MERCURY IN ARTISANAL AND SMALL SCALE GOLD MINING: IDENTIFYING STRATEGIES TO REDUCE ENVIRONMENTAL CONTAMINATION IN SOUTHERN ECUADOR

by

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

in

The Faculty of Graduate Studies
(Mining Engineering)
THE UNIVERSITY OF BRITISH COLUMBIA
(Vancouver)

August 2010

Abstract

This investigation builds on research about mercury use in custom processing centers in Portovelo-Zaruma Southern Ecuador, where around 3000 people are directly involved to produce around 9 tonnes/annum of gold. The lack of understanding about mercury dynamics during gold processing reduces the development of appropriate solutions to mitigate the environmental contamination.

The analysis of the amalgamation systems in 8 centers indicated that 12 to 40% of the total mercury used in the process has been evaporated when amalgams are burned, 40 to 60% of mercury has been recovered and 1 to 35% of mercury has been lost with the tailings. The amalgamation of the whole ore in barrels ("Chanchas") contributes to the highest concentrations of mercury in tailings (350 ppm Hg). Around 1.5 tonnes/annum of mercury has been likely released to the environment in Portovelo from which 71% goes to the air and the remaining mercury enters the cyanidation process. As amalgamation does not extract all the gold present in the ore, the mercury rich-tailings are processed with cyanide preferentially through Merrill-Crowe or Carbon in Pulp (CIP) system. The analysis of 7 cyanidation processing plants revealed that 51% and 14% of mercury is released as dissolved mercury from CIP and the Merrill-Crowe process respectively. Approximately 27% of mercury is released to the atmosphere with the Merrill-Crowe when zinc shavings are burned. The CIP process releases 3.72% of mercury during carbon elution. A laboratory cyanidation test confirmed that mercury dissolution from tailings is much slower than gold dissolution.

The established division of labor in place among miners and owners of processing centers forces the use of mercury in amalgamation combined with cyanide leaching. As miners do not understand the actual process, they accept low levels of gold recovery by amalgamation, leaving the rich tailings to the owners of processing centers. This generates dependency on mercury and reduces the opportunity to improve the system.

One lesson gleaned from this study is that a participatory integrated assessment approach may contribute to learning, increasing awareness, and it can help identify practical and effective options for reducing mercury contamination in artisanal gold mining operations.

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List of acronyms

ASGM – Artisanal and small scale gold mining

APROPLASMIN – Asociación de Propietarios de Plantas de Beneficio Mineral

CIP – Carbon in Pulp

CIMA – Compañía Industrial Minera Asociada

EIA - Environmental Impact Assessment

ENSO – El Niño Southern Oscilation

FUNGEOMINE – Fundación Geologica Minera

FUNSAD – Fundación para la salud

GEF – Global Environmental Facility

Ha – Hectare

PRODEMINCA – Proyecto de Desarrrollo Minero y Control Ambiental

SADCO – South American Development Company

UN-COMTRADE – United Nations Commodity Trade Statistics

UNIDO – United Nations for Industrial Development Organization

UNEP – United Nations Environment Programme

USEPA – US Environmental Protection Agency

WHO – World Health Organization

Acknowledgments

Firstly I would like to thank to my supervisor, Dr. Marcello Veiga and the co-supervisor Dr. Ken Hall for the guidance and direction provided during this PhD. I am heartily thankful to Marcello Veiga whose friendship, guidance and support from the early to the final level enabled me to develop an understanding of the subject of gold processing and foundations to apply research in mining communities. Dr. Hall guidance has allowed me discerning complex issues which also strength my capacity for this doctorate, and his suggestions pointed me in the right direction to perform this thesis. Apart of my supervisors I would like to recognize my appreciation to Margot Parkes for her preliminary assistance on the road to achieve this thesis.

I am thankful to the University of British Columbia and especially to professors, colleagues, and staff of the Norman B. Keevil Institute of mining engineering for support received to achieve my studies.

My thanks to several funding sources for this achievement. I would like to express my gratitude to Dr Jerry Spiegel, who in addition to serving on my thesis committee, supported my PhD through the CIDA, University partnership of Cooperation and Development TIER 1 “Sustainable managing environmental and health risk in Ecuador” project University Partnership. In addition I thank authorities of the Technical University of Machala, from Ecuador for their support to accomplish this goal. Additional funding was also received from The United Nations Industrial Development Organization through the Global Mercury Project under direction of Marcello Veiga for whom I also express my gratitude.

As I spent most of my office time at the Health Promotion Research (Global Health Institute), I would like to thank my colleagues and friends for their help and assistance provided in every moment I needed.

This thesis would not have been possible without the opportunity I found through many people in Ecuador. Owners of processing centers, miners,

technicians, and community members from Portovelo, Zaruma and Ponce Enriquez, who without a doubt were the most important actors of this work for whom, I express my appreciation and deep respect. To them, my gratitude for granting the opportunity to learn together and for giving me the chance to enter a new life experience.

Finally I must be thankful to each one of my family members, close relatives and special friends for their comprehension and support during the difficult times I experienced during these years. Many limitations and frustrations were borne thanks to their understanding for whom I express my appreciation and gratitude.

I offer my regards and blessings to all of those who trust and supported me in any respect during the completion of this PhD program.

Chapter 1 : General introduction

1.1 Background

Since the second half of the 18th century, Southern Ecuador has been recognized as having in particular excellent potential for mining and extraction of gold and silver (Paredes, 1980). Preliminary investments in gold mining exploration and processing by international companies and the Government left the people of Portovelo, Ecuador, with a strong dependency on gold mining. The artisanal operations in Ecuador began in the 1980s, and it is believed that currently artisanal and small scale gold mining (ASGM) produces 85% of the total gold production of Ecuador. In 2002, it was estimated that there were around 100,000 artisanal miners actively working within the country most of them mining gold, and it was also estimated that in Portovelo-Zaruma alone, 80% of the population of 25.000 inhabitants depend on this activity (Sandoval, 2001).

Artisanal mining operations have received special attention since the release of heavy metals, suspended solids and cyanide are associated with their activities (Tarras-Wahlberg et al., 2000; Malm et al, 1999; Salomons, 1995). It has been estimated that 1,000 tonnes/a of mercury are released to the environment (Swain et al., 2007) by 10 to 15 million of artisanal and small gold miners worldwide (Veiga and Baker, 2004). Impacts and contamination resulting from the release of mercury from the amalgamation process is of great concern due its effects on human health (Lacerda, 1997). As the price of gold increases, ASGM activities are expanding

around the world (Spiegel and Veiga, 2005), to the point where approximately 100 million people are estimated to be involved in ASGM activities.

In response to the environmental contamination and miner's health concerns, a large study undertaken in ASGM communities reports the existence of conflicts between artisanal operators and large mining companies (Veiga et al., 2001; Hilson, 2000) as well as disputes regarding land use; (Tarras et al 2001; Hilson 2002; Hilson et al., 2007).

There has been a great deal of research conducted worldwide on the impacts of mercury from ASGM, as well as risk assessments on biota, sediments, and water (Palheta and Taylor, 1995; Ogola et al., 2002; Dai et al., 2003; Serfor-Armah et al., 2004). Most of these researchers have brought evidence of heavy metal pollution, in particular mercury bioaccumulation in fish and risk of human exposure through mercury vapour and fish consumption. Mercury is a highly toxic element that under favourable environmental conditions can be transformed into its most toxic form, methylmercury which is rapidly bioaccumulated by aquatic biota (Meech et al., 1998).

An important literature exists in Ecuador regarding environmental contamination and the negative impacts caused by artisanal gold mining. The PRODEMINCA (Proyecto de desarrollo minero y control ambiental) project was one of the most important actions in which a vast sampling and analysis of biological and geochemical materials were conducted in the main Ecuadorian ASGM sites (PRODEMINCA, 1999). Another project that undertook actions to minimize environmental contamination with special attention to mercury was the COSUDE

project conducted by the Swiss Development Cooperation (Sandoval, 2001). From the results of these studies which focused on the consequences of artisanal mining operations in Ecuador, Tarras-Wahlberg et al. (2001) published the findings regarding the effects of those practices and the way they are associated to aquatic ecosystem contamination with heavy metals and cyanide. The authors also highlighted the loss of biodiversity and the bioaccumulation of metals including mercury in the lower sections of the Puyango River system which drain from artisanal gold mining operations. In 2003 the cumulative loads of total suspended solids in association with heavy metals, including mercury, into the Calera and Amarillo Rivers in the Zauma-Portovelo region, which are tributary to the Puyango River, were determined (Tarras-Wahlberg et al., 2001; Tarras-Wahlberg and Lane, 2003). Mercury contamination with concentrations reaching 15 mg/kg of sediment on river banks has been reported (Appleton et al., 2001). In Nambija, another mining district in Ecuador, mercury pollution was also identified in concentrations of 5.5 mg/kg of mercury in sediments (Ramírez-Requelme et al., 2003). Other documents revealed the presence of mercury as well as other heavy metals such as cadmium, zinc, copper and arsenic from ASGM, contaminating aquatic resources (Tarras-Wahlberg et al., 2000). These studies show evidence of the most relevant impacts of gold mining in the Ponce Enriquez area, where ASGM operators are situated near a watershed which is close to agricultural and aquaculture areas. ASGM contaminants commonly make their way into agricultural areas, and, further downstream, reach the largest shrimp farming industry in Ecuador. Mercury contamination in coastal zone of Southern Ecuador was also

reported by Solorzano (1989). The most recent study supported by the International Development Research Centre (IDRC) from Canada, confirmed the environmental problems of mercury and other heavy metals (Betancourt et al., 2005). Other studies presented evidence of anomalies in the health of children exposed to mercury in ASGM activities in Ecuador (Counter et al., 2002; Counter, 2003; Counter et al., 2006). Sandoval (2001) reported land use conflicts due environmental problems caused by artisanal mining in Ecuador. Also he estimated that about 5 tonnes of gold were produced in the country in 2000 by ASGM, and thus emphasized the importance of this sector in the local economy.

From the literature review, it is clear that despite the knowledge about mercury contamination little research has been conducted in Ecuador and elsewhere to better understand how mercury is released to the environment from ASGM operations as well as what are the main pathways of mercury contamination. Both Tarras-Walhberg et al. (2000) and a more recent study by Veiga et al. (2009) discussed the practice of mixing mercury and cyanide in artisanal gold processing, and emphasized the risks associated with this poor practice, particularly with regards to the bioavailability of mercury-cyanide complexes to the aquatic biota. The resulting impacts including the physical transformation, and biological and chemical changes observed in Ecuador ecosystems are worrisome as mercury association with cyanide can exacerbate the risks to the environment and human health (Hylander and Meili, 2005; Veiga et al., 2009).

During the last 5 years of the present study, a steep increase of the price of gold has been observed from about US $ 450/ oz (September 2005) to US$

1220/oz (May 2010). This increase in gold price has been linked to the expansion of artisanal mining operations in Ecuador and around the world, and it has been motivated by the extensive levels of poverty in rural communities in developing countries. Moreover, ASGM communities continue to lack thorough and adequate knowledge regarding the impacts of their mining activities. Research regarding ASGM in other regions of the world has also indicated severe environmental contamination and human health issues due to mercury exposure (Olivero et al., 2002; Limbong et al., 2003; Castilhos et al., 2006). Subsequent studies have begun to consider possible solutions to this problem. Hinton et al. (2003) made an overall analysis of the problem of ASGM with regard to sustainability of mining communities and suggested regularization, organization and the creation of environmental management plans as the principal guidelines for managing the problem. The authors addressed the need to develop clean technologies through institutional support and technological development through education. Other researchers emphasized the issue of formalization (Heemskerk, 2005) and focused on making international donors aware of issues regarding the sustainability of mining communities (Sinding, 2005).

While alternatives to manage the problem of ASGM contamination have been discussed by Tarras-Wahlberg, (2002) the persistence of mercury in the processing operations constitutes a local risk since mercury interacts with other chemicals present in the ASGM tailings (Veiga et al., 2009; Velásquez-López et al., 2010) forming more bioavailable species (Coles and Cochrane, 2006).

Suggesting that poverty and lack of education are the factors mainly responsible for the creation of environmental contamination, some researchers have proposed the creation of interventions in ASGM communities rather than simply assessment of the environmental impacts. The challenge to resolve the problem of environmental contamination was oriented toward actions which could begin to build sustainability within artisanal mining communities (Spiegel and Veiga, 2005; Heemskerk, 2005; Hilson, 2006). Specific approaches to reaching the goal of sustainability include a focus on international cooperation, the banning of the use of mercury, and the formation of local partnerships with miners (Spiegel et al., 2005). Out of these initiatives, recent publications refer to the work of the United Nations Industrial Development Organization (UNIDO) (Spiegel, 2009a), that assisted artisanal miners from several developing countries through an integrated educational campaign in which misunderstandings and fantasies about mercury use were addressed, and pieces of equipment locally made were demonstrated throughout mining communities to reduce the levels of mercury exposure (Shandro et al., 2009). In Ecuador, opportunities for strengthening capacities to address issues of environmental contamination such as ASGm communities has received particular attention (Spiegel et al., 2007; Yassi et al., 2007)

Beyond the published information about social and economical factors, technological alternatives to mitigate mercury pollution in artisanal gold processing have been also suggested. However, some considerations such as clear technology transfer (Hylander et al., 2007) and the efficient use of equipment

(Vieira, 2006; Sousa and Veiga, 2009) reveal that efforts made towards international cooperation with developing countries have not been effective either because only short term assistance was provided, and/or because of the lack of presence of local Governments. To facilitate the dissemination of methods to replace mercury, awareness about the problem and mercury dynamics in the system of artisanal mining must first be understood. Miners must also need to get involved in training programs and participate in research to be able to proceed to a good decision making process in their daily lives and techniques to recover the gold (Hilson, 2006). Technical support and ongoing training can help miners develop techniques to extract gold inexpensively, and with fewer mercury emissions in the amalgamation process (Veiga, 1999). Miners and community participation through policy for proper technology can allow conflict resolution and alternatives to decrease effects as well as improve the productivity of artisanal miners (Hilson et al., 2007).

From the literature on the topic, it becomes clear that approaches to understanding mercury dynamics, its loads and the forms through which it is released to the environment are lacking, and there are major gaps in our understanding of ASGM systems and how they contribute to environmental contamination. Environmental pollution is directly related to human health and well being (Burger, 2002; Parkes et al., 2003), and so, assessing mercury at the source of the pollution provides the key to find alternatives and improve the health of ASGM communities.

1.2 Statement of the problem

While the use of mercury in the ASGM is considered a global problem affecting the environment and human health, scientists' limited knowledge about its discharge pathways reduces the development of solutions to eliminate or reduce emissions. Information about quantification of the mercury emissions from processing sites as well as the distribution of the mercury is needed to establish priorities and policies to change the miner's attitude in processing operations.

Despite the important research that has been conducted on mercury contamination from the amalgamation process (Lacerda, 1997; Malm, 1998; Dai et al., 2003; Dhindsa et al., 2003), very little is known about the behavior of mercury when it interacts with cyanide (Spiegel, 2009a). Few studies aimed at understanding the interaction of both contaminants have been conducted within artisanal operations. As Sinding (2005) suggests, "addressing the impacts of ASGM is a herculean task" and it reveals the limits of conventional methods in dealing with this complexity. Despite the extensive work undertaken on the environmental contamination of artisanal and small-scale gold mining, mercury loads, its mobility and its subsequent fate are still highly controversial and not well understood.

The most recent publications show evidence of the existence of social and economical problems in some mining communities (Spiegel, 2009b). For example, a socioeconomic evaluation developed by Tarras-Wahlberg and colleagues regarding the case of Ecuador reveals the importance of this activity in generating income, but at the same time reflects the lack of consciousness and interest of

miners for the improvement of their conditions during processing and waste management (Tarras-Wahlberg et al., 2005).

Within the ASGM system, the use of mercury and its associated impacts are clearly the result of a complex scenario in which socio-cultural, technological and biophysical factors are highly interconnected, and these factors together have led to high levels of environmental pollution and human health problem (Spiegel, 2009b). While these problems are considered to be global in nature (Hylander and Meili, 2005), scientists' limited knowledge about mercury discharges has hindered the development of appropriate solutions regarding the reduction of environmental contamination and human exposure to the metal. One of the barriers which have been identified for resolving the problem of mercury use in mining communities is the poor sharing of information (Hylander et al., 2007). For some researchers, these barriers are considered to be the major constraint for mitigating contamination levels (Hilson, 2006a). The interactions between different social agents (stakeholders) in the ASGM system have been described as being responsible for the evolution of the problems of environmental contamination (Siegel and Veiga, 2009). Such lack of understanding is exacerbated when artisanal miners misuse mercury and leach mercury-rich tailings with cyanide (Metcalf, 2008). Therefore, it is essential to understand how mercury is used in the ASGM in order to predict and manage the risks. The approach of assessing the pathways and amounts of mercury in the gold processing system is essential for understanding the system, improving awareness, and determining management's options to reduce mercury contamination.

1.3 Approach of the thesis

Through an investigation into the reasons for mercury use and the pathways of mercury contamination, this study explores how an integrated assessment can serve as the foundation for managing mercury pollution in ASGM. Using an integrated approach to analyze the use of mercury in ASGM systems allows us not only to help stakeholders understand the causes and effects of mercury contamination, but also to explore policies that can be implemented to manage the environmental and health risks. Despite the extensive research which has been conducted to elucidate the dilemmas faced by miners with regard to mercury, it is clear that the conclusions of these studies have not been well communicated to miners, and/or understood by them in a meaningful way. As such, because either the information has been incomplete or not properly understood, it was important to consider a research approach in which miners and community members are deeply involved in the assessment and in the discussions of the solutions.

One of the major constraints to implement effective actions involves the current lack of understanding of mercury's pathways and mobility through the ecosystem. In fact, although assessments of mercury have been conducted at the level of environmental impact, there is a very poor understanding about the behavior of mercury in gold processing systems. An integrated analysis of mercury within the ASGM system not only increases the opportunity for understanding the problem in a holistic manner, but it also presents an opportunity for miners to change their behavior when working with mercury. An integrated assessment helps identify contaminant pathways, target components for intervention (Gitau et al., 2009) as

well as provides opportunities for strengthening the main players' understanding of the complex problems involved (Pahl-Wostl, 2007). These steps would thereby help increase the capacity for remediation and the management of environmental contamination (Bridges, 2003; Briggs, 2008). Through an examination of the effects of AGSM on the ecosystem, this study implements an integrated environmental assessment protocol of mercury pathways during gold processing which includes the following aspects:

a) A technological characterization of the gold processing system.
b) The establishment of a mass balance of mercury during both the amalgamation and cyanidation processes to estimate mercury losses to the environment
c) The establishment of a link between knowledge and the evidence of mercury pathways in gold processing considering the perceptions of different stakeholders.

This approach was useful from the point of view of interacting with, and informing the ASGM communities regarding the nature of the problems that are occurring on their own land, as well as helping them understand how their actions have the capacity to contribute to solutions regarding mercury use.

1.4 Research questions

The main questions considered in this research were as follows:

- How is mercury used and released to the environment in Southern Ecuador ASGM operations?
- What and where are the main losses of mercury during gold processing?

- What kind of management and methods are required to reduce mercury contamination from ASGM practices in the Southern Ecuador?

1.5 Research objectives

The objectives of this research were as follows:

- Gather technological information on gold processing patterns, the organization of miners, gold processing systems, and waste management in order to identify the negative impacts of mining activities on the environment.
- Assess mercury levels during amalgamation and cyanidation, in order to identify and quantify mercury losses, and forms in which mercury reach the ecosystem.
- Integrate technological process and stakeholder perceptions regarding the effects of ASGM to identify alternatives for reducing mercury emissions and managing environmental pollution.

1.6 Thesis outline

The following information has been gleaned through this study:

Chapter 2 describes the methods and design elements of this study which focuses on the use of mercury in the artisanal gold mining operations in Southern Ecuador. It outlines the participatory assessment approach that was applied to obtain data.

Chapter 3 describes the study site and reviews the historical development of gold mining, as well as the rise of Artisanal and Small Scale Gold Mining (ASGM)

in Southern Ecuador. It also explains how the ASGM system works, describing the location and the types of processing centers, and characterizes the people involved.

Chapter 4 describes the results of the main pathways and loads of mercury in different amalgamation systems. This part of the research examines the mercury balance in different systems of amalgamation, and the technical reasons that influence the use of mercury in Southern Ecuador. By a participatory assessment approach, information on how mercury is managed during three amalgamation systems as well as the quantity of mercury being discharged into the environment were obtained. Feasible recommendations on procedures to reduce mercury emissions from artisanal gold mining were discussed with stakeholders.

Chapter 5 describes the mercury releases when mercury-rich tailings are exposed in the cyanide leaching processes. This chapter describes the characteristics of cyanidation systems in ASGM and evaluates mercury losses during cyanidation in processing centers in Portovelo-Zaruma region. This information on mercury during the cyanide leaching process becomes an essential step to complement the understanding of the mercury behavior during gold recovery.

Chapter 6 presents an analysis of the problem of mercury contamination caused by ASGM activities in an integrated manner understanding different systems of gold recovery and nature of mercury emissions with stakeholder perceptions based on meetings and discussions. The aim is to give an overview about mercury dynamics in the ASGM system, reporting the concerns of mining

and non-mining communities. Analyses of different options to mitigate mercury pollution based on community ideas are discussed. This chapter also addresses the main hurdles to implement options and discusses legislation regarding artisanal gold mining processing in Ecuador.

In general this study identifies alternative methods to reduce mercury contamination and environmental management as well as further questions and insights to use in subsequent research. The study also makes suggestions regarding implementation of similar research in other regions of the world which are affected by the same kind of problems. Findings regarding the interaction of mercury in the gold extraction process have functioned to guide the attention of miners and local policy makers who can make use of this scientific information to create alternatives for better practices. As a result of this research, two publication in peer-reviewed journals has been generated.

1.7 Significance of the work

As mining activities increase in the Southern region of Ecuador and in other sites worldwide, concerns related to mercury contamination are growing, both within mining communities and Governments. The existence of a variety of players involved in the ASGM system renders a more complex scenario as the effects of mercury are not merely restricted to mining sites but also to the surrounding ecosystems. Therefore, the approach of this study was an in-depth exploration of the ASGM process with regard to mercury. The processing systems were investigated in order to construct baseline research for developing management criteria based on mercury emissions and the factors that determines its distribution.

The understanding of mercury pathways from their sources as well as the reasons for the use of mercury in ASGM communities leads to a better comprehension of the dynamics of the whole system. This in turn also helps determine mercury behavior and infer the mobility in the environment.

The final results of this research and its methodology will assist environmental scientists, Government and international agencies that deal with the problem of mercury in artisanal gold mining in the decision-making process.

As mercury is a contaminant of concern for every artisanal miner, miners' knowledge about its use, transport and distribution in artisanal operations would undoubtedly be valuable for understanding how to manage it. Furthermore, education of miners is one of the entry points to address the problem of environmental contamination. Therefore, the participatory approach used in this research is a significant and important asset for the decision-making process in mining and resource management.

The protocol for mercury assessment in the ASGM process provides an useful tool for further research in other artisanal gold mining sites.

Chapter 2 : Methodological approach

2.1 Study design

In order to address the problems of mercury use and the environmental impacts caused by artisanal gold mining activity, this study examined multiple sources of evidence of mercury contamination at both the gold processing centers and according to the stakeholder's perceptions. Fig 2.1 shows the steps taken for this research. Integrated assessment has been suggested by several authors as a tool through which to evaluate and analyze complex problems (Toth and Hizsnyik, 1998; Hisschemoller et al., 2001; Bridges, 2003; Suter et al., 2005; Bridges and Bridges, 2004). The active involvement of stakeholders in research is considered to change behavior or for constructing opportunities for change (Lal et al., 2001).

A holistic understanding of the issue of environmental pollution requires more than one level of analysis (Waltner-Toews et al., 2002; Dooris, 2006) as is emphasized by the "ecosystem approach to human health" (Lebel 2003). The nature of the process of gold extraction within the artisanal mining community makes it necessary to combine different methods of research (Johnson and Onwuegbuzie, 2004) including direct observation (Jorgensen, 1989), and the assessment of mercury during amalgamation and cyanidation in processing centers. Interacting with stakeholders facilitate more effective use of research and opportunity to gather as much information as possible (Hanney et al., 2003).

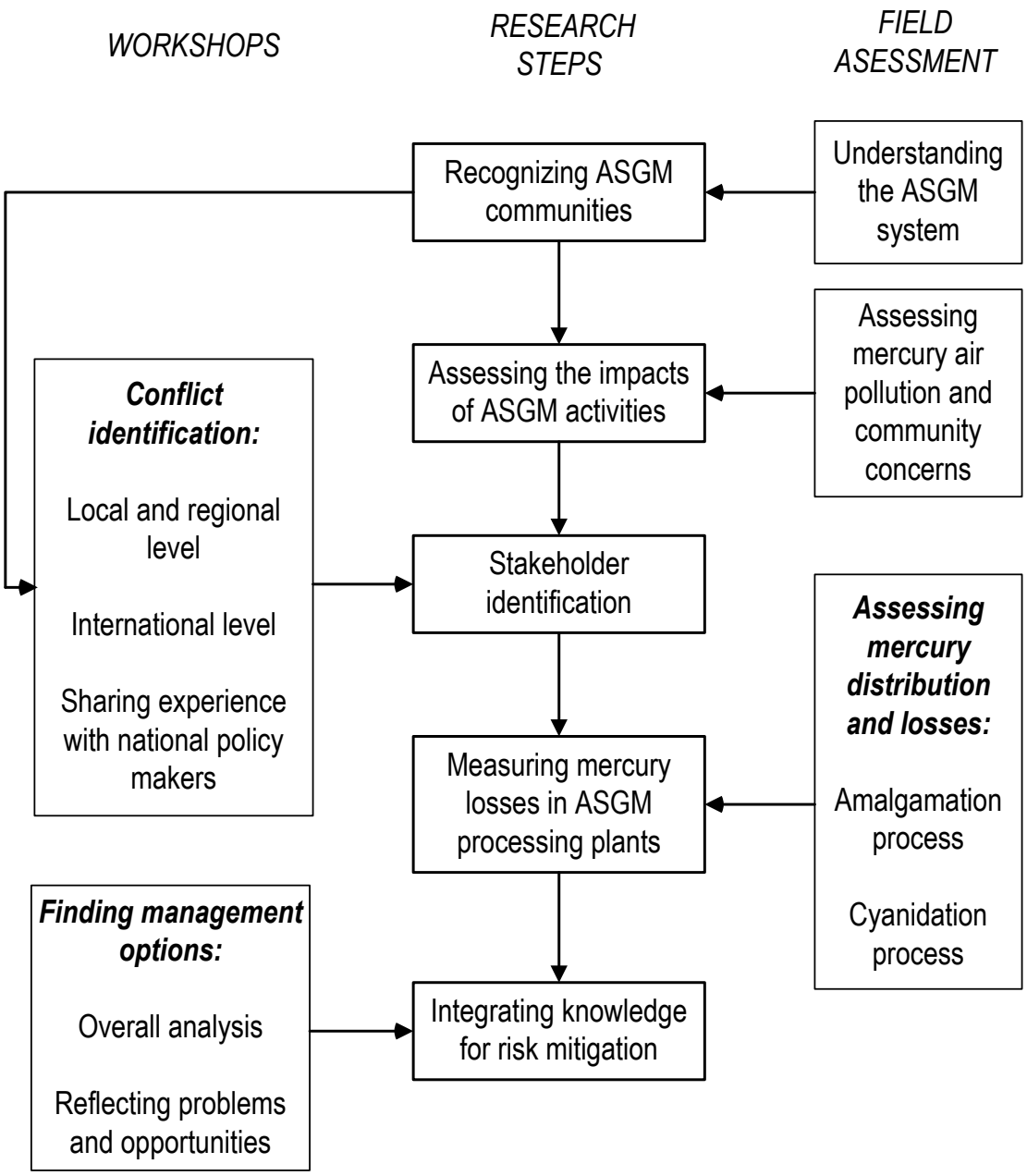

Fig 2.1: Diagram of the study approach of mercury in ASGM system.

During the field assessments of processing centers, the use of a LUMEX portable mercury analyzer (LUMEX OHIO, 2009) offered the opportunity for obtaining fast results. It also facilitated the interchange of knowledge with the miner in the field during the study. Any methodology used for the study of artisanal

mining operations would require the researcher to establish an informal, integrated and friendly relationship with the miner, operator or the community associated with this activity. The study constitutes an approach to learning which was carried out in conjunction with the miners, while at the same time providing an analysis of the complexity of mercury use in the ASGM processing systems. This was done with the goal of eventually finding viable and practical alternatives for mitigating environmental contamination.

The overall study includes three steps:

a) Field observation for a characterization of the gold operation system at the processing centers localized in the Portovelo-Zaruma mining district in connection with Ponce Enriquez.

b) A assessment protocol for determining mercury pathways and releases during gold processing operations;

c) Options for management were addressed through coalescing the knowledge acquired from mercury assessments, documentary review and other information that have been acquired through participating in different workshops and discussions with the miners.

2.2 Data gathering

As mentioned above, the sources of information for this study were gleaned from: a) modes of practices as well as miner's perceptions about how and why mercury is used and managed in different processing systems; b) a historical review regarding the ASGM system in Southern Ecuador; c) quantitative data about mercury lost and mercury recovered by the miners during gold processing

operations; d) Information generated during brainstorming workshops and discussions in the field with the miners.

2.3 Selection of ASGM processing centers

The study was concentrated on specific processing centers in El Pache, site which is located along the Calera River in Portovelo, a town in the Province of El Oro. However, due the nature and personal characteristics of the people encountered and their processing operations, it was necessary to visit the processing centers at Ponce Enriquez a town in the Province of Azuay (Fig 2.2).

Mercury assessment involved weighing and/or analysis of mercury at the beginning of the process (amalgamation – cyanidation), and an analysis of the tailings and solutions at the end of the process. For system characterization and assessment of mercury pathways during the amalgamation process, 7 different processing centers were visited in Portovelo and 1 in Ponce Enriquez. To examine the cyanidation process, 7 different cyanidation plants in Portovelo were studied in order to assess the pathways of mercury behavior during the cyanidation process.

Selections of processing centers were performed according to the current operations and opportunities offered by miners at the time of the field research. The processing plants were selected, with assistance from key informants from the mining community who made the preliminary connections with miners and owners of processing plants. During the field work, the processing centers were visited and scheduled according the miner's daily work plans. Although there was an opportunity for miners to schedule operations, this was never applied since the way miners performed their work did not always happen according to a schedule.

Therefore, it was important to keep tracking the miner's activities until they were ready to begin processing.

Fig 2.2: Location of Portovelo-Zaruma and Ponce-Enriquez.
(Tarras-Wahlberg et.al., 2000)

2.4 Integrated assessment of mercury use in processing centers

After system characterization, mercury distribution during both the amalgamation and cyanidation processes were assessed (Fig 2.3).

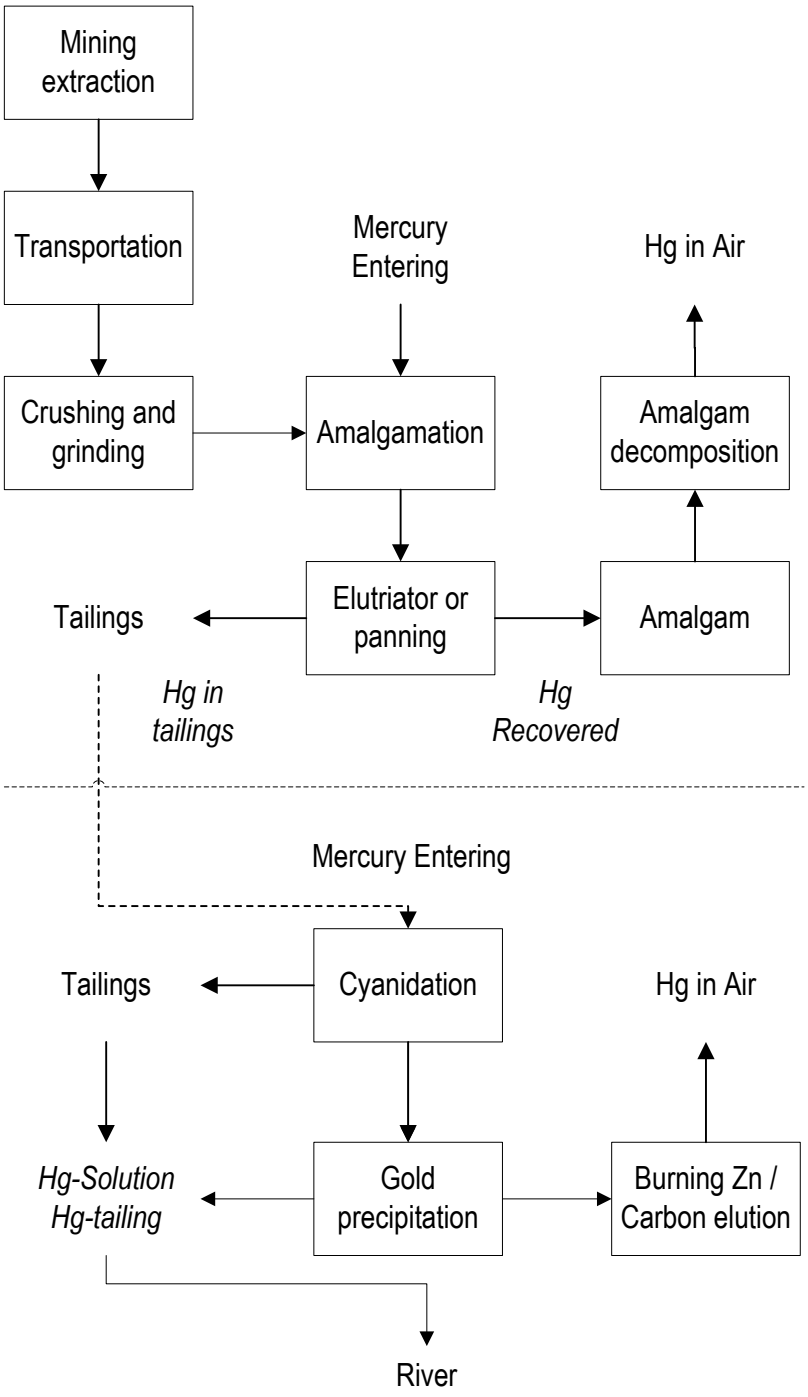

Fig 2.3: Diagram of assessment of mercury in gold processing system.
(amalgamation and cyanidation)

2.4.1 Assessing the amalgamation process

An assessment was made of mercury distribution during amalgamation by weighing the total amount of mercury that miners used, and weighing the mercury recovered after they squeezed the excess of mercury from the amalgam. Table 2.1 shows the procedures applied for the balance of mercury in the amalgamation process.

Table 2.1: Methods for Measuring Hg during amalgamation process.

Evaluation	Procedure
Mercury entering the system	Mercury was weighed before being introduced into the amalgamation process.
Mercury recovered (excess Hg)	Mercury was weighed after squeezing the amalgam to eliminate excess Hg.
Mercury evaporated when amalgam was burned	Amalgam was weighed before burning to evaporate mercury, and the doré was weighed after burning.
Mercury evaporated when the doré was melted	Gold doré was weighed before being melted. The mercury released during doré melting was obtained by weight difference before and after melting.
Mercury lost with tailings	This is estimated by the weight difference between mercury entering the process and mercury recovered and lost by burning. Tailings represent the mix of water and solid material.

The approach was to make in-depth observations of the actions and interactions of artisanal and small-scale miners as they worked their ore, including crushing, grinding and milling the ore.

2.4.2 Assessing the cyanidation process

A mercury balances was also conducted in cyanidation plants. A protocol for mercury assessment was created according to the operational environment of each cyanidation plant. Mercury assessment was followed in seven different cyanidation plants (6 Merrill Crowe systems and 1 Carbon in pulp). In both Merrill-Crowe and CIP, the tailings and solutions were sampled in each tank following the scheme, procedures and operational system of each processing plant.

Samples from the cyanidation tanks were collected at the beginning and end of the cyanidation process. The solid and liquid samples were then analyzed for total mercury. After draining the tanks, the mercury trapped at the bottom of the tanks was recovered and weighed. Analyses of total mercury in both solid and liquid samples were performed using a RA-915+ portable LUMEX flameless atomic absorption spectrophotometer with a pyrolisis chamber (RP-91C) (LUMEX OHIO, 2009). Solid and liquid samples were also analyzed for mercury in commercial labs in Vancouver, Canada and Guayaquil, Ecuador using flameless atomic absorption. In order to investigate the behavior of mercury during cyanidation in the Merrill-Crowe circuit (a five day process), liquid samples were taken daily in both leaching and effluent tanks and analyzed using the LUMEX spectrophotometer.

a) Merrill-Crowe:

At the beginning of the cyanidation process, in each tank of the Merrill-Crowe system, the pulp density was determined in order to know the amount of solids and liquids placed in the tank for cyanidation.

Once the process of cyanidation began, samples were taken according the following steps:

a) Sample from the material entering the cyanidation tank.

b) Sample from the effluent solution.

c) Initial (before adding cyanide) and final (end of process) sample of the agitated pulp.

d) Sample of the final tailing remaining inside the tank after total effluent drainage.

As a final approach in the Merrill-Crowe study, after the miner's had drained the tank, mercury from the final tailings and the bottom cone were manually extracted and weighed. The calculation of total mercury precipitated on the zinc shavings (Merrill-Crowe Process) was based on the difference between the amount of mercury present in the head solution (leaching tank) and the amount of mercury in the effluent solution (effluent tank). The calculation of total mercury in the system was based on the summation of the total mercury analyzed and weighed in all processing products, such as: Hg trapped in the cup at the bottom of the tanks, Hg in tailings, Hg in solution, Hg precipitated in zinc. Based on the overall calculations, a mass balance of mercury was obtained indicating the amount of mercury entering and leaving each unit operation.

In order to understand mercury behavior during the 5 days of cyanide leaching in the Merrill Crowe circuit, solutions were sampled daily in both leaching and effluent tanks and analyzed. The solutions were obtained before gold precipitation with zinc.

b) CIP

The mechanisms of the Carbon-in-Pulp (CIP) process were different from that of the Merrill-Crowe process, and therefore the samples were obtained according to the following protocol:

a) Sample of the solid material entering the cyanidation tank.

b) Sample of the pulp before adding cyanide.

c) Sample of the pulp after cyanide reaction and before carbon addition.

d) Sample of the pulp after activated carbon activity.

The solution was obtained after decanting the pulp. The mercury trapped in the bottom cone of the tank was extracted and weighed. The calculation of mercury absorbed on the activated carbon (CIP) was based on the difference in the amount of mercury entering the tank with the sum of Hg in solids, Hg in solution and Hg trapped. The total calculation of mercury in the system was based on the summation of the total mercury analyzed and weighed in all processing products, such as: Hg trapped in the cup at the bottom of the tanks, Hg in tailings, Hg in solution, Hg adsorbed with activated carbon.

Additionally in the CIP process an analysis of the suspended solids from the cyanide solution was included. After filtering the liquid in a 0.45 µm membrane the solids were analyzed in a scanning electron microscope (SEM) with energy dispersive X-ray spectrometer (EDS) to characterize the filtered sample. For SEM/EDS analysis the samples were previously coated with evaporated carbon. The SEM/EDS analysis was performed at Earth and Ocean Sciences laboratory of the University of British Columbia.

2.4.3 Assessment of mercury in the environment

Mercury concentrations in the air were assessed at the end of the processes of amalgamation when miners burned the amalgam. Similarly mercury concentrations were measured when the zinc shavings were burned at 900 °C in an open gas furnace. During cyanidation mercury concentrations in the air was assessed 3 m from the gas furnace during the process of zinc heating, and burning. Total mercury concentrations of ambient air were determined using the LUMEX portable atomic absorption spectrophotometer (RA – 915+) (LUMEX OHIO, 2009).

2.5 Laboratory test of mercury dissolution in cyanide solutions

Laboratory cyanidation tests were conducted using amalgamation tailings to evaluate the rate of mercury dissolution in cyanide. In four 4L plastic bottles, 500 g of tailings were mixed with varying concentrations (1, 3, 6 and 10 g/L) of 1L cyanide solution (pH 10.5). The bottles were rolled for 12 hours, and tests were conducted in duplicate. The pH was adjusted at 10.5 and maintained at ambient temperature of around 25 ^{o}C. At the end of the experiment, the mercury was analyzed in the tailings and in the solutions.

Gold concentrations were determined by Absorption Atomic spectrophotometry in a local laboratory which offers service to the miners. Free cyanide concentrations were determined by titration using silver nitrate and potassium iodide as indicator (International Cyanide Management Institute 2002)

2.6 Quality control

To ensure the reliability of the data gathered by sampling and laboratory

analysis, a quality assurance control was applied. Samples were taken from different tailings tanks or agitated tanks, from which a composite sample was packaged in a plastic bag and transported to the laboratory. In the case of effluents, different samples were taken from the tanks, and then a composite sample was carried on to the laboratory in Portovelo for analysis. All glassware material was cleaned with a 10% concentration of nitric acid to avoid any type of contamination in the laboratory. The LUMEX spectrophotometer used for mercury analysis was calibrated with Mercury Soil Standards from the OHIO LUMEX Co. For a comparison of the results, some samples were analyzed in other laboratories in Ecuador and Canada. The analysis of mercury was replicated a few times, using the LUMEX spectrophotometer. The laboratory test of mercury rich tailings leached with cyanide was conducted at different concentrations of cyanide, and two replicates were done to ensure the reliability of this test.

2.7 Data analysis

A statistical analysis of the data was applied for the results of mercury assessment during the amalgamation and cyanidation processes and the laboratory experimental work. Summary statistical analysis (arithmetic mean, standard deviation) was performed for all systems studied.

To calculate mercury released in amalgamation process, it was considered the number and labour intensity of each processing unit in Portovelo-Zaruma. An estimate of the total amount of mercury that miners can recover and recycle when

using retorts was calculated based on the quantity of mercury released into the atmosphere and the mercury recovered during amalgamation process.

Based on the knowledge of mercury present in amalgamation tailings, the quantity of mercury that could be released from cyanidation was established. For this, the quantity of mercury-rich tailings produced during amalgamation and the part (%) of mercury released through cyanide leaching was considered.

2.8 Integrating knowledge

While field trips were taken to conduct observations and make mercury assessments, meetings were also set up to characterize the amalgamation and cyanidation processes, interchange knowledge, and construct dialogue with stakeholders about mercury use and environmental contamination. This knowledge regarding mercury distribution and processing operations was integrated with the overall information gathered in the processing plants. Researchers have emphasized the importance of participatory research as a mechanism of learning and establishing better system organization (Hisschemoller et al., 2001; Kok et al., 2006). Although participatory research has been conducted in other areas, such as Agro-ecosystems, this is the first study of artisanal gold-mining of its kind, using an integrative methodological approach. The field observations and discussions with the miners were important for planning, and identifying the weaknesses and strengths related to the current level of knowledge concerning the use of mercury for gold processing. The intention was to get information about their practices and skills towards mercury use and waste management. The interaction with the miners, facilitate the processes of learning together, assessing problems vs.

solutions, discussing knowledge and evidence gathered in the field; applying practical examples of good practices, and exploring together technological alternatives. The approach of engagement of different actors in research and development is considered crucial to address complex problems, but more essential for the acceptance of beneficiaries over the scientific and technological knowledge (Guimaraes-Pereira et al., 2006).

Beyond the fieldwork and the knowledge acquired during the field observations and mercury assessments, I participate in several meetings and workshops conducted by the Governmental institutions of Ecuador and the University partnership Tier 1 Project (Spiegel 2009). These meetings served disseminate information related to mercury, research findings and gather miners' impressions and concerns about the problem. The way by which conferences were offered helped in the study's overall understanding of the way miners perceive the nature of their own activities in their operations.

Workshops and meetings (Table 2.2) functioned as particularly important mechanisms for sharing and gathering information with policy makers. The first workshop was held in Piñas, a town near Portovelo and was coordinated by representatives of the Subsecretary of Environmental Protection from the Federal Ministry of Mines of Ecuador. In this workshop, the miners and owners of processing centers met with the representatives of the affected communities. As an invited speaker, the main objective as part of this meeting was to explore risk-related behavior for-- and the attitudes of –the stakeholders. The intention was to find out how interested and open people in the mining industry were towards

changing their ways of work and perceptions regarding mercury use, specially focusing on the problem of aquatic ecosystem contamination. Another opportunity to disseminate information was through a workshop developed in Zaruma, meeting the miners, owners of processing centers and representatives from the Ministry of Environment. This was focused on disseminating findings regarding pathways and total emissions of mercury in the Portovelo-Zaruma mining district. Options for reducing mercury pollution were also discussed. The aim of this workshop was to receive impressions from people directly involved in gold extraction regarding their views of the mercury and cyanide problems and their attitudes towards mitigating pollution. A final participation was in a workshop held in Portovelo and coordinated by the University partnership project CIDA TIER 1. As part of this project I had the opportunity to share experiences with other researchers, the miners and meet several representatives from the main artisanal mining organizations and APROPLASMIN as well as representatives from the Government.

The opportunity to participate in meetings coordinated by Governmental offices allowed disseminating information and gathering opinions about actions to control or manage the problem of ASGM and environmental contamination. This approach also helped highlight the ways in which external people view and interact with the miners to resolve the problem. The results led the way towards further analysis to construct an overall discussion about the research findings and explore alternatives for management.

Table 2.2: Workshops and meetings participation.

Date and place	Organization, and context	Participants
Piñas, October 5, 2008	Workshop- conference organized by the Sub-secretary of Environmental Protection of the Ministry of Mines and Petroleum of Ecuador. I offered a conference about measures to mitigate mercury pollution. The purpose was to structure concerns from affected communities and actions from Ecuadorian authorities as well as to observe impressions and reactions of miners and owners of processing plants.	Owners of processing centers and representatives of artisanal mining associations and local mining companies. Peruvian representatives from Governmental health and environmental institutions as well as scientists from the University of Tumbes, Peru. Around 100 participants attended this workshop
Zaruma, February 2008	Workshop organized by the Ministry of Environment about mercury contamination during gold processing. The preliminary results about mercury distribution in ASGM were shared with the participants. The purpose was to get impressions from owners of processing centers about mercury contamination and mercury emissions. Preliminary discussion with owners of processing plants about the results of the study.	Owners of processing centers and other researchers from the mining institute - UBC participated in this meeting. Representatives from the Sub-secretary of Environmental Quality of the Ministry of Environment of Ecuador. Around 50 participants attended the workshop
May 2008. Machala-Zaruma-Ponce Enriquez and Loja.	I participate in three sequential meetings organized by the Sub-secretary of Environmental Protection from the Ministry of Mines. Round table discussions to talk about main issues of concern about mining development in Ecuador. This was a suitable opportunity to listen opinions from different stakeholders.	Different community members and miners in each site such as Machala, Zaruma, Ponce Enriquez and Loja. Around 15 participants in each session related to environmental issues and mining development in Ecuador.
Quito, Septiembre 2008	Conference about mercury contamination in Ecuador and its relationship with artisanal and small scale gold mining. Mercury balance in amalgamation system and environmental contamination was analyzed and discussed with participants. The conference was held as part of UNITAR-UNEP agreement for the Mercury Management Program in Ecuador	Several stakeholders from different perspectives. Representatives of UNEP, Ministry of Environment and Ministry of Health of Ecuador. Cooperative Bella Rica (Ponce Enriquez). Representative of Nambija artisanal mining association. APROPLASMIN from Portovelo and scientists. Around 40 participants attended the conference
Portovelo, July 2009	Workshop organized by the CIDA TIER 1 University partnership project. The purpose was to get in depth analysis of how miners, community members and owners of processing centers interact framing the problems and opportunities to work together.	Community representatives. Representatives of different mines associations and the APROPLASMIN. Researchers and students from mining engineering UBC attended to this workshop. Around 50 persons participated.

Chapter 3 : Artisanal and small scale gold mining in Southern Ecuador: development and characterization

3.1 Geographical location of the study site

Artisanal and small scale gold mining operations, namely extraction and processing, are carried out on the western flanks of the Andes region in close proximity to the Gulf of Guayaquil (see Fig 2.1). This study focuses on mercury contamination in processing centers located in Portovelo-Zaruma region, the most important mining district of Ecuador. Ponce Enriquez located nearby, is another important ASGM site that has connections with Portovelo-Zaruma and is also considered in the study. Despite several studies of the situation in the Portovelo-Zaruma region, which connects the Puyango river basin in Ecuador with the Tumbes river basin in Northern Peru, no effective policies for resolving international conflicts over heavy metal contamination and its impacts on human health have been developed.

The city of Portovelo and its immediate surroundings are part of the foothills of "*Cerro Rico en Oro,*" an area that remains in the centre of informal mining production of gold. These foothills are surrounded by the banks of the Calera River and the Amarillo River. These rivers flow into Río Puyango, which then flows into the Pacific Ocean in Peruvian territory. Although Portovelo is still an important mining region, most of the material processed comes from surrounding sites.

The district of Portovelo-Zaruma is located close to several mineral-rich deposits including “Cerro Pelado,” “Torata,” “Cangrejos,” and “La Tigrera” among others. The aforementioned areas are all undergoing exploitation by ASGM. The

most remarkable aspect is that Portovelo has become the main processing centre in the region, thus the effects of environmental contamination are the worst here.

The mineralogical characteristics of the district of Portovelo-Zaruma consist of some free-gold and high presence of sulfides such as arsenopyrite, galena, pyrite, pyrrhotite, chalcopyrite and bornite (Vikentyev et al., 1998). The encapsulation of fine gold in minerals is not common in the district, but it has been detected, mainly in the North part of Muluncay near Portovelo-Zaruma, and it is particularly associated with silver minerals. The gold was formed in several mineralization stages, along with sulfides and quartz. The gold grade of many operations is around 10 g/t of Au. Nevertheless, in certain zones, gold contents can exceed 30 g/t. As the price of gold rises, additional areas of gold deposits are being worked by artisanal miners.

The use of mercury in the two gold mining districts is seriously compromising ecosystem health along the plain of the Andes in the Southern part of Ecuador. The water from the mines flows through important aquatic resources that flow to the Gulf of Guayaquil and eventually to the Pacific coast. The Gulf of Guayaquil is the largest estuarine ecosystem in the Western Pacific Coast of South America. This ecosystem handles 95% of the Ecuador's imports and 50% of its exports (Cucalon, 1989). The strength of the banana agriculture industry in the county has ensured Ecuador as the world's largest banana exporting country. In 2001, Ecuador exported 4.5 million tonnes of bananas, earning about US$ 900 million. Aquaculture of marine shrimp renders Ecuador the third largest shrimp-exporting country in the world. Both activities are centralized along the coastal zone in the

Southern region below the Gulf of Guayaquil, between the Provinces of Guayas and El Oro. Ecuador's geography along the Pacific coast connects the region's mining, agriculture and aquaculture activities due to their connectivity with the rich aquatic river system of the region. These aquatic resources are important for the operations of these industries, as well as the sustainability of the local ecosystem and economical investment in the region. ASGM activities create environmental damage on aquatic ecosystems and the impacts can be felt many kilometres from the mines downstream from the Amarillo, Calera, and Puyango Rivers in the Portovelo-Zaruma mining district and Siete, Tenguel, Chico, and Balao Rivers in the Ponce Enriquez mining district. Due to the existence of gold reserves in Southern Ecuador, other important rivers such as Santa Rosa and Arenillas are also compromised (Tarras-Wahlberg et al., 2005).

3.2 Historical gold mining development in Southern Ecuador

An overview of the history of gold mining in the Southern region of Ecuador has been carried out by Astudillo, (2007). Active production in the Andes region predates arrival of Europeans to the Americas, and is believed that the Incas gathered seven-hundred tons of gold (Sweat of the sun) and silver (Tears of the Moon) to purchase the freedom of their king, Atahualpa, from Pizarro and his conquistadors (Lourie, 1998). The main mining district in this region, Portovelo dates back to the year 1549, when indigenous people and African slaves worked small excavations (Lane, 2004). Next to Portovelo, about 10 km is Zaruma, also known as "Cerro Rico en Oro," (mountain rich in gold) which was founded in 1595, forming the largest gold mining district of Ecuador.

In 1896, the American company SADCO (South American Development Co.) acquired the properties of the Zaruma Gold Mining Limited, a British corporation which had been founded in 1880. Lack of capital to operate the mine forced the British company to leave in 1896 (Paredes, 1980). This occurred at a time when American companies began to invest in Latin-America as gold prices became more attractive. From 1896 to 1950, SADCO operated the mine, controlling almost 40 km^2 of concessions and extracting 1000 tonnes of Au, 500 tonnes of Ag and 1500 tonnes of Cu (Astudillo, 2007). Several strikes organized by worker unions and disputes with the Ecuadorian Government bankrupted SADCO's operations. In 1951, the mine was sold to the Ecuadorian company CIMA (Compañía Industrial Minera Asociada) which was a company formed by ex-workers of SADCO in a strategic partnership with the Municipal Government of Zaruma. Until 1978, CIMA extracted 11 tonnes of Au, 85 tonnes of Ag and generated 80,000 tonnes of tailing. A lack of vision, poor technical management, as well as high inflation in the country contributed to CIMA's bankruptcy in 1978 (Paredes, 1980).

During the 1970's, the United Nations provided technical assistance to the Government of Ecuador with geochemical studies (Sandoval, 2001). A gold rush began when the price of gold increased, reaching more than US$ 800/oz in January 1980. This attracted artisanal miners to re-work the mines that previously were exploited by the old SADCO. During the 1980s, assistance from Belgian Government, studies were carried out regarding the extent of mineral resources in Portovelo- Zaruma and to map the ore deposits of the region (Astudillo, 2007).

The cessation of CIMA's operations gave way to a rise of informal mining, which led to an overall increase in local prosperity. In 1978, artisanal gold mining activity started with the development of processing centers, locally known as "*plantas de beneficio,*" where very rudimentary technology and the use of mercury for gold recovery were employed (Sandoval, 2001). As the older miners attest, they used tonnes of mercury without any consideration for environmental or health impacts. Such artisanal mining persists to this day as the main economic activity in Portovelo.

During the 1990s, three international enterprises: Newmont, RTZ, and Placer Dome made explorations around the Portovelo area (Astudillo, 2007).

During colonial times, the mining camp of Portovelo was consolidated as a city with 700 inhabitants, which, from that time to the present, has increased to 22,000 inhabitants. Out of this population, 80% are involved in different mining activities (Tarras-Wahlberg et al., 2005), including ore processing, gold extraction and refining. The miners sell the gold, both in the city of Portovelo to local customers, and to buyers outside Portovelo, especially in Cuenca and Machala.

In 1989, the BIRA Company was formed with private capital, and they installed their operations in the hills of Zaruma. This organized company still operates, and it is believed that they manage the system of gold production in a proper and responsible manner.

Between 1993 and 1996, the Government of Ecuador gave titles and created agreements with the miners, cooperatives and owners of processing centers in Portovelo-Zaruma, formalizing their activity. In 2000, Tarras-Walhberg et al. (2000)

described the existence of 65 processing centers i.e. plants to crush, grind concentrate, amalgamate, and sometimes leach with cyanide material brought by the miners. With the price of gold on the rise, by 2005, there were 86 processing centers (Veiga et al., 2009) in the area. In 2008, the processing plant units increase to 104 and according to the locals, not all of them were operating legally. The majority of processing centers are concentrated in Portovelo, with facilities for crushing, grinding, amalgamation and cyanidation. In 2008, the Ecuadorian Government initiated the re-organization of these processing centers through legalization and obligating them to present environmental management plans for their operations.

After El Niño Southern Oscillation (ENSO) wreaked havoc on the coastal plain of Ecuador in the 1980´s, the mining town of Ponce Enriquez emerged on the edges of Azuay and El Oro. In those days, several local investors focused on gold mining as a new opportunity for mitigating the regional disaster. Ponce Enriquez district is located at 45 meters above sea level, 20 km distant from the ocean and about 110 km from Portovelo. It was primarily an agricultural area until the discovery of mining resources in 1982, when the ENSO climatic event disrupted the area. In 1984, mining became a primary focus in the area. Near Ponce Enriquez there are two important sites of gold reserves named San Gerardo and Bella Rica which have been actively developed and where mining has taken over from agriculture as the primary source of subsistence activity. Processing centers in San Gerardo, Bella Rica and surroundings are dispersed along the hillsides, with very rudimentary facilities for the processing of ore with mercury. They also have

small facilities connected to associations and cooperatives. This artisanal mining activity has developed over time and has evolved to a place where people's livelihoods depend far more on mining than agriculture, which has taken on a secondary role in the subsistence economy of the region.

3.3 Previous work at the site

Supported by the World Bank, between 1995 and 2000 the "*Programa de Desarrollo Minero*", known as PRODEMINCA (Programa de Desarrollo Minero y Control Ambiental), made regular evaluations of the environmental impact of mining and the contamination of aquatic resources. It also addressed technical solutions for the pollution problems associated with artisanal gold mining in the South of Ecuador (PRODEMINCA, 1999). In particular, they have studied the situation in Portovelo-Zaruma and the Puyango-Tumbes River Basin since this became a site of international conflict over contamination. This program has also taken actions in the Ponce Enriquez River Basin, studying the contamination of the basins of Siete and Tenguel Rivers. Concerned about the possible effects of mining on the estuarine environment in the coastal area, as well as its ramifications for the important shrimp industry in the region, the project raised awareness regarding the risk of mining waste on the shrimp farming industry.

Another project with cooperation of the Swiss Government Technical Cooperation undertook actions to minimize the levels of mercury pollution in two phases from 1993 to 1999, and from 1999 to 2001. The description provided by Sandoval (2001), reveals that the project assisted the artisanal miners with technology for gold recovery - mainly amalgamation and mercury management

which included the development of retorts for mercury recovery. This project also took action to support local institutions in managing artisanal mining communities. Sandoval (2001) also describes the existence of an environmental study of 58 processing centers. This intervention resulted in the foundation of APROPLASMIN, an association of owners of processing centers that signed an agreement with local Municipal Governments to create a plan for waste management. Another important result of this project was an overall environmental assessment of mercury in soil, water and biota in Portovelo-Zaruma and in Ponce Enriquez. In addition to these activities, it has also analyzed alternatives to the use of mercury in ASGM (Sandoval, 2001). However, it is believed that one of the main barriers to replace mercury has been the resistance of miners to change their methods of gold recovery and the easiness of amalgamation process compared with other processing methods.

Based on that project results, in 2001, the Government took an important legal step that led to further studies regarding the implementation of new regulations and framework for the legal disposition of previous consultation "Consulta previa" in mining (Bermeo, 2006, personal communication). This legal action would force companies or miners to take their plans through a community consultation process before implementing any mining operations, and would also introduce feasibility studies of the mining concessions. However, due to political pressure, the objective of this legal action was frustrated. It was not until recently that Governmental decisions about previous consultation regarding mining projects became a reality, and have been used as a formal instrument for the political and social development

of gold mining. Within the mining community, the main problems encountered have been related to the personal interests of individuals, which consequently have affected the opportunity for collaborative management (Sandoval 2001). Between 2001 and 2007, artisanal mining operations, and some companies, worked without any control on their activities and under a minimally developed regulatory framework. Environmental problems have always been an issue and have resulted in conflicting relationships between miners and communities. In the year 2004, FUNGEOMINE “Fundación Geológica Minera” in agreement with APROPLASMIN conducted an environmental impact assessment of the processing centers located along the Calera and Amarillo River. However, such studies did not make any observation or analysis of mercury, heavy metals, or cyanide.

In 2001, FUNSAD “Fundacion para la Salud,” a non-Governmental organization from Quito, with Canadian sponsorship, conducted more studies on the environmental impacts of artisanal mining and human health. Such studies confirmed the results of previous studies developed by PRODEMINCA regarding the impact of heavy metals and suspended solids released by ASGM on aquatic ecosystems, and complemented evidence of human exposure to mercury in communities located along the watersheds (Betancourt et al., 2005).

In 2005, international projects, “Sustainably managing of Environmental and Health Risk in Ecuador” (Spiegel et al., 2007; Yassi et al 2007; Spiegel, 2009; Parkes et al., 2009) and the “United Nations Global Mercury Project” (Velasquez-Lopez, 2007) initiated studies and building capacity within artisanal gold miners

focusing on developing an ecosystem approach to building sustainability in mining and impacted communities

In early 2008, a sound political action initiated by the Government of Ecuador resulted in the revocation of hundreds of mine concessions (around 500 mining contracts) because the companies had failed to pay fees on concessions for reserves of copper and gold and other important minerals. With this decision, the Government of Ecuador embarked upon a chapter involving the reorganization of mineral resources and artisanal mining in Ecuador. As such, it indicated a clear intention to resolve the problems of organization and environmental contamination of the affected ecosystems.

As the mining concerns and interests of local and international investors are increasing, the significance of the resources for mineral exploitation has also grown during the last several years. As such, the environmental impacts of mining operations have the potential to become devastating without adequate control both in the ore extraction process and in the processing centers built along the rivers, and concerns regarding such possibility have grown.

3.4 The artisanal miner

The understanding of the relationships that exist between people and gold processing techniques is important in environmental risk management since it can be useful for establishing the patterns in the ways environmental impacts occur (Reiman and Oedewald, 2007). This becomes particularly complex when there is

lack of organization and regulation within the system as a whole (Smircichs, 1983), as is the case with regard to ASGM activities (Hentschel et al., 2002)

In Ecuador, the definition of the terms artisanal and small scale mining is based on the amount of ore extracted. A small scale miner is considered to be one who extracts or processes less than 300 tonnes of ore per day. An artisanal miner is defined as a person without technical skills, who has poor knowledge, and who works using rudimentary tools to extract and process the ore for his own subsistence (Registro oficial, 2009). The new mining law does not describe the tonnage mined by an artisanal miner. Confusion among community members and policy makers about these classifications persist – i.e, owners of processing centers are considered artisanal miners. But some of them do not mine anything and just process the ore brought by the miners.

Topographical and geological surveys are currently used by organized companies, associations and cooperatives to locate and estimate gold deposits. However, due to lack of resources, artisanal miners use empirical methods such as using branches of the verbena tree, pendulums, and advice from shamans, healers and wizards to locate gold deposits. These methods have also been described by other researchers in other ASGM sites elsewhere (Veiga and Hinton, 2002; Veiga et al., 2005; Heemskerk, 2005).

Although some miners are poor and from low income communities (many of them coming from unsuccessful experiences in agriculture, dairy production or aquaculture), the majority of miners used to be from the middle class in Ecuador and they have at least a secondary school education (Rivera, 2009). On the other

hand, many families that have abandoned rural farming to get into mining are getting rich very quickly. With success and only primary school education, some of them often feel that they do not need higher education. Others receive mining skills as inheritances from their parents and ancestors. This is a common situation in developing countries (Heemskerk, 2005), and it reduces the motivation for the pursuit of education as a method through which to improve peoples' lives, because with luck, artisanal miners get rich without the need of education. For example, many people of Ponce Enriquez who previously earned their living through agriculture left this activity in favour of the much more lucrative artisanal mining. Artisanal miners switch their labor between agriculture and mining activities. This is because agricultural farming products fetch low prices, while working in gold production continually fetches higher incomes. Southern Ecuador is very rich in natural resources, and there are plenty of opportunities in both agriculture and aquaculture (Guest, 1999), and although mining is far more dangerous, the high price of gold means that anybody can get rich.

In Southern Ecuador, miners typically form partnerships with other artisanal miners to extract ore, making up groups of about 5 to 10 people. If a miner does not have his/her own concession, the ore extracted by the miner is shared with the owner of the land. Once the ore is extracted, the artisanal miners rent facilities for ore processing in one of the processing centers in the region. New people enter gold mining industry every day, particularly in Ponce Enriquez region. Miners with little knowledge or experience begin working on new deposits, making shafts while looking for a vein of gold. Because of inexperience, a new artisanal miner cannot

be sure whether a sack of rock mined will provide enough money to pay the bills. Some people also search for low grade gold in abandoned tailings. Among this group are people known as “jancheras,” usually women who live close to small companies and who collect small pieces of waste rock material. A lack of proper management of waste rock on the part of some small gold mining companies gives these poor people the opportunity to settle around these abandoned mines. The “jancheras” are even less skilled than ordinary miners, and usually work with low-grade ore, using mercury.

Among the artisanal miners and small plant operators, there are also people who buy processed sands (tailings) from different areas, to treat them with cyanide. Another group of people within the ASGM community are the gold buyers and jewelers who buy amalgamated gold or gold doré. i.e. gold resulted from burning amalgam with a propane blow torch that evaporates mercury. Mining and processing plant workers are often hired on a temporarily basis, depending on the intensity and organization of the current activity. There is not a clear census about the number of artisanal miners and workers of processing centers in Portovelo-Zaruma. The locals estimate that around 3000 people are directly involved in gold production.

3.5 Gold processing methods

Gold amalgamation emerged in the world in the middle of the 16th century, and has been responsible for a sharp increase in mercury consumption in the world (Hylander and Meili, 2005). Amalgamation is the preferred method used by artisanal and small-scale miners to recover free gold from alluvial/colluvial or

primary ores (Veiga, 1997; Veiga et al., 2006). Worldwide, 10 to 15 million artisanal gold miners in more than 70 countries extract on average 350 tonnes/year of gold, and in the process it is estimated that they release 640 to 1350 tonnes/year of mercury into the environment (Telmer and Veiga, 2008).

In Portovelo, after extracting rocks, artisanal miners transport the material to processing centers which still operate along the nearby natural streams and rivers. As a preliminary processing step, some miners pass the mined material through a jaw crusher to reduce the ore to 5 cm pieces, but the majority of miners reduce the material size with manual hammers. They produce 1000 to 2000 bags of ore in 2-3 weeks of mining (each bag weighing 40-45 kg), with grades ranging from 3 to 30 g Au/tonne of ore. This material is then taken to any of the processing centers.

About 10 years ago, only amalgamation was used in the processing centers to extract gold but today, in several countries artisanal miners combine amalgamation and cyanidation to recover gold (Metcalf 2008). In the past, the miners from Portovelo extracted residual gold from tailings using cyanidation in percolation vat-leaching (Sandoval, 2001) a practice that is almost disappearing in the region. Nowadays they use more efficient process such as cyanidation in agitated tanks followed by either the Merrill-Crowe process (precipitation of gold from cyanide solutions with zinc) or Carbon-in-Pulp (CIP) process (carbon adsorbs gold from cyanide solutions) (Marsden and House, 2006). Combined use of mercury and cyanide in ASGM processing centers has been observed in several other developing countries, such as Brazil, China, Colombia, Indonesia, Mozambique,

Peru, the Philippines, Venezuela (Veiga et al., 2009); and Zimbabwe (Metcalf, 2008).

Despite the presence of a large number of rudimentary processing centers in Ecuador, there are some small groups of miners who provide good models for gold processing applying cleaner technologies. Local miners have been able to develop cooperatives and associations, producing around 300 grams of gold per day without using mercury. These processing plants include the use of ball mills, flotation, cyanidation, and direct melting of concentrates. Those plants belong to small organized companies that have their own mines and eventually buy ore from artisanal miners. The tailings are disposed in well designed ponds covered with geotextile to prevent soil erosion. These plants use hydrogen peroxide for the destruction of cyanide. Most of these plants hire technicians from Peru, since Ecuador lacks trained professionals in mining and gold recovery.

3.6 The gold processing centers

Geographically, the majority of gold processing centers are located along the Calera and Amarillo Rivers (Fig 3.1).

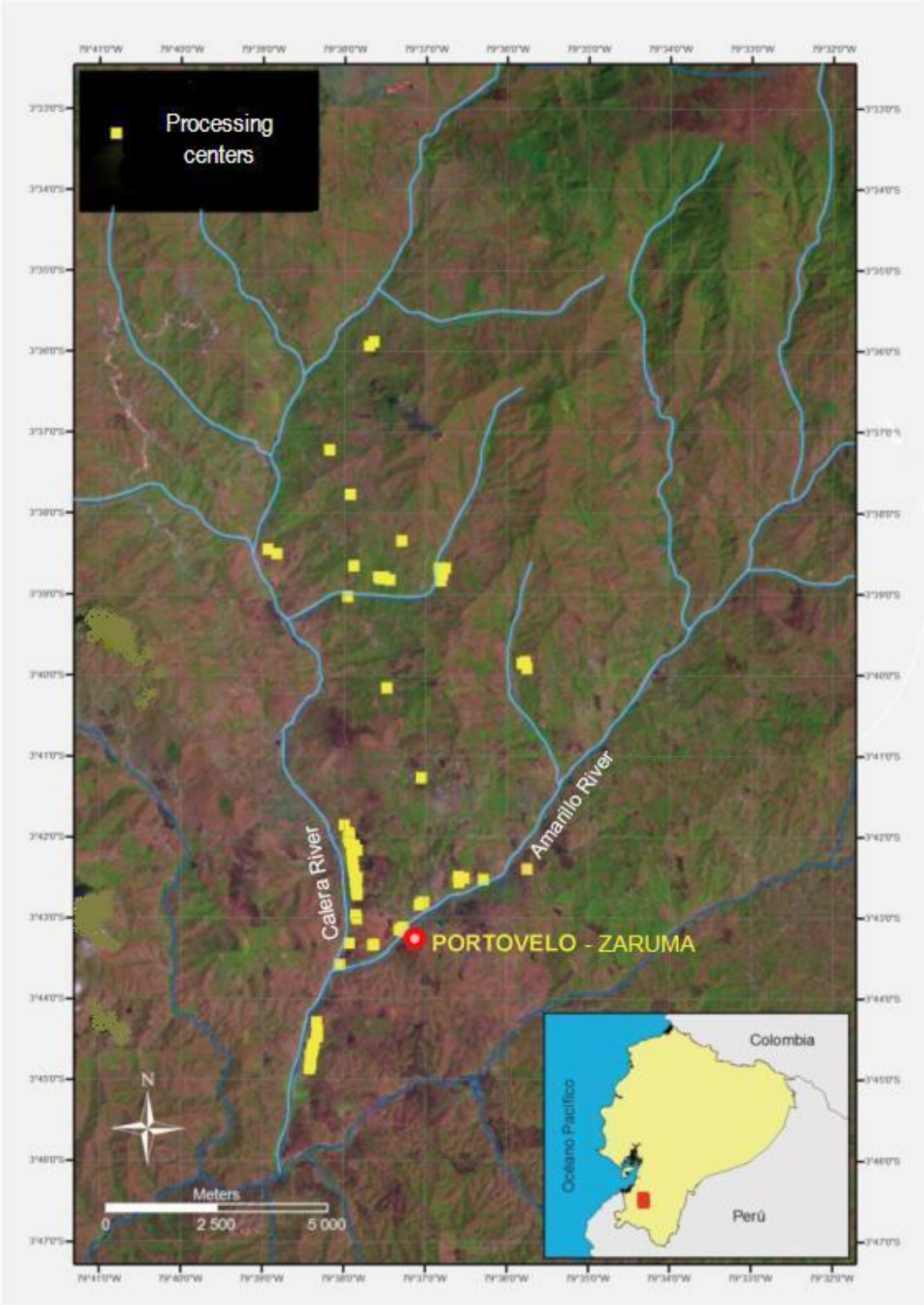

Fig 3.1: Location of processing centers.
Along the Calera and Amarillo Rivers in Portovelo-Zaruma mining district.
Source: Direccion Nacional de Minería y Protección Ambiental, Ecuador.

These processing centers are situated between 600 to 1300 meters above sea level. The processing centers receive material from the Portovelo-Zaruma gold mining sites from other mining camps such as Torata, Cangrejos, La Tigrera, located in the Province of El Oro and from San Gerardo, Pijili and Ponce Enriquez, located in the Province of Azuay.

In general, all processing centers in Portovelo together can process almost 1000 tonnes of ore per day in 110 Chilean mills, and all cyanidation units together can process approximately 1500 tonnes of ore per day. The reason for the difference between milling and cyanidation capacity is that Portovelo receives mercury-rich tailings and other related material from other mining sites, especially from the Azuay province. It is known that ore extracted in other sites located in other Provinces such as Azuay, Zamora, Santo Domingo de Los Colorados and from the Province of Bolivar, is transported to Portovelo for processing.

Processing centers offer different types of service a) milling-amalgamation-cyanidation, b) milling–amalgamation, and c) cyanidation only. Custom processing centers which offer service only for amalgamation are also distributed in different places in Ponce Enriquez and its surroundings situated in the Province of Azuay. Fig 3.2 shows the choices that a miner has for processing his/her gold ore. There are basically two types of artisanal processing centers: 1) The “Chancha” processing centers and 2) The Chilean mill processing centers. These two processing centers produce mercury rich tailings which are sent to the cyanidation process.

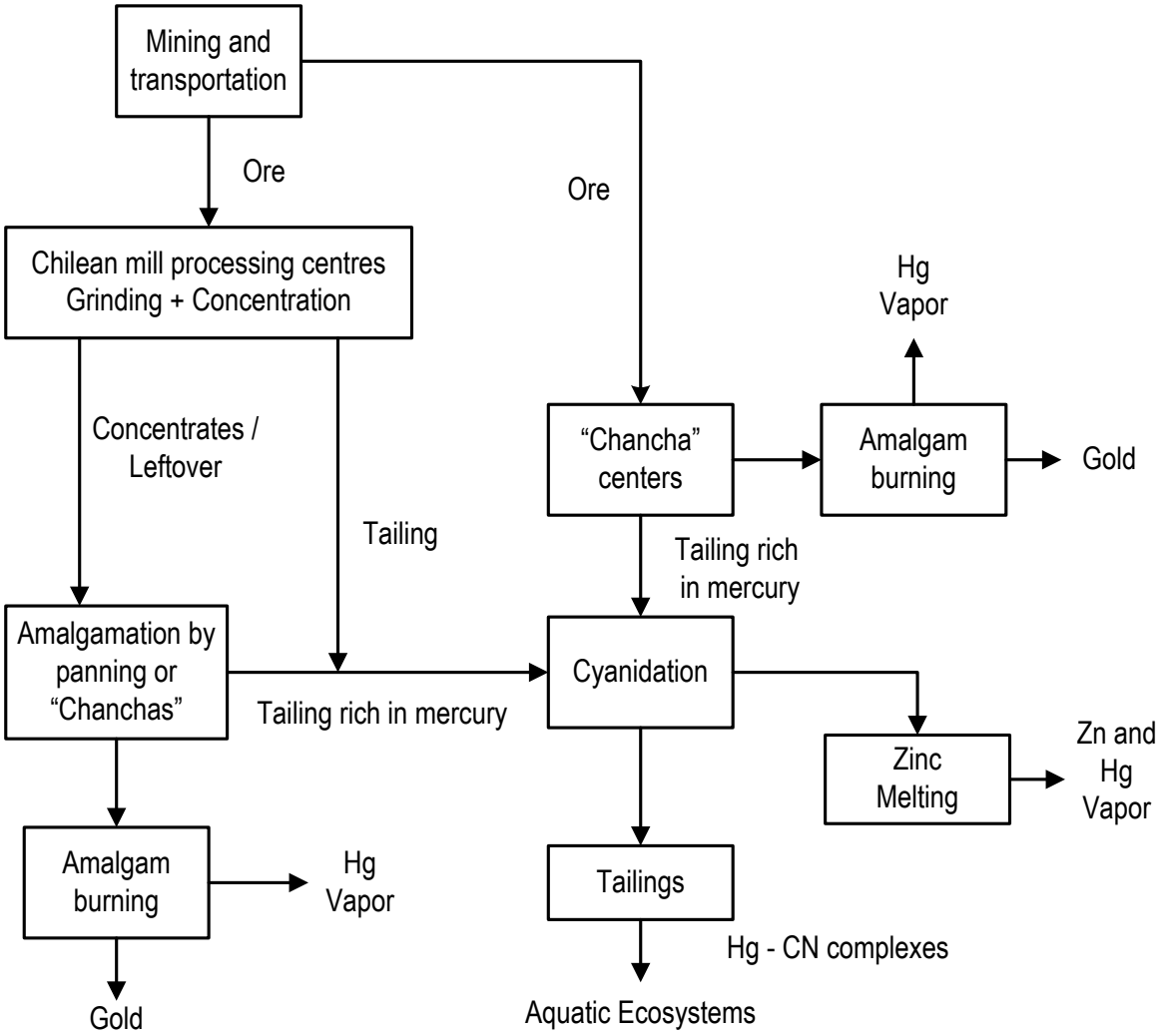

Fig 3.2: Flowchart of processing system of ASGM in Southern Ecuador.

3.6.1 The "Chancha" processing center

The "Chancha" processing centers (Fig 3.3) are rustic processing centers that provide services to artisanal miners to extract gold from the ore.

Fig 3.3: Typical “Chancha” processing center.

At “Chancha” processing centers, miners do not use any gravity concentration method and perform direct amalgamation (1 to 2 tonnes) of the whole ore in a drum or barrel locally known as “chancha". The process is done in one step of crushing-milling and amalgamation and mixing all material in the barrel (Priester and Hentschel 1992). In Southern Ecuador, for the process of amalgamation the “Chanchas” are filled with steel rods or round river rocks. It has been observed that miners add 454 g (1 lb) of mercury, 1.5 kg of brown sugar to the drum. The “Chanchas” rotate for 3 to 6 hours and miners typically recover less than 70% of the mercury added. Around 30 % of mercury is pulverized and lost with the fine particles (Veiga, 1997). The Hg contaminated tailings become the property of the “Chancha” center owners. They accumulate 5 to 6 tonnes of tailings, and every 3

to 6 months they rent a cyanidation plant in Portovelo to leach and recover 50 to 60% of residual gold. This process usually yields 200 to 300 g of gold every six months. Employees of the “Chancha” centers burn the amalgam using rudimentary fume hoods or retorts.

As most artisanal miners from remote sites do not understand or know much about the mineralogical characteristics of the ore material, they do not know how much gold they will get from their process. In consequence, there is the risk to add more mercury than needed in an unknown grade of gold ore.

The use of the “Chancha” and its operating process differ from site to site. For example the most prominent form of gold processing in Ponce Enriquez uses the “Chancha”. The lack of facilities for cyanidation, and in some cases lack of knowledge about gold processing in remote areas from Ponce Enriquez and surroundings mining sites such as Pijili, San Gerardo, San Fernando, force miners and owners of the “Chanchas” processing centers to stock-pile amalgamated tailings to further treat them with cyanide. In Ponce Enriquez and surrounding areas, there are about 24 “Chancha” processing centers, each one with 6 to 8 *“Chanchas”,* and nearly 25 “Chilean mills” combined with “Chanchas” and agitation tanks for cyandiation. As in Ponce-Enriquez, and surroundings sites “Chancha” processing centers are more predominant, the use of mercury to amalgamate the ore in chanchas” becomes the main technique for gold recovery. The owners of the “Chanchas” centers may or may not charge their clients for services, depending on the origins of the ore. If in a quick panning they notice that the ore is rich in gold, they do not charge the miner. A fee is applied to the miner with low grade ore ,

which at this time is around US$ 2/h. In Portovelo, there are only two “Chancha” processing centers with a total of seven “Chanchas”.

The “Chanchas” are also present in other centers that offer service for milling and/or cyanidation, with some centers having 1 to 4 “Chanchas” (Fig 3.4).

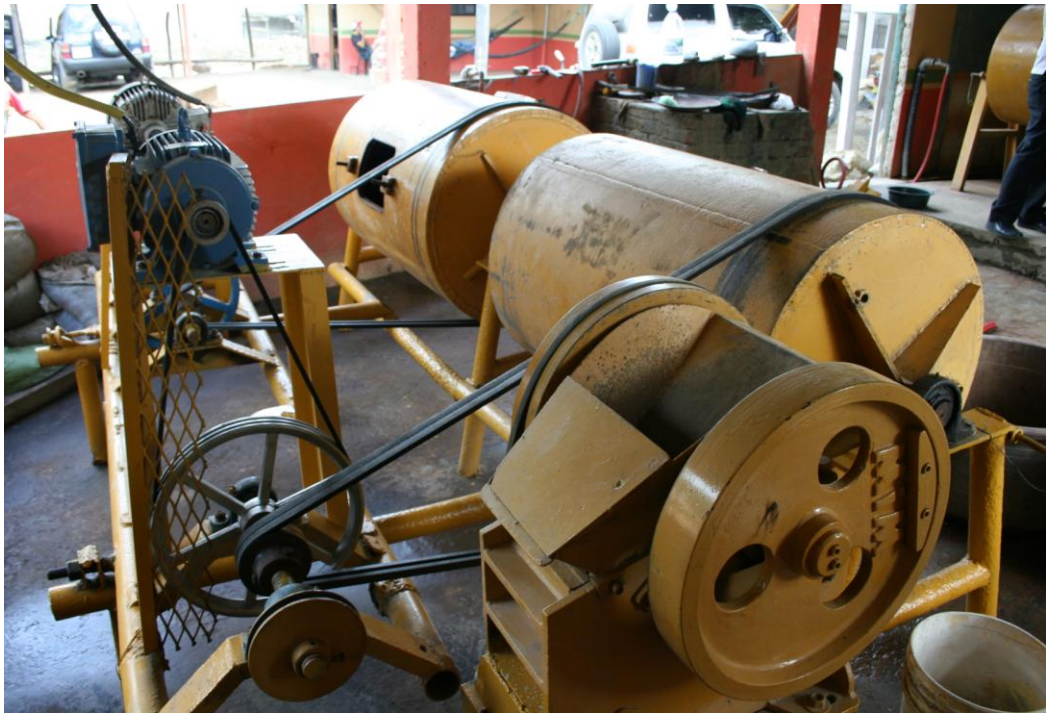

Fig 3.4: “Chanchas” or drums.

3.6.2 The Chilean mill processing center

Among the stakeholders of ASGM, the owners of Chilean mill processing centers are the most powerful people in the ASGM sector. Their power results from the fact that these owners have the ability to provide process for a large majority of miners. These centers provide the service of crushing, milling, concentrate and

amalgamate the ore. The most common milling equipment used in Southern Ecuador is the “Chilean mill” (Fig 3.5).

From the approximate 104 processing centers in Portovelo-Zaruma region, some have one or more Chilean mills, whereas others do not have any and provide only a cyanidation service. In Portovelo there are approximately 110 Chilean mills.

Fig 3.5: The Chilean mill center for crushing and milling the ore.

A Chilean mill consists of two or three heavy cement wheels with steel rims connected to a 20 HP electric motor. The wheels rotate over a 25 cm wide, 2-inch thick steel plate. The Chilean mills are widely used and work by means of the

circular movement of the wheels on a 25 cm wide steel plate. The milling capacity of Chilean mills is about 8 to 12 tonnes in 24 hours.

The mined material entering the center usually ranges in size from 4 to 20 cm as a result of blasting with dynamite and manual excavation with picks. For primary fragmentation, the material is usually fed into a jaw-crusher which reduces the sizes of ore to 2.5 - 5 cm. (1-2 inches). Some miners, who do not have access to a jaw-crusher, crush the rocks manually using hammers. The Chilean mill wet-grinds 0.5 tonnes/h of ore and is manually fed by an operator using a shovel.

For the milling process, continuous flow of water is added to the mill to form a slurry with 6 to 14%, of solids. The effectiveness of the Chilean mills depends on certain variables, including: a) the speed and weight of the wheels; b) the amount and regularity of the feeding and the size of the material; c) the amount of water used inside the mill; and d) the physical and mechanical characteristics of the ore.

The slurry with the ground ore is discharged by overflow through a 0.2 mm nylon screen into cement sluice boxes 6.8 m long and 0.46 m wide. The sluice boxes are covered with wool carpets and are locally named “balletas”. The sluice boxes have a low angle (5 to 10°) in order to trap fine gold particles. However, this makes the concentrate accumulate more quickly, and miners must discharge the concentrate from the carpets every hour. From approximately 40 to 80 tonnes of ore milled, five bags or 200-225 kg/day of concentrate (or 2.5-3% of the ore mass) is recovered, usually with a grade ranging from 10 to 30 g Au/tonne.

Concentrates are further reduced by manual panning in a water tub that yield 10-15 kg of concentrate which is amalgamated. The tailings from the sluice boxes

belong to the owner of the processing center, who receives this material as payment for the use of the mill. These tailings are accumulated in dams to be processed with cyanide.

After grinding the whole ore, miners wash the interior of the Chilean mill to remove the heavy and harder pieces of ore usually with 10 to 20 Au/tonne (known as “las ollas”) retained inside the mill. The Chilean mill processing centers also make available to the miners a “Chancha”. This “Chancha” is used to amalgamate “las ollas”. Typically, “las ollas” represent around 1% of the total mass of the material ground in the Chilean mills and they are richer in gold than the origincal ore material.

3.6.3 Cyanidation processing center

Most Chilean-mill Centers also have cyanidation facilities. However, in Portovelo, there are also facilities available for rent that only consist of leaching tanks for the processing of tailings, ores or gravity concentrates. Specifically, there are approximately 375 cyanidation tanks in Portovelo, with capacity ranging from 14 to 40 m^3. There are two types of cyanidation circuits: 1) Carbon-in-Pulp (CIP) process, that represents 60% of the cyanidation tanks and 2) Merrill-Crowe process that represents 40%. As miners are starting to learn about the advantages of using cyanidation versus amalgamation, some are now paying the owners of the centers to rent their cyanidation tanks to extract gold from gravity concentrates obtained in the sluice boxes. Many artisanal miners prefer to use the Merrill-Crowe process as it is a less expensive option than the CIP circuit, and there is a lack of knowledge associated with CIP process. The owners of the “Chancha” processing

centers recover gold from the tailings left in their premises usually renting a Merrill-Crowe plant (i.e. cyanidation with agitated tanks followed by precipitation of gold from solution with zinc shavings). The Merrill-Crowe plants are also rented to any miner interested in leaching gold from gravity concentrates.

3.6.4 Merrill-Crowe process

There are approximately 160 Merrill-Crowe cyanidation tanks in Portovelo. The Merrill-Crowe cyanidation plants use a high concentration of NaCN (1 to 5 g/L) and the cyanide consumption ranges from 1.5 to 5 kg NaCN per tonne of tailings, depending on the amount of copper minerals in the ore. The residence time of the material in the cyanidation is around 72 hours. The pH is kept around 10.5. Very few processing centers eliminate cyanide and most dump their cyanide pulps, which contain cyanide complexes into the Calera River.

As cyanidation tanks used in the Merrill-Crowe process are similar in size, the leaching procedures are identical in all leaching facilities. The cyanidation tanks have a cup at the bottom to trap any metallic mercury that settles. After 12 hours, the agitation is halted and the pulp settles for about 6 hours. The gold-rich solution is then drained from the top of the settled pulp through a 10-cm diameter pipe to a settling tank. From the settling tank, cyanide solution flows to a concrete box containing several PVC tubes (12 cm wide x 50 cm large) each one filled with zinc shavings (Fig 3.6). Gold precipitation (cementation) occurs according to the following reaction (Marsden and House, 2006):

$$2Au(CN)_2^- + Zn = 2Au + Zn(CN)_4^{2-}$$

Silver and mercury and eventually copper from sulphide minerals, dissolved in cyanide, are also reduced by metallic zinc. In this precipitation process, dissolved oxygen must be avoided as gold can be re-dissolved in the cyanide solution (Marsden and House, 2006) :

$$2Au + 4CN^- + O_2 + 2H_2O = 2Au(CN)_2^- + H_2O_2 + 2OH^-$$

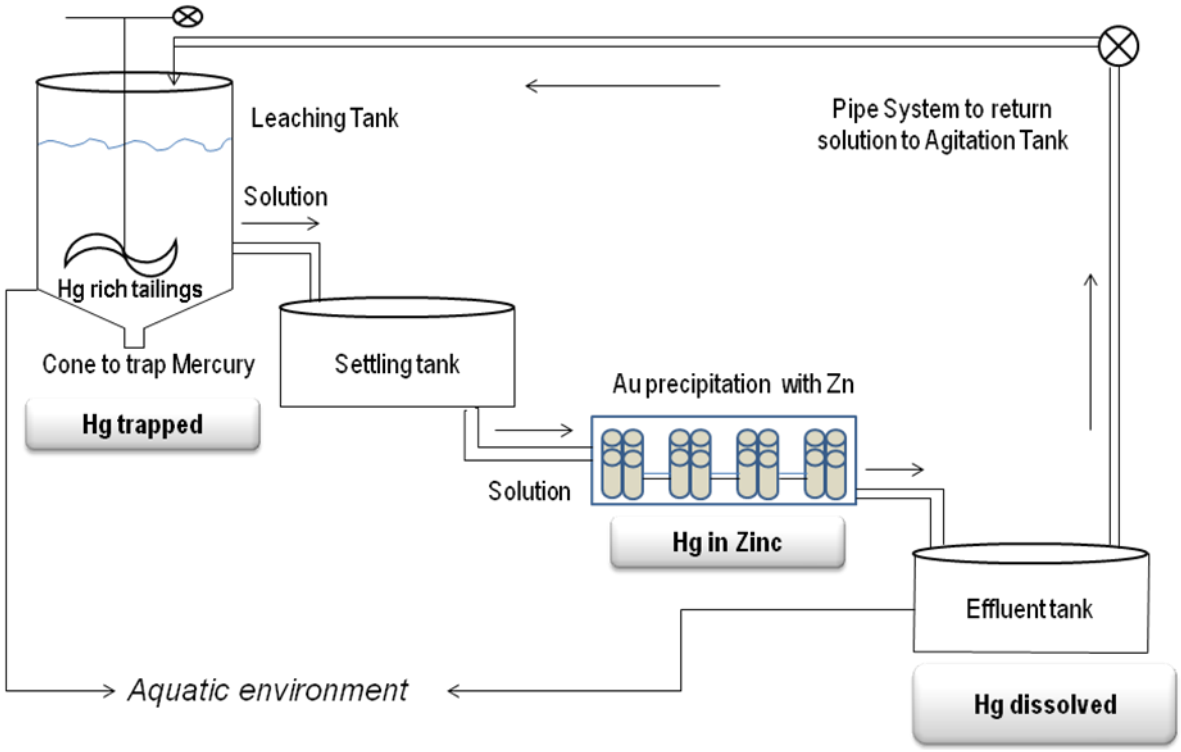

Fig 3.6: Diagram of cyanidation of Merrill-Crowe process.

After gold precipitation, the solution is pumped up from the effluent tank back to the leaching tank where the solids are settled. The pulp is again agitated for about 6 hours, it settles down and the solution is again removed. This cycle occurs consecutively for five to six times during five to six days which means that the total

agitation time is about 36 to 42 hours. At the end of the process, when miners visually notice that there is no more gold being precipitated on the zinc shavings, they discharges the pulp, rich in zinc-cyanide, along with some residual mercury-cyanide complexes, directly into the rivers.

Artisanal miners must reserve the Merrill Crowe tanks to process their ore, tailing or concentrate up to 2-3 months in advance. There is high demand for this service. The mercury rich tailings produced in Ponce Enriquez and surroundings are transported to Portovelo for cyanidation.

3.6.5 CIP process

In most developed processing centers the tailings are de-watered and stored for leaching in CIP (Carbon-In-Pulp) cyanidation tanks owned by the Chilean-mill processing centers. There are approximately 225 Carbon-in-Pulp cyanidation tanks ranging from 30 to 40 m^3 each in Portovelo. The tailings added into the CIP circuit ranges from 15 to 20 tonnes. The agitation system consists of impellers of up to 15 HP that create a rotational speed of 130 rpm. Some tanks work with the Pachuca system, using compressed air to produce air-lifted pulp.

Usually the processing centers consist of a series of 3 CIP tanks, although some centers, such as the CIP plant studied, works exclusively with amalgamation tailings and use only one tank. Most developed plants have 8 tanks in series, where the pulp is transferred in sequence and carbon moves in counter-flow. Around 6.25 kg of $Ca(OH)_2$ per tonne of material is added to the first CIP tank together with 1 to 4 kg of NaCN per tonne of material. The amount of NaCN added depends on the type of tailing being processed. When a tailing is rich in sulphides,

such as bornite (Cu_5FeS_4) the cyanide consumption increases to levels up to 15 kg NaCN per tonne of material. The CIP plants have better control of the pH (usually ranging from 10 to 11) than the Merril-Crowe plants and the pulp density is constantly measured with a Marcy scale. The tanks usually work with 30% solids in the pulp. The concentration of cyanide is around 2 to 3 g/L. After 12 hours of leaching, 20 to 30 kg of activated carbon/tonne of material is added to the tanks. The carbon contacts the cyanide solution for further 12 hours. Some miners control the process by analyzing gold concentration in the solution using atomic absorption spectrometry. When no gold is detected in the solution, miners open a valve to drain the pulp on rotating screen with opening of 2 mm to retain the activated carbon. The carbon is then sent to the desorption circuit. Miners do not realize that the attrition of carbon in the pulp generates fines and gold and mercury can be lost through the 2 mm screen. Activated carbon is partially reactivated using nitric acid followed by washing to neutralize the acid.

The desorption circuit usually works with a hot solution (80-90 °C) comprised of 1 g/L NaCN, 10 to 20 g/L NaOH and 6.4% CH_3CH_2OH (ethanol). The process lasts 72 hours and the eluted solution is sent to the electrowinning process, depositing gold onto cathodes. The desorption towers in Portovelo usually work with 700 to 800 kg of gold-loaded activated carbon. Therefore, miners need to accumulate this amount of carbon before using the desorption process. This typically takes more than one month and thus, it is not convenient for some artisanal miners, who prefer amalgamation followed by the Merrill-Crowe process to produce gold faster.

According to the miners the CIP process is only to leach gold from gravity concentration tailings (via sluice box). But recently, processing center owners have been using CIP tanks to process amalgamation tailings as well. Miners are currently mixing gravity concentration tailings (with no mercury) with Hg-contaminated amalgamation tailings. During the field observations it was found that only one owner of processing center is dedicated to purchasing mercury-rich tailings to process by CIP in Portovelo. As the miners attest, those tailings come from “Chancha” processing centers located not only in Portovelo but also in other villages from the province of Azuay such as Ponce Enriquez, Pijili, San Fernando, San Gerardo. The price per bag of 40-45 kg of amalgamation tailings ranges from US$ 1 to 30 depending on the estimated gold grade evaluated by simple panning.

3.7 Organization of people and processing centers

The main organizational structure of the gold mining industry in Ecuador is administered by two chambers: The Artisanal Mining Chamber and the Mining Chamber, independent bodies created by people in the industry with no Government affiliation. Both bodies play similar roles in the social organization of people who work in mining. While the former is believed to support artisanal miners, the latter is concerned with industrial associations which include small companies, cooperatives, and international junior companies in the region. Representatives of both associations are people with some economic power. Due to their deprived conditions, the real artisanal miners are not part of any association. The association of owners of processing centers from Portovelo-Zaruma (APROPLASMIN), which represent all processing centers has 65

members. This infers that there are people who own at least two processing centers. This unique association of processing center owners has considerable power in the region and in the decision making process since they represent themselves and the artisanal miners who work in their plants.

3.8 Mercury contamination from ASGM

Air, soil, and water are important pathways for organisms and thereby determine human exposure (Gochfeld, 2003). Health effects associated with human exposure to unsafe levels of mercury have been reported in sites near gold mine processing centers around the world (Akagi et al., 2000; Akagi and Naganuma, 2000; Feng et al., 2004) although exposure to families' communities is also of concern. Work practice is the most relevant aspect of mercury exposure among mining communities (Drasch et al., 2001, Spiegel, 2009c). Due to the disorganization of miners, the amalgam burning is usually done at another site moving the amalgam and mercury contamination with it. When the amalgam is transported to jewellers, it releases another proportion of mercury into urban environments (Veiga and Baker, 2004).

In Ecuador the project developed by PRODEMINCA (1999) revealed the existence of mercury bioaccumulation in several fish species along the Puyango River (Table 3.1). They also reveal important information about mercury contaminated food in fruits and other organism from the estuary. The alteration of mercury concentrations in aquatic ecosystems determines effects on other socio-economic groups, such as fishermen, natives, and even urban people not directly involved in mining activities.

Table 3.1: Concentration of mercury in sediment, water and biota.
Ecosystem connected with Artisanal Gold Mining in Southern Ecuador

	Sediment Hg (mg/kg)	**Water Hg (µg/L)**	**Biota Hg (mg/kg)**	**Reference**
Rio Amarillo, Filtered water, Dry season Wet season		0.25 0.10		Betancourt et al., 2005
Rio Puyango, water Dry season Wet Season	 0.85 0.34	 0.57 3.3		Tarras et al., 2001
Rio Siete, Dry season Wet Season	 0.5; 2.0	 1.11 <0.02		Tarras Wahlberg et al., 2001
Raspabalsa fish from Rio Chico near Ponce Enriquez			0.74–0.06	Tarras Wahlberg et al., 2001
Uncontaminated rivers: Gala River near Ponce Enriquez and Buenavista – Santa Rosa River		 0.12 0.1		Tarras-Wahlberg et al., 2001
Ponce Enriquez, Siete River, near shrimp farming Portovelo-Zaruma, Amarillo River	13 3.0	0.9 0.1		Appleton et al., 2001 Appleton et al., 2001
Fruits from Portovelo: bananas, mango, coffee			 0.02 0.29 0.31	PRODEMINCA (1999)
Fish from Amarillo River: Vieja (*Cichlasoma festivum*)			 0.55	PRODEMINCA 1999
Seafood, Tumbes, Peru shrimp Shellfish			 0.30 0.11	PRODEMINCA (1999)
Uncontaminated river at Portovelo area: Vieja(*Cichlasoma festivum*) liver body			 1.04 0.52	PRODEMINCA (1999)

Tarras-Walhberg et al. (2001) and Appleton et al. (2001)'s research confirmed the presence of mercury in many aquatic species. A vast amount of research at other ASGM sites around the world confirmed the human exposure of mercury through fish consumption near artisanal gold mining operations (Ikingura and Akagi, 1996; Hacon et al., 1997; Malm, 1998; Olivero et al., 2002).

This study confirmed mercury concentrations in the sediments from the Calera River, around 2.49 ± 1.26 mg/kg, and of about 2.75 ± 1.47 mg/kg in sediments from the Amarillo River in two sampling stages. High concentrations above normal levels were also found along the whole Puyango River at several stations. Seasonal River flooding causes the dispersion of gold mining tailings and mercury pollution of pristine areas reaching the coastal zone (Appleton et.al., 2001; Solorzano, 1989). The Canadian guidelines for the total mercury allowed in river sediments indicate a limit of a concentration of 0.17 mg/kg (Canadian Council of Ministers of the Environment, 2002). To protect aquatic life in freshwater ecosystems, these guidelines delimit the total mercury concentration to 0,026 µg/L. For livestock water supply, the guidelines indicate that mercury concentrations must not exceed 3.0 mg/L. For irrigation water, the maximum concentration should not exceed 2.0 mg/L; and for water for primary use, such as drinking and swimming, the maximum concentration allowed is 1.0 mg/L (Canadian Council of Ministers of the Environment, 2007). To protect human health, the maximum concentration of total mercury permitted in edible fish and shellfish should not exceed 0.5 mg/g wet weight, which must be adjusted according people's diets and amount consumed.

The concentrations of mercury in sediment found by PRODEMINCA, and values confirmed by this research exceed the limits of Canadian Guidelines, however the concentrations of mercury in water are still safe for some uses such as irrigation.

This research also found mercury concentrations of 4.57 and 3.27 mg/kg were found in flooded areas of a banana farm and edges of a shrimp farm, respectively near Ponce Enriquez in the coastal zone of the Province of El Oro. These concentrations are above the quality criteria limits of Canada for mercury in soils which is 0.8 mg/kg (Canadian Council of Ministers of the Environment, 1999).

Chapter 4 : Results and discussion about mercury in the amalgamation process

4.1 Balance approach

The assessment in amalgamation process was followed at five Chilean-mill processing centers and three “Chancha” processing centers. The mercury balances presented in Fig. 4.1, 4.2 and 4.3 show the results of six evaluations of mercury losses in amalgamation of concentrates by panning, eight evaluations of mercury losses in “las ollas” (left-over) in “Chancha”, and three evaluations of whole ore amalgamation in “Chanchas”.

4.2 Mercury balance in amalgamation of concentrates

From approximately 40 to 80 tonnes of ore milled the miners take around 200 kg of concentrate obtained from the carpets or “balletas”. The re-concentrated material is obtained by manual panning and a miner can be able to get on average around 16 kg of concentrate from the milled material. Amalgamation of concentrate ores by panning, which takes about 3 - 5 hours, is done by sprinkling small quantities of mercury several times on the ore. Sequentially, the miners mix the mercury with the ore making circular movements on the material, subdividing the mercury particles and re-milling the concentrate until the miner notices that all gold has been extracted. During this process, small pieces of brown sugar locally named “panela” are added to clean the amalgam (Veiga et al., 2009).

The Figure 4.1 shows the pathways and the amounts of mercury used, recovered, and released during the process of amalgamation of concentrate ores.

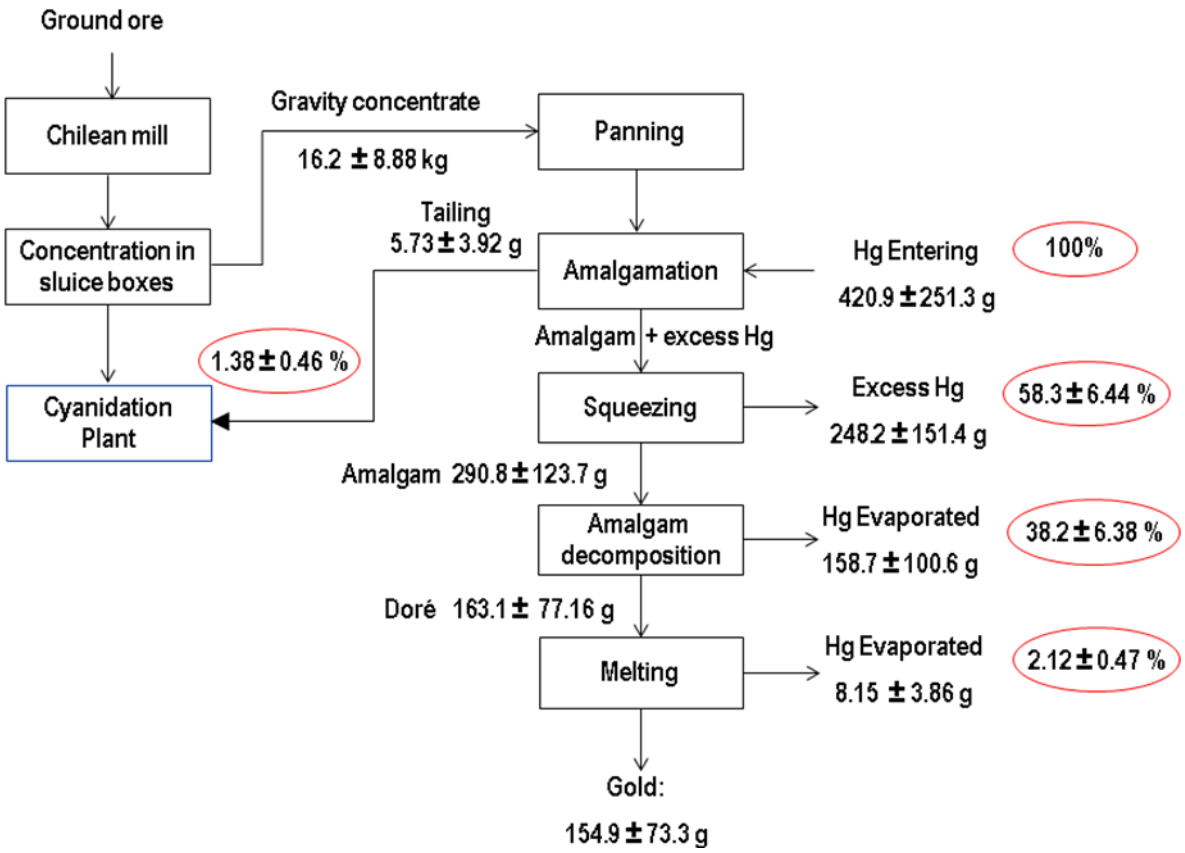

Fig 4.1: Mercury balance during amalgamation of **gravity concentrates**.
Average ± Standard deviation. n= 8.

After the amalgam is collected from the pan, the excess mercury is squeezed out by a cloth and miners recover 58.3 ± 6.4% of the mercury entering the process. The remaining amalgam containing mercury and gold is decomposed by burning off the mercury with a blowtorch, which releases 40.3 ± 6.85% of the mercury. In the processing centers, this burning process is often done in an open pan but sometimes in a retort, which recovers the evaporated mercury and allows miners to recycle it. After this process, approximately 1.38 ± 0.46% of mercury ends up in the

tailings, which are usually discharged into nearby streams or mixed with the non-amalgamated tailings material to be leached with cyanide.

The amalgamated tailings are composed by solid material and water. Most of the mercury goes with the solid phase and the mercury in the water phase is negligible. The tailings are accumulated over time in the processing plant.

4.3 Mercury balance in amalgamation of the left-over material

At the end of the operation of the Chilean mills, miners extract the remaining heavy material and the rest of the concentrate, which remains at the bottom of the mill known as “las ollas” that constitutes the left-over. The miners also use mercury as the best alternative for gold recovery from this coarse material. On average, the left-over material constitutes around 5-10% of the total material ground. The left-over material is placed in a “Chancha” for amalgamation using steel rods or river stones and brown sugar.

The material is kept in the “Chancha” for 3 hours. The amount of mercury added varies around 446 g. At the end of the amalgamation process in the “Chancha”, the miners extract the material by pouring it into a plastic container placed below the “Chancha”. The extraction of the slurry from the “Chancha” is hard work and due the difficulties in managing the “Chancha”, part of the pulp is released from the container discharging solids in which mercury is attached. From the process, the miners extract an amalgam of gold and mercury. By squeezing the amalgam, the miners recover 50.2 ± 14.6% of the mercury. Then, after burning up the amalgam, 31.7 ± 14.9% of mercury is evaporated. Therefore, 18.2 ± 7.13% of the mercury entering the process is lost with the tailings (Fig 4.2). The resulting

tailings from the amalgamation are stocked and mixed with non-amalgamated material to be submitted to cyanide leaching.

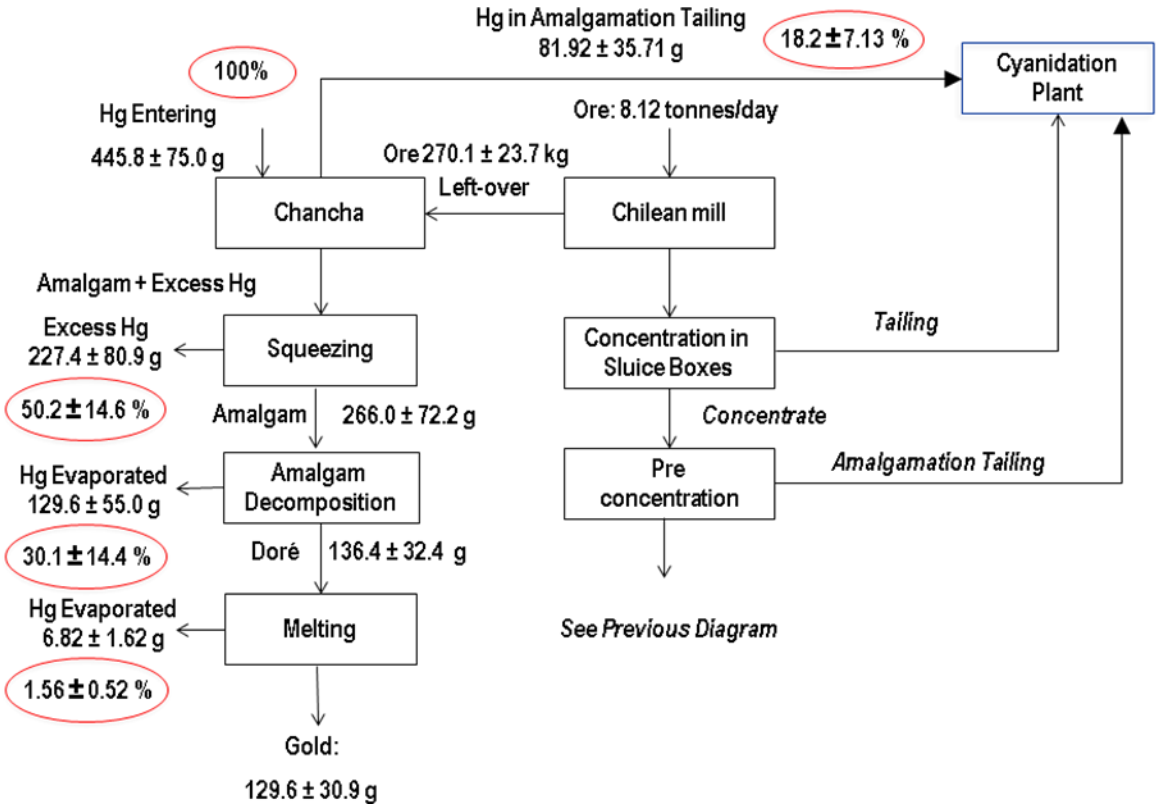

Fig 4.2: Mercury balance during the amalgamation of **left-over material.**
Average ± Standard deviation. n= 8

At the end of the process, the miners extract small pieces of amalgam attached to the wall of the “Chancha”. In some centers, when the miners decide to amalgamate the left over and other concentrated material, it was observed that after the amalgamation in “Chanchas”, the slurry is placed in a manual centrifuge where it is washed with water to form additional amalgam. During this process, high amount of suspended solids overflow from the centrifuge and are dispersed

around the “Chancha”. Mercury concentration of 758 mg/kg was found in tailings taken from the floor around the “Chancha”. The total mercury from the tailings calculated includes all this material released around the processing center.

4.4 Mercury balance in amalgamation of the whole ore

Mercury distribution in the whole ore extraction process is shown in figure 4.3.

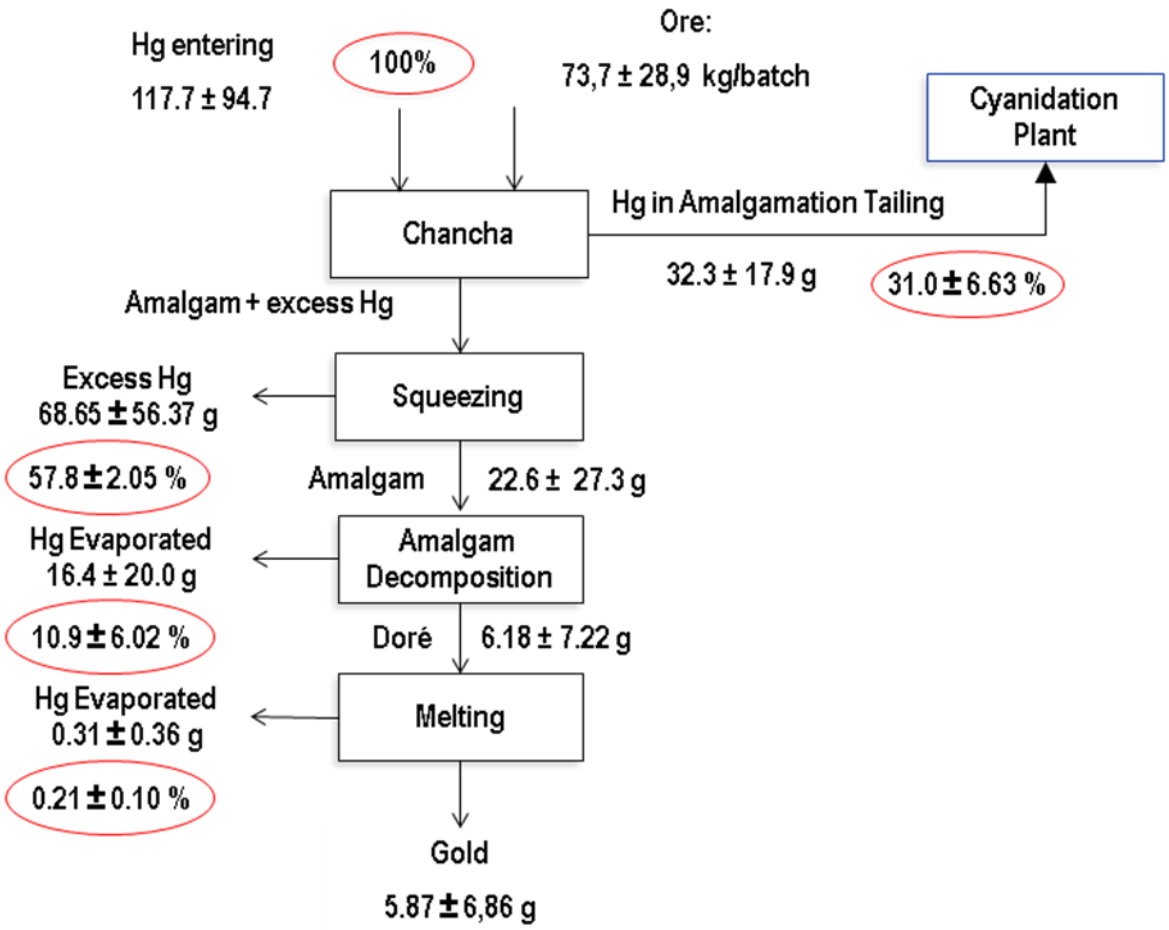

Fig 4.3: Mercury balance for the amalgamation of the **whole ore.**
Average ± Standard deviation. n=3

This process is often conducted in “Chancha” processing centers. After the amalgam is collected, the excess mercury is squeezed out, so that 57.8 ± 2.05% of

it is recovered. The remaining amalgam, usually containing 50% of mercury and 50% of gold and silver is decomposed by burning off the mercury with a blowtorch and 11.1 ± 6.12% of mercury is vaporized. If a retort is available in the “Chancha” centers the miners recover the evaporated mercury and recycle it.

The determination of mercury releases shows a similar trend in all ore material assessed, but the difference is that when the whole ore is amalgamated, 31.0 ± 6.63% of mercury is released with the tailings, which is higher than when concentrates are amalgamated (18.2 ± 7.13 % of Hg is released with tailings).All the tailings are accumulated over time in the processing centers until enough material is available for cyanidation.

The whole ore amalgamation has been observed in current practices in other countries such as Venezuela, Indonesia, Brazil, Colombia, Philippines and Zimbabwe (Veiga and Baker, 2004). The result of this process is a substantial loss of mercury and high environmental contamination through the tailings. Some mercury is recycled by small miners, who keep the metal with them at home. But because mercury is not reactivated for further use, it becomes dirty and loses its amalgamation ability affecting the amount of gold the miners could be able to recover.

4.5 Mercury recovery and losses

The excess mercury recovered when the amalgam is squeezed off in a piece of a cloth represents in all cases an average of 56% (51.02 to 59.03%) of the total mercury used in the amalgamation process. The amount of mercury evaporated when the amalgam is decomposed with a torch and when the *doré* (amalgam after

burn) is melted represents in all cases an average of 29% (14.9 to 39.7%) of the total mercury introduced into the system. As the amalgam burning is conducted in an open pan or in fume hoods, all of the evaporated mercury is either lost or partially recovered in the rudimentary water tanks attached to the fume hoods. The *doré,* has on average 5% mercury and 95% gold. This is comparable to (2 to 5% Hg) what exists in *doré* from the Brazilian Amazon mines (Veiga, 1997). The *doré* is sold in one of the 20 gold shops in the region. The gold shops do not have filters or condensers to trap evaporated mercury when the *doré* is melted. This is a significant human health problem since the gold shops are located in the urban area of Portovelo-Zaruma or other cities nearby.

Comparing balances of mercury determined in the three amalgamation systems studied, it is clear that the main mercury losses occur when miners process the ore in “Chancha” processing centers (Fig 4.3). Most of the miners and owners of processing centers from Portovelo indicated that all amalgamation tailings are either collected and directly leached with cyanide or mixed with other primary gravity tailings to be leached with cyanide (Rivera 2009).

The impacts on the environment from the whole-ore amalgamation are mainly due to a lack of knowledge by some miners who inefficiently amalgamate the whole ore in “Chanchas”. The owners of the “Chancha” processing centers” exacerbate the problem exposing those tailings to cyanide.

Table 4.1 shows the amount of mercury release per tonne of ore processed in Portovelo-Zaruma. The concentrations of mercury in the tailings range from 360 to 430 mg Hg/kg. In table 4.1, one can notice that more mercury per tonne of material

is used when the concentrates are amalgamated. This gives the impression that the amalgamation of concentrates requires more mercury, but in fact miners amalgamate approximately 15 kg of concentrates per batch whereas the whole ore amalgamation contaminates 200 kg of tailing per batch.

Table 4.1: Average mercury distribution in Processing Centers.
(g Hg/tonne of material processed)

Hg Distribution	Material					
	Whole ore*	%	Left-over**	%	Concentrate***	%
Hg Entering	1460 ± 620	100	1660 ± 320	100	25540 ± 2.630	100
Hg Recovered	850 ± 380	58.2	850 ± 320	47.0	14960 ± 2800	58.6
Hg Evaporated	180 ± 170	12.3	500 ± 190	30.1	10220 ± 1360	40.0
Hg in Tailings	430 ± 90	29.5	380 ± 140	22.9	360 ± 140	1.40

Note: * amalgamation of the whole ore occurs in “Chancha processing centers”
** this occurs when “las ollas” are amalgamated in “Chanchas”
*** gravity concentrates manually amalgamated
Arithmetic mean ± standard deviation; n= 3 whole ore, 8 left-over, 6 concentrate

Assessing the amount of mercury per tonne of material processed, approximately 1.4% of mercury is lost with tailings when miners amalgamate only gravity concentrates, whereas 22.9% is lost when the whole ore is amalgamated in “Chancha” processing centers or when “las ollas” are amalgamated in “Chanchas”. From the determinations of mercury losses in the three amalgamation systems, it is clear that the method of amalgamation practiced in the artisanal and small-scale gold mining sector influences the distribution and impact of mercury in the ecosystem.

Significantly, the use of “Chanchas” is the most inefficient way to amalgamate gold compared with manual panning amalgamation. Table 4.2 shows an annual estimation of the total mercury emitted based on kg of mercury released per annum. The mercury emissions from artisanal and small-scale gold mining depend on the method of amalgamation, intensity of the operations as well as the efficiency of the system applied. Mercury releases per annum are estimated assuming that the Portovelo-Zaruma mining district has two “Chancha” centers dedicated to amalgamate the whole ore, and 110 Chilean mills which produce concentrates that are manually amalgamated and use “Chanchas” to amalgamate “las ollas” (left-overs). This considers that all Chilean-mills in Portovelo-Zaruma process approximately 30,000 tonnes of ore/month and nearly 1% of this is left-over (“las ollas”). It was also estimated that all “Chanchas”, on average, process 63 tonnes of ore/month. Approximately 1.5 tonnes/annum of mercury is released in Portovelo-Zaruma, from which 71% (1.04 tonnes) is emitted into the air and 29% (0.43 tonnes) is released with tailings (Table 4.2). Lack of maintenance of fume hoods in processing plants, and preference of artisanal miners to burn amalgams in open environments, do not help the recovery of the evaporated mercury.

The estimation of annual mercury release allows analysis of the impact of each amalgamation system related to the intensity of the operation in the area. The processing intensity of the whole ore amalgamation in “Chancha” processing centers in Portovelo-Zaruma is low compared to the numbre of Chilean mills. When the amounts of Hg released per annum is divided by the number of operation units (7 “Chanchas” and 110 Chilean-mills), it is clear that the amalgamation of the

whole ore releases 24.1 kg of Hg per “Chancha” and the manual amalgamation of concentrates releases 5.12 kg of Hg/ unit.

Table 4.2: Estimated total mercury releases per annum in the Portovelo Zaruma area.

Material	Estimated kg of Hg Released per annum		
	Air	Tailing	Total
Whole Ore	49.91 ± 18.40	118.98 ± 9.98	168.89 ± 28.38
Left-over	445.60 ± 15.30	289.16 ± 11.85	734.76 ± 27.15
Concentrate	543.24 ± 54.49	20.16 ± 5.74	563.40 ± 60.23
Total	1038.75 ± 88.19	428.30 ± 27.57	1467.05 ± 115.76

Note: Arithmetic mean ± standard deviation, n= 3 whole ore, 8 left-over, 6 panning concentration

When miners amalgamate only the gravity concentrates, the quantity of tailings produced is low, and therefore it is feasible to remove mercury by panning or other processes and hence it is disposed safely.

The use of retorts can be a temporary alternative until total elimination of mercury from the gold recovery system is achieved.

4.6 Hg –Au ratio

A relationship between the Hg_{lost} and $Au_{produced}$ was calculated in order to establish the proportion of mercury that has been released into the environment in relation to the amount of gold produced (Lacerda, 2003; Telmer and Veiga, 2008). The ratio also known as emission factor is the amount of mercury released per kg of gold produced (Veiga and Baker, 2004). The whole ore amalgamation in

“Chanchas” has a Hg_{lost}: $Au_{produced}$ ratio of 12.04 ± 5.48. The average ratio for amalgamation of “las ollas” is 1.76 ± 0.64 and for the amalgamation of concentrates is 1.06 ± 0.21. This ratio shows that the highest level of mercury releases occurs when the whole ore is amalgamated in “Chanchas”. This ratio can be reduced to as low as 0.001 if retorts are used and only concentrates are amalgamated (Veiga and Backer, 2004). In the Northern Amazon, a mercury emission factor from 2.0 to 4.0 has been reported (Telmer and Veiga, 2008). Lacerda and Salomons, (1998) used an emission factor of 1.5 to calculate mercury pollution in different countries. It is clear that the ratio of Hg_{lost}:$Au_{produced}$ varied from one operation to another and is very dependent on the type of ore brought in by the miners, the amount of gold produced, and the social and economic situation of the miner.

The ratio Hg_{lost}:$Au_{produced}$ of 1.76 when the left over material is amalgamated gives the impression that mercury emissions are low. But as the gold grade is high, the material needs more mercury. Therefore the ratio Hg_{lost}:$Au_{produced}$ does not provide an actual idea of the efficiency of the method.

The form by which the miners manage amalgamation in “Chanchas” produces greater losses of mercury in tailings. In “Chanchas”, mercury loses coalescence forming droplets that can be attached to walls of the equipment. The mercury also is dispersed when miners discharge the slurry during the manipulation of “Chanchas” at the end of the process.

Gravity concentration of gold followed by panning amalgamation is definitely the best way to use mercury, since it achieves better gold recovery and lower losses of

mercury. Techniques that emphasize gold concentration will improve gold recovery and reduce mercury losses and must therefore be communicated to the miners and processors (Vieira, 2006). The eradication of mercury in Portovelo-Zaruma can become a reality if efficient gold processing systems are disseminated.

4.7 Air mercury contamination during amalgam burning

An important exposure pathway occurs when miners burn amalgam or Hg-contaminated zinc in both the amalgamation and cyanidation processes (Veiga, 2010). When artisanal miners add mercury during the amalgam formation, the levels of mercury in air increase from 25 ng/m^3 to 12,500 ng/m^3. At the moment of amalgam squeezing, the mercury levels can reach 12,500 ng/m^3. At the beginning of the amalgam burning, the air concentration suddenly increases to 36,000 ng/m^3, eventually reaching the highest level at 193,000 ng/m^3. These levels were recorded with LUMEX for 20 minutes producing a dense smoke from the amalgam burning was produced. After burning the amalgam, mercury exposure was inferred measuring its concentration in the exhaled air of three miners exposed to the amalgamation process when they blow into the LUMEX RA 915 Hg-spectrophotometer. Before the process the miners exhaled mercury levels of 147.3 (± 6.4) ng/m^3, and after burning amalgams they exhaled mercury levels of 1,513.3 (± 480.1) ng/m^3.

Chapter 5: Results and discussion about mercury in cyanidation process

The cyanidation process in Portovelo is conducted in conical cement agitation tanks. These tanks can be found in Chilean mill processing centers, but there are also processing plants which only provide the service of cyanidation. Artisanal miners prefer to use the Merrill-Crowe process which requires 5 days followed by the precipitation of gold from the clear solution. Before leaching with cyanide, amalgamation tailings rich in mercury are mixed with gravity concentration tailings, obtaining a product consisting of 150 to 350 mg/kg of mercury and 1.5 to 5 mg/kg of gold. The technical characteristics of the Merrill Crowe process are shown in Table 5.1. In the Merrill-Crowe process, about 6,000 to 7,000 kg of tailings with grain size below 0.2 mm are added to cement agitated tanks of 14 m^3. Merrill-Crowe tanks are similar in every processing plant and processing methods are similar too. The amount of water added ranges from 8,000 to 11,000 litres. The resulting slurry with 35 to 45% solids by weight is agitated for 12 hours. Usually miners add 25 kg of lime ($Ca(OH)_2$) per tank to the pulp to raise the pH above 10. Overall, the pH values in the agitated tanks in Portovelo at the beginning of the cyanidation process were highly alkaline, with an average of 11.2 ± 0.5. At the end of the process, the pH was slightly lower, with an average value of 11.0 ± 0.5. Calcium hydroxide increases pH in the solution however some tanks can have with higher pH than the initial value due to reactions of mineralogical characteristic of the tailings containing carbonaceous material such as the ore from Portovelo-Zaruma (Vikentyev, et al., 2005)

The pH is considered a critical parameter in the cyanidation process, since gold dissolution decreases with excess $Ca(OH)_2$, making the reaction very slow and preventing the contact between gold and cyanide (Marsden and House, 2006). A pH above 12 is not ideal and practically inhibits the gold dissolution. In each leaching tank, miners add 50 kg of NaCN which results in a solution with 4 to 6 g/L of CN.

Table 5.1: General conditions of Merrill-Crowe and Carbon in Pulp process.

Batch Characteristics	Cyanidation Processing Plant						
	MC1	MC2	MC3	MC4	MC5	MC6	CIP
Solids (kg)	10,435	11,093	10,846	8,634	9,810	9,210	8,231
Liquid (litre)	8,513	9,050	8,848	7,044	8,003	7,513	22,251
CN (g/L)	4.79	4.51	4.61	5.79	5.10	5.43	2.25
Initial pH	12.30	11.70	10.18	11.40	11.05	10.60	10.9
Final pH	10.76	10.45	11.70	11.30	10.50	11.23	10.7

Merrill-Crowe (MC) Carbon in pulp (CIP)

5.1 Balance approach

In order to assess mercury in cyanidation, the process was followed in seven different processing centers (6 Merrill-Crowe and 1 CIP). This evaluation resulted in a mass balance of mercury through the cyanidation process.

5.2 Mercury balance in Merrill-Crowe process

The mercury balance in the Merrill-Crowe process is illustrated in Fig. 5.1. In this system around 24% of the mercury is trapped at the bottom of the tanks. Important quantities of mercury are associated with the solid tailings and in solution.

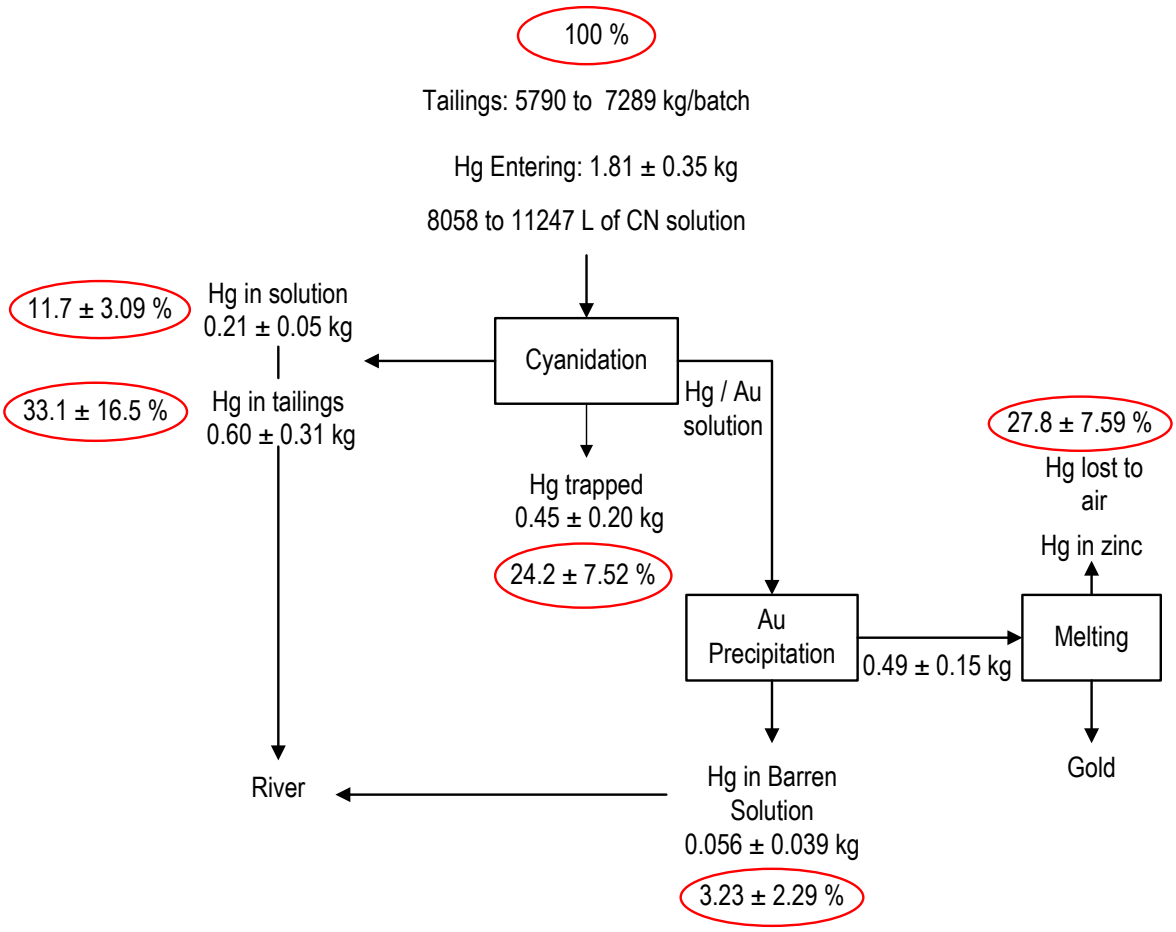

Fig 5.1: Balance of mercury in Merrill-Crowe cyanidation plants.
Average ± standard deviation, n=6 processing batches.

Approximately 31% of mercury was reported flowing to the zinc precipitation cells from which a minimum proportion (3.23%) was released with the final barren solution. Remaining mercury (27.8%) was precipitated in the zinc shavings and evaporated during the burning process.

Figure 5.2, illustrates the mercury and gold dissolution rate during the five days of gold leaching in a Merrill-Crowe circuit. The material being leached was an amalgamation tailing with 101.2 g/tonne of gold and 255.5 g/tonne of mercury.

Approximately 88.4% of the total gold and 27.8% of mercury was extracted in the 5 days.

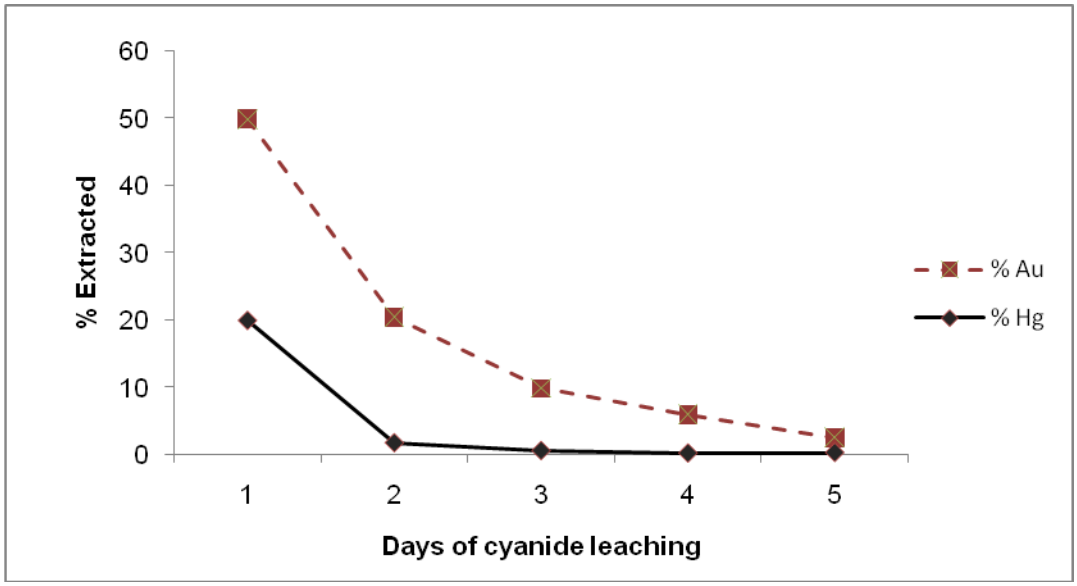

Fig 5.2: Mercury and gold leached during five days in Merrill-Crowe system. Data correspond to analysis in tank MC4.

Higher yields were likely possible, since processors do not re-grind the material and gold occluded inside the gangue minerals likely remains in the tailings. This is an interesting point, since some processors estimate gold content by simple panning. Other processors leach the tailings with cyanide in a lab and estimate gold recovery without grinding. They subsequently compare gold recoveries in the plant with the amount of gold calculated by panning or lab results. These estimations provide a false impression that 100% of the gold was leached, but in fact only the gold exposed to cyanide is leached, not the total gold in the sample. The process of cyanidation needs fine grains (<0.2 mm) and larger grains can be present in the ore reducing the recovery efficiency. It is not unusual to hear from

miners that their recoveries are around 98% when in fact they recover less gold. Fig 5.2 shows that 23.2% of the mercury and 50 % of the gold entering the cyanidation tank of Merrill-Crowe system were dissolved in the first day (12 hours agitation). In the second day, only 2.71% of the mercury was leached whereas 20% of the gold was dissolved. Mercury leaching basically stops after the third day and gold dissolution continues.

The mixing characteristics of the agitated tanks in the Merrill-Crowe process can contribute to the lower solubility of mercury in the cyanide solution. Mercury droplets likely have settled to the bottom of the tank, reducing their contact with the cyanide solution. Gold particles, due to the fact that they are exposed but not necessarily liberated from the silicates (otherwise they would be amalgamated), do not follow the same pattern. It is suggested that the agitation process is not strong enough to keep some of the mercury droplets in suspension. The cyanidation tanks in Portovelo are conical at one third the height from the bottom with little conic box at the bottom. It is clear that the practice of daily settling of solids each day during the course of the process (5 days) allows mercury to precipitate at the bottom of the tank. All these features of this process help to trap part of the mercury present in the tailings. In fact, miners and plant owners believe that the cone-shape tanks trap all residual mercury from the tailings ignoring the fact that over 42.8% (27.8 + 11.7 + 3.23%) of the mercury is dissolved and one third of the mercury is discharged to the environment with tailings, likely as fine droplets. Considering the mercury trapped at the bottom of the tank, which is eventually dumped into the

river, the amount of metallic mercury released by the cyanidation plants is almost 58% of the mercury entering the leaching system.

Another important consideration related to the lower dissolution of mercury from the tailings is the different rates in which mercury and gold react in the cyanidation process. The cyanidation test conducted in rolling bottles with a tailing with 141 mg Hg/kg and 38.1 mg Au/kg confirm the reaction rates of gold and mercury with cyanide. It was observed that in 12 hours of leaching with 1 g/L of NaCN, only 1.5% of mercury was dissolved (compared to 90% of gold) (Figure 5.3).

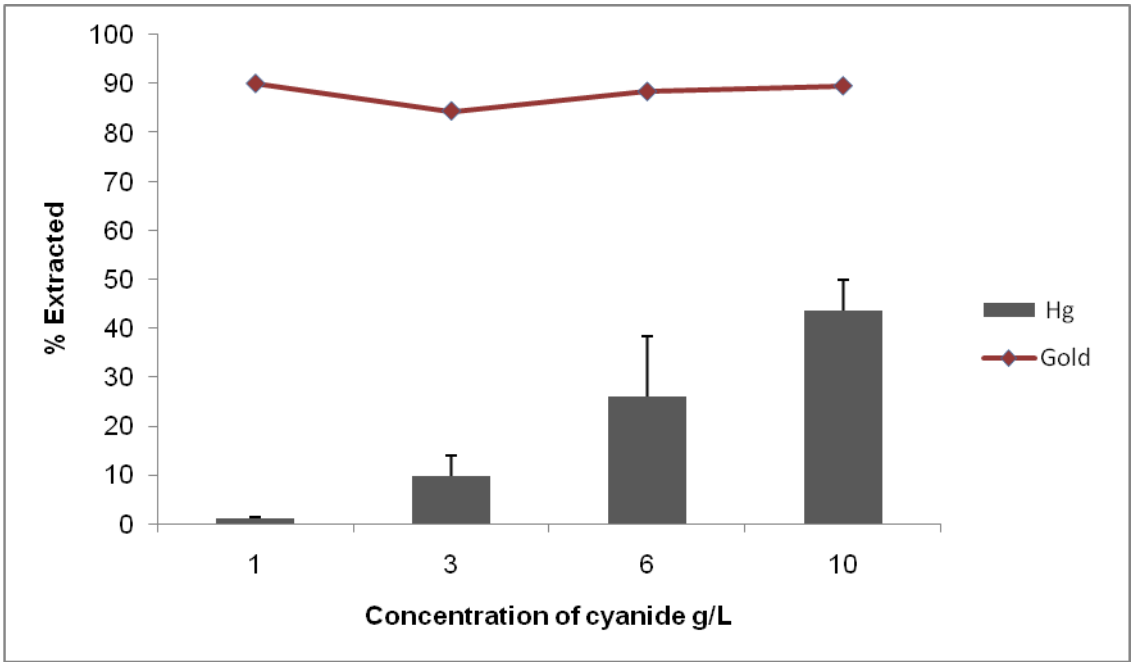

Fig 5.3: Mercury and gold dissolution at different cyanide concentrations. Bars are arithmetic means and standard ±deviation, n=2 of mercury. Diamond symbols show the gold dissolution. (Leaching time 12 h).

By increasing the concentration of sodium cyanide to 10 g/L, the dissolution of mercury increased to 43%. The amount of gold dissolved remained practically

constant at approximately 90%, indicating that there is gold occluded in the gangue, not accessible to cyanide. This lab experiment confirms that dissolution rate of gold is much faster than the mercury rates.

5.3 Mercury balance in CIP process

In the CIP circuit, the concentration of mercury in the tailing entering the system was 166 mg/kg. The amount of solids was approximately 8,200 kg and the pulp density with 27% solids was well-agitated and aerated thanks to an impeller operated by a 6 HP electric motor.

The total mercury dissolved in the discharged pulp was 50.8% of the mercury entering the system. The amount of metallic mercury released with solids in the pulp was 42.8%. The amount trapped at the bottom of the tank was 2.68%. Only 3.72% was adsorbed by the activated carbon (Fig 5.4).

The dissolved mercury was determined by decanting the solids from the agitated pulp followed by filtering the solution in a 0.45 µm Millipore filter. It was observed that prior to filtering the slightly turbid solution with 0.5% solids, the concentration of mercury was 56.9 mg/L. After filtration, the solution had a concentration of 35.1 mg Hg/L which represents 0.78 kg of mercury dissolved in the process. This suggests that 31.6% of the total mercury entered in the system was associated with extremely fine suspended particles. Aaron et. al. (2005) reported that when mercury is exposed to cyanide solution the mobilization of mercury occurs as colloidal particles.

The scanning electron microscope analysis of suspended particles retained on the Millipore filter revealed the presence of fine particles of calcite, muscovite,

chlorite, quartz, arsenopyrite, pyrite, iron oxide, vanadinite, and bismuth telluride. Very little mercury was identified and it was mainly associated with arsenopyrite and telluride.

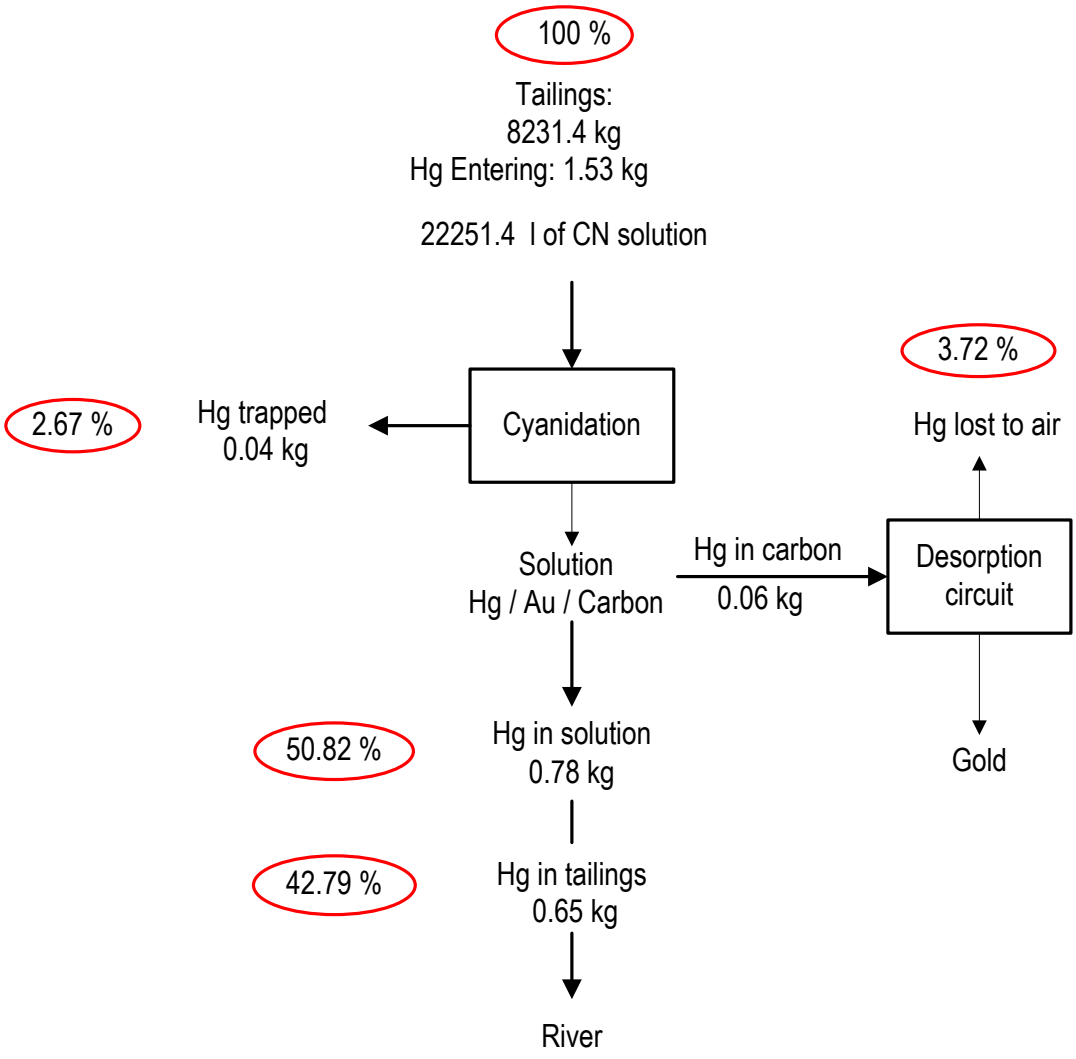

Fig 5.4: Balance of mercury (kg) in CIP process in one processing plant.

The findings of this study reveal that the cyanidation process of mercury-contaminated tailings is probable more dangerous than the amalgamation process.

From its formation constant it is likely the presence of soluble mercury cyanide complexes in the tailings being discharged into the rivers. The miners of Portovelo produce mercury rich tailings from the whole ore amalgamation in “Chanchas” and amalgamation of left-over material and concentrates. This determines the amount of material exposed to cyanidation.

Associated with cyanide operations, important quantities of mercury are discharged in solutions and final tailings. An estimation of mercury discharges per tonne of material processed is presented in Table 5.2.

Table 5 2: Estimated mercury discharged during cyanidation.

Cyanidation process	Estimative Hg released (kg)			
	Hg in Tailings	Hg in Solution	Hg to atmosphere	Hg trapped
MC	0.093 ± 0.049	0.042 ± 0.02	0.078 ± 0.027	0.070 ± 0.031
CIP	0.17	0.09	0.007	0.005

Kg of Hg per tonne of material processed during cyanidation of mercury rich tailings in Merrill-Crowe (MC) and CIP process in Portovelo-Zaruma.
Values for MC process are arithmetic means ± standard deviation, n=6.

The CIP process releases more mercury in solution and tailings than the Merrill-Crowe. However Merrill-Crowe releases more mercury to the atmosphere. Measuring with LUMEX spectrophotometer when miners roasted the zinc shavings, mercury concentrations in air increased from 2,500 to 25,000 ng/m³. After zinc burning, mercury concentration values increased up to 100,000 ng/m³ and fluctuated around 25,000 ng/m³ for two hours, which is the time of drying and burning the zinc shavings. At the end of the melting process, the atmospheric Hg concentrations stabilized around 6,000 ng/m³. During the zinc burning, miners observed the mercury concentration in the LUMEX spectrometer. This allowed

them to witness the contamination they were producing. The zinc burning process is quite obsolete since most industrial mining companies using Merrill-Crowe process dissolve zinc with sulphuric or nitric acid to be later recovered by cementation and recycled to the process (Marsden and House, 2006).

The ways by which mercury is transported to the environment differ in the two cyanidation systems namely Merrill-Crowe and Carbon in Pulp. The Merrill-Crowe process allows the miners to trap part of mercury but, because of the more severe and more continuous agitation of the pulp in the CIP system, no mercury is trapped at the bottom of the tank. The CIP process also increases the percentage of dissolved mercury (50% compared with 15% in the Merrill-Crowe). The CIP process is performed in a more diluted medium maintaining the agitation of the pulp during the process including the discharge of the pregnant solution, which can allow more contact of mercury with cyanide. Due to operation mechanisms the surface contact between mercury and cyanide is likely greater in CIP than in Merrill-Crowe. It is clear that increasing the pulp density leads to more power consumption and affects the agitation rate of the pulp. The miners and processors do not control the pulp density particularly those that use the Merrill-Crowe system. The settling of the solids before discharging the pregnant solution in the Merrill-Crowe system also explains why the miners trap more mercury in this process than the CIP process. In the CIP plants in Portovelo leaching Hg-contaminated tailings, a large amount of mercury, around 31.6%, is associated with fine suspended particles. These fine particles are of particular concern since they can be transported long distances in aquatic systems. This was not observed in the

Merrill-Crowe plants, since mercury droplets were either dissolved or settled down in the tank.

In the mercury balance, the amount of mercury that is trapped and can be eventually recovered in the Merrill-Crowe system represents almost one quarter of the mercury entering the system. Particles of metallic mercury (Hg^o) are often visible at the bottom of the cyanide agitated tank in the tailings (Fig. 5.5). The metallic mercury present in the tailings may hinder an exact determination of the total amount of mercury due to nugget effect. However, the methodology employed in this investigation allows for an approximation of the amount of mercury lost to the environment. The mercury trapped at the bottom of the Merrill-Crowe tanks could be easily recycled but, as mercury is cheap (US$ 50/kg) and recycling would involve further steps of cleaning to re-establish the coalescence of the mercury droplets, miners simply discharge this material into the rivers. Miners also developed CIP tanks with a cone-trap at the bottom to collect the mercury. They also have the idea to develop devices to trap mercury before introducing the tailings into the cyanidation system or by washing the tailings in water in a preliminary tank. Operators of the processing centers work based on their own experience and skills, by their own intuition and without any concern about the risks of mercury and cyanide poisoning. Due to poor organization and lack of space to make tailing ponds, most processing centers discharge their cyanidation tailings into the Calera and Amarillo rivers. In most cases, cyanide is not destroyed.


(a).


(b)

Fig 5.5: Metallic mercury in solid tailings after cyanidation.
(a) Bright spots of metallic mercury dispersed in wet tailing at the bottom of the cyanide agitated tank before recovery.
(b) Metallic mercury in the residual tailing from bottom of the tank after recovery and 24 h dry-off at room temperature.

The main loss of gold in both cyanidation systems, is related to the lack of accessibility of cyanide to the gold particles in the gravity concentration tailings. Re-grinding is badly needed to increase the gold extraction from this type of tailing. As the gold precipitation on the zinc shavings is not conducted in vacuum part of

the gold is lost to the effluents and dumped into the rivers. The loss of gold was discussed with the miners in one of the processing plants and it was important to demonstrate such assumption, sampling the tailings and analysing the gold. The analysis of waste solution at the end of the cyanidation in one processing centre (MC 4) revealed gold concentration of 1.92 g Au/m^3. The solution volume was around 11 m^3 and the Merrill-Crowe process produced 350 g of gold. Therefore this represents a loss of 6% of the total gold that was already in the solution.

Chapter 6 : General discussion

6.1 Alternative livelihood

While the ASGM system provides economic subsistence for the miners and surrounding communities at the local level, it also contributes to environmental contamination at local and regional levels. A more efficient gold recovery method and waste management system would change miners' perceptions and help control the dynamics of the release of mercury and other contaminants into the environment.

Community members and artisanal miners still believe in agriculture as an option for their sustainability. In fact, some people consider that the site "El Tablon", which has been chosen for communal tailings processing, is the best land on which to develop an integrated agriculture project. While community representatives desire to restore local biodiversity in the rivers and on the land (Rivera, 2009), they can't ignore the fact that mining is becoming one of the most important national industries in Ecuador.

It is important to emphasize that Ecuador is known to be one of the world's most biologically diverse countries, with over 1500 bird species in the country. This can be roughly 1/6 of all bird species in the world. Ecuador has twice the plant and animal species of the United States and Canada together, four times more than all Europe, and the largest number of plant species per unit of area in the Americas. High deforestation occurs in Ecuador due to several land use activities (Mosandl, 2008) that include agriculture, aquaculture, and mining. Due

to deforestation, only 6% of the country's rich tropical forests remain (Estrella et.al., 2005). Southern Ecuador on the Pacific Ocean coast is irrigated by many rivers that flow down from the Andes. This is characterized as the most productive area of the country (Cucalon, 1989).

Agriculture and fishing has been traditionally the main activity of Ecuadorian people (Hanratty, 1989). In the colonial times cocoa was the mainstay of the country economy. The cocoa was known by the locals as “pepa de oro” (gold nugget) due to its high profitability. The crop was nearly wiped out by a fungal disease in the 1920s. Low world prices during the great depression discouraged production, and the plantations ended being transformed into rice, sugar, corn, and bananas (Larrea, 2006). Coffee was introduced in Ecuador early in the nineteenth century, and remained one of Ecuador's top export crops through the 1970s. Ecuador became one of the top banana producers locally named “oro verde” (green gold) also due its high profitability. Cocoa, coffee, bananas and other types of agriculture products were cultivated in small farming systems of about 5 to 10 hectares (Hanratty, 1989; Larrea 2006) but, over time, those small farmers lost their land due low prices and large scale infrastructure development. Coffee was the preferred crop of people from Portovelo-Zaruma, but it has almost disappeared. Some of the reasons Bebbington(1993) offers to explain these changes are: the introduction of modern technologies, the promotion of monocultures, and the demand for speedy and lucrative cash returns. Most of the cocoa, coffee and bananas were produced in the Western foothills of the Andes, Southern Ecuador. Zaruma was recognized for the production of the best coffee

of the region characterized for its flavor and aroma known as “café Zaruma”. A transition in production from coffee to bananas, or cocoa to shrimp farming or artisanal gold mining was observed in the last two decades. With a lack of interest from the local people, Ecuador's coffee production began declining in the 1980s. Coffee was often left unharvested because of low prices and, in terms of world coffee production, Ecuador now accounts for less than 1% (Vega, 2009). The main reasons for this are the high production costs and the low international prices.

In some cases shrimps and bananas have also experienced low prices driving more people to become gold miners. Currently 80 % of the population of Portovelo-Zaruma and many surrounding sites of the highlands of the Province of El Oro depend only on the artisanal mining operations (Tarras-Wahlberg 2002). The high prices of gold compared with the lower prices of agriculture products makes easy for locals to choose gold mining as a better alternative for subsistence. The same transition from agriculture to gold mining has been observed in Ponce Enriquez and San Gerardo in the Province of Azuay.

Around Portovelo-Zaruma and similarly in the area of Ponce Enriquez, many small farms still subsist by planting coffee, cocoa, citrus fruits, baby-bananas, mangoes, or small sugar cane. However, those farmers are worried about mercury contamination and its effects on their crops.

Known for its rich mineral deposits, the water and soil in the region are highly productive, resulting in good agricultural yields in the coastal zone of Southern Ecuador (Hanratty, 1989). Moreover, due to the climatic conditions, water

availability as well as other geochemical characteristics of the land, the quality of the fruits and vegetables cultivated in the region is highly considered all over the country. The Government of Ecuador sees mining as a more attractive economic alternative than agriculture. Another issue is the perception that Ecuador has huge potential for mineral exploitation. If this is true, mineral resources cannot be used in an irresponsible way. As mining is not sustainable, the Government as well as the local miners should start projects to reinforce and diversify the economy of the Southern Ecuador. Agriculture of high value products is definitely an interesting option. Organic agriculture and food production is beginning to be developed in small farms in Southern Ecuador, and due to the climatic characteristics of the region this can be a viable option (Muller, 2009; Crucefix, 1998).

It is important to remember that the arable land in Ecuador is very limited, with 0.1 hectares per capita (Nation Master, 2005), which leaves the country 132^{ndth} in the list of 199 countries with potential for agriculture. With only 5% of arable land, it is clear that the extensive plantation of bananas is not a clever solution for the use of land. A broader discussion of the use of land and natural resources in Ecuador is badly needed (Breilh, 2008). The stakeholders should first confirm and understand the potential and geological vocation of the country but also the long term sustainability on other alternatives.

6.2 ASGM communities and mercury dynamics

Addressing the ASGM system in a more integrated way allows for classification of the system on different levels, which helps us understand the

system as a whole and the interconnectedness of each unit, for each of which mercury plays a vital role. In this case, community, processing centers, amalgamation systems, and cyanidation systems are the integrated units (Fig 6.1). It is recognized that the dynamics of mercury mobility, which occurs throughout the whole system, have negative effects on the health of the ecosystem (Lacerda and Marins, 1997).

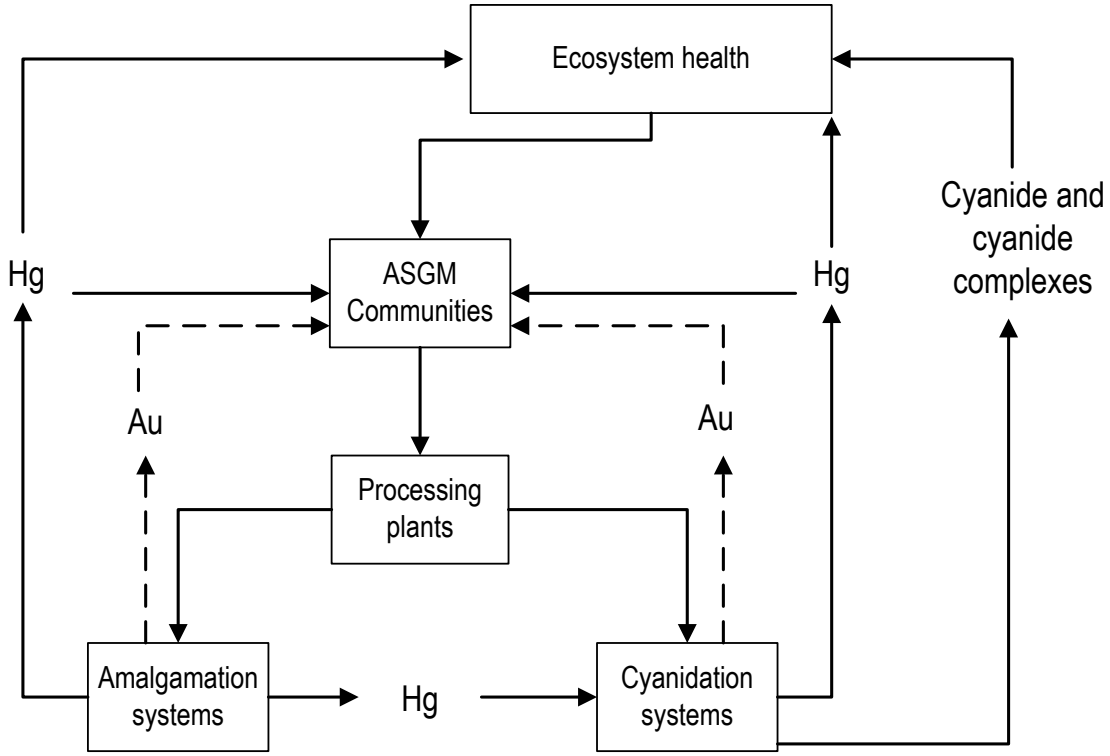

Fig 6.1: System dynamics of mercury from ASGM in Southern Ecuador.

In general, the gold mining community is defined in two levels, i.e., artisanal miners, and owners of processing centers. For gold processing, the artisanal

miner depends on access to different types of processing equipment, such as “Chanchas”, “Chilean mills” and/or cyanidation tanks. Decision-making about how to process the gold is not frequently an obvious process. If an artisanal miner has to choose between amalgamation and cyanidation, they would most likely choose the amalgamation process, for the simple reason that it is the fastest, simplest, and cheapest way to recover gold (Telmer and Veiga, 2008). The processing centers provide mercury to the artisanal miners to amalgamate the gold. Although there are “free mercury” alternatives, artisanal miners still rely on amalgamation because it is the cheapest and simplest technique to extract gold (Vieira and Passarelli, 1996). In Portovelo, the miners say that mercury enters Ecuador from Peru, and it was observed that mercury is easily purchased in many local shops in Portovelo. The amalgamation and cyanidation processes constitute separate systems which can be understood separately according to specific scenarios of work in each mining community. The miners must decide which type of process fits their skills and needs to recover the gold. They have to decide how to process their ore, either by amalgamating the whole ore, or concentrating it before amalgamation. In general, the artisanal miners are able to get only 30 to 40% of the gold present in the ore since their gravity concentration is a rudimentary process. After amalgamation, the miners sell their amalgamated gold to any of the 20 gold shops located in Portovelo-Zaruma or other cities, such as Piñas or Machala. The gold shops refine their gold with nitric acid, usually without using fume hoods.

The production of mercury-rich tailings depends on the amalgamation process as seen in Chapter 3. The miners leave the tailings for the owners of processing centers or sell to a third party who makes profit from those tailings using cyanidation. As consequence, the mercury rich tailings are transported from one site to another spreading the pollution to other communities. As observed in Chapter 3, when only concentrates are amalgamated, around 1 - 2% of mercury goes with the tailings. This generates less contaminated material.

The cyanidation process also comprises different types of systems, such as cyanidation in percolation tanks, a practice that is almost disappearing in the region, Merrill-Crowe and CIP leaching. Using mercury-rich tailings in the cyanidation process, the final tailings are still rich in metallic mercury and stable mercury-cyanide complexes are formed. An important proportion of the mercury entering the system is also released to the air (27.8 ± 7.59%). A remaining part is usually trapped and could be recovered when the miners use Merrill-Crowe process. Unfortunately this does not occur and all mercury, even the part trapped in the leaching tanks, is impacting the surrounding environment.

Inefficient amalgamation occurs because gold is occluded in the minerals which cause inadequate liberation. Amalgamation is not efficient when particles are finer than 0.07 mm while cyanidation performs well in grains below 0.2 mm (Hylander et al., 2007). The lack of basic information about grinding, milling, amalgamation and cyanidation are the main reasons for the existence of mercury rich tailings and its further exposure to cyanide (Hylander et al., 2007). Also, the unfair labor division between miners and owners of processing plants forces the

use of both types of gold extraction processes. As miners cannot afford the pieces of equipment for cyanidation and as they do not have the level of education to operate cyanidation, they accept low levels of gold recovery by amalgamation (30 to 40%), leaving the rich tailings to the owners of the processing centers. Therefore, it is not simple to completely eliminate the use of mercury. One option would be to have miners and processors working together in the same company.

It is clear that the whole system is interconnected and socio-economically dependent (Spiegel, 2009b). The desire to become part of the mining business is not only due to a person's economic resources (or lack thereof) but also depends on their skills and knowledge (Sousa and Veiga, 2009), such as a simple gold grade analytical procedure. This labor model that involves miners, processors, and community, in combination with the different systems of gold processing, not only contributes to an inequity in the distribution of resources but also creates an irresponsible waste management. This makes it difficult to apply regulations, not only in Ecuador but also in many areas around the world (Swain et al., 2007). The current increase in the number of artisanal miners, and in particular, processing centers, are issues that also influence the dynamics of the whole system. While this model has provided work opportunities for many people for over 20 years, it has come with the high cost of environmental contamination and human health related problems.

The same adverse effects of mercury from ASGM operations on the ecosystems observed in Ecuador (Appleton et al., 1999) has been observed

elsewhere, including The Philippines (Appleton et al., 1999), Tanzania and Zimbabwe (van Straaten, 2000), Indonesia (Limbong et al., 2003), China (Feng et al., 2006) and Brazil (Veiga and Hinton, 2002). Artisanal miners have been vulnerable, in the hands of those who are more powerful and can have either the knowledge or/and economical resources to run a gold mining processing operation. Due to this hierarchical structure of the gold production sector, miners have had little control within the system and have been forced to use methods which have harmed both them and the environment.

Most miners and communities have demonstrated weak political and technical will to address the problems of environmental pollution (Hilson, 2002; Hilson, 2006; Spiegel, 2009a; Siegel and Veiga 2010).

An interesting observation made with regard to the dynamics of artisanal mining communities in Ecuador is the way in which miners are continually changing their techniques. For example, to achieve better results in cyanidation, the miners have incorporated agitation tanks to replace old percolation tanks and have begun to use activated carbon instead of zinc to recover gold from the pregnant solution. In fact, owners of processing centers are very good at assimilating new techniques and incorporating them into their daily work. Some of them are able to invest through their families, others through associations or cooperatives.

There are large variations in terms of business arrangements between owners of the processing centers and miners, depending on whether the miners leave the tailings for the centers or they decide to leach them with cyanide

elsewhere. While some processing centers have their own mines, many also count with the ore brought by the miners. Since the artisanal miners do not understand some of the “new” techniques such as cyanidation, and particularly, they want to extract gold rapidly to pay their bills, they continue to see amalgamation as the most convenient technique for recovering gold. As a consequence, owners of processing centers take advantage of the fragility of the miners’ financial situations and exploit them.

6.3 Stakeholder perceptions and interests

The local community members of Portovelo characterized the mining activity as a contaminant of air, soil, and water and mercury as a potential risk for their health. They are concerned about aquatic ecosystem, particularly the loss of aquatic biodiversity due water contamination. The local community members are not opposed to mining activities, but they are strongly in favour of adopting techniques to reduce mercury emissions. The miners on the other hand do not view the risk of mercury as serious and voiced concern about the economic consequences in having environmental control of mercury. All miners demonstrate strong desire for more education and training. While miners are concerned about the economic aspects of their work, all community members are eager to consider technical alternatives to reduce or even eliminate mercury pollution.

The Table 6.1 and 6.2 describe what miners see as problems and what they see as opportunities to maintain their activity. Interestingly, when miners are invited to talk about mercury contamination, their reflections identify the problem

of mercury in relation to other occupational exposure issues. For example, discussing mercury and human health, they express their concerns about cyanide use, and the exposure to toxic gases in processing centers, especially when there is lack of equipment for personal protection during their work. Reflecting on their problems, miners and community members expressed that issues related to organization are their main concerns (Table 6.1). While miners concerns are related to poor techniques and occupational exposure during gold processing, the community members show more concern about the contamination of the environment. While the artisanal miners also made clear that their organization is plagued with miscommunications and disagreements among themselves, local residents generally displayed an attitude of low self esteem and lack of interest in the problems. This suggests that problems caused by the miners affect not only the environment (Lacerda et al., 2004) but also the attitudes of the local communities. Most of the owners of processing centers live outside Portovelo as they want to stay far away from contaminated sites. The citizens of Portovelo have very little esteem for their town. The artisanal miners are not as organized as the owners of processing centers, and therefore, participate less in educational projects. The owners of processing centers, argue about their low financial capacity, and because of uncertainties with the new regulatory framework for ASGM they are not confident to invest in improving their facilities.

Table 6.1: Categories of problems of ASGM.

1. Technical concerns
A. Gold processing
Location of processing centers
Misuse of mercury and other hazards used in ASGM
Zinc melting in open air environment
Exposure to mercury, cyanide, and other toxics chemicals
Alternatives for waste management
Losses of gold, silver, and other minerals in the process
B. Miners organization
Informality in mining
Lack of capital to improve processing conditions
Miscommunication between miners and local companies
Disagreement between miners and processors
Classification and organization of processing centers
2 Community concerns
A. Gold processing
Mercury and other heavy metals in the environment
Water pollution
Human health
Processing centers around rural communities
Loss of fish diversity
B. Miners organization
Inequity in resource distribution
Low community self esteem
Lack of local interest in the problem
Disagreements between miners and community

The miners from Portovelo demonstrate their negative perceptions about the presence of international mining companies in Ecuador. They claim they need a more equitable management of gold mining resources, as they rely on it for their

subsistence. One representative of a Canadian mining company operating in the region stated that artisanal mining is having the most deleterious effect on the environment, which is quite evident. However this company is doing nothing to help the miners improve their methods and reduce pollution.

Since all the municipal garbage has been discharged for decades into the local rivers, the stakeholders of the mining sector do not see them as the main polluters. Both miners and owners of processing centers argue that widespread environmental contamination is occurring because of the local culture about waste disposal and lack of waste treatment facilities in Portovelo-Zaruma.

All the miners and community representatives, nevertheless, are in agreement with the proposed changes that represent opportunities to resolve the problem, which are: education, organization, environmental impact assessment, and environmental restoration (Table 6. 2). Therefore, they developed the idea of creating a training centre for artisanal and small scale gold miners in Portovelo-Ecuador. They believe that education could help them develop the right attitudes, skills, and knowledge that would lead to efficient gold practices and the elimination of mercury.

According to one of the leaders in the Mining Chamber, education is a priority. Within their actual infrastructure and experience, members of the ASGM system face three main training needs: a) Technical: geology, and gold recovery; b) Economic: credits to invest in technology and build safe processing centers; c) Environmental: community participation and management.

Table 6.2: Categories of opportunities associated with ASGM.

A. Training / Education /Promotion
Technology for gold recovery
Waste management (treatment and reuse of water)
Organization of miners and community
Promotion of other technical alternatives for cleaner production
Social relations, communication and participation
Economic and environmental management
Policies and regulations for mining
B. Organization
Formalization and legalization of artisanal and small miners
Equitable relationship between miners and owners of processing centers
Strengthening consciousness of owners of processing centers
Accountability of Government authorities (local and national)
C. Environmental health
Relocation of processing centers (distant from water courses)
Protection of headwaters, aquatic resources, and forests
Remediation and restoration of impacted rivers
Effluent treatment in processing centers (e.g. cyanide destruction)
Community participation

Miners introduced the option not only to develop integrated projects that would include safe mineral extraction, but also to look at the development of other types of skills for their sustainability. They also stated that any project in the area must consider the human capital in Portovelo-Zaruma in relation to its historic mining development.

Some community members entertain the idea of tourism development and agriculture as alternative ways to sustain their families. Miners look at this option

as an advantage over working for large mining companies. Nonetheless, the opportunities for both miners and community members to enter into another activity such as agriculture are viewed with frustration because of the historic contamination of local ecosystems.

Local and downstream communities demand the protection of aquatic resources and habitat restoration. Habitat destruction near headwaters, or surface and underground water pollution, were some of the major complaints made against ASGM. With regard to aquatic contamination, the affected communities have made strong attempts to establish a long-term monitoring system of the lowlands in the estuarine regions. While agriculture and aquaculture farmers of the Southern region have insisted on organic production systems in order to increase the prices of their products for the global market, they also feel that heavy metals such as mercury can contaminate such foods as bananas, shrimps, and fish, but scientific studies or monitoring data are required to confirm such impact.

6.4 Reasons for the use of mercury in ASGM

The use of mercury in ASGM has been influenced by cultural, social, technical and economic factors. Some of the most important historical and economic forces driving the ASGM system are: a) amalgamation was inherited from parents with poor technical education and lack of knowledge about efficient procedures of gold processing, b) the lack of economical resources to invest in a more organized technique, c) lack of Government support, d) amalgamation is a simple and cheap process.

When looking at the interactions of political, socio-economic, and educational factors in the region, it is easy to see the rationale behind the ASGM systems. Southern Ecuador has been linked historically to mining activities but lacking in education, organization, planning, and control. This makes it easy for the locals to engage in venture projects. Particularly the people from Portovelo-Zaruma have had a long-standing association with gold mining for many years. This fact has given them basic skills for mining and gold extraction, but they need advanced technological education. Nonetheless, to them, some traditional knowledge is tried and true. An example of the application of traditional knowledge in the gold processing is the use of brown sugar or “panela” and molasses in the amalgamation process. Nobody knows exactly the function of the sugar, but in fact it promotes more coalescence to the amalgam, and less mercury is lost with the tailings during the amalgamation. The miners from Portovelo-Zaruma claim that their mining activity has been passed down for generations, including the education they received about mining from their parents and ancestors who worked for the old SADCO Company. In contrast, artisanal miners from Ponce Enriquez still lack the necessary skills to properly manage the ore, which is why the use of rudimentary techniques to amalgamate the ore is more prominent there. The existing gold reserves in conjunction with the poor regulations have encouraged local miners to continue with this activity in an informal way.

While in Portovelo-Zaruma mining has long been practiced as a traditional occupation, in Ponce Enriquez, and other sites, such as San Gerardo and Pijili,

the devastating effects of the El Niño in 1997 forced both agriculture and aquaculture farmers to look for opportunities elsewhere, finding that gold resources can provide a quick return of investment. Talking with different people in Machala, the capital of the Province of El Oro, not everyone has had success with gold mining, and they perceive mining as being just a matter of “luck”. The recently lowered prices of agriculture and aquaculture products have pushed more people to work in mining. Another fact that stimulates both investment in mining and its informality is the perception about existing large gold reserves in the region. Some miners and local community members believe that the gold will never end in the region.

The less developed the knowledge in an area, the more severe the pollution problem. A survey of miners working in processing centers developed by Rivera (2009) during this research revealed that 50% of the miners have completed elementary education and only 10% of these miners were aware about the effects of mercury. Around 90 % of the interviewed miners confirmed the use of cyanide to process the amalgamated tailings, and the rest said that they discharge tailings to the river or leave in the processing plant (Rivera, 2009). This reveals that some miners are still not aware of the value of their tailings. This is one reason why owners of processing centers, usually with complete secondary education or university degrees, take advantage of the miners. Low and middle-income people find opportunities to make small investments either by purchasing sands or tailings, and/or developing rustic processing centers. Artisanal and

small miners have worked by their own intuition, so to speak, without appropriate guidance.

To sum up, a combination of low education, inefficient technology, lack of organization and poor Government control has forced the irresponsible use of mercury and cyanide together. In the Province of Azuay, it is usual to allow the miners to use mercury, i.e. no Governmental control, but the cyanide use, is supposed to be controlled. In El Oro Province, the use of both mercury and cyanide is more common than in the Azuay Province due to less enforcement. Thus, mercury-rich tailings produced in the Province of Azuay are transported to Portovelo to be processed with cyanide.

6.5 Mercury releases to the environment

In Chapter 3 it was estimated that around 1.5 tonnes of mercury per annum are discharged to the environment around Portovelo from the amalgamation plants. Assuming that all amalgamation tailings are exposed to cyanide, and considering that miners prefer the Merrill-Crowe process for cyanidation, an estimation of mercury discharges is presented in Fig 6.2. This figure not only shows the mercury releases from all processing centers in Portovelo-Zaruma, but also includes the amount of mercury released to the air from amalgamation and the mercury released to both air and the aquatic environment after the cyanidaton process. This estimate considers that Portovelo-Zaruma has 42 “Chanchas” producing on average 63 tonnes of ore/month, and all Chilean mills together process 30,000 tonnes of ore/month from which 1% of the ore mass is left-over. This left-over is amalgamated in “Chanchas”. The tailings from all

amalgamation system end in the cyanide circuit from which mercury is released to the environment in the solid tailings, solutions and to the atmosphere when zinc shavings are burned.

Despite the low mass of material being produced as left-over, this generates a higher load of mercury being released than amalgamation of the the whole ore or just the concentrates. As the number of Chilean mills in the region is high (110), and as there are around 40 “Chanchas” dedicated to amalgamation of left-over material, the amount of mercury lost is significantly high when the left-over is amalgamated. In opposition the amount of “Chanchas” dedicated to amalgamate the whole ore is low (n=7) producing less amount of Hg-contaminated tailings than the left-over. As a matter of fact the whole ore amalgamation in “Chanchas” is disappearing in Portovelo.

Many miners and owners of processing plants from Portovelo believe that, as they are reducing the amalgamation in “Chanchas”, there is no mercury contamination, minimizing the problem. But, in fact, this study reveals that, due to the number of Chilean mills in the region and the persistence of the use of mercury in the amalgamation of left-over material, there is still a significant contribution to the overall contamination.

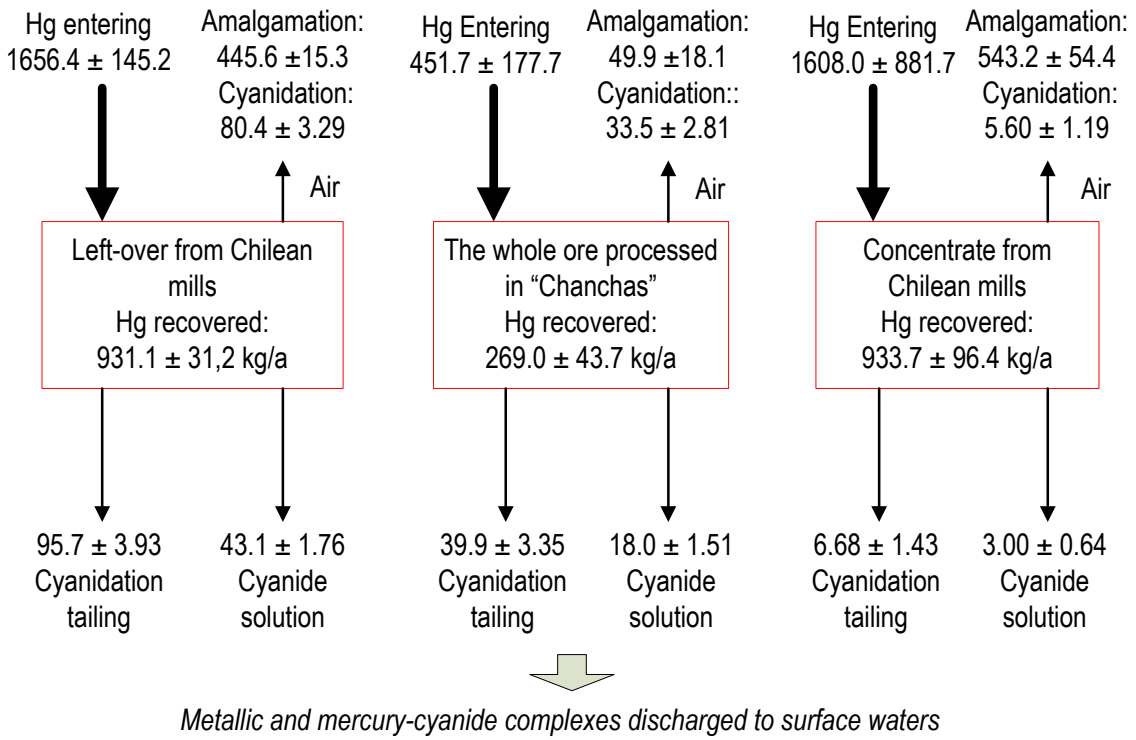

Fig 6.2: Estimate of mercury discharges by ASGM in Portovelo–Zaruma.
Estimates (kg/annum) are based on the mercury released from different types of material used in amalgamation processes and the further exposure of mercury rich tailings to cyanidation in Merrill-Crowe processing plants.
Values represent the arithmetic mean ± standard deviation, n=3 whole ore, 8 left over, 6 concentrate.

The mercury discharges from the gold recovery, in which amalgamation and cyanidation process are combined, are presented in three boxes above, each of which represent amalgamation systems, followed by the discharge from the cyanidation tailings. The amount of mercury recovered corresponds to that squeezed off in the amalgamation process plus the amount of mercury trapped in the cyanidation. This assumes that the mercury trapped in the Merrill-Crowe could be recovered by the miner. The amount of mercury trapped at the bottom of the cyanidation tanks are as follows: 1) Hg in the left-over around 69.9 ± 2.9

kg/a, 2) Hg in the whole ore about 29.2 ± 2.4 kg/a, and 3) Hg in the concentrate 4.8 ± 1.0 kg/a. Following the cyanidation of each one of these types of materials, part of the mercury goes into the air and another portion stays with the cyanidation tailings (solids and liquids), to be directly discharged into the river. After examining each system in all the processing plants, it is clear that it is the left-over material that contributes the highest contamination.

The amalgamation tailings produced in other regions and transported to Portovelo to be processed with cyanide are also significantly impacting the local environment. Assuming that a single CIP plant processes 100 tonnes of Hg-rich tailings (around 350 ppm Hg) per month, this means that 209.7 kg/a of mercury is discharged with tailings in Portovelo. In addition 113.8 kg/a of mercury is released as dissolved mercury in the cyanide solution. This suggests that this single processing plant which uses Hg-contaminated tailings from other regions is the main source of mercury contamination in Portovelo-Zaruma region. It is important to emphasize that the CIP processing plant studied works with Hg-rich tailings purchased in “Chanchas” processing centers from other mining sites but not produced in Portovelo. This means that the amalgamation system generates mercury rich tailings, which then undergo further exposure to cyanide, making them more poisonous. After comparing each amalgamation system as a single mechanism for gold recovery, it was found that the “Chanchas” processing centers generated the highest impact. Although in Portovelo the “Chanchas” processing centers are disappearing, the use of this method on other sites is also contributing to the overall contamination of the region. This is an issue that

requires organization and control within the processing plants and the whole system. It is the labor model and the system dynamics that influence the mercury contamination in ASGM.

Increasing processing capacity, intensity of operations can increase the amounts of mercury discharged and the impacts on the environment. After amalgamation, the major impact results from the use of mercury rich tailings being processed with cyanide. The miners prefer cyanidation using the Merrill-Crowe process, but the adaptability of miners to CIP process can certainly modify the distribution of mercury discharged to the environment.

In General, while most of the mercury vapor caused by amalgamation and cyanidation goes into the atmosphere, significant quantities of metallic mercury are discharged with the final cyanidation tailings, along with stable mercury complexes. The mercury behavior in both the amalgamation and cyanidation processes in ASGM can vary from site to site. These systems are advanced or degraded, not only by technological development, or the lack thereof, but also by social, cultural, political, and educational factors. For example, an economically disadvantaged area will not have the most beneficial technology, or, in an area in which the politicians do not share the people's environmental concerns, the systems used may not help to mitigate the contamination problem. The estimated mercury loads can be reduced through new technology, awareness, regulations, and integrating all these factors to create a new model for mining and sustainable development at both the local and regional levels. If these are not put into place

and current practices and disorganization persist, mercury and cyanide pollution will continue to contaminate this area.

6.6 Impacts of mercury contamination

Metallic mercury vapor, free cyanide and metal-cyanide complexes, comprise the main forms of contamination impacting the environment at local and regional level. The contamination of the ecosystem is changing the attitude of small farmers increasing conflicts in the region. According to the agricultural communities living close to ASGM activities, the soil contaminated by gold mine tailings is useless for growing any kind of agricultural crop and even local vegetation becomes stunted in such soils. The fish farmers living near processing operations in Ponce Enriquez say that, when the contaminated water from the rivers enters through the pond-gates, the fish behave abnormally and then die. Because of this perception, most small farmers in the area have decided not to use the river for any purpose, neither for agricultural irrigation nor fish culture.

The local and affected communities have strong concerns about the increasing effects on human health, such as tremors, headaches, and anxiety problems. Neurophysiological anomalies as a result of occupational exposure in ASGM regions in Ecuador have been documented by Counter (2003). It is suggested that cyanide and other heavy metals such as cadmium, arsenic, and lead also affect the nervous system (Counter et al., 2002). A recent study (Lopez, 2009) on the effects of gold mining on the health of miners in both processing centers and mines in Portovelo, reported health problems in miners, such as psychological issues, respiratory trouble, neurological impairments, and

dysfunctions of the motor system. Some of these symptoms have been suggested to be caused by mercury (Hyman, 2004). It is also recommended that the cumulative exposure to mercury and other substances such as cyanide, zinc, and lead from shavings burning and melting processes are having deleterious effects on the health of the miners (Lopez, 2009). Another recent study developed by Gonzalez (2009) in Portovelo demonstrated the exposure of the community of Portolvelo to unsafe levels of mercury vapor confirming that air pollution is one of the main pathways affecting humans. Mercury exposure can suppress the immune system and makes the people more vulnerable to illness and diseases such as malaria (Silbergeld et al., 2005).

Gold mining impacts through tailings discharges into the streams have been observed on the small agriculture, and aquaculture farming (PRODEMINCA, 1999). As mercury is spread in the air, soil and water, the impact over the whole region can be impacting other economic activities in the El Oro Province. Those activities are socio-economically relevant for the sustainability of the region. While banana production brings annually an estimated US $ 75 million/a, shrimp farming contributes with $30 million/a, and gold mining contributes with $6 million/a (Gobierno Provincial de El Oro, 2006). However it is believed that the gold production estimate is not accurate. One particular gold miner from Portovelo believes that, based on the number of processing centers and companies on the site, the total production of gold can be as high as 9 tonnes of gold per annum. This represents a value of over US$ 300 million produced on ly in Portovelo. Although artisanal and small scale gold mining is a good source of

income, the benefit might not be worth the harm it is causing to the ecosystem at both the local and regional levels.

The impact of mercury exposure when artisanal miners burn the Hg-contaminated zinc was 10 times greater than when amalgam was burned. To confirm this type of mercury contamination, a recent survey in Antioquia, Colombia revealed that the average mercury concentration in the air was around 616,000 ng/m³. This was measured with a JEROME mercury spectrometer located about 5 meters from the zinc shaving furnace (Veiga, 2010). This confirmed this research's new discovery of the occurrence of mercury contamination through zinc burning in ASGM communities, which can also be applied to other ASGM sites around the world. The limit for public exposure to inorganic mercury vapour is 1,0 ng/m³ (WHO, 2000). In industrial environments where workers are subjected to long-term exposure to Hg vapour, WHO (2000) has mentioned that the LOAEL (lowest-observed-adverse-effect-level) might be around 15,000 to 30,000 ng/m³. The recommended health-based exposure limit for metallic Hg is 25,000 ng/m³ for long-term exposure (TWA - time weighed average concentration for a normal 8 hour/day and 40 hour/week of work to which nearly all workers can be repeatedly exposed without adverse effect). The normal atmospheric levels of Hg in rural areas are about 2–4 ng/m³, and in urban areas about 10 to 20 ng/m³ (Veiga and Baker, 2004). In the town of Portovelo in the processing centers, the usual levels of mercury in the air are high, around 10,000 ng/m³ in the dry season, and around 5,000 ng/m³ in the rainy season (Gonzalez, 2009). The present study confirmed that not only amalgam burning

but also Hg-contaminated zinc is an important source of mercury to contaminate the environment. Mercury vapour can be oxidized and, depending on wind speed and direction, it can travel long distances from the source of the contamination, contaminating other areas (Lacerda and Salomons, 1998; Morel et al., 1998).

From ASGM operations the impact of cyanide is another issue of concern. The miners use either NaCN or KCN from different companies including Talkwang, Dupont, and a Russian company and a Czech Republic company. In January 2009, the cost of Taekwang (South Korean) sodium cyanide in Zaruma-Portovelo was US$ 3.5/kg. Currently the processing centers decided to use a Russian sourced sodium cyanide at US$ 2.3/kg from JSC Energy Invest, but they complain about the low quality of this product. Dupont-Sodium cyanide is also available at US$ 2.8/kg (May, 2010).

Considering the number of processing plants and the amount of cyanide assessed during this study, it is estimated that approximately 8,000 kg of NaCN/day are consumed in all Merrill-Crowe systems in Portovelo-Zaruma. The CIP systems consume approximately 9,000 kg of NaCN/day. This means that the region consumes around 6,100 tonnes of cyanide per annum. CENDA in 1996, calculated an amount of 6,000 tonnes of cyanide consumption in the sector (CENDA, 1996). With more cyanidation plants than in 1996, it was expected that the amount of cyanide would be higher nowadays than it was in 1996. The cyanidation plants in 1996 used only vat-leaching (percolation ponds) for 15 to 20 days, adding much more cyanide than what it is needed today. As miners attested, in old times they added cyanide up to 20 g/L. Despite the larger number

of cyanidation plants than in 1996, the cyanidation system has been improved and the amount of cyanide per plant has, in fact, been reduced. However, with better cyanidation practices, they may be able to reduce more than 50% of the cyanide currently used. Cyanide dealers should also take some responsibility for the problem of cyanide misuse in ASGM, by training the miners and showing them better practices of gold recovery with the use of cyanide to avoid the risks to the environment and people's health. This research has revealed that cyanidation in ASGM is an important step that has not been properly addressed, up to this point.

6.7 Mercury and cyanide in the aquatic environment

The Figure 6.3 illustrates how cyanide and mercury from gold processing plants are released to the aquatic environment showing the possible mechanisms of chemical transformations. Cyanide is a complex issue since it dissolves several heavy metals present in the ore (Akcil, 2006; Mudder and Boltz, 2001), and the resulted complexes interact with other elements along the rivers and watersheds. Mercury behavior can be influenced by the competition with other metals present in the gold mining waste and in the river.

Flying and McGill (1995) summarize the forms that mercury takes in the cyanide solutions as a function of pH in the gold extraction systems. The reactions of mercury and cyanide may form the complex $[Hg(CN)_4]^{2-}$ which is stable at pHs above 8.5 and $Hg(CN)_2$ (aq) at pH below 7.8. Between these pHs the complexes $Hg(CN)^-_3$ is the predominant compound. The specie $Hg(CN)_2$ is more easily absorbed on the activated carbon than $[Hg(CN)_4]^{2-}$ (Adams, 1991).

This explains the low amount of mercury adsorbed on the activated carbon in the studied CIP plant in Portovelo (3.72%), operating at pH 10 to 11. The mercury cyanide-complexes affect gold dissolution and enhance mercury mobility (Coles and Cochrane, 2006).

In cyanide solutions, species such as CN^-, SCN^-, SO^{2-}_3, SO^{2-}_4, can form complexes with metals (Allen, 1993) particulary mercury (Ferguson, 1990; Zagury et al., 2004). Thiocyanate is formed through the interaction of cyanide with sulfur compounds, such as sulfide minerals like pyrite, pyrrhoite, chalcopyrite or arsenopyrite. These are minerals typically found in deposits from Southern Ecuador (Vikentyev et al., 1998). The presence of sulphide ores can lead to the production of dissolved sulfur compounds such as S^{2-} that can precipitate mercury as HgS and influences the speciation of mercury and its mobility in cyanide solutions (Aaron et al., 2005).

In the aquatic ecosystems all cyanide carbon is converted to carbon dioxide or bicarbonate and the majority of nitrogen is converted to ammonia, nitrite and nitrate (Akcil et al., 2003). During cyanide degradation cyanate and thiocyanate are formed (Mudder and Boltz, 2001). Cyanate (CNO) is the primary by-product of cyanide degradation mediated by chemical oxidation processes. Thiocyanate is formed through the interaction of cyanide with sulphur-containing compounds. Sulphide minerals such as pyrite, pyrrhotite, chalcopyrite, or arsenopyrite, can be a source of sulphur.

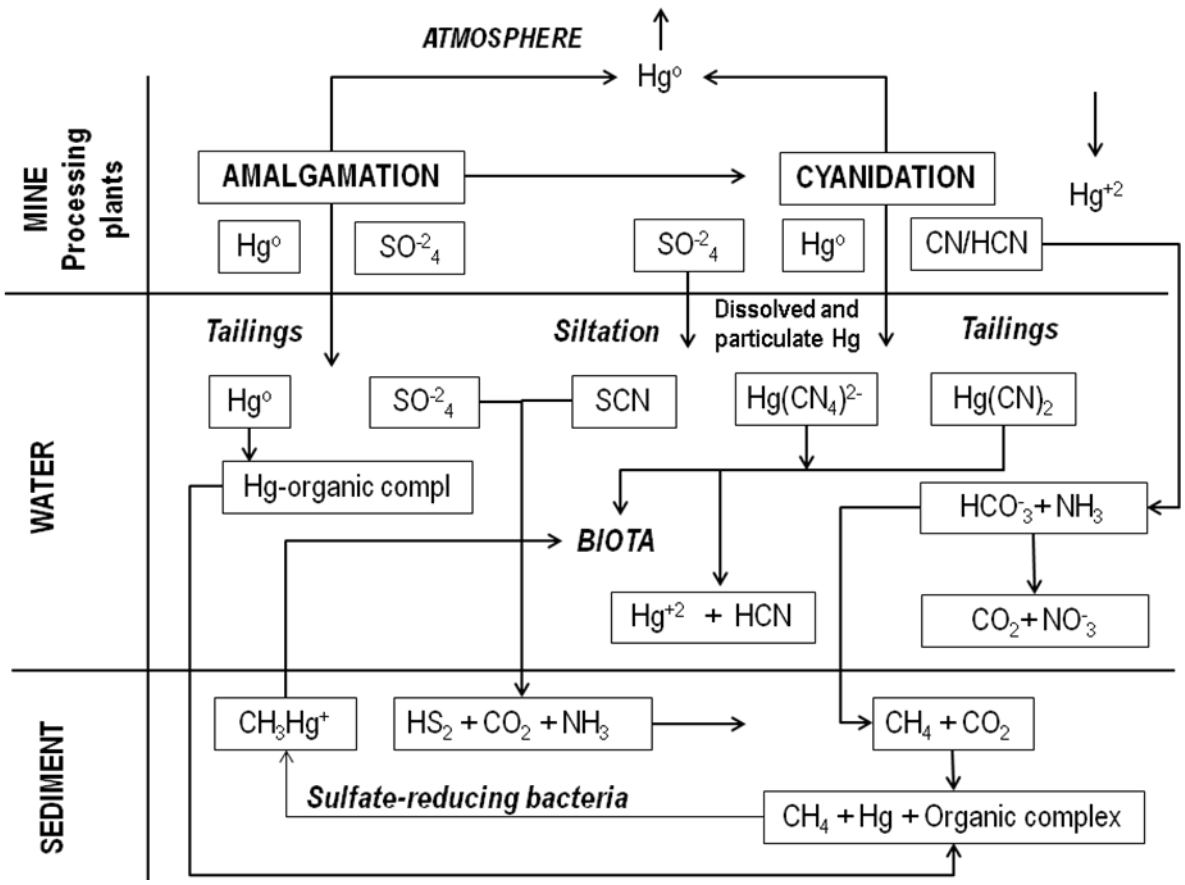

Fig 6.3: Mercury and cyanide in aquatic ecosystems.
Adapted from Mudder et.al., 2001.

Thiocyanate (SCN^-) is a potential problem for its toxicity and its characteristic degradation forming ammonia (eq. 1).

$$SCN^- + 2H_2O + 5/2O_2 = SO^{2-}{}_4 + HCO^-{}_3 + NH_3 \qquad \text{(eq. 1)}$$

Cyanide can be degraded to ammonia and carbonate (eq. 2).

$$CN^- + 1/2\ O_2 + 2H_2O = HCO^-{}_3 + NH_3 \qquad \text{(eq. 2)}$$

The presence of thiocyanate and its transformations can result in a combination of ammonia, carbonate and also sulphate. Ammonia is a breakdown product of cyanide and forms through the hydrolysis of cyanate (Akcil and

Mudder, 2003). Ammonia is a water quality problem for several reasons, including its own toxicity, its ability to consume oxygen in streams during nitrification, and the toxicity of its breakdown products, nitrite and nitrate (Randall and Tsui, 2002).

The following conversion of ammonia to nitrate occurs through the conventional two-step nitrification process, with nitrite as an intermediate product and producing nitrates as a final product (eq.3 – eq.4).

$$NH_3 + 3/2\ O_2 = NO^-_2 + H+ + H_2O \qquad \text{(eq. 3)}$$

$$NO^-_2 + 1/2\ O_2 = NO^-_3 \qquad \text{(eq. 4)}$$

Many artisanal miners and technicians from Portovelo believe that cyanide is easily to manage due to its natural degradation. However all final cyanide by-products such as ammonia, nitrites and nitrates need to be managed properly and according to the conditions of the ecosystem where discharges are occurring. Several environmental problems associated with cyanide can be detected if it is not properly managed. The concern is with toxicity to aquatic organisms, since ammonia is toxic to wildlife (Randall and Tsui, 2002; Batley and Simpson, 2009). The removal of ammonia and nitrates from mine waters is necessarily required (Zaitsev et al., 2008). Low concentrations of dissolved oxygen enhance toxicity of ammonia mixed with cyanide in the water (Alabaster et al., 1983). Nevertheless, while both cyanide and its transformed chemical compounds are toxic to aquatic life, the toxicity levels would also depend on the quality of the aquatic environment and the physiological conditions of the biota. The sensitivity of aquatic organisms to ammonia is highly specific to the aquatic

species, and it is also affected by pH, temperature and oxygen content of the aquatic environment, as well as the life stage and condition of the organism (Carvalho and Phan, 1997). Overloading of inorganic nitrogen can cause eutrophication of water bodies increasing microalgae biomass which in turn affects the biodiversity, increases organic matter and depletes oxygen content in the aquatic ecosystems. Changes in nutrients ratio are associated to harmful algal blooms in coastal waters (Anderson et al., 2002).

It has been suggested that organic enrichment of aquatic ecosystems can favor mercury methylation. As inorganic mercury is present in the tailings the mercury cyanide complexes and the breakdown products of cyanide itself can contribute as a source of mehtylmercury production mediated by bacterial activity. But this needs further investigation to be proved. Methylmercury is a potential neurotoxin that is rapidly accumulated by aquatic biota and can potentially harm human beings through fish consumption (Mason et al., 1995; Trasande et al., 2010; USEPA, 2001; Guimaraes et al., 2000).

Mercury impacts in aquatic ecosystems will depend on the hydrodynamic condition of the river system and the resilience of affected community (Wang et al., 2004). Watershed characteristics, such as land use and the soil organic content as well as the quality of organic matter have been considered important aspects in methylmercury formation (Mason and Sullivan, 1998). The releases of suspended solids from ASGM activities increases not only the level of contamination but also the mobility of heavy metals to downstream environments contaminated by artisanal and small scale mining operations (Telmer and Veiga

2008; Tarras-Wahlberg and Lane, 2003). Methylmercury production and bioaccumulation process in estuarine ecosystems is suggested to be influenced by biogeochemical conditions and the concentration and nature of organic matter in sediments and water (Chen et al., 2008).

Research developed by European scientists in sediments of the Puyango River shown that 46% of mercury is associated to sulphides and organic material, and another proportion of 40% is associated with iron oxides (PRODEMINCA 2009). The geochemical characteristics of the Portovelo-Zaruma region have demonstrated that the water is rich in carbonates which keep the river in a slightly alkaline condition (Tarras-Wahlberg et al., 2001). The fact that this alkalinity may reduce the bioavailability of heavy metals in aquatic ecosystems (Mudder and Boltz, 2001), indicates the capacity of some naturals systems to cope with the problems associated with heavy metal contamination. Fish mortalities and bioaccumulation of mercury has been revealed by Appleton (2001) while other researchers have suggested low methylmercury formation in the Puyango River (Betancourt et al., 2005). In depth investigation is needed to understand the possible mechanism of complexation and precipitation of mercury, with water quality conditions of the region.

The presence of mercury-cyanide complexes can be directly bioaccumulated or can promote the formation of methylmercury in the aquatic environment especially in stagnant waters. The impacts of cyanide and mercury can vary depending on characteristics and the intensity of ASGM as well as the conditions of the aquatic ecosystem. Site specific research is suggested in

different ASGM impacted sites. The bioavailability and toxicity of the mercury-cyanide complexes are not well-known but highly Hg-contaminated fish have been reported in artisanal gold mining areas where cyanidation is applied to leach residual gold from Hg-contaminated tailings (Castilhos et al., 2003; Veiga and Baker, 2004). It is unknown if fish accumulates Hg-cyanide or methylmercury formed in the sediments. The simple analysis of methylmercury in fish muscle cannot provide direct evidence of the bioaccumulation process since methylmercury can be formed by methylation of Hg(II) cyanide complexes in the intestines of living organisms (Hinton and Veiga, 2009). Methylation of mercury-cyanide complexes in the aquatic environment is still a subject not clearly identified by researchers and not well understood yet. A variety of factors, such as temperature, pH, redox potential, and the presence of both organic and inorganic complexing agents, as well as microorganisms activity, are also important in the process of methylmercury formation (Morel et al., 1998; Ullrich et al., 2001).

6.8 Strategies for reducing mercury contamination

Hinton et at (2003) states that the major needs to resolve the problem of mercury contamination in ASGM activities are organization of miners, development of clean technologies, legalization of those miners and institutional support (Hinton et al., 2003). Hilson (2005) in his overview about the problem of mercury contamination criticizes the extensive research carried out on environmental and health impacts and poor technological communication with

mining communities about the understanding of mercury dynamics in the system (Hilson, 2002). Recently Spiegel, (2009a) also referred to interventions developed by UNIDO in an education integrated approach to mitigate mercury contamination and the author stresses the importance of training and organization of miners to solve the problems.

As 71% of the total mercury lost in Portovelo-Zaruma operations is emitted to the air, the main focus of any educational campaign should be on the use of retorts to condense mercury evaporated when amalgams are burned. Individual retorts are not commonly used due to perceptions that gold will “disappear” or will become lodged in its steel parts. Some believe that the gold recovered using retort is of bad quality. Artisanal miners prefer to burn amalgam in open pans or in fume hoods with a blow torch. In processing centers, miners also use a blowtorch to evaporate mercury but they operate inside of a fume hood with a condensing system. They believe that most of the mercury is collected in a water tank attached to the fume hood of the exhaustor. In many cases, the water tank where the evaporated mercury condenses is not accessible (sometime sealed). Most of these systems are not maintained and the exhausting fans do not work properly and high levels of mercury vapour (as high as 150,000 ng/m^3) are released to the air as confirmed by analysis with LUMEX RA 915+ portable atomic absorption spectrometer. Individual retorts (Veiga et al., 1995) must be promoted in the region for artisanal miners and processing centers. A kitchen-bowl retort was demonstrated in Portovelo (Fig. 6.4) to show that mercury from amalgams could be evaporated safely.

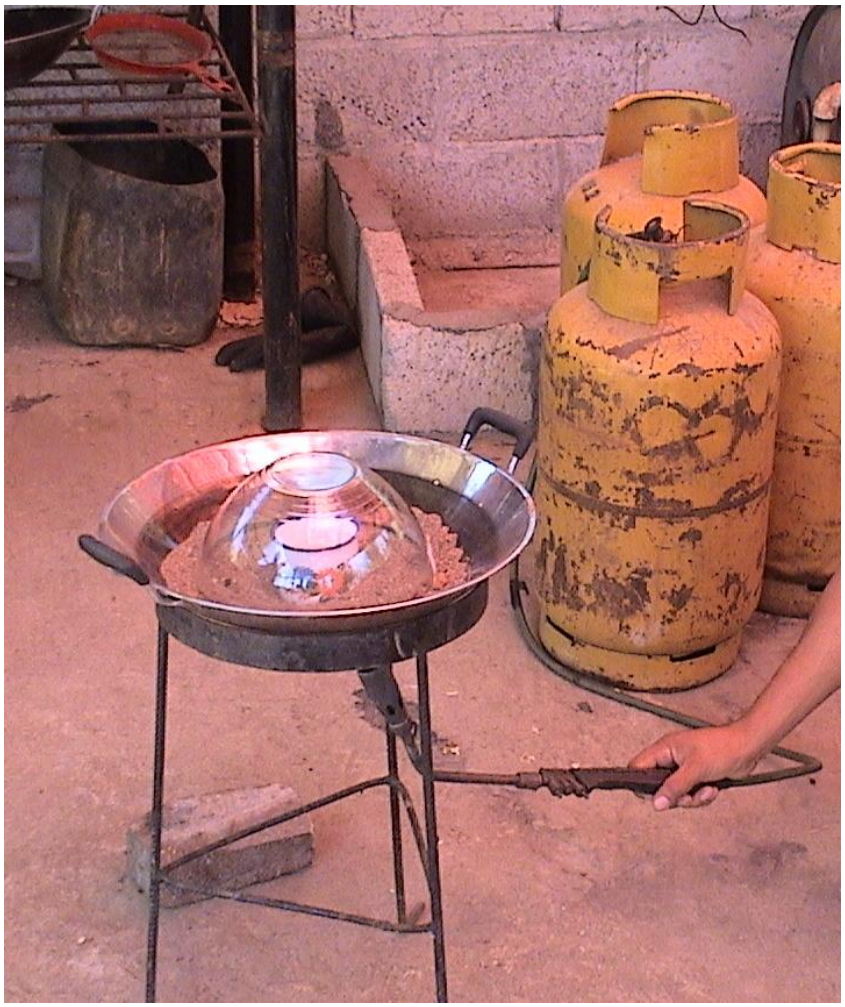

Fig 6.4: Demonstration of the kitchen-bowl retort.

The kitchen bowl retort consists of two salad bowls (one of glass and another of stainless steel) placed on top of each other and a small stainless steel cup inside where the amalgam is burned from the bottom. Mercury evaporates and condenses on the glass bowl, and is re-activated and recycled. This is a simple, inexpensive solution and the whole burning process is visible, which minimizes concern over gold being lost (Shandro et al., 2009).

The idea of recycling mercury after condensing it with water was disseminated in the region, but there is no proof that this is in fact occurring. A mercury activation technique, using a car or motorbike battery, was demonstrated to the miners in Portovelo-Zaruma. This cleans the mercury surface, forming sodium amalgam which improves the amalgamation process (Pantoja and Alvarez, 2000).

The amalgamation of the whole ore as well as left-over material in Chanchas should be stopped, as mercury losses with tailings can be close to 30%. A campaign to use small concentration procedures for small amounts of ore could add another dimension to the “Chancha” processing centers. Local and federal Governments should provide training for the “Chancha” centers to avoid the amalgamation of the whole ore, replacing this with cyanidation in small scale (Veiga et al., 2009).

In regards to air mercury contamination from cyanidation process, if Hg-rich zinc burning continues, authorities must assist the miners to install gas scrubbers to capture both zinc and mercury.

Comprehensive regulations, enforcement and technical assistance are the keys to reduce mercury releases and even eliminate its use in Ecuador. Producing 9-10 tonnes/year of gold, processing centers in Portovelo-Zaruma are releasing around 1.5 tonnes/year of mercury, 71% of which is discharged into the atmosphere and 29% in tailings. But although it may reduce mercury consumption, the use of cyanide to leach Hg-contaminated tailings is also a major environmental concern in Southern Ecuador.

From the determination of mercury losses in ASGM process the following steps are suggested to reduce/eliminate mercury contamination in the Portovelo-Zaruma region: a) elimination of whole ore and left-over amalgamation using "Chanchas"; b) allow miners to amalgamate only gravity concentrates; c) promotion of cyanidation of concentrates either in agitated tanks or using the "Chanchas" for mill-leaching (Veiga et al., 2009), d) promotion of the use of individual retorts when amalgam is burned and filters when the *doré* is melted, and e) mercury removal before cyanidation of mercury rich tailings. Using retorts, it is estimated that nearly 97% of the total mercury introduced in the process can be recovered when only gravity concentrates are amalgamated (Velasquez-Lopez et al 2010). Maintaining the whole ore amalgamation, even using retorts, the maximum amount of mercury that can be recovered would be 70%

To reduce emissions of mercury or its elimination from the ASGM system only the amalgamation of concentrates should be permitted. Thus, mercury can be recycled and as the quantity of tailings is low miners can dispose them safely. While amalgamation of concentrates is performed in the ASGM system the use of retorts to recover mercury can be a temporary alternative. Once miners understand the basics of concentrating the ore and efficiently using the amalgamation process, they will be able to apply other gold extraction systems, such as cyanidation of concentrates. The government can accomplish this by incorporating an adaptive process of education and management into the ASGM system. From the determination of mercury in the amalgamation process the

suggested alternatives should be considered as policy options in the ASGM system of Southern Ecuador to mitigate mercury contamination.

Importantly, the mercury removal before the cyanidation is urgently needed since mercury cyanide compounds in the effluents form strong and stable complexes, which are hard to remove from effluents (Tassel et al., 1997; Matlock et al., 2002; Coles and Cochrane, 2006). To address this problem one could consider two options: a) physical removal of mercury from tailings; b) chemical precipitation of mercury from cyanide solutions. In the first case, miners in Portovelo use a small agitated tank to form a pulp with 27-30% solids before introducing it into the leaching tanks. Miners believe they remove half of mercury from the pulp, but in fact less than 3% of mercury is trapped at the bottom of this tank. The region is fraught with misperceptions that either all mercury is recovered in the cyanidation tanks or stays in an “inert” metallic form with the tailings discharged into the rivers. The same situation has been observed in cyanidation tanks in Talawaan, Indonesia (Veiga and Baker, 2004). If the miners would get basic knowledge and better understanding about efficient gold recovery, they would be in a better position to improve their systems reducing mercury emissions and increasing gold recovery.

The miners demonstrated an interest in the methods and techniques for extracting mercury from the tailings. Veiga et al. (2005) describe a zigzag sluice with four silver-tin-copper Goldtech plates where residual mercury can be trapped. They show that this method removed up to 95% of the mercury from tailings in Venezuela and Brazil. Coles and Cochrane, (2006) described to the

use of reagents such as potassium salts, sulfides, hydroxides and carbonates to precipitate and remove mercury from cyanide solutions. Tassel et al. (1997) suggested the use of dimethyl dithiocarbamate to precipitate mercury from cyanide solution which has been used in gold mines in US (Wickens, 2001). All these precipitation procedures are effective, but reagents may be inaccessible in ASGM sites and the cost and procedures to use them must be carefully investigated.

An alternative such as elimination of amalgamation in “Chanchas” and enhancing the implementation of clean gold technologies are issues to discuss among different stakeholders in the ASGM sector in Ecuador. Another important point that needs to be addressed is the promotion of environmental and human health awareness campaigns in mining communities in order to reduce citizens’ exposure to mercury and cyanide and their effects on health.

By using modern cyanidation practices, gold can be recovered more efficiently than by present practices (Metcalf, 2008). Natural processes to manage cyanide wastes exist such as bacteria degradation (Ezzi and Lynch, 2005; Akcil and Mudder, 2003; Dhillon and Shivaraman, 1999), photochemical oxidation (Sarla et al., 2004; Akcil and Mudder, 2003) to minimize impacts. However, it is evident that ASGM do not have knowledge or access to such procedures. More information to the miners about cyanide leaching and its environmental and human health risk also is necessary. Cyanide is a highly poisonous chemical used in gold extraction (Haiduc, 2005; Amegbey and Adimado, 2003; Dzomback et al., 2006) and concentrations above normal levels

have been reported in Southern Ecuador (Appleton et al., 2001). Cyanide effluent is usually not destroyed before being discharged into the Calera and Amarillo Rivers. When destruction does take place operators typically report the free cyanide values, not total cyanide. To some degree, cyanide destruction is limited by the lack of space to take advantage of the natural degradation of cyanide by sunlight and aeration. In general, operators are not using any chemical oxidation processes before discharging effluents to the streams, and Government is not prepared to enforce its discharge guidelines.

The resulted mercury-cyanide complexes have been reported to be highly poisonous compounds (Labat et al., 2004), which constitutes an overall risk for people and organisms. Mercury impacts are almost impossible to manage and it should be eliminated from the system. Regional, authorities and processing centers should take coordinated actions to eliminate mercury use and promote information and knowledge transfer to implement cleaner technologies. Better labor organization between miners and processors is badly needed. Partnership with small companies (foreign or not) must be promoted since miners and plant owners feel that further investment is needed to increase and improve their gold production, eliminating completely the use of mercury.

Furthermore, an important issue that needs to be addressed by the Ecuadorian Government is the easy accessibility of mercury by miners. There is no need for training or skills to buy or sell mercury in the region. Based on UN-COMTRADE, (Telmer and Veiga, 2008) it was estimated that Ecuador imports officially only 9.5 tonnes/a of Hg but 10 to 20 tonnes/a of mercury is used in the

small-scale gold mining industry. Local miners in Portovelo-Zaruma stated that the mercury they use is sometimes smuggled from Peru. The price of US$ 40/kg of mercury is still low when compared with other countries such as Brazil, where the price in mining sites is US$150/kg (Sousa and Veiga, 2009) or Laos, where in 2006, it was being sold to miners at US$ 80/kg (Veiga et al., 2006). Many miners and owners of processing centers have received information about the toxic effects of mercury vapour and methylmercury through a number of projects conducted in the region since 1998, but the lack of permanent technical assistance and control inhibit any sustainable cleaner practice.

Through this study, the stakeholders recognized the inefficiency of the amalgamation and leaching systems, how much mercury is discharged to the local streams and how much gold is lost. This participatory approach study is a first step to introduce cleaner techniques in the cyanidation process. The presence of mercury-cyanide complexes in the effluents and tailings should be a paramount concern for human exposure and also for further planning for environmental restoration, treatment, and safe disposal of ASGM tailings in Southern Ecuador.

6.9 Perspectives for the future to mitigate mercury contamination

6.9.1 Governmental actions

The municipal decree of September 26th, 1988 approved by the Municipal Government of Zaruma stipulates the control of mercury emissions (Municipalidad de Zaruma 1988). This document says that all processing centers must have facilities to recover mercury, cyanide or others toxic materials. It is

prohibited to releases industrial wastes into the rivers or natural streams (Clause 10). Another clause says that the gold shops must use retorts and filters for mercury recovery during amalgam burning (Clause 19). This document clearly states that all processing centers must provide equipment such as retorts for the miners (Clause 24). However for many years this law has not been enforced or respected by the miners and owners of processing centers. It is clear that the processing centers must provide facilities for artisanal miners to manage the chemicals. The processing centers do have a communal fume hood usually with no filter or condenser.

Recently the Government of Ecuador has initiated a new organization of the mining sector through new regulations (Registro Oficial 517, 2009). In 2008, the Government, through the Ministry of Mines, held consultations with miners and owners of processing centers about the new mining laws and the regulatory framework for artisanal and small scale gold mining. Based on these actions, the Government of Ecuador has put several objectives on the agenda to resolve the problem of environmental contamination. Some of these preliminary discussions led to a new regulatory framework, the goals of which were: a) a reorganization of the extraction practices of mining companies; b) institutional reorganization; and c) a plan to address the contamination problem associated with mining. This is the most progress that has been made in the history of mining in Ecuador. Under the old model, the Minister of Mines not only gave concessions to certain parties, but also oversaw the environmental impact of mining, which can clearly be seen as possibly leading to a conflict of interests. Under the new model,

however, the mining management is under the Ministry of Mines, while the environmental impact of mining practices will be overseen by the Ministry of Environment. Provisions for research and technology development, as well as education and community participation, are also included in these new laws.

Regarding the installation of processing centers the new Ecuadorian mining law (Clause 45) authorizes "*the operation of processing centers exclusively dedicated to crushing and grinding, with a capacity of 10 tonnes/day and also authorizes the operation of other processing centers for crushing, milling, flotation and/or cyanidation with a minimum capacity of 50 tonnes/day*" (Registro Oficial 517, 2009). Concentration is not stated in the law. It is also clear that the law differentiates diverse types of processing centers. In fact the participants of the workshop conducted in Portovelo expressed the need of organization and classification of processing centers. Another section of the law (Clause 45) also states that it is not a requisite to have a mining concession in order to get the permit for installation of a processing center. In this way, the new law is doing little or nothing to change the relationship between the two types of stakeholders, namely, the owners of processing centers and the miners; nor does it clearly define their activities or circumscribe the nature of their relationship. This, in fact, maintains the status quo of the system, since the current model reveals that the processing center owners exploit the miners.

As awareness about human health and the restoration of affected areas become a priority for the Ecuadorian Government, the new law appears to be open to a new model that promotes organization, cooperation and generation of

work. The Ecuadorian mining law promotes the development of small mining in associative or cooperative form and individually, but also forces the miners to work without contaminating the surrounding ecosystem.

The mining law gives an ambiguous characterization of processing centers. In the first place, a center must exist to grind and concentrate the gold, not only for crushing and grinding, as mentioned in clause 45. In the same clause, the fact that the gravity concentration process is never mentioned allows for the continued use of “Chanchas”, in which miners amalgamate the whole ore—a more polluting method of gold recovery than gravity concentration.

The mining law recognizes artisanal mining as a legal way to subsist, which can be performed individually, by families, or other types of associative forms. This is an interesting point because the law is promoting partnerships among the miners. In other documents, “special guidelines for artisanal and small scale mining” and “environmental guidelines for mining activities” were laid down (APROPLASMIN, 2009). The owners of processing centers are actively participating in discussions with policy makers to build these special guidelines for artisanal mining activity. In the preliminary draft of these guidelines the use of mercury is allowed. It is also permitted the use of “Chanchas” or barrels for the process of amalgamation. Knowing that “Chanchas” lose around 27% of mercury with the tailings, the law should be clear to forbid this contaminating process or any other process that promotes the whole ore amalgamation. In contrast the amalgamation of the concentrates loses only 1.36% of the mercury entering the system. In this case, the amalgamation of gravity concentrates is

accepted by the guidelines, but the document does not specify this option as the main policy point for mercury reduction. In another set of guidelines, gravity concentration is not mentioned, a fact that reveals an inconsistency in the two documents. Amalgamation of the whole ore should be stopped. Although the special normative in the guidelines for artisanal and small scale gold mining is ensuring the need to reduce or eliminate mercury from the system, there is a clear lack of specific policy to mitigate contamination during gold processing. This is due to a lack of research and knowledge about the system. The present work is showing how to ensure the reduction or elimination of mercury.

Since ASGM contamination in the large Puyango River is a concern due to the pressure of Peruvian communities, the Government of Ecuador has taken actions to manage the problem particularly in Portovelo-Zaruma. A Government action supervised by the Ministry of Environment of Ecuador is the initiative to organize the processing centers and tailing management in Portovelo. The topography of Portovelo-Zaruma is steep with frequent erosion caused by high rainfall. Slopes are unstable, rivers are active and valley bottoms are narrow. There is insufficient room for tailing ponds for the 104 processing centers that have been permitted to operate along the Calera River. However, the main concern of the Government is to remediate the problem of environmental contamination with particular attention to the area of Portovelo-Zaruma due to the contamination of the watershed formed by the Amarillo and Calera Rivers which discharge to the Puyango-Tumbes River. The Ministry of Environment is promoting a plan to relocate the old tailings and all processing centers to a

plateau about 5 km South of Portovelo-Zaruma that hosts terrain suitable for a large “communal” tailings pond. The idea of communal tailing management was suggested by Tarras-Wahlberg, (2002) after the PRODEMINCA intervention project, and it is being analyzed by the owners of processing centers and Government officials. The plan involves pumping the existing tailings through a pipeline following the river few km downstream, and then uphill about 400 meters to the proposed site for impoundment. It is believed that removing the tailings from all processing centers will solve the problem of river contamination. It is expected that reprocessing the tailings will bring funds to justify the project and support the relocation of the tailings. This action has provoked much discussion and disagreement among community members and owners of processing centers. On one side, the local community of Portovelo defends the use of the chosen site for agriculture. On the other side, the owners of processing centers look at this option as the only way to maintain the systems that keep their businesses profitable, while also offering the services for artisanal miners. Beyond the discussions, the continued presence and proposed movement of mercury-rich tailings constitute a risk if stakeholders do not take measures to diminish or eliminate mercury from the system. This proposal would only promote the mixing of mercury rich-tailings (from amalgamation and cyanidation) with non-amalgamated tailings, which not only constitutes a great concern for the community but also runs the risk of contaminating a wider and more pristine area. As previously discussed, removing mercury from the tailings (Veiga et al., 2005) or its chemical precipitation (Matlock et al., 2002), should be considered as

a management alternative prior to moving mercury rich tailings to another site, which only transfers the problem.

The continue increase of the number of processing centers and the material received from other mining sites in Ecuador to be processed in Portovelo is a problem for an effective planning of the project of communal tailing management. Therefore the construction of more processing centers or the increase of processing capacity of the actual processing plants should stop.

Due to the importance of aquatic ecosystems and the diversity of activities hosted in the region, the idea of an integrated watershed management system has also been raised by Ecuadorian Government officers in charge of water policies. Although it is a promising idea for regional sustainability, this idea has not yet been developed in detail particularly in regards to gold mining and its connectivity with other land use activities. The new Constitution of Ecuador strongly sustains the participatory management and specially the protection of water resources. In fact the new law for water resources is the one that the majority of miners think as the most difficult to comply. Most of mining resources in Southern Ecuador are in close proximity to headwaters and important streams. Mineral processing centers have not yet introduced water reclamation methods and they still do not have the technology to comply with the mining code.

Another recent action in regards to mercury is the mercury assessment carried out by the Ministry of Environment from Ecuador with support of US Environmental Protection Agency (USEPA) and the United Nations Environment Programme (UNEP). The project evaluated the source of mercury pollution in

several activities including mining and has developed a framework for mercury risk reduction and management (Resabala, 2008). However in relation to ASGM this document does not address key issues related to where and how mercury is used and discharged.

6.9.2 Stakeholder participation and knowledge interchange

Some miners are exploring alternatives to improve their activities and reduce mercury use in their system. As an example, in Portovelo almost all processing centers have eliminated the whole ore amalgamation process. However, whole ore amalgamation using “Chanchas” has persisted in remote areas around Ponce Enriquez and the situation is worse in Loja and Zamora. Despite the high contamination generated the use of “Chancha” is the only alternative for those miners with small amount of ore since it provides quick cash to miners.

Artisanal miners are usually legal owners of mining concessions but they do not have processing facilities, therefore they hire processing centers to extract their gold. The miners have taken a creative action establishing joint ventures projects, such as the formation of cooperatives or small gold mining companies. As an example, there is a processing plant that offers custom milling and cyanidation using Merrill-Crowe when miners want to process their gravity concentrates. The plant includes a CIP system that is used to extract gold from gravity concentrate tailings. This center runs 4 Chilean mills from which 3 of them are rented on an hourly basis to mines that process batches of roughly 6,000 kg of ore. The owner of this processing plant developed a partnership with 9 small associations of artisanal miners, through which they were able to share

knowledge and resources for both mining and processing operations. This association resulted in a win-win solution for both the miners and the owners of the processing plants. Although this is an excellent partnership, it was noticed that some of these partners were still using mercury in gold extraction. Nonetheless, they did express an interest in replacing amalgamation with another cleaner process. With participation of miners from this processing plant and local technicians it was explored alternatives to eliminate mercury such a direct melting of concentrate ore. It is believed that the direct melting of concentrate ore can be applied to a rich material with up to 30% of gold (Wotruba 1998). Although the direct smelting of concentrates requires in depth investigation of the chemistry of the concentrate, it was noticed that it consumes the same time as amalgamation, and performs with slightly better economic results than amalgamation. The miners processed 5.9 kg of concentrate and this produced 41.1 g of gold that after refining with nitric acid, it was obtained 99.9 % pure gold. The advantage over amalgamation with mercury was that by direct melting the pure gold has higher price. The chemical reagents are locally available and non toxic such as borax, sodium carbonate and silica. The reagents and fluxes added to the concentrate to help the melting process can differ according to the mineralogical characteristics of the ore (Wotruba et.al., 1998). In this process the gold is obtained from the ore by heating beyond the melting point in the presence of chemicals and oxidizing agents and the miner can see their product quickly. The most important advantage of this system is the total elimination of mercury. The participation of the miners was valuable to open

their minds to alternatives to replace mercury and optimize their skills. More practical and participatory research on options such as direct melting of concentrates can increase confidence and reliability to new alternatives and make them available for the local miners. Some of the limitations to improve technology are the need to invest in a concentrator such as shaking table or centrifuge and implementation of gas furnaces. However the miners expressed “we will find the way to eliminate mercury” showing the desire for change and confidence in implementing other techniques. The owners of processing centers in Portovelo can easily incorporate alternatives techniques for gold recovery however one of the main barriers still forcing them to maintain their system is that they give their tailings to the owners of processing centers in payment of a cheap concentration process. Moreover the actual model or relationship between miners and owners of processing plant need to be fixed in a more equitable form of work.

It was also demonstrated to the miners a system of cyanide leaching in “Chanchas” and further recovering of gold with activated carbon (Veiga et al 2009). The demonstration of cyanide leaching in “Chanchas” motivated some miners to improve their gold extraction by removing material left inside the Chilean mills (left-over), followed by re-milling the ore, and implementing cyanidation with activated charcoal on a small scale. The technique of the elution of activated carbon using a cooler was certainly new to the miners who believed that this process could only be done with large amounts of activated carbon in a complex system i.e., in an industrial process with 700 to 800 kg of carbon in large

elution facilities. The aim of this practice was to eliminate both mercury and zinc from their cyanidation process. Since zinc accompanies mercury and also represents another environmental pollutant, the use of activated carbon can also reduce zinc contamination. Although the miners did not continue with the cyanidation in “Chanchas” for long, it has been noticed that they increased confidence in new methods and learned that it was possible to adapt small facilities for activated carbon elution without dependency on the owners of processing centers. The cyanidation in “Chanchas” need to be reinforced to strength the skills and adaptation of the miners to the process.

Local miners are becoming increasingly aware of the economic advantages of using cyanide on concentrates, and if an educational campaign is carried out, the days of using mercury in Portovelo will most certainly be numbered. Any procedure to improve the gold recovery from ore using more sophisticated gravity concentration methods (e.g. centrifuge) will require investment from the owners of processing centers. The cyanidation of gravity concentrates is a procedure capable of increasing gold recovery substantially without threatening the *status quo* of the owners of the processing centers. The main challenge of eliminating mercury use in Portovelo-Zaruma is that not all poor miners can afford to wait additional one or two weeks for the cyanidation of concentrates to produce their gold in spite of higher gold recoveries. They need to pay their bills accumulated during three weeks of mining, grinding and gravity concentration. This is why amalgamation - a faster process – continues to be popular. However the

intensive cyanidation of gravity concentrates with hydrogen peroxide can reduce the gold extraction time substantially (Veiga et al., 2009)

Demonstrating different alternatives to the miners allows them to increase their knowledge and skills in cleaner processing methods. A positive action is that miners seem motivated to trap the mercury in the cyanidation system when they amalgamate cyanidation tailings. To reduce mercury use, a longer term and systematic training and wide community participation is needed (Hilson et al., 2007). This approach strengthens links between trainers and miners (Spiegel, 2009d), legitimizing innovations. Government policy and control are also needed to sustain new methods and attitudes (Spiegel 2009d; Sousa and Veiga, 2009).

Effective participation of miners in identifying solutions to the problem of mercury use in gold processing is important to address to minimize environmental pollution. The total replacement of mercury with cyanidation of gravity concentrates in “Chanchas” developed by Veiga et al., (2009) and direct melting of concentrates can be demonstrated by local technicians and be implemented with active participation of miners. Significantly the miners were potential contributors to explore alternatives to replace mercury in the gold recovery. Their knowledge was valuable to set up procedures and implement techniques. Therefore, this was a process of mutual learning about options to eliminate mercury. This shows that miners and owners of processing plants from Portovelo are ready to cooperate in finding solutions to their problems. Win-win solutions are technically feasible between owners of processing plants and miners. For the owners of processing centers the cyanide leaching process in

“Chanchas” and direct melting of concentrates does not threat their business since the miners will still need grinding and gold concentration. But, the question is: why miners are not implementing new alternatives yet? The main reasons explained by a local miner were: 1) lack of knowledge and capital, 2) afraid of being a “pioneer”, 3) lack of technical assistance if something goes wrong. The presence of the Government providing support to implement cleaner technologies as well educating the miners to be more confident in changing technical procedures is badly needed.

The region has also several good examples of small cleaner operations. In Portovelo a small local company processes 100 tonnes of ore/day using CIP cyanidation plant with ore grades ranging between 2.3 and 4.5 Au/tonne. The process of gold recovery includes milling and cyanidation. There are 30 people employed at the plant, working in 3 shifts a day and 25 people employed in the mine. The plant engineers believe that 85-95% of the gold in the ore is soluble in cyanide. The gold comes from the company’s mine which is located on a 200 ha concession near Portovelo. The ore contains 1 part of silver for every part of gold. Pulp and waste solution is stored in a lined tailings dam on the edge of he Calera River. The plastic membrane gives additional strength to the impoundment. About 40 % of the process cyanide solution is separated from the solids by decanting in the tailings ponds and recycled to the plant. This solution contains 200 mg of CN/L and 0.1 mg Au/L. The final cyanide destruction occurs in an agitated concrete tank where six parts of H_2O_2 (50% vol.) are required to neutralize 1 part of cyanide. The material is agitated and FeOOH is precipitated.

This compound is an efficient adsorbent of metals in solution. An analysis of the hydrous ferric oxide revealed 0.5% Cu, 2% Zn, and 1.5% As (1,500 ppm). After the ferric oxides settles, the waste solution is neutralized with nitric acid to pH 7, and the overflow passes through an activated carbon filter before being discharged to the river. The intention is to eventually reclaim this discharge water. It is believed that this discharged solution yields very little cyanide but total cyanide has not been measured.

Another mill operated by a Peruvian engineer located in Portovelo introduces a concentration process before cyanidation reducing the use of cyanide and consequently the generation of contaminated tailings. The flotation technique separates the ore mineral from gangue. By this way the plant reduces 10 to 20 times the amount of material to be subjected to cyanidation. Their technicians said that ore grade is around 3 g Au/tonne and 0.3% of Cu. Much of the gold is free or associated with chalcopyrite. Interestingly with an exception of a Peruvian-made ball mill and a Chinese jaw crusher all pieces of equipment (jig, flotation equipment, conveyors, etc) were manufactured in Ecuador and most of them locally. The plant includes a small chemical laboratory with atomic absorption spectrophotometer and free assay facility. The upgrade ratio of the flotation is about 15:1, with the rougher concentrate containing 30-40 g Au/t, 8-10 oz Ag/t, and 5% of copper. The plant operators expressed that 60% of the concentrate ore is treated with cyanide, and 40% containing 21% of Cu is sold to Peru.

The miners and owners of processing centers also have the idea of an integrated mineral processing to recover all the minerals present in their ore. With the flotation investment the operating cost can be reduced when a small mass of concentrate is leached with cyanide in batch. There is also the advantage of disposing acid-generating tailings, since miners would deal with small mass of material.

One small enterprise in Ponce Enriquez has become a responsible association that brings together several local investors who were artisanal miners. Their processing system includes flotation, cyanidation, and direct melting of concentrates, extracting 95% of the gold. This partnership stands as a model of what can be accomplished, when the right economic model (cooperative) and the right technology are in place. They have completely eliminated the use of mercury and incorporated waste treatment and cyanide destruction into their system. The waste water treatment includes the operation of wetlands to remove heavy metals and other contaminants. This partnership in Ponce Enriquez also promotes other subsistence alternatives, such as organic agriculture.

Despite the complexity of ASGM's environmental problems, it is clear that solutions can be found within the same system and local people. A cooperative is the way to stop the exploitation of the owner of processing centers over the artisanal miners. This creates a reasonable economic system that can find cleaner and more efficient techniques at the level of small mining. The miners are

highly cooperative and can create whatever is needed to improve their work. Policy actions are badly needed to force all parties to adopt new ways of working.

It is clear that the strategic integrated management of mercury in processing centers can be the initial step to either the reduction of mercury or its elimination from the ASGM system. To begin the process of mitigation of mercury contamination from ASGM operations some actions must be achieved. Despite the existence of chemical methods to precipitate mercury present in amalgamate tailings (Tassel et al., 1997; Matlock et al., 2002; Coles and Cochrane, 2006), the best option for risk mitigation is avoid the exposure of mercury-rich tailings to cyanidation. Elimination of the whole ore amalgamation in “Chanchas” will bring benefits to the miners since the amalgamation of concentrates is the most efficient way to reduce mercury losses (Hylander et al., 2007). The amalgamation of concentrates minimizes the amount of contaminated tailings to be processed with cyanide. In the near future mercury can be totally eliminated by intensive cyanidation of concentrates (Veiga et al., 2009) or other existing techniques (Vieira, 2006). In Chilean mills processing centers the concentrate can be leached with cyanide or concentrated again to be directly melted. For the Ecuadorian scenario and particularly in Portovelo-Zaruma this framework is factual and effective to be implemented in processing centers with cooperation of all parties involved.

The involvement of miners and owners of processing centers in this research was crucial not only from the point of view of receiving their impressions about the issues, but also because this promoted consciousness about the problem.

Participatory research is well recognized as an effective way to strength capacity (Yassi et al., 2001) and to promote environmental health (Parkes et al., 2003). Artisanal and small-scale mining in the Southern Ecuador is a complex operation but rich in local experiences. The participatory development through knowledge exchange and public involvement play a key role in both development and environmental management. Through the course of this study, the participants recognized the inefficiency of their gold processing methods. They realized where the weak points in knowledge are and how gold is lost as well as how environmental contamination by the misuse of mercury and cyanide occurs. Because of the vulnerability of Ecuadorian ecosystems, the challenge of creating and maintaining sustainable livelihoods within mining and non-mining communities requires an integration of all sectors and strong investments in education, and technology (Hilson et al., 2007; Hinton et al., 2003).

Although both the miners and owners of processing centers have increased their awareness about the environmental contamination problem and about the risks of dumping mercury and cyanide into the rivers, the level of their knowledge needs to be further strengthened. Although the use of mercury is a complex problem, it is one which can be managed through the use of adaptive mechanisms of learning and consciousness (Pahl-Wostl, 2007; Waltner-Toews et al., 2002), and these can range from minimizing mercury use to its complete elimination from the ASGM system.

Environmental management must be achieved at both the local and regional levels. Mercury use can be decreased achieving medium and long-range

objectives by working with miners and owners of processing centers to implement existing cleaner technologies. Mercury emissions in contaminated areas can persist for many years being a permanent risk for humans living near polluted environments (Churchill et al., 2004; Craw and Chappell, 2000; Strode et al., 2009) but the actions to reduce atmospheric emissions in Portovelo-Zaruma must be a priority to reduce the risks of health effects.

The application of integrated approaches to the problem of mercury and environmental contamination caused by ASGM can bring a new perspective to the attempts of managing the risks of ecosystem health (Kay et al., 1999; Parkes and Horwitz, 2009). Since mercury is already present in several watersheds, an overall integrated framework of environmental management is necessary (Parkes et al., 2008). This should involve the participation of miners, agriculture workers, people who make their living in aquaculture, as well as other stakeholders who directly or indirectly share the responsibility for keeping Ecuador's aquatic resources clean. The fact that the connection between ASGM wastes (such as mercury and cyanide) and other land activities has not been acknowledged and addressed at either the environmental assessment or management levels, is of great concern for watershed sustainability, and is a concern for further research and intervention.

Responsible mining can interchange knowledge to integrate management of natural resources promoting other activities such as agriculture or aquaculture. Mining waste water is usually considered a negative issue, but it can also been seen as a positive aspect if it is properly managed and used in other activities

such as irrigation for agriculture and aquaculture. As an example the forms of nitrogen from cyanide wastes and its destruction, could probably play an interesting role in this respect through the use of inorganic nitrogen to promote primary productivity in soils. Research indicates that micro-organisms convert nearly all of the cyanide carbon to CO_2 and bicarbonate and the majority of nitrogen to ammonia, nitrite, and nitrate (Nesbitt et al., 1960, Mudder et al., 2001).

Moreover, as an alternatives for development aquaculture activities have been analyzed as an alternative for post mining sites (Otchere et al., 2002; Miller 2008), and the use of mining water as well (D'Souza et al., 2010). The combination of mining and aquaculture can be a potential and promising source of sustainability for small mining communities in developing countries.

Environmental health risk management will need to integrate different disciplines in order to restore the health of the affected areas (Burger, 2002; Burger, 2003). This study has emphasized that all stakeholders must accept that efficient risk management can only be achieved with a thorough knowledge of the systems that cause the contamination (McDaniels and Small, 2004). This will lead to positive action to control mercury and other heavy metal contamination (Vallentyne, 1993). Using integrated approaches is highly advantageous not only because it creates a greater understanding of the degree of impacts of the processing centers, but it also facilitates the development of alternative gold processing options. Furthermore, it can also help the development of policies through which efficient management could be put in place to safeguard the

environmental and health conditions (Hanney et al., 2003; Lal et al., 2001) for the miners and the surrounding communities. The creation of appropriate management policies for the proper use of technology could also facilitate conflict resolution between different players (Gitau et al., 2009) within the ASGM system as well as the whole ecosystem.

What is needed is the strengthening of education, participation of local miners and more presence of the Government to provide assistance and organization as a first step for future formalization of the ASGM sector. This will also creates trust among all stakeholders. The main interests of miners and local communities lie in their abilities to upgrade themselves from artisanal to small-scale miners, while, at the same time, maintaining the quality of the ecosystem. It is hard to satisfy the needs of miners with new technologies, and other resources, when miners need first organization and education to be formalized and strength thei capacity for decision making. It is important to implement different mechanisms of education to demonstrate the value of local ecosystems and consider other economic opportunities for local livelihoods (e.g. agriculture, aquaculture).

Another important key point regarding mercury pollution from ASGM involves the need to address the role of local institutions in research and environmental health management and policy making (Hanney et al., 2002). The participation of local community is also critical as such support would assist in building system organization and establishing the transparency necessary for honest change (Anex and Focht, 2002)

Sustainable development demands partnership involving all sectors of the industry (McLellan et al., 2009), from the artisanal miners to larger enterprises now being established in the region and including local, regional and national Governments (Spiegel et al., 2005). Constructing alliances which work towards clear objectives (Holdgate, 1996) such as mercury reduction and elimination, and implementing actions according to the nature of the local people and ecosystems would benefit all partners involved in the ASGM sector. However there are many barriers in the establishment of successful partnerships within the ASGM sector including poor communication, lack of local funds and the poor regulatory framework in developing countries for more stable investment (Siegel 2007).

Ecuador is now facing a potential turning-point with regard to mineral policy since the new regulations support small mining development and enforce social and environmental responsibility. The challenge facing ASGM communities and the expansion of gold mining activities in the Southern Ecuador is to find effective ways of developing mining extraction and processing which would function to conserve the rich biodiversity and maintain the health of the whole ecosystem.

The enforcement of existing regulations must be improved, which could be achieved by strengthening the central authority in charge of supervision and control of mining activities. Good governance will require that the both local and provincial Governments take responsibly and encourage local public participation in environmental management. The actual ASGM system of Ecuador would need a clearly defined policy for mercury and cyanide use and management and the appropriate environmental regulations to control them. The reorganization of

small operations into medium-sized units or cooperatives would give the artisanal scale miners the strength they need to sustain rational gold extraction, while meeting environmental obligations.

While it is clear that technological developments to address the mercury problem are on the rise in some areas, the ASGM technological approach is based on miners' creativity, and without technical guidance, economic support, institutional supervision or regulations. In general, the process evolves slowly. A number of miners and owners of processing centers hire engineers from Peru to improve gold recovery techniques. Some foreigners (from Canada for example), invested in building small operations and this brought considerable improvement in processing plant technology and tailing management. However, still both the artisanal miners who work in the mines and the owners of processing centers need support to move forward in order to develop the appropriate technology and education to build an equitable model of work.

Chapter 7 : Conclusions

This study addressed the main research questions as follows:

- How mercury is released to the environment during ASGM activities in Southern Ecuador?
- What and where are the main losses of mercury?; and
- What forms of management could be incorporated to minimize environmental and human risks?

From those question, the following conclusions can be drawn:

- The artisanal miners of Southern Ecuador have three procedures to conduct gold amalgamation, and the system they choose to use is selected according their resources and level of knowledge. About 11 to 40% of the total mercury entering the amalgamation process has been evaporated, 40 to 60% of mercury has been recovered and 1 to 35% of mercury has been lost with the tailings.
- Significantly, when compared with manual panning amalgamation, the use of “Chanchas,” or amalgamation in barrels, creates the most mercury contamination. Amalgamation in barrels (“Chanchas”) of the whole ore or “las ollas” (left-over retained inside the Chilean mills) contributes significantly to the high concentrations of mercury lost with tailings, with an average of 18 and 31% of the mercury entering the system. But when miners amalgamate only concentrates, an average of 1.38% of mercury is lost.

- This research concludes that around 1.5 tonnes/a of mercury used in the amalgamation processes has likely been released into Portovelo's environment, from which 71% is evaporated; the remaining mercury goes with the tailings into the cyanidation process.
- When using retorts, it is estimated that nearly 97% of the total mercury introduced in the process can be recovered when only gravity concentrates are amalgamated. When the whole ore is amalgamated, even using retorts, the maximum amount of mercury that can be recovered would be 70%.
- The inefficiency of gravity concentration followed by amalgamation is the main factor by which cyanidation is used after amalgamation. The unfair labor division between miners and owners of processing plants forces miners to use both gold extraction processes. As miners do not understand the whole process of gold recovery and cannot afford equipment for cyanidation, they accept low levels of gold recovery by amalgamation, leaving the rich tailings to the owners of processing centers.
- Since all amalgamated tailings contain residual gold, the owners of the processing centers and the miners leach the remaining gold using cyanide, either using the Merrill-Crowe or the CIP system. During both systems mercury is dissolved by cyanide forming cyanide-mercury complexes which are released with the effluent solution to the rivers.

- In the CIP system, the tanks maintain the pulp in agitation, causing the mercury to behave differently than it does in the Merrill-Crowe system. While Merrill-Crowe discharges 15% of dissolved mercury, the CIP plant releases 51% of dissolved mercury. Both systems also differ in the amount of mercury trapped. While CIP only traps 2.67%, the Merrill-Crowe traps 24% of mercury. The mercury released into the atmosphere is 27% in the Merrill-Crowe system when zinc shavings are burned and only 3.72% of the mercury attaches to the carbon in the CIP process.
- The mercury contamination in Portovelo-Zaruma depends not only on the amount of mercury rich tailings produced on site, but also on the amount of amalgamated tailings introduced from other sites, which significantly contribute to the overall contamination.
- The main pathway of the release of mercury from the processing plants in Portovelo is through the atmosphere, which receives mercury from both amalgam and the burning of zinc shavings. When miners burn amalgams in open pans or without adequate fume hoods 11 to 40% of the total mercury entering in the system is released to the air. This variation depends on the amalgamation procedure. The contribution to air mercury contamination from Merrill-Crowe was 27 ± 7.59% contaminating the environment significantly.
- Air mercury concentration was determined to be as high as 150,000 ng/m^3 when miners burn amalgam in the open air and when Hg-contaminated zinc shavings are burned. The lack of safety conditions in the amalgam

and zinc burning processes exposes miners to unsafe mercury air concentrations. Therefore, individual retorts for amalgam burning, implementation of gas scrubbers for Hg-contaminated zinc burning, technical assistance, and environmental control must be made priorities.

- Artisanal miners have been governed by those who are more powerful (owners of processing centers) or who have either the knowledge or/and economical resources to run a gold mining processing operation. Due to the hierarchical structures and economic realities within the gold mining sector, artisanal miners have had little control over the system and been forced to work according to methods that have harmed both them and the surrounding communities.
- Assessing the mercury problem with the miners' participation was the best course to take in trying to understand the problem in a holistic way, as it not only allowed us to gain the miners' trust, but also helped us build their accountability, while enhancing their awareness of the environmental contamination that resulted from their practices. Awareness is the path to becoming more sensitive to the problem, and the beginning of change of attitudes and perceptions about mercury in the artisanal mining sector.

Chapter 8 : Claim to original research

This investigation contributes to a better understanding of the pathways and mercury behavior in artisanal and small scale gold processing systems.

In this respect this dissertation delivers several new contributions to the field, including:

- An integrated methodological framework for assessment of mercury in artisanal and small scale gold mining systems.
- First time an interactive work has been developed involving miners and ASGM communities and policy makers in which mercury monitoring program has been established and discussed.
- First time a mercury balance in amalgamation and cyanidation system in ASGM operations have been assessed and the form in which mercury is released to the environment was suggested.
- This was the first time that a study reveals and quantifies mercury discharges to the atmosphere after cyanidation of mercury-rich tailings.
- First time the interactions of mercury and cyanide complexes in cyanidation effluent have been identified in artisanal and small scale gold mining processing systems.
- Recommended set of policy options from technological and community perspective to mitigate local and regional contamination.

Chapter 9 : Suggestions for further work

From the results of this investigation future work is suggested in the following areas:

The cumulative social, economic, and health effects of mining waste, especially cyanide and heavy metals, have not been thoroughly investigated. This is still unknown and constitutes one of Ecuador's serious problems. As such, further monitoring and research in terms of geochemical interactions of mercury and cyanide is clearly needed.

Mercury and cyanide have historically been discharged into water bodies in Ecuador and other artisanal gold mining sites in the world, and since processing centers are discharging soluble mercury-cyanide complexes, it is still unknown whether these complexes become readily bioavailable. Further research is needed to understand the bioavailability of mercury cyanide complexes.

Significant loads of mercury take place in watersheds of the Southern Ecuador. It is important to recover precise information to estimate the likelihood of adverse affects of mercury through fish consumption. This can determine the risk and set up actions for decision making to protect human health against methylmercury.

The role of traditional knowledge in artisanal and small scale operations is an important scenario for scientific research. Issues such as the effect of the brown sugar in amalgamation process can help the understanding of mineral

processing and local alternatives for gold recovery. This also can help understand the advantage of local knowledge in gold processing.

Linking knowledge to policy and education is necessary in artisanal and small gold mining communities, therefore research and interventions are priorities for further actions to mitigate mercury contamination and assist the miners in implementing new methods of gold recovery.

In depth research to investigate and promote alternatives for local livelihood is badly needed in mining communities of developing countries particularly valuing local knowledge and integrating different systems of land production which can include small-scale mineral extraction, agriculture and aquaculture systems.

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APPENDIX I: Assessment of mercury during the whole ore amalgamation

Process	Ore (kg)	Hg enter (g)	Recov Hg (g)	Amalgam (g)	Doré (g)	Hg burnt (g)	Gold Prod (g)	Melting (g)	Hg tailing (g)
Whole Ore 1	106	227.00	133.70	54.00	14.50	39.50	13.78	0.73	53.08
Whole Ore 2	65	61.50	34.10	8.61	2.48	6.13	2.36	0.12	21.15
Whole Ore 3	50	64.56	38.15	5.11	1.57	3.54	1.49	0.08	22.79
AV	73.67	117.69	68.65	22.57	6.18	16.39	5.87	0.31	32.34
MIN	50.00	61.50	34.10	5.11	1.57	3.54	1.49	0.08	21.15
MAX	106.00	227.00	133.70	54.00	14.50	39.50	13.78	0.73	53.08
SD	28.99	94.68	56.37	27.27	7.22	20.06	6.86	0.36	17.98

APPENDIX II: Assessment of mercury during the left-over amalgamation

Process	Ore (kg)	Hg enter (g)	Recov Hg (g)	Amalgam (g)	Doré (g)	Hg burnt (g)	Gold Prod (g)	Melting (g)	Hg tailing (g)
Left Over 1	300	350.00	105.40	388.40	197.32	191.08	187.45	9.87	43.65
Left Over 2	259	453.60	166.00	248.20	123.91	124.29	117.71	6.20	157.11
Left Over 3	265	340.22	128.34	234.09	79.53	154.56	75.55	3.98	53.34
Left Over 4	243	453.50	295.00	223.41	137.06	86.35	130.21	6.85	65.30
Left Over 5	253	458.00	290.41	200.70	127.23	73.47	120.87	6.36	87.76
Left Over 6	255	465.36	278.50	224.83	137.16	87.67	130.30	6.86	92.33
Left Over 7	310	465.35	301.00	235.60	139.73	95.87	132.74	6.99	61.49
Left Over 8	276	580.10	254.72	373.00	149.50	223.50	142.03	7.47	94.41
AV	270.13	445.77	227.42	266.03	136.43	129.60	129.61	6.82	81.92
MIN	243.00	340.22	105.40	200.70	79.53	73.47	75.55	3.98	43.65
MAX	310.00	580.10	301.00	388.40	197.32	223.50	187.45	9.87	157.11
SD	23.68	75.02	80.87	72.17	32.45	54.99	30.82	1.62	35.71

APPENDIX III: Assessment of mercury during the amalgamation of concentrates

Process	Ore (kg)	Hg enter (g)	Recov Hg (g)	Amalgam (g)	Doré (g)	Hg burnt (g)	Gold Prod (g)	Hg Melting (g)	Hg tailing (g)
Panning 1	22.9	598.00	385.75	416.20	223.00	193.20	211.85	11.15	7.90
Panning 2	28.4	770.34	409.35	424.32	275.00	335.00	261.25	13.75	12.24
Panning 3	19.7	546.67	360.6	355.80	185.29	170.51	176.03	9.26	6.30
Panning 4	5.9	159.61	98.00	133.70	79.5	54.20	75.53	3.97	3.44
Panning 5	8.0	195.78	101.15	199.67	113.25	86.42	107.59	5.66	2.55
Panning 6	12.3	254.7	134.59	215.35	102.32	113.03	97.20	5.12	1.96
AV	16.20	420.85	248.24	290.84	163.06	158.73	154.91	8.15	5.73
MIN	5.90	159.61	98.00	133.70	79.50	54.20	75.53	3.97	1.96
MAX	28.40	770.34	409.35	424.32	275.00	335.00	261.25	13.75	12.24
SD	8.88	251.34	151.40	123.66	77.16	100.64	73.30	3.86	3.92

APPENDIX IV: Assessment of mercury during the cyanidation in Merrill-Crowe system

Batch characteristics	Cyanidation tank					
	T 1 MC	T2 MC	T3 MC	T4 MC	T5 MC	T6 MC
Initial date	09/05/2008	22/05/2008	29/05/2008	13/06/2008	04/06/2008	01/05/2008
Final date	13/05/2008	26/05/2008	03/05/2008	17/06/2008	10/06/2008	06/06/2008
Pulp concentration	37%	41%	35%	45%	42%	39%
Material Tailing (Kg)	6,031.13	7,289.98	6,057.14	6,594.21	6,812.63	5,790.96
Water	10,266.25	10,490.01	11,246.61	8,057.70	8,842.40	8,511.89
Hg IN (mg/kg)	141.00	184.00	245.00	165.00	228.00	224.00
Mercury IN (kg)	0.85	1.34	1.48	1.09	1.55	1.30
CN (g/L)	4.87	4.77	4.45	6.21	5.65	5.87
Initial pH	12.3	10.18	11.7	11.40	11.05	10.60
Final pH	10.76	11.70	10.45	11.30	10.50	11.23
Hg OUT solid tailing (mg/kg)	26.92	90.50	45.00	115.00	122.00	159.00
Hg OUT solid tailing (kg)	0.16	0.66	0.27	0.76	0.83	0.92
Hg solution (mg/kg)	79.20	56.10	105.90	76.30	82.30	71.00
Hg solution (kg)	0.81	0.59	1.19	0.61	0.73	0.60
Hg solution discharged mg/Kg	79.20	56.10	105.90	76.30	82.30	71.00
Hg solution discharged (Kg)	0.57	0.44	0.89	0.46	0.55	0.39
Hg sol remaining in tank (kg)	0.24	0.15	0.30	0.15	0.18	0.21
Hg barren Sol (mg/L)	8.20	5.60	10.50	2.66	2.50	3.76
Hg barren Sol (kg)	0.08	0.06	0.12	0.02	0.02	0.03
Hg trapped weight (kg)	0.32	0.48	0.71	0.16	0.57	0.45
In Zinc (kg)	0.48	0.38	0.78	0.44	0.52	0.36
Total	1.30	1.73	2.17	1.53	2.13	1.98

APPENDIX V: Distribution (%) of mercury in Merrill-Crowe cyanidation plants.

Batch Characteristics	Cyanidation tanks Merrill Crowe system															
	Distribution of Mercury in kg and %															
Processing plant	Material	Hg Enter	Trapped	%	Tailing	%	Solution	%	Sol released	%	Sol in tank	%	Barren Solution	%	Hg Zinc	%
T1 MC	6,031.13	1.30	0.32	24.70	0.16	12.53	0.81	62.77	0.57	43.94	0.24	18.83	0.08	6.50	0.48	37.44
T2 MC	7,289.98	1.73	0.48	27.77	0.66	38.17	0.59	34.05	0.44	25.54	0.15	8.51	0.06	3.40	0.38	22.14
T3 MC	6,057.14	2.17	0.71	32.66	0.27	12.54	1.19	54.79	0.89	41.10	0.30	13.70	0.12	5.43	0.78	35.66
T4 MC	6,594.21	1.53	0.16	10.44	0.76	49.46	0.61	40.10	0.46	30.08	0.15	10.03	0.02	1.40	0.44	28.68
T5 MC	6,812.63	2.13	0.57	26.77	0.83	39.04	0.73	34.18	0.55	25.64	0.18	8.55	0.02	1.04	0.52	24.60
T6 MC	5,790.96	1.98	0.45	22.78	0.92	46.62	0.60	30.60	0.39	19.89	0.21	10.71	0.03	1.62	0.36	18.27
AV	6429.34	1.81	0,45	24.19	0.60	33.06	0.76	42.75	0.55	31.03	0.21	11.72	0.06	3.23	0.49	27.80
MAX	7289.98	2.17	0.71	32.66	0.92	49.46	1.19	62.77	0.89	43.94	0.30	18.83	0.12	6.50	0.78	37.44
MIN	5790.96	1.30	0.16	10.44	0.16	12.53	0.59	30.60	0.39	19.89	0.15	8.51	0.02	1.04	0.36	18.27
SD	569.11	0.35	0.19	7.52	0.31	16.48	0.23	13.03	0.18	9.51	0.06	3.97	0.04	2.29	0.15	7.60

APPENDIX VI: Assessment of mercury in one CIP cyanidation processing plant

Batch characteristics	CIP
Pulp concentration	27%
Material Tailing (kg)	8,231.4
Water (L)	22,251.3
Hg IN (mg/kg)	165.7
Mercury IN (kg)	1.36
Hg IN (mg/kg)	68.2
Mercury IN (kg)	1.52
Carbon (kg)	240
CN g/L	2.25
Initial pH	10.9
Final pH	10.8
Hg OUT solid tailing (mg/kg)	20.9
Hg OUT solid tailing (kg)	0.17
Total Hg Dissolved (mg/L)	56.9
Total Dissolved (Hg kg)	1.27
Hg Dissolved (mg/L)	35.1
Hg Dissolved (kg)	0.78
Hg Trapped (kg)	0.04
Hg in Carbon (mg/kg)	0.04
Hg in Carbon kg	0.06
Total	1.54

APPENDIX VII: Assessment of mercury during the 5 days of cyanide leaching.

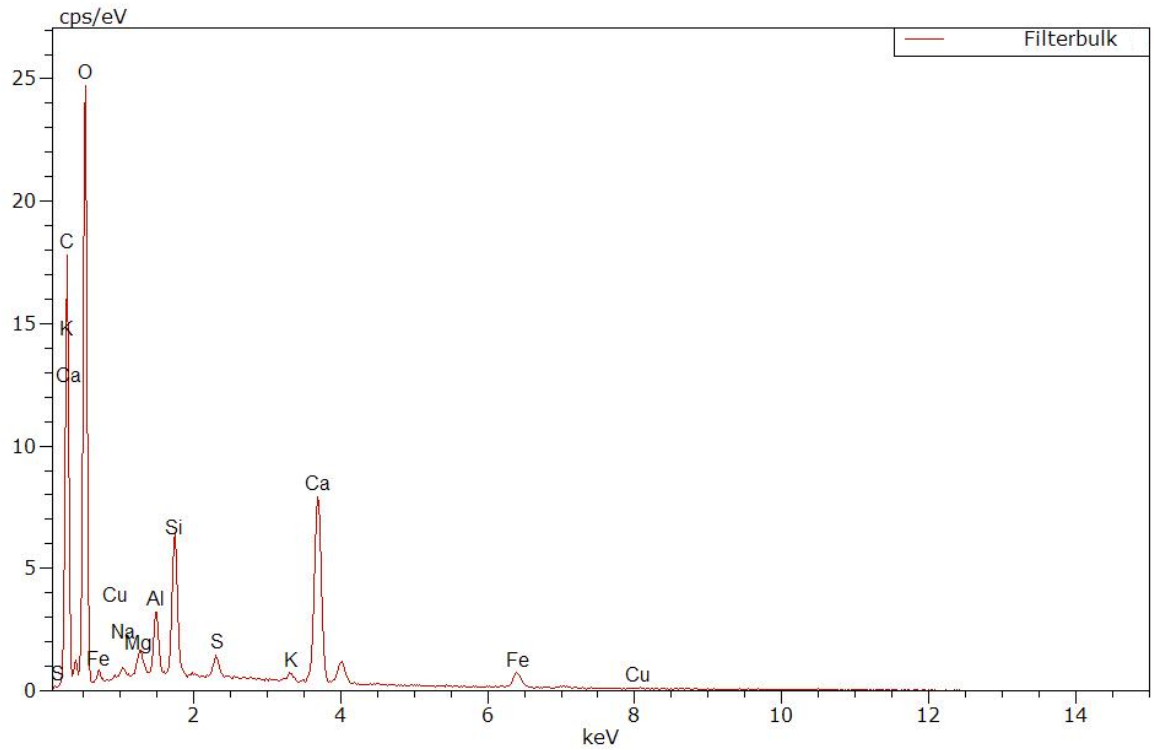
CN leaching	CN	pH	GOLD					Mercury				
	Tailing Solution	Tailing Solution	Head solution mg/L	Tailing Solution mg/L	Estimated total Gold Dissolved	Gold discharged (g)	g. Gold Acc in Zinc	Head solution mg/L	Tailing Solution mg/L	Hg in Zinc	Hg discharged (g)	Hg acc in Zinc (g)
Day 1	4.9	11.41	49.34	5.43	397.55	298.10	265.29	58.8	11.2	47.6	355.27	287.60
Day 2	3.9	11.41	20.22	4.52		122.19	94.88	6.9	2.4	4.5	41.69	27.19
Day 3	5.2	11.38	9.77	3.33		59.00	38.88	2.5	1.07	1.43	15.11	8.64
Day 4	4.7	11.42	5.93	2.14		35.84	22.91	1.07	0.74	0.33	6.46	1.99
Day 5	4.1	11.07	2.49	2.04		15.06	2.74	1.41	0.66	0.75	8.52	4.53

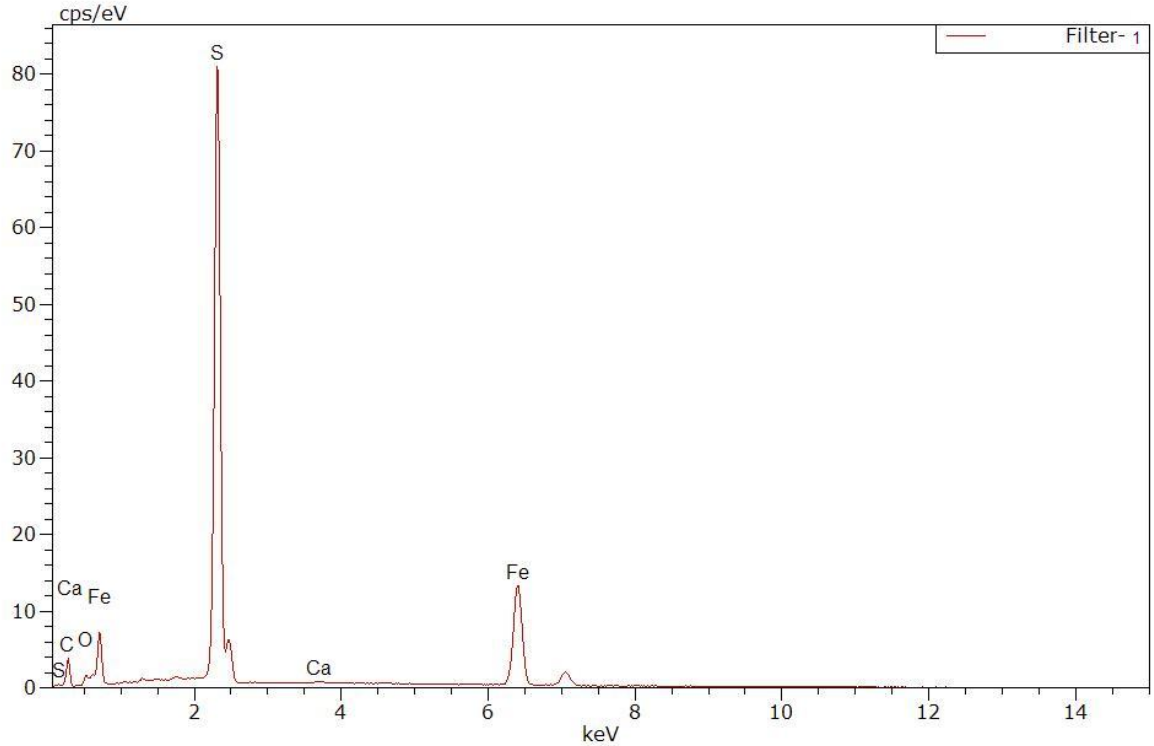
APPENDIX VIII: Mercury and gold leaching at different NaCN concentrations.

Experiment Characteristics	Cyanide concentration				
	1	3	6	10	Control
Dry weight (g)	500	500	500	500	500
Water (ml)	1,000	1,000	1,000	1,000	1,000
Total Hg (mg/Kg)	141	141	141	141	141
CN (g /L)	1	3	6	10	0
Gold in solution (mg/Kg)	34.29	32.13	33.66	34.1	0
% Gold	90	84.33	88.35	89.50	0
Hg solution(mg/L) R1	1.7	9.2	24.3	67.7	0.15
Hg solution(mg/L) R2	1.4	17.9	48.9	55.4	0.2
% of Hg in solution R1	1.21	6.52	17.23	48.01	0.11
% of Hg in solution R2	0.99	12.70	34.68	39.29	0.14
Average Hg	1.10	9.61	25.96	43.65	0.12
SD	0.15	4.36	12.34	6.17	0.03

APPENDIX IX: Elemental chemical composition of suspended solids (CIP process).

EDS (Energy-Dispersive X-ray Spectrometer) analysis of spots. Cps/eV means count per seconds/electronVolt. keV means kiloelectronVolt

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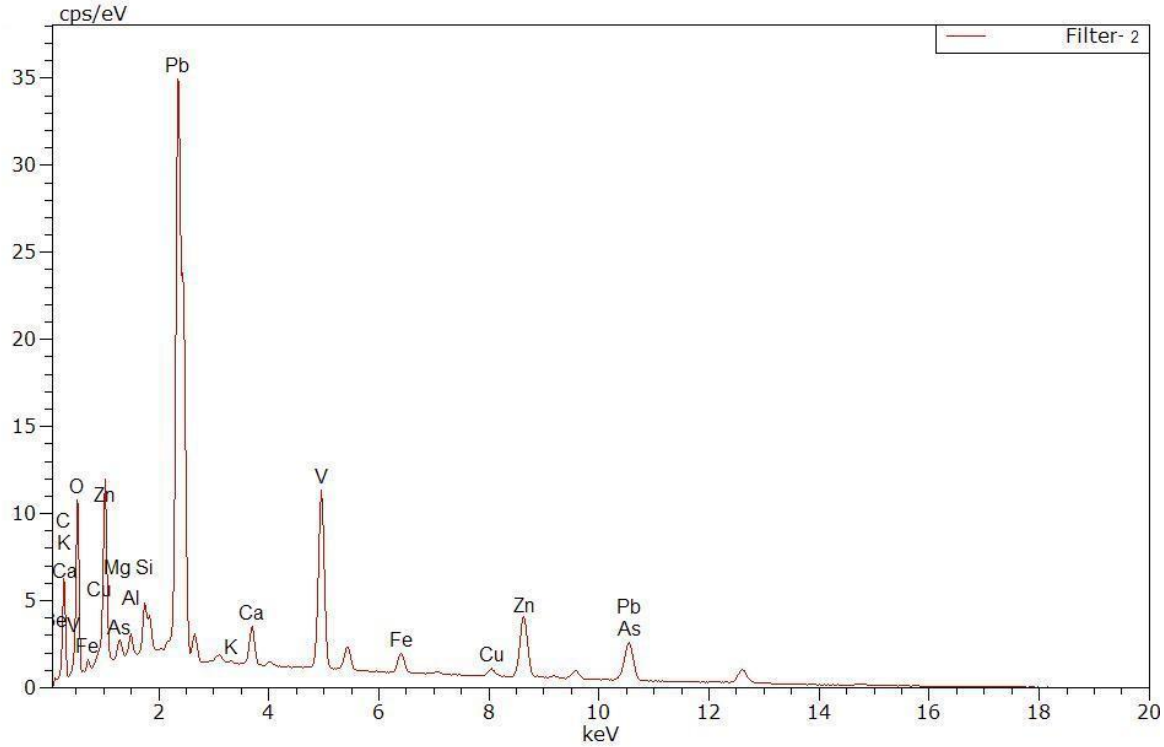
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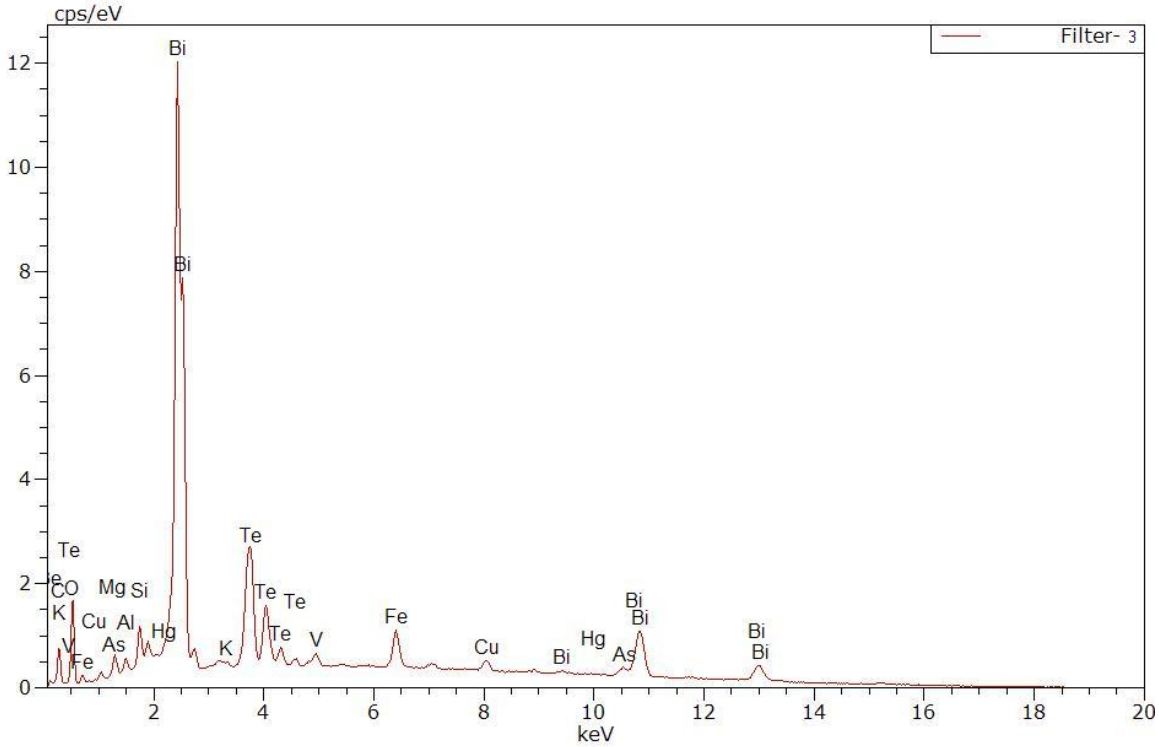
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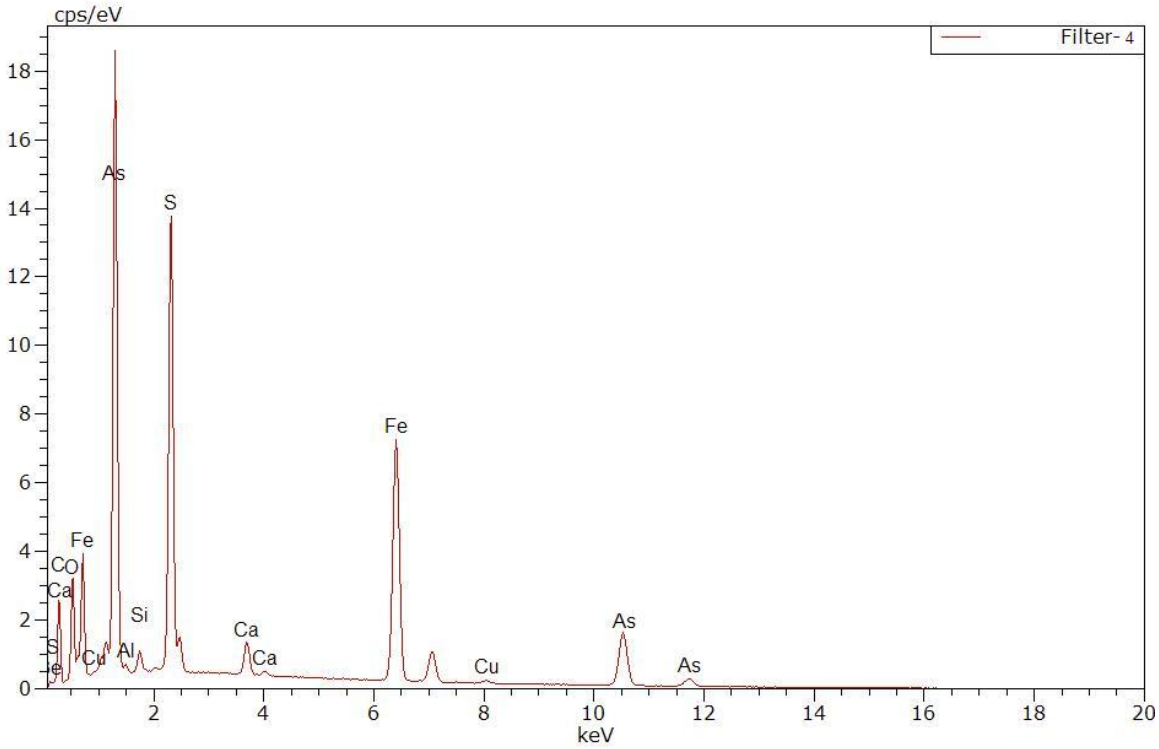
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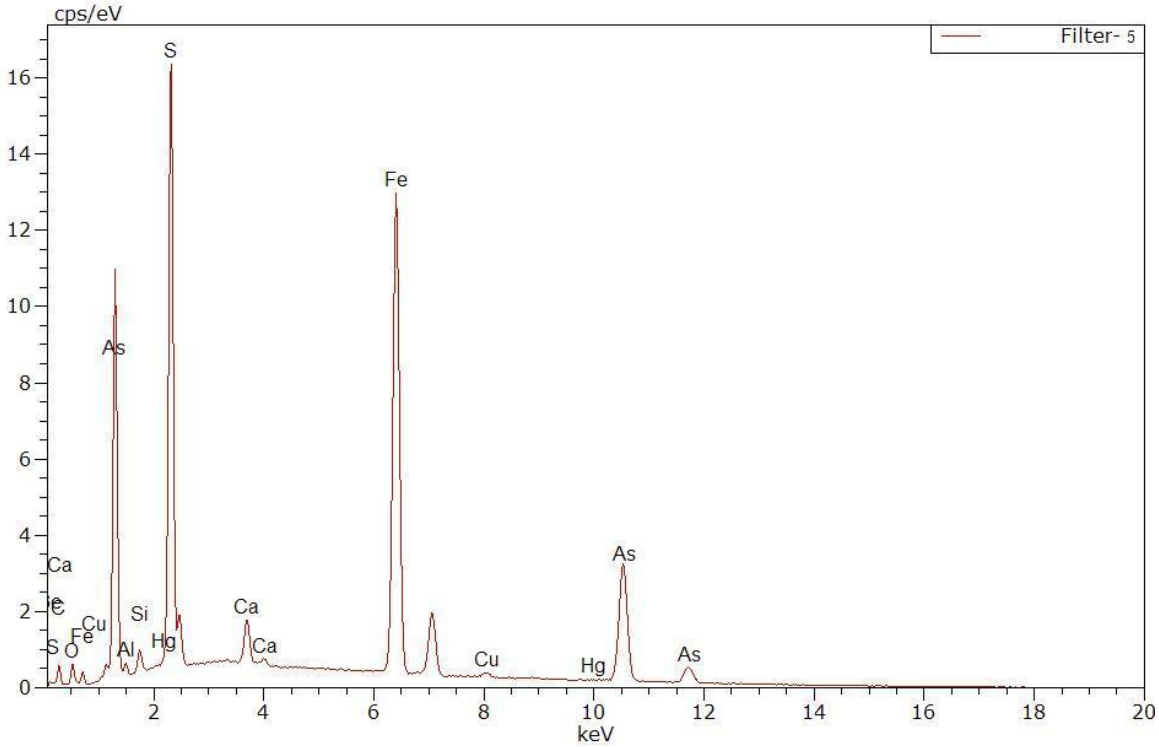
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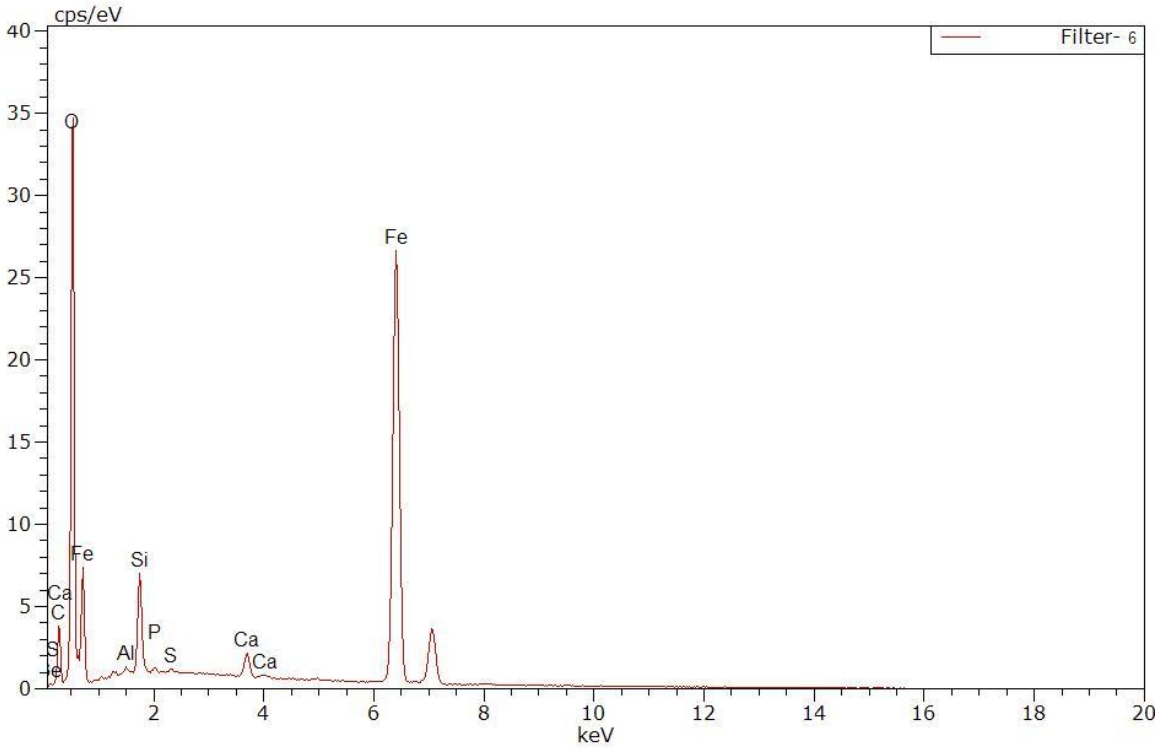
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