnivorous	7.20	<	0.124	1
perciforme	cichlidae	Tilapia zillii	Omnivorous	24.50	330	0.173	2
perciforme	cichlidae	Tilapia zillii	Omnivorous	12.60	70	0.105	2
perciforme	cichlidae	Tilapia zillii	Omnivorous	13.40	80	0.100	2
perciforme	cichlidae	Tilapia zillii	Omnivorous	12.50	60	0.108	2
perciforme	cichlidae	Tilapia zillii	Omnivorous	11.50	50	0.247	2
gnathostomes	centrachidae	*Micropterus salmonides*	Carnivorous	15.20	60	0.912	2
gnathostomes	centrachidae	*Micropterus salmonides*	Carnivorous	13.10	50	0755	2
cypriniformes	cyprinidae	*Labeo cylindricus?*	Omnivorous	12.10	40	0.166	2
cypriniformes	cyprinidae	*Labeo cylindricus?*	Omnivorous	12.20	60	0.187	2
cypriniformes	cyprinidae	*Labeo cylindricus?*	Omnivorous	11.10	40	0.183	2
cypriniformes	cyprinidae	*Labeo cylindricus?*	Omnivorous	10.90	30	0.232	2
cypriniformes	cyprinidae	*Labeo cylindricus?*	Omnivorous	13.80	50	0.261	3
perciforme	cichlidae	Oreochromis macrochir ?	Omnivorous	12.00	50	0.189	3
perciforme	cichlidae	Tillapia rendali ?	Omnivorous	11.80	40	0.361	3
perciforme	cichlidae	Tilapia zillii	Omnivorous	9.50	30	0.321	3
perciforme	cichlidae	Tilapia zillii	Omnivorous	8.80	20	0.243	3
perciforme	cichlidae	Oreochromis macrochir ?	Omnivorous	16.30	130	0.046	4
perciforme	cichlidae	Oreochromis macrochir ?	Omnivorous	16.20	110	0.043	4
perciforme	cichlidae	Oreochromis macrochir ?	Omnivorous	16.30	90	0.040	4
perciforme	cichlidae	Oreochromis macrochir ?	Omnivorous	16.30	140	0.053	4
perciforme	cichlidae	Oreochromis macrochir ?	Omnivorous	16.20	130	0.038	4
perciforme	cichlidae	Oreochromis macrochir ?	Omnivorous	15.50	150	0.038	4
perciforme	cichlidae	Oreochromis macrochir ?	Omnivorous	16.00	140	0.036	4
perciforme	cichlidae	Oreochromis macrochir ?	Omnivorous	16.20	140	0.030	4
perciforme	cichlidae	Oreochromis macrochir ?	Omnivorous	15.50	130	0.030	4
perciforme	cichlidae	Oreochromis macrochir ?	Omnivorous	15.60	130	0.030	4

Family	**Genus**	**Species**	**Food regime**	**Standard lenght (cm)**	**Body weight (g. fw)**	**[Hg] µg g^{-1} (g. fw)**	**Sampling spot**
characiformes	brycinus	*Brycinus imberi*	Omnivorous	12.90	50	0.829	5
characiformes	brycinus	*Brycinus imberi*	Omnivorous	12.20	60	0.496	5
characiformes	brycinus	*Brycinus imberi*	Omnivorous	12.20	60	1.187	5
characiformes	brycinus	*Brycinus imberi*	Omnivorous	13.00	60	0.963	5
characiformes	brycinus	*Brycinus imberi*	Omnivorous	13.00	80	0.570	5
characiformes	brycinus	*Brycinus imberi*	Omnivorous	13.20	60	0.989	5
characiformes	brycinus	*Brycinus imberi*	Omnivorous	13.70	70	1.221	5
characiformes	brycinus	*Brycinus imberi*	Omnivorous	12.60	50	0.888	5
characiformes	brycinus	*Brycinus imberi*	Omnivorous	13.30	50	0.747	5
characiformes	brycinus	*Brycinus imberi*	Omnivorous	13.40	50	0.901	5
gnathostomes	centrachidae	*Micropterus salmonides*	Carnivorous	19.60	130	0.869	6
gnathostomes	centrachidae	*Micropterus salmonides*	Carnivorous	17.50	110	2.00	6
gnathostomes	centrachidae	*Micropterus salmonides*	Carnivorous	17.00	100	0.634	6
gnathostomes	centrachidae	*Micropterus salmonides*	Carnivorous	18.90	140	0.915	6
gnathostomes	centrachidae	*Micropterus salmonides*	Carnivorous	17.50	90	0.953	6
gnathostomes	centrachidae	*Micropterus salmonides*	Carnivorous	17.50	100	1.383	6

Appendix 4

Characteristics of each fish specie (identification, diet)

Family	Genus	Species	Diet	Diet composition
Characiformes	Brycinus	Brycinus imberi	Omnivorous carnivorous	Insects, tiny fishes, crustaceans and vegetable matters
Cypriniformes	Cyprinidae	Labeo cylindricus	Omnivorous herbivorous	Plants, phytoplankton, periphyton and diatoms
Gnathostomes	Centrachidae	Micropterus salmonides	Only Carnivorous	Fishes, crayfish and frog
Perciforme	Cichlidae	Oreochromis macrochir	Omnivorous herbivorous	Detritus, plants, zooplankton, phytoplankton and diatoms
Perciforme	Cichlidae	Tilapia zillii	Omnivorous herbivorous	Plants, zooplankton and invertebrate
Perciforme	Cichlidae	Tilapia rendali	Omnivorous herbivorous	Plants, algae, zooplankton insects and crustaceans

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