ANALYSIS OF GOLD EXTRACTION PROCESSES OF ARTISANAL AND SMALL-SCALE GOLD MINING IN PORTOVELO-ZARUMA, ECUADOR

by

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF APPLIED SCIENCE

in

The Faculty of Graduate and Postdoctoral Studies
(Mining Engineering)

THE UNIVERSITY OF BRITISH COLUMBIA
(Vancouver)

August, 2016

Abstract

Artisanal and small-scale gold mining (ASGM) play a significant role in local economies and communities of several developing countries. Worldwide, ASGM is one of the biggest sources of mercury pollution. Every year, artisanal miners release approximately 727 tonnes per year of mercury to the environment. Globally, nearly 16 million people are directly or indirectly involved in ASGM activities using rudimentary techniques. Even though there are substantial potential socio-economic benefits of ASGM, it can be extremely damaging environmentally and often has serious health and safety consequences for workers and surrounding communities.

This study focuses mainly on the operations of gold processing centers in Portovelo-Zaruma in southern Ecuador, which represent the largest source of environmental contamination in the Puyango-Tumbes River Basin. Furthermore, this study aimed to characterize the types of processing centers currently operating in Portovelo-Zaruma to determine the amount of gold produced, the amount of mercury and cyanide used and lost by these processing centers, and the amount of tailings produced in the region. This study explains how contamination is generated by artisanal and small-scale miners through a comprehensive analysis of the processing centers and also analyzes aspects of different intervention approaches.

Approximately 1.6 million tonnes/annum of tailings with cyanide and heavy metals have been produced by the 87 processing centers in the studied region. In 2015, approximately 6.0 tonnes of gold/annum were produced by all processing centers. In 2015, there was an increase of NaCN use of approximately 31% in comparison to 2013. Each plant uses on average 2.05 tonnes/month of NaCN, totalling 24.6 tonnes/a/plant. Considering that 95% of the plants are using cyanidation to process ore or gravity separation tailings, this would amount to an estimated yearly consumption of NaCN of approximately 1550 and 2040 tonnes for 2013 and 2015, respectively. In 2013, 78% of the processing centers were using amalgamation with 1.5 tonnes/a of mercury lost to the environment. In 2015, 65% of the plants were still using amalgamation, mainly *chanchas*, and the total mercury lost decreased to 576 kg/a in which 243 kg/a was lost with tailings and 333 kg/a lost to the atmosphere.

Preface

This dissertation is the original, unpublished, and independent work by the author, Adriana de Oliveira Gonçalves. The author conducted the fieldwork described in this thesis. This study obtained the approval of The United the Nations Industrial Development Organization (UNIDO) and the Canadian International Resources and Development Institute (CIRDI).

Chapters 1, 2, and 3. These chapters present, respectively, an introduction to the research, a literature review of artisanal and small-scale gold mining, and the characterization of the processing centers in southern Ecuador.

Chapter 4. This chapter describes the methodological approach designed for the proposal of this study.

Chapter 5. This chapter illustrates the results of the field work and discusses the results obtained in this study in comparison with others research carried out in the mining district of Portovelo-Zaruma.

Chapter 6. This chapter outlines the ecological and environmental risk exposure analysis.

Chapter 7. This chapter shows the key findings resulted from this study conducted by the author.

Chapter 8. This chapter describes the originality of this thesis.

Chapter 9. This chapter details recommendations for future action in the study region.

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List of Acronyms

Au – Gold

APROPLASMIN – Association of Owners of the Processing Plants

ASGM – Artisanal and Small-scale Gold Mining

CIMA - Compañía Industrial Minera Asociada

CIIED – Canadian International Institute for Extractive Industries and Development

CIP – Carbon in Pulp

IBRD – International Bank for Reconstruction and Development

ICMC – International Cyanide Management Code – For the Gold Mining Industry

ILO – International Labour Organization

INIGEMM - Ecuadorian National Geology, Mining & Metallurgy Research Institute

NaCN – Sodium Cyanide

SADCO - Southern American Development Company

SME – Society for Mining, Metallurgy Exploration

UNEP – United Nations Environmental Programme

UNIDO – United the Nations Industrial Development Organization

USGS- United States Geological Survey

WHO- World Health Organization

XRD- X-Ray Diffraction

Acknowledgements

First and above all, I praise God, the Almighty, for providing me with this opportunity and granting me the capability to proceed successfully. There are many people whose direction, advice, support, and contributions have provided invaluable along the way. I would like to offer my sincere thanks to all of them.

To Dr. Marcello Veiga, my esteemed champion, my heartfelt gratitude for accepting me as a M.Sc. student, for supporting me in my research endeavors and allowing me to choose a topic I am interested in and passionate about it. This study would not have been possible without his patience, support, motivation, enthusiasm, and immense knowledge. To you, my eternal appreciation for granting the opportunity to learn and for giving me the chance to pursue a new career.

I would like to thank my entire committee, including Dr. Bruce Marshall and Dr. Bern Klein, for their patience, flexibility, and support as I worked to finish this master's thesis.

I would like to acknowledge both Ryan Jackson at Newlox Gold Ventures Corp and Mitacs Accelerate research program which provided me with a summer internship. This internship was integral in developing a background in artisanal and small-scale mining issues worldwide and ultimately in selecting to undertake my field research in Ecuador. This master's thesis would not have been possible without my experiences at this research program.

I would like to express my profound thanks to all of the people from Ecuador in Portovelo-Zaruma who took the time to participate in this study, especially Danilo Castilho from APROPLASMIN for his assistance and help in accessing the processing centers and Dr. Colon Velásquez-López for his knowledge and discussions. I would like to thank those who facilitated my travel throughout Ecuador and to the processing centers owners, the miners, and technicians I spoke with and visited. I would also like to thank The United of the Nations Industrial Development Organization (UNIDO) and the Canadian International Resources and Development Institute (CIRDI) for partially funding this research and for their support to accomplish this goal.

I am thankful to the University of British Columbia, to the professors, colleagues, and especially the staff and technicians of the Norman B. Keevil Institute of Mining Engineering. My special thanks to Pius Lo, Sally Finora, Leslie Nichols, Solgi Narges and Maria Liu for all their guidance, encouragement, and patience.

My friends have been an incredible source of support for me throughout my master's program, and I could not have done it without help, especially from Catherine Van der Lely, Mariel Plummer and Pedro Cordeiro. Their patience in reading over my work, helping with revisions, and listening to my ideas has been appreciated greatly.

Many friends have helped me stay sane through these last two difficult years of my life. Their support, prayers, and care have helped me overcome setbacks and stay focused on my graduate study. I greatly value their friendship and I sincerely appreciate their belief in me: Ana Carolina, Bernardo Ranieri, Barbara Avelar, Carol Miwa, Caroline Leony, Caroline Marques, Cristina Dias, Diana Bauer, Douglas Ramos, Gabriel Jimenez, Yolanda Aguilar, Ingrid Iwaszko, Maria Clara, Maria Silva, Mauro Kesselman, Mikhaela Meznaric, Nuno Alves, Pastor Jim Walton and his wife Louise Walton, Peipei Shi, Rennan Mendonca, Rebecca Milanello, Samara Menezes, Sonia Veiga, Vanessa Amaral and Victor Batinovic who have helped keep me motivated both academically and encouraged me to maintain a balanced life. I warmly appreciate the generosity and understanding of my friends.

Most vitally, none of this would have been possible without the love of my family. I deeply thank my parents, Avelar and Zelia, sisters Andrea and Angela, brother Gustavo, nephews Arthur and Heitor, and brothers-in-law Fabiano and David for their unconditional trust, timely encouragement, and endless patience, during the difficulties times I experienced during these years. This dissertation is dedicated to them, who has been a constant source of love, concern, support, and strength. It was their caring love that raised me up again when I got weary. I would like to express my heartfelt gratitude to my family.

I offer my blessings and heartwarming kindness to all of those who trusted and supported me in any aspect during the completion of this master's program.

Chapter 1: Introduction

1.1. Statement of the Problem

Artisanal and small-scale gold mining (ASGM) is defined based on the rudimentary processes used in mining and processing gold ores, which is a characteristic of small operations (Veiga, 1997). Small-scale mining operations are not necessarily always artisanal, as worldwide, especially in Ecuador, many small mines and processing centers that use semi-conventional and more appropriate technologies are producing less than 300 tonnes of ore per day (Veiga et al., 2014b). Frequently, the term artisanal and small-scale are used as interchangeable but the term “artisanal” refers to the rudimentary practice of a miner and “small” refers only to the size of the operation. For this thesis, in order to avoid misinterpretations, the term ASGM is used to encompass all small processing activities in Ecuador that use rudimentary or semi-conventional techniques to process gold ores.

Worldwide, ASGM encompasses a contingent of approximately 16 million miners (Seccatore et al., 2014) that release 1000 to 1400 tonnes/a of mercury to the environment (UNEP, 2013; Veiga et al., 2014b). The environmental and health impacts of this pollution has been confirmed in many countries. In the mining district of Portovelo-Zaruma in South Ecuador, the discharge of 1.6 million tonnes/a of mercury-enriched tailings into the Puyango-Tumbes-River reaching Peru, 160 km downstream (UNIDO, 2016).

When artisanal miners use mercury, it is released into the environment in two forms: 1) mercury associated with tailings, which can be metallic or mercury-cyanide complexes, and 2) mercury vapour, when amalgams are burned in open pans. Metallic mercury can be oxidized and converted to methylmercury (Meech et al., 1998). The bioavailability of mercury-cyanide and the conversion of these complexes to methylmercury are still unclear (Guimarães, et al., 2011).

As most of the processing centers in the Portovelo-Zaruma have routinely discharged tailings into the Puyango-Tumbes River, the associated pollution has created a diplomatic conflict over this issue between Peru and Ecuador in recent years (Velásquez-López et al., 2010; Veiga et al., 2014a). Given the different types of processing centers in southern Ecuador, understanding the variety of mercury-contaminated tailings generated by those centers is important to develop new strategies to alleviate the environmental degradation of mercury and cyanide pollution. Identification of the different types of processing centers and the tailings they generate will also contribute to determining strategies for waste minimization and pollution prevention.

Any solution implemented in the Portovelo-Zaruma region regarding the reduction of pollution from ASGM must start with a clear understanding of the mercury and cyanide discharges and the potential of the miners to move towards cleaner production methods.

1.2. Justification of the Thesis

Gold processing plants have increased considerably in the region of Portovelo-Zaruma over the last twenty years, both in number and in ore processing capacity. This thesis provides an analysis of the evolution of the processing centers and looks critically at how previous assessments contributed to managing the growth, both technically and environmentally. This approach allows for the understanding of how the information is disseminated to stakeholders and the identification of the barriers they face in achieving better gold recovery and using cleaner technologies. These steps would thereby help manage the environmental and health risks generated in this mining district. This approach is essential for the management of gold mining and processing activities in Portovelo-Zaruma.

This study also provides general information about where and how the processing center owners obtained knowledge and experience to establish their operations. This information is applied to existing processing centers to further understanding the level of knowledge and gaps to improve operations. A technical description of the gold processing system also helps understand the perceptions of different stakeholders. Furthermore, this analysis helps understand what is still missing in gold processing systems in Ecuador to contribute for the further alleviation of mercury-cyanide pollution.

1.3. Research Questions

The primary idea of this study was to understand if the cleaner gold production methods being introduced in the region are in fact being disseminated and reaching all stakeholders in Portovelo-Zaruma. To understand this scenario, the following research questions were asked:

1. What is the amount of gold produced and mercury and cyanide used and discharged at the processing centers in the mining district of Portovelo-Zaruma?
2. How did miners and operators of the processing plants acquire knowledge regarding mineral processing and did they have access to the relevant information and technology?
3. What are the challenges for tailings management in Portovelo-Zaruma?
4. Are the methods currently used by the processing centers to extract gold beneficial for the environmental and local communities?

1.4. Research Objectives

This research primarily focuses on evaluation and classification of the different types of processing centers in the largest gold mining district in Ecuador. Through an assessment of the current processing centers in the region of Portovelo-Zaruma, this research aimed to understand the quantities of mercury and cyanide both use and lost using different processing methods, and assesses how these methods have evolved over time. These objectives were accomplished by performing an on-the-ground integrated assessment of 52 processing centers located in the Province of El Oro in the region of Portovelo-Zaruma, in Ecuador. The objectives for this research are as follows:

- Assess the current gold processing centers in Portovelo-Zaruma by observing gold production to quantify the amount of cyanide and mercury both use and lost to the environment.

- Determine the different types of equipment being used by the processing centers, the level of technology and the most common practices to extract and recover gold in the region of Portovelo-Zaruma.
- Understand the different types of tailings being generated and the waste management facilities in the processing plants to identify the potential health and environmental impacts.
- Gather information about the experiences of miners and processing center owners that can provide input to improve the implementation of training programs to achieve cleaner gold production.

1.5. Applied Contribution of Research

Efforts to understand and improve the negative impacts of ASGM continue to pose challenges for researchers and policy makers worldwide. As mining activities are increasing and improving in southern Ecuador, the concerns related to mercury and cyanide contamination are growing among communities living downstream of the mines. The different types of processing systems in Ecuador are not well described, and it is crucial for the implementation of a new framework to address the problems associated with current ASGM activities. The knowledge of miners and processing center owners regarding cleaner practices is different amongst these two groups and evolving at a different rate. Therefore efforts to implement successful training must utilize methods that recognize a knowledge gap between miners and plants owners.

Specifically, this research presents the opportunity to understand the problems associated with different types of processing centers in Portovelo-Zaruma while identifying the benefits for miners and other community members. Additionally, this thesis aims to clarify the steps essential to the improvement of artisanal gold processing practices in Portovelo-Zaruma and how this can be reproduced elsewhere. The findings here can help international agencies, governments, academics, miners and processing center owners understand the current reality and how the pollution can and must be reduced.

1.6. Academic Contribution of Research

As the use of cyanide in gold processing plants has increased significantly in all artisanal mining operations worldwide in the last 20 years, the concerns associated with the interaction between mercury and cyanide during gold processing operations is increasing. However, the public is still largely unaware of the environmental and health consequences of this pollution. Before this study, research and case studies undertaken in Ecuador did not evaluate the different types of tailing components and the interaction of these mercury-cyanide rich tailings, which contributed to high levels of pollution in the environment and surrounding mining communities. This research builds on the understanding of how cyanide is being used at processing centers, in terms of varying and amounts necessary. Additionally, this thesis highlights the gap in the knowledge that exists in understanding, monitoring, and managing the risks in the surrounding watersheds in southern Ecuador. Based on the findings, there is a need for the implementation of long-term monitoring programs in ASGM to assess mining effluents. Focus should be concentrated on introducing and teaching cleaner technologies for both artisanal miners and processing center owners. This approach is crucial to improving the artisanal gold mining practices in deveolpming countries. A consistent methodology evaluating variables in gold processing systems is a valuable tool for the management of mercury pollution by the decision makers in Portovelo-Zaruma.

1.7. Thesis Structure

This research gathered the following information:

Chapter 1 – Introduction provides a brief introduction to this investigation, identifies its purposes and objectives, address the applied and academic contribution of this research and outlines the information contained herein.

Chapter 2 - Artisanal and Small-Scale Gold Mining Framework provides literature review of mercury and artisanal gold mining activities documenting different approaches used by universities, government and non- government organizations, ASGM associations and international contributors to support and regulate ASGM activities.

Some of the environmental and health impacts of mercury and cyanide derived from artisanal and small-scale gold mining are also highlighted.

Chapter 3 – ASGM in southern Ecuador outlines the history of artisanal and small-scale gold mining in southern Ecuador focusing on the mining district of Portovelo-Zaruma. This chapter also provides a synopses of the different types of processing centers and methods in use to extract and recover gold ore in Portovelo-Zaruma.

Chapter 4 – **Methodological Approach** provides information on the methodology used for this research and the data acquisition methods obtained for this study.

Chapter 5 - **Results and Discussions** shows the results and discusses the analysis obtained in this study including: the source of technology used by the processing centers, the amount of gold produced, the amount of mercury and cyanide discharged, the treatment of tailings, the engineers involved in the mining operations, the different processing techniques and equipment used at the processing centers and the mineralogical analysis of the samples collected during field work. Prior assessment of mercury losses and releases are also discussed.

Chapter 6 – **Environmental Concerns** provides a general discussion of the ecological risk exposure analysis from mercury use and tailings management of the artisanal and small-scale gold mining in Portovelo-Zaruma. It also provides suggestions for managing systems for gold recovery in mining communities and the increased use of cyanide in Portovelo-Zaruma.

Chapter 7 - **Conclusion** lists and discusses the key findings of this thesis in a bullet form, including an updated assessment of cyanide, mercury and other heavy metals, released in 2015 in the Puyango-Tumbes River Basin, uncertainties associated with the operations of gold processing plants, recommendations for future work in the region, as well the tailings management of the processing sites.

Chapter 8 – **Originality** describes the originality of this thesis.

Chapter 9 Opportunity for Future Research consists of recommendations for future actions for the artisanal and small-scale gold mining communities in Portovelo-Zaruma.

Chapter 2: Artisanal and Small-Scale Gold Mining Framework

2.1. Artisanal and Small-Scale Gold Mining – An Overview

Artisanal gold mining is considered one of the most important sources of subsistence income for rural communities in many developing countries, particularly when economic alternatives are restricted (Appleton et al., 2001; Sandoval, 2001; Hentschel et al., 2002; Hentschel et al., 2003; Hinton et al., 2003; Betancourt, 2005; Veiga et al., 2006; Velásquez-López & Veiga, 2007; Veiga et al., 2014a). ASGM is practiced in more than 70 developing countries (Veiga, 1997; Veiga & Baker, 2004; UNEP, 2012, UNEP, 2013; Veiga et al., 2014; CIIED, 2014) and it employs more people than large-scale mining (Veiga, 1997; Siegel & Veiga, 2010; UNEP, 2012). Globally, it is estimated that approximately 30 million people work directly in ASGM and approximately 100 million people rely directly or indirectly on artisanal mining activities, compared to about 7 million people worldwide in industrial mining (CIIED, 2014; Veiga et al., 2014a). Gold is an excellent commodity for improving wealth inequality, considering that producers get 70% or more of the international price in remote areas. Gold is the most economically valuable metal extracted and it can be easily processed by the miners using amalgamation process (Veiga et al., 2005). It is less vulnerable to the instability of local and national governments when compared to other base metals (e.g. copper, iron, lead, manganese, nickel and zinc) which cannot be mined on a small-scale level (ILO, 1999). ASGM produces approximately 380 - 450 tonnes of gold per year, which accounts for 15-20% of the global output of mineral and metals (Buxton, 2013; Seccatore et al., 2014; Veiga et al., 2014a). Artisanal mining is a source of poverty alleviation for miners and for the communities who live in the surrounding areas. Even though the benefits of artisanal mining are clear, unfortunately artisanal and small-scale mining operations are often associated with problems including poverty, gender inequality, child labour and health and environmental impacts (Hilson, 2002). The artisanal mining sector is decentralized and it often occurs in remote areas where the government has very little or no engagement with the communities (Veiga, 1997). Due to this non-management, the negative impacts associated with ASGM in remote areas is even worse.

Mercury (Hg) is often used in artisanal and small-scale gold mining to help separate gold from heavy minerals (Castilhos et al., 2006), as amalgamation is the preferred method used by artisanal and small-scale miners to recover free gold from alluvial and colluvial, primary ores or concentrates (Velásquez-López et al., 2011; Veiga et al., 2014b; Veiga et al., 2015). Miners combine mercury with gold-laden silt to form an amalgam, which is then heated in order to evaporate the mercury, leaving behind a *doré*, a mixture of gold, silver, copper and 2-5% of residual mercury (Veiga, 1997). Wordwide, ASGM is considered the largest source of mercury pollution and releases yearly between 1000 and 1600 tonnes/a of mercury into the environment (Veiga et al., 2009, Velásquez-López et al., 2010; Cordy et al., 2011; Cordy et al., 2013; CIIED, 2014; Seccatore et al., 2014; Veiga et al., 2014a). Due to its persistence in the environment, mercury contamination is a legacy that transcends generations, geopolitical boundaries, environmental media and trophic levels (Veiga, 1997, Meech et al., 1998; Van Straaten, 2000; Cordy et al.; 2013; Adler-Miserendino et al., 2013; UNEP, 2013; UNIDO, 2016).

2.2. Artisanal and Small-Scale Mining Definition

There are many definitions of the term “artisanal mining”. Generally, the term is associated with individuals that work in mining activities using minimal machinery and little technology to mine small mineral deposits (Hentschel et al., 2002). It is hard to find a common term which defines this sector, because the definition varies in the legislation from county to country (Veiga et al., 2014b). The term “artisanal” seems to describe the way in which the miners operate and not necessarily the size of the operation. Commonly, the terms “artisanal” and “small-scale miners” are applied together to describe individuals who pan for gold or precious stones at riverbanks (Veiga, 1997; Hinton et al., 2003). There are many artisanal mines that cannot be considered small operations and there are many small operations that cannot be regarded as artisanal (Veiga et al., 2014b). The definition of artisanal mining should include a broad range of individuals: from the micro-miners panning in the rivers to large operations using excavators and other mining equipment. Typically an artisanal miner works on instinct, driven by the need to feed his family and pay the bills. Artisanal miners normally do not undergo any geological exploration, drilling, engineering studies or establishment of proven reserves or ore tonnage estimates.

(Veiga, 1997). The primary attribute that differentiates between conventional and artisanal activities lies in the technologies applied on site and in the processing of ore (Angeloci, 2013). The lack of distinction between small-scale conventional mining and artisanal mining is usually the source of many legal problems in the vast majority of the developing countries where artisanal mining is relevant.

Artisanal miners are usually not good examples of tax payers. Typically, the gold extracted is sold locally to gold shops or on the black market (Veiga et al., 2014a). Since there is a distinct resemblance between artisanal and small-scale miners, “artisanal mining” includes small, medium, informal, legal, and illegal miners who use basic techniques to extract any kind of mineral element (Table 2.1) (Hentschel et al.; 2003; Lovitz, 2006; La Republica, 2013a Veiga et al., 2014b). “Informal mining” is another confusing term found in many forms of legislation related to artisanal mining. Informal minining is a broad term that comprises all types of mining that operate without labor or social protection (Veiga, 1997). This term is usually mixed up with “illegal mining”. Illegal mining is often identified when the activity is conducted without a proper title, authorization, or concession issued by the competent authorities, whereas informal mining is a set of insufficiencies in environmental management, technical assistance and development, access to information and adequate working conditions (Hentschel et al., 2002; Angeloci, 2013; Veiga et al., 2014b).

In many countries, the definition of artisanal mining is attached to the type of ore allowed to be exploited by these miners. These definitions are very vague since artisanal miners exploit alluvial, colluvial, weathered and hard rocks using all types of mining methods. Artisanal miners have never respected laws that have restricted them to a particular kind of ore to be exploited, as it is established in some legislation, such as the Brazilian Mining Code (Veiga, 1997).

Table 2-1. Theoretical differences of artisanal and conventional mining.

Type of Mining	Size	Legal situations	Mechanization
Artisanal (rudimentary)	• Micro • Small • Medium • Large	• Illegal • Informal • Legal	• Micro • Small • Medium
Conventional	• Small • Medium • Large	• Legal	• Mechanized

Artisanal and small-scale mining account for 20 - 25% of all non-fuel mineral production (Hentschel et al., 2003). ASGM supplies 80% of sapphire mining, 20% of gold mining and up to 20% of diamond mining globally (Collins & Lawson, 2014). ASGM operations are widespread worldwide, especially in developing countries in Africa, Asia, Oceania, Central and South America (Buxton, 2013; UNEP, 2013). However, in many countries and for certain minerals, these numbers could be much higher (UNEP, 2013).

Gold is the dominant metal extracted by artisanal miners, as gold is quickly sold and transported across borders and is less vulnerable to the instability of local governments (Veiga, 1997; Meech et al., 1998; Hinton et al., 2003, Veiga et al.; 2005; Lovitz, 2006; Guiza, 2013; Veiga et al., 2014a). It has been estimated that one in every nine hundred Latin Americans is employed in gold and silver artisanal mining operations (Veiga, 1997; ILO, 1999). Seccatore et al. (2014) estimated that over 16 million people are directly involved in artisanal gold mining activities worldwide in which approximately 1.7 million miners are in South America producing 8.4% of the total global gold production.

Despite the noticeable economic benefits, many ASGM activities propagate outside the government radar and are regularly accompanied by socio-economic, health and environmental problems (Van Straaten, 2000; Hentschel et al., 2002,2003; Veiga & Baker 2004; Chen, 2007; Telmer & Veiga, 2008; Böse-O'Reilly et al., 2008; Siegel & Veiga, 2010; Cordy et al., 2011; Dillard, 2012; Adler-Miserendino et al., 2013) (Table 2.2). According to Siegel & Veiga (2010), the increasing number of ASGM titles relies on the increasing development of strategies towards formalization of the miners and many governments have taken the initiative to formalize the sector. The Mongolian government is a good example of this type of action (UNEP, 2013).

Table 2-2. Mining impacts associated with ASGM.

Environmental	Health	Socio-economic
• Acid rock drainage • Deforestation • Soil erosion • River siltation • Soil pollution • Water pollution • Mercury pollution	• Mercury in fish • Mercury vapor exposure • Cyanide exposure • Zinc vapor exposure • Sexual transmitted diseases • Physical problems • Neurological problems • Respiratory diseases	• Narcotics consumption • Gambling • Prostitution • Alcoholism • Sexual diseases • Tax evasion • Money laundry • Child labor • Gender inequality

Despite the efforts undertaken to improve ASGM practices, the lack of policies and socio-economic incentives for miners, such as granting permits and licences to operate, is still a challenge for the local governments, especially in lesser-developed countries (Adler-Miserendino et al., 2013; Vangsnes, 2015; Collins & Lawson, 2014). In order to address these concerns, the transformation of artisanal mining into small-scale organized mining requires a systematic approach, including political and institutional support, formalization of artisanal miners, and appropriate and affordable technologies in consideration of local environmental, social and economic conditions (Hinton et al., 2003; Velásquez-López, 2010; Adler-Miserendino et al., 2013; Veiga et al., 2014a).

According to Angeloci, (2013) few countries in South America have established mining laws based on production capacity. Some that do include Peru (Law 27651 of 1992) and Ecuador, (Law of January 29, 2009, Chapter 2 Art. 138), which states that small-scale mine cannot exploit and process more than 300 tonnes of ore per day. In this particular example, small-scale miners do not mine for subsistence unlike artisanal miners, who are not subjected to royalties (Art.134) (Angeloci, 2013). ASGM legislation worldwide is littered with confusing definitions about the type of operation, size, skills of the miners, regions, and type of ore, among other things (Veiga, 1997; Velásquez-López, 2010;

UNEP, 2012). Even though there are many publications and programs to understand the barriers and to promote new technologies in the artisanal and small-scale gold mining communities, lamentably, the hazards associated with artisanal mining are difficult to measure and address, due to deficient technical knowledge of the different stakeholders. This is reflected in poor policies and conflicts between governments and artisanal mining communities (Hinton et al., 2003; Siegel & Veiga, 2010; Adler-Miserendino et al., 2013; Vangnes, 2015). The governments need to play their role and strengthen partnerships with the miners in order to reduce unwanted externalities and to legalize the artisanal mining activities towards a sustainable mining operations.

2.3. Mercury Use and Environmental Impacts Associated with ASGM

Worldwide, artisanal and small-scale gold mining has been recognized as the most damaging mining activity, due to mercury pollution. In developing countries, ASGM is the world's largest intentional users of mercury (UNEP, 2013). Unfortunately, often artisanal mining operations are associated with the degradation of the environment and contribute to social and health problems of the miners and people in surrounding mining areas. Over the last four decades, the health and environmental hazards associated with the use of mercury in ASGM operations have been well addressed in many studies (Björnberg et al.; 1988; Veiga et al., 1995; Malm et al., 1995; Villas-Boas, 1995; Appleton, 1996; Veiga,1997; Meech & Veiga, 1997, Meech et al., 1998; SGBA-Prodeminca, 1998; Tarras-Walhberg et al., 2000, 2001; Appleton et al.; 2001; Carmouze et al., 2001; Hinton et al., 2003; Tarras-Walhberg & Lane, 2003; Hyman, 2004; Veiga & Baker, 2004; Veiga et al., 2005; Coles & Cochrane, 2006; Veiga et al., 2006; Castilhos et al., 2006; Swain et al., 2007; Bose-O'Reilly et al., 2008; Telmer & Veiga, 2008; Pirrone et al., 2010; Siegel & Veiga, 2010; Velásquez-López, 2010; Velásquez-López et al., 2000,2011; Cordy et al., 2011; Guimarães et al., 2011; Adler-Miserendino, 2012; Cordy et al., 2013; UNEP; 2012,2013; Jønsson et al., 2013; Gibb & O'Leary, 2014; Kessler, 2015; Grimaldi et al., 2015; Kiefer et al., 2015, UNIDO, 2016).

According to UNEP (2013), mercury use in ASGM represents one-third of all global anthropogenic Hg consumption. Mercury has been used in more than 50 countries over the last three decades. The global antropogenic mercury emission to the atmosphere by

ASGM, (727 tonnes/a), are responsible for approximately 37% of the total Hg emissions to the environment from anthropogenic sources (UNEP, 2013). Mercury contamination from ASGM is a huge problem in many countries in Latin America, Africa and Asia where most of the gold produced comes from artisanal mining operations (Veiga, 1997; Collins & Lawson, 2014).

2.4. Mercury Rate and Releases

In ASGM operations around the world, the ratio between mercury lost to gold produced ($Hg_{lost}:Au_{produced}$) varies tremendously among artisanal and small-scale gold mining operations, especially during the grinding circuit. Various studies have estimated $Hg_{lost}:Au_{produced}$ values that range from 1 to 100 (Veiga et al., 2005; Veiga et al., 2006; Telmer & Veiga, 2008; Velásquez et al., 2010; Cordy et al., 2011), making a global average difficult to determine (Veiga & Baker, 2004). Mercury releases from ASGM activities were estimated by Swain et al. (2007) and UNEP (2013) at 1000 and 1400 tonnes/a, respectively, indicating a global average of $Hg_{lost}:Au_{produced}$ of approximately 3.5:1 (Angeloci, 2013), taking into consideration the gold production suggested by Seccatore (2012, 2014).

ASGM releases mercury to the environment in two pathways: 1) mercury atmospheric emissions when the amalgam are burned, and 2) mercury-contaminated amalgamation tailings when small amounts of residual mercury is washed out along with tailings into local water bodies. For example, processing centers in the region of Portovelo-Zaruma in southern Ecuador discharge high concentrations of mercury cyanide complexes that acummulate in water, sediments and soils and can be transported long distances along the Puyango-Tumbes River (Veiga et al., 2014a). Additonally, there are others sources of mercury polution, which includes soil erosion from desforastation in the basin.

In Portovelo-Zaruma, poor disposal of mercury-contaminated tailings generated by the processing centers has caused a major environmental impact (Guimarães et al., 2011). In 2008, according to Velásquez-López et al. (2010), approximately 29% of mercury used in gold processing in Portovelo-Zaruma was lost when burning the gold and mercury amalgams and 30% lost with the tailings. Conversely, when miners amalgamate gravity concentrates from sluice boxes, only an estimated 1.4% of the mercury initially added to the process is lost with the tailings, whereas the *chanchas* cause losses of more than 30% of the initial mercury added to the mills. These authors calculated that whole ore amalgamation in *chanchas* generates a Hg_{lost}:$Au_{produced}$ ratio of 12.04 ± 5.48. With amalgamation of concentrates, this ratio is reduced to 1.06 ± 0.21.

2.5. Mercury Environmental and Health Impacts

Mercury is a silvery white heavy metal that occurs naturally in the environment and it can be found in different forms (UNEP, 2012). It is the only metal that is liquid at standard conditions of temperature and pressure and it easily amalgamates with others metals (e.g. gold, silver, tin, copper,), with the exception of platinum and iron (Veiga & Meech, 1999). Mercury is a trans-boundary pollutant that reaches great distances when in the air or associated with particulate matter in the rivers (Meech et al., 1988; Guimarães et al., 1999). Mercury evaporates easily into the air and is recognized as a chemical of global concern due to its long-range transport in the atmosphere (UNEP 2012; 2013).

In ASGM, when mercury and gold amalgams are burned, mercury vapor is released into the air, where it is directly inhaled by workers and contaminates the surrounding community (Risher, 2003; Kiefer et al., 2015). When released in tailings, metallic mercury can be transformed into a more toxic form, methylmercury (CH_3Hg^+), which is easily bioaccumulated in the aquatic biota (Watras & Bloom, 1992; Veiga & Hinton, 2002; Coles & Cochrane, 2006).

The exposure of elemental mercury is extremely dangerous and children are considered very vulnerable to it effects (Clarckson, 1997; Hinton et al., 2003; Bose-O'Reilly et al., 2008; Spiegel & Veiga, 2010; Oscar Betancourt et al., 2015). Exposure to mercury in pregnant women and women of childbearing age may cause severe neurodevelopmental problems in the developing fetus and exposure to high levels can be fatal (Jones, 1971; Hyman, 2004; Counter, 2006; WHO, 2007).

When miners burn the amalgam, they expose themselves and the surrounding community to mercury vapor and the mercury concentrations vary tremendously: 0.1 – 6,315 µg/m^3 with a mean of 183 µg/m^3 in Venezuela (Drake et al., 2001) and from 50 to 50,000 ng/m^3 (UNIDO, 2016) in Portovelo. However, monitoring of Hg emissions during the burning of amalgams at gold shops and processing centers in Porovelo-Zaruma have showed maximum spikes over 2,000,00 μg/m^3 (UNIDO, 2016). According to Hu et al. (2013), methylmercury (CH_3Hg^+) is formed from inorganic Hg (II) by the action of anaerobic organisms that live in water bodies. The contamination of humans by methylmercury occurs by the ingestion of food and not by contact with contaminated water or sediment (IPCS, 2003; Dellinger et al., 2012).

Methylmercury is a potent neurotoxin that impairs the nervous system. According to the World Health Organization (WHO), the limit for public mercury exposure to humans is 1.0 μg/m^3 (UNEP, 2012). Fetuses and young children are more sensitive to methylmercury exposure than adults (WHO, 2000, 2007). Methylmercury can cause many types of problems in children, including damage to the brain and nervous system, mental impairment, seizures, abnormal muscle tone, and problems in coordination (Counter et al., 2002; IPCS, 2003; Hyman, 2004; USGS, 2005). Women of childbearing age are also susceptible to contamination. Depending on the frequency and degree of exposure, effects can be diverse, ranging from sterility to spontaneous abortion (Counter et al., 2002; Hinton et al., 2003). Therefore, the consumption guidelines in areas where methylmercury (CH_3Hg^+) is known to occur in fish at potentially harmful levels tend to be more restrictive for children as well as for pregnant women, nursing mothers, and other women of childbearing age (Hinton et al., 2003; Counter et al., 2006; Bose-O'Reilly et al., 2008).

Table 2-3. Risks associated with mercury use in ASGM.

Risks to Human Healthy	Risks to the Environment
• Consumption of contaminated fish • Improper handling of contaminated sediments • Inhalation of mercury vapors • Municipal drinking water supplies safe • Some mine waters unsafe for consumption	• "Hot spots" at mine sites • Contaminated sediments • Transformation to methylmercury • Transport to downstream areas • Bioaccumulation an biomagnification in food chain

Table adapted from USGS, 2005

2.6. The Minamata Convention on Mercury

In January 2013, The United the Nations Environment Programme (UNEP) created the first regulation associated with the use and production of mercury – the Minamata Convention on Mercury (MCM) in Japan. According to UNEP (2013), the international convention aims to protect human health and the environment from the damaging effects of mercury. The principal objective of the Convention is to alleviate anthropogenic emissions and releases into the environment, and cease the use and trade of mercury by 2020 (Veiga & Marshall, 2016). To date, a total of 128 countries signed and 28 ratified the agreement to take actions which include both enforced and intended procedures to discontinue the trade the use of mercury (UNEP, 2016). The Ecuadorian Government signed the agreement on October 10, 2013; however, it has still not been ratified (MCM, 2016). According to Kessler (2013), the approach adopted in the convention allows the countries that agreed with it components to develop in a positive matter their own action plan to implement measures to reduce and eliminate the use of mercury. In November, 2012, UNIDO implemented a project in Ecuador with the objective of protecting people's health and the environment and minimizing mercury releases from ASGM operations, which affects the transboundary Puyango-Tumbes River Basin in the south of Ecuador and north of Peru. However, the results obtained in this project, which was completed in June 2016, are still under evaluation.

In less developed countries, the use of mercury remains a problem that cannot be solved without outside support, since it can easily be obtained and used, and artisanal gold miners mainly disregard the health risks associated with the use of mercury. The Convention has made it more difficult for artisanal miners to access mercury, since the average cost of mercury is constantly increasing worldwide, as observed by Veiga & Marshall (2016). -

2.7. Cyanide Use in Artisanal and Small-Scale Gold Mining

Sodium cyanide (NaCN) has been used in gold mining for over 100 years to recover gold from the ore and concentrates in solution, with significant increases in gold recoveries (Habashi, 1987; Velásquez-López & Veiga, 2007). According to ICMC (2014), approximately 1.1 million metric tonnes of sodium cyanide are produced worldwide annually, however only 6% is used to produce cyanide reagents for mining operations to recover gold (Hilson & Monhemius, 2006). In 1998, Korte & Coulston (1998) estimated that the amount of cyanide hydrogen cyanide (HCN) that escapes into the atmosphere from gold mining operations is 20,000 tonnes annually and the halftime persistence of cyanide in the atmosphere of approximately 267 days. The cyanidation processes can be classified as either a destruction-based process or a recovery-based process (Botz, 1999), and its application in artisanal gold mining is mainly used to recover gold from solution or slurry, depending on the level of treatment required.

The use of cyanide in gold processing centers in Ecuador has increased substantially in the last two decades (Tarras-Walhberg et al., 2000; Veiga et al., 2009; Velásquez-López, 2010 ; Veiga et al., 2014a), due to a desire to avoid the dangers of using mercury while at the same time increasing gold recovery. In Ecuador, the processing plants use cyanide in agitated tanks using either the Carbon-in-Pulp or Merrill Crowe process to extract gold from the ore (Velásquez-López et al., 2010). There are only a few studies that address the interaction of the the mercury-cyanide complexes downstream (Botz, 1999; Appleton et al., 2001; Velásquez-López et al., 2010; Guimarães et al., 2011; Veiga et al., 2014b).

Every year, mercury and cyanide are released into rivers, severely damaging the environment (Tarras-Wahlberg et al., 2000; Hinton et al., 2003; Castilho et al., 2006; Velásquez-López et al., 2010; Adler-Miserendino et al., 2013; Veiga et al., 2014b). Artisanal miners have attempted to use alternative methods of gold extraction, but with limited success due to the lack of knowledge and capital of the miners (Veiga et al., 2005; Vieira, 2006; Veiga et al., 2009; Velásquez-López et al., 2010; Veiga et al., 2014b).

2.8. Cyanide Environmental and Health Impacts

Cyanide is a natural chemical compound formed in the enviroment and it can be produced naturally by bacteria, numerous species of plants and through incomplete combustion during forest fires, which is a major environmental source of cyanide (ICMC, 2014; UNIDO, 2016). Once released in the environment, the reactivity of cyanide can provide numerous pathways (Table 2.4) for its degradation and attenuation (ICMC, 2014). However, it is used in the mining industry to extract gold and silver from ore, and it can be extremely toxic in low concentrations to aquatic life, wild life and people according to the International Cyanide Management Code (ICMC, 2014). For the safety of humans and the aquatic environment, cyanide is rigorously regulated. The cyanide discharged from mines, especially when cyanide is combined with mercury during cyanidation processes, is considered the greatest threat to aquatic life and aquatic environments (Davies, 2014). Therefore, water monitoring and water management on mine sites are vital (Korte & Coulston, 2000; Puño, 2014).

The long-term health effects of cyanide have been observed in people with a diet high in cyanide-containing plants such as bamboo, cassava and sorghum, where goiters and depressed thyroid function were observed (Eisler & Wiemeyer, 2004). In order to determine the toxicity of sodium cyanide to humans, the nature of the exposure is considered. Typically, it can be expressed as the concentration or dose that is lethal to 50% of the exposed population (LC50 or LD50) (ICMC, 2014). According to ICMC (2014), the LC50 for gaseous sodium cyanide is 100-300 parts per million, and the inhalation of cyanide in this range can cause death within 60 minutes. Inhalation of highly concentrated cyanide gases - 2,000 parts per million - can causes death within one minute. The LD50 for ingestion is considered between 1-3 milligrams per kilogram of body weight, calculated as sodium cyanide. But once in the bloodstream, cyanide form a stable compound and at high concentrations, cyanide poisoning effects organs and systems in the body, including the heart (ICMC, 2014).

According to Eisler & Wiemeyer (2004), “despite cyanide toxicity, there have been no documented accidental human deaths definitively related to cyanide poisoning in the Australian and North American mining industries over the past 100 years which indicates that the hazard of cyanide to humans has been controlled by minimizing the risk of its handling and of industrial exposure”. Formalized, large-scale mining has strict standards and safety protocols to follow when working with cyanide (ICMC, 2014); however in ASGM operations, in developing countries, there is a lack of information, awareness and about the dangers of cyanide.

The environmental and social impacts caused by ASGM operations in Ecuador are similar to other countries where ASGM is common (Prodeminca, 1999; Tarras-Wahlberg et al., 2000; Velásquez-López, 2010; Adler-Miserendino et al., 2013; Guiza & Aristizabal, 2013). Most impacts are caused by mercury and cyanide use in the processing of gold, as well as the sedimentation and related pollution associated with tailings mismanagement and alluvial extraction activities, especially in rivers and other watersheds (Veiga et al., 2014a). The resulting water contamination has a direct impact on the ecosystem, but also on water use for other economic activities and on the health of the population.

Table 2-4. Cyanide pathways in the environment (Adapted from ICMI 2014)

Complexation	Cyanide form complexes of varying stability with many metals. Most cyanide complexes are much less toxic than cyanide but weak acid dissociable with complexes such as those of copper and zinc are relatively unstable and will release cyanide back to the environment
Precipitation	Iron cyanide complexes form insoluble precipitates with iron, copper, nickel, lead, cadmium, tin and silver over a pH range of 2 - 11
Adsorption	Cyanide and cyanide metal complexes are adsorbed on organic and inorganic constituents in soil, including oxides of aluminium, iron, manganese, certain types of clays, feldspars and inorganic carbon
Cyanate	Oxidation of cyanide to less toxic cyanate requires a strong oxidizing agent such as ozone, hydrogen peroxide or hypochlorite
Thiocyanate	Cyanide reacts with some less sulfurs species to form the less toxic thiocyanate. Potential sulfur sources include free sulfur and sulphide minerals such as chalcopyrite ($CuFeS_2$), chalcocite (Cu2S) and pyrrhotite (FeS), as well as their oxidation products, such as polysulphides and thiosulfate
Volatilization	At the pH typical of environmental systems, free cyanide will be predominately in the form of hydrogen cyanide evolving slowly over time. The amount of cyanide lost through this pathways increases with decreasing pH, increased aeration of solution and with increasing temperature. Cyanide is also lost through volatilization from soil surfaces
Biodegradation	Under aerobic conditions, microbial activity can degrade cyanide to ammonia, which then oxidizes to nitrate. This process has been shown effective with cyanide concentration of up to 200 parts per greater than 2 parts per million are toxic to theses microorganisms
Hydrolysis	Hydrogen cyanide can be hydrolyzed to formic acid or ammonium formate. Although this reaction is not rapid, it may be of significance in ground water where anaerobic conditions exist
Effects on wildlife	Cyanide react readily in the environment and degrades or form complexes and salts of varying stabilities, it is toxic to many living organisms at very low concentrations.
Aquatic Organisms	Fish and aquatic organisms are particularly sensitive to cyanide exposure. Concentration of free in the aquatic environment ranging from 5.0 to 7.2 micrograms per liter reduce swimming performance and inhibit reproduction of many species of fish. The toxicity of cyanide to aquatic life is probably caused by hydrogen cyanide that has ionized, dissociated or photochemically decomposed from compounds contained cyanide
Birds	Reported oral LD50 for birds range from 0.8 milligrams per kilogram of body weight (American racing pigeon) to 1.1 milligrams per kilogram of body weight (domestic chicken). Ingestion of Weak Acid Dissociable (WAD) cyanide solutions by birds may cause delayed mortality.
Mammals	Cyanide toxicity to mammals is relatively common due to the large number of cyanogenic forage plants. Although present in the environment and current in many plants species, cyanide toxicity is not widespread because cyanide has low persistence in the environment and is not accumulated or stored in any mammal.

Chapter 3: ASGM Processing Centers in Southern Ecuador

3.1. Historical Perspective: Artisanal and Small-Scale Gold Mining in Ecuador

Southern Ecuador has been recognized for its potential for mining and extraction of precious metals (i.e. gold and silver) since the second half of the 18th century (Paredes, 1980). However, African slaves and indigenous people had been working small excavations for gold in southern Ecuador since the 1550s (Lane, 2004). Since the colonial era, the mining camp of Portovelo has increased from 700 inhabitants to 22,000 today, where approximately 80% of the population are involved in mining activities in some capacity (Astudillo, 2007; Velásquez-López, 2010).

Industrial mining began in 1880, when the British Zaruma Gold Mining Limited Company was acquired by SADCO (South American Development Company) (Paredes, 1980), when lack of operating capital forced the British company to leave the mine in 1896 (Paredes, 1980). Between 1896 and 1950, SADCO operations extracted 1000 tonnes of gold and 1500 tonnes of copper, generating approximately 80,000 tonnes of tailings (Astudillo, 2007). In 1951, disputes between union workers and the Ecuadorian Government culminated in the bankruptcy of the SADCO operations. The mine was sold to CIMA (Compañía Industrial Minera Asociada), an Ecuadorian company that included former SADCO employees partnered with the municipal government of Zaruma.

According to Vangsnes (2015), the development of artisanal and small-scale gold mining activities in Ecuador can be summarized into three historical periods: 1) the late 1970s, when informal ASGM started emerging in the mining district of Portovelo-Zaruma, 2) the early 1980s, when gold deposits in Nambija and Ponce Enriquez were explored and re-worked, and 3) the beginning of 1990s, when ASGM mining in southern Ecuador became more consolidated in conjunction with the rapid establishment of processing centers (UNEP, 2012).

By 1978, CIMA had extracted 11 tonnes of gold and 85 tonnes of silver, however, inflation and mismanagement ultimately led to bankruptcy (Sandoval, 2001). Between 1978 and

1980, the price of gold substantially increased, reaching more than US$ 800/oz. During this time, artisanal miners became attracted to the high value of gold and began reworking abandoned mines in the region. The United Nations assisted the Ecuadorian Government in the 1970s by providing technical assistance with geochemical studies of the region (Sandoval, 2001). During this period, the Belgian Government also carried out few studies of the mineral resources in Portovelo-Zaruma and mapped the ore deposits of the region (Sandoval, 2001; Astudillo, 2007).

In 1978, poverty-stricken miners invaded the old SADCO pit and began ASGM activities. During this period, informal mining increased and artisanal gold mining activities started with the development of processing centers (Sandoval, 2001; Velásquez-López, 2010).

In 1994, local entrepreneurs started building processing centers to offer gold processing services to the miners (Tarras-Wahlberg et al., 2001). Between 1993 and 1996, the Ecuadorian government gave titles and created agreements with miners, cooperatives and owners of processing centers in Portovelo-Zaruma, formalizing their activity (Velásquez-López, 2010).

Artisanal and small-scale gold mining is the primary source of gold production in Ecuador, accounting for 85% of the country gold production (Veiga, 1997; UNEP, 2012). In Latin America, Ecuador is in the top four for both estimated gold production and in total number of artisanal and small-scale gold miners (Veiga, 1997). The mining district of Portovelo, located in the Province of El Oro in Ecuador, has a small town and is considered the largest mining district of Ecuador. Zaruma is located about 10 km from Portovelo. These two areas form the largest gold mining district of Ecuador (Sandoval, 2001; Velásquez-López, 2010). There are four top gold mining areas in southern Ecuador including: Portovelo-Zaruma in the Province of El Oro, Ponce Enriquez in Azuay Province, and Nambija and Guayzimi in Zamora Province (Sandoval, 2001). In 2000, it was estimated that approximately 100,000 artisanal miners were actively working in all Ecuador, which equated to 4% of the country's population relying directly on ASGM activities to sustain their livelihood (Appleton et al., 2001; Sandoval, 2001; Betancourt, 2005; Velásquez-López & Veiga, 2007).

More than 15 years ago, it was reported that there were close to 400 mines operating in the Portovelo-Zaruma region, with 65 processing centers offering services to recover the gold, including crushing, grinding the concentrate, amalgamating and sometimes leaching with cyanide (Tarras-Wahlberg et al., 2000). In 2006, when the price of gold increased considerably, there were 63 mining concessions, 800 mining partners, a large number of small miners and 110 processing centers in the region (Lovitz, 2006). By 2010, the number of processing centers had decreased to 104 and the Ecuadorian Government closed the ones that did not hold a legal license to operate (Velásquez-López, 2010). Currently, there are 240 mine concessions and 87 processing centers, of which 78 have a legal operating permit (Veiga et al., 2014a).

According to Guimarães et al. (2011), there are annual releases of 650 kg of inorganic mercury and 6000 tonnes of sodium cyanide into the local river system, from over 880,000 tonnes of tailings and mining waste generated by the processing centers in Portovelo-Zaruma. When mercury is released both with tailings and also via atmospheric emissions, water bodies over a large area can become contaminated, culminating in Hg bioaccumulation in aquatic organisms and mercury biomagnification up food chains (Watras & Bloom, 1992; Hinton et al., 2003, Veiga & Marshall, 2016).

It has been determined that the discharge of cyanide complexes, mercury and other heavy-metals in fluvial environments becomes associated with suspended particles and river bed sediments, which can then be carried far downstream, affecting areas hundreds of kilometers away from the point of discharge (Tarras-Wahlberg et al., 2001; Guimarães et al., 2011). In the region of Portovelo-Zaruma, the large releases of contaminants into the Puyango-Tumbes River is directly related to inadequate management of the waste and tailings produced at processing centers, showing that better policy, governance and enforcement are necessary in order to achieve more sustainable mining practices (Adler-Miserendino et al., 2013; Veiga et al., 2014b). Over the last fifteen years, small-scale miners have begun to replace the use of mercury with cyanidation methods (Eisler & Wiemeyer, 2004; Tarras-Walhberg et al., 2000; Veiga et al., 2009; Velásquez-López, 2010). There are only few studies that analyzes the interaction of mercury with cyanide and the risks to miners and to the environment (Velásquez-López, 2010; Guimarães et al., 2011; Veiga et al., 2014a).

3.2. Site Description

The mining district of Portovelo-Zaruma is located in the Province of El Oro in southwest Ecuador. Zaruma is a town in the southern part of Ecuador located in the Province of El Oro, in the western range of the Andes mountains, at an elevation about 1200 meters above sea level. The Zaruma mountainous area is surrounded by deep valleys, where many rivers originate such as the Salvias, Ortega, Amarillo, and El Salado Rivers (Velásquez -López, et al., 2010). Portovelo is a small city located at 7 km from Zaruma where the majority of the processing centers are located. The majority of the processing centers selected and studied were located in Portovelo in the region known as El Pache, where a large number of processing centers are found, in the catchment of the Amarillo River. The Amarillo River joins the Calera and Pindo Rivers just downstream of the processing centers in Portovelo and form the Puyango-Tumbes River (UNIDO, 2016).

The Puyango-Tumbes River watershed is located in the southwestern region of the Andes and approximately 160 km from El Oro Province. It is the most significant aqua system along the Pacific coast in South America (Clark & Hakim, 2014). The Puyango River connects with Portovelo-Zaruma in Ecuador, but is called the Tumbes River once it enters northwest Peru. This bi-national watershed is a vital source of water for people in Ecuador and Peru especially for the processing centers in the region of Portovelo-Zaruma. According to Velásquez-López (2010) and Puño (2014), the Puyango-Tumbes River Basin represents a region of major international dispute between these two countries because of the high levels of heavy metal contamination coming from Ecuador, which causes negative effects on human health. The Puyango-Tumbes River basin is divided into three zones: 1) the upper basin, 2) the middle basin and 3) the lower basin. This study is mainly focuses in the upper basin which includes the region of Portovelo-Zaruma, where the Puyango River is formed, which then flow into the Pacific Ocean, polluting the Peruvian waters (UNIDO, 2016).

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). Gold is mainly extracted from sulfide-rich ores and is processed at one of the 87 processing centers using mercury (Hg) and cyanide (NaCN). Both of these hazardous chemicals used for amalgamation and leaching of the gold-rich ore, respectively, are inappropriately disposed of into the surrounding environment. The environmental impacts from these processes are severe and include: discharge of heavy metals (i.e. arsenic, mercury, manganese, lead), cyanide pollution, discharge of suspended solids into the rivers due to poor disposal and non-treatment of the tailings, absence of information about mineral reserves, wastewater, pollutants from industrial activities including domestic sewage, petroleum, soil disturbance from agriculture, and erosion contributing to the deterioration of water quality in the basin (SGAB-Prodeminca, 1998; Prodeminca, 1999; Appleton et al., 2001; Tarras-Wahlberg et al., 2001; Betancourt et al., 2005; Guimarães et al., 2011; Puño, 2014).

In October 1998, Ecuador and Peru signed a bi-national agreement, with the objective of improving the water quality standards in the Puyango-Tumbes watershed, effectively ending more than 150 years of territory disputes, particularly in the Amazon region (Clark & Hakim, 2014). Since this accord has been signed, both nations have demonstrated a strong commitment to working together to address trans-border concerns (UNIDO, 2016).

Figure 3.1. Location of Processing Centers in the mining province of Portovelo-Zaruma within the Puyango-Tumbes binational watershed (Adapted from Tarras-Wahlberg et.al. 2000).

3.3. Gold Processing Centers in Portovelo-Zaruma

Artisanal and small-scale gold mining processing centers (Figure 3.2) in southern Ecuador have flourished in recent years in response to the miners' need to have facilities to crush, grind, concentrate and amalgamate the gold they extract, without having to invest their own money in processing equipment (Veiga et al., 2009; Velásquez-López et al., 2010; Veiga et al., 2014a). In Ecuador, gold is extracted mainly from sulphide-rich ores using hard-rock methods of crushing and grinding, followed by gravity concentration (Tarras-Wahlberg et al., 2000). In the region of Portovelo-Zaruma, miners stay at a site for 14-21 days at a time, resulting in production of between 40-80 tonnes of ore. They then transport this ore generally by truck in 50 kg plastic bags to one of the many processing centers, to be processed by "specialized" operators[1] where gold is extracted using different techniques (Velásquez-López et al., 2010; Veiga et al., 2014a). The centers either do not charge the miners, with the condition that the miners leave the gold-rich tailings in their facilities, or charge a nominal fee depending on the amount of ore processed and the method selected by the miners to recover the gold (Velásquez-López, (Velásquez-López et al., 2010; Veiga et al., 2014a). Regardless of whether the tailings are contaminated with mercury, they are then subjected to cyanidation (Velásquez-López et al., 2011; Veiga et al., 2014a).

[1] **"Specialized" operators refers to the engineers who manage the operations of the processing centers.**

Figure 3.2. Processing centers in the mining district of Portovelo-Zaruma. Photo by A. Gonçalves, 2015.

Sandoval (2001) estimated that there were approximately 100,000 workers directly employed in artisanal and small-scale gold mining operations in Ecuador. In 2010, according to an official inventory undertaken by the Ecuadorian Ministry of Energy and Mines (MEM), 1349 artisanal miners were extracting gold in Ecuador (MRNNR, 2013), including a total of 541 in the Province of El Oro (which includes Portovelo-Zaruma). Velásquez-López, (2010) estimated that approximately 10,000 people were directly involved in ASGM in the region, although this could be as low as one tenth of the actual number, considering that only 20% of the miners are legally formalized. The Association of Owners of the Processing Plants (APROPLASMIN) estimated that approximately 9 tonnes of gold were produced in 2012. According to MEM (2013), the official gold production in Ecuador is approximately 10 tonnes/a, in which 80% of this is generated by ASGM (Veiga et al., 2014a).

The processing centers in southern Ecuador are known by the local communities as "plantas de beneficio" (Velásquez-López, 2010). The gold is recovered from the processing centers mainly through the use of rudimentary techniques using mercury and cyanide (Veiga et al., 2014a). As a result, every year, tonnes of mercury are used and released into the environment (Tarras-Wahlberg et al., 2000; Velásquez-López et al., 2010; Veiga et al., 2014a, Kiefer et al., 2015; Nichols et al., 2015).

In 1990, custom milling emerged in the region, due to some individuals taking advantage of the lack of capital and knowledge of the miners and establishing processing centers to crush, grind, concentrate and extract the gold by amalgamation using mercury (Velásquez-López, 2010; Veiga et al., 2014a). Unfortunately, because there were no alternative method to process the ore, small-scale and artisanal miners in Ecuador still use the amalgamation method with *chanchas*[2] to extract the gold, resulting in extensive environmental degradation (Velásquez -López, 2010; Veiga et al., 2014a; UNIDO, 2016).

The processing centers in the Province of El Oro are coordinated by APROPLASMIN. Founded in 1996, this unique and powerful association brings together more than 60 plants in the Portovelo-Zaruma region, representing the processing plant owners and their workers (Velásquez-López, 2010). The operating capacity of the plants has increased in recent years, due to increases in the number of artisanal miners working in the region and the amount of ore being processed (Velásquez-Lopéz, 2010; Veiga et al., 2014a). APROPLASMIN has been working to find ways to mitigate environmental impacts caused by gold processing, with proposals in recent years for better management and disposal of tailings. However, in comparison, no solutions have been proposed as of yet to address the informality of thousands of artisanal miners who use the processing centers to recover their gold. Mining activities are still not well organized in the Portovelo-Zaruma region and thousands of artisanal and small-scale miners operating in concession areas are working clandestinely (Veiga et al., 2014a).

[2] **A "*chancha"* is a small ball mill commonly used for gold amalgamation in Ecuador. It refers to both the machinery and the process using the machinery**.

According to Ecuadorian legislation, the mining code acknowledges three categories of miners: 1) “artisanal miners”: those processing less than one tonne of ore a day, who are usually informal and normally illegal, 2) “small”: those processing up to 300 tonnes/day, and 3) “large”: those processing more than 300 tonnes/day (CIIED, 2014). According to Veiga et al. (2014a), the processing plants in Portovelo-Zaruma cumulatively treat 3,000 tonnes of ore per day. From this, it was determined that approximately 10% of the processing centers process less than 10 tonnes of ore per day, 60% between 10-50 tonnes/day, 25% between 50-100 tonnes/day, and only 5% more than 100 tonnes/day, using their own captive mining operations (Veiga et al., 2014a).

According to Velásquez-López (2010), almost half of the ore processed in Portovelo-Zaruma is transported from different locations, including Torata, Cangrejos and La Tigrera in the Province of El Oro, Ponce Enriquez in the Province of Azuay, San Gerardo in El Salvador Province, Pujilli in Cotopaxi Province, Santo Domingo de Los Colorado in Santo Domingo de Los Tsáshilas Province, Bolivar Province, and also Suyo, a mining site located in Piura in northern Peru. Usually, the ores that come from other localities are richer in arsenic, lead and other heavy metals than local ore (Velásquez-López, 2010; Veiga et al., 2014a). Additionally, miners have also brought mercury-contaminated tailings from the Ponce-Enriquez region to the processing centers in Portovelo-Zaruma, as the processing centers have more resources to deal with tailings, including the use of cyanidation tanks.

Processing centers line the banks of the rivers, which allows for easy access to water needed for ore processing. However, most of these processing centers have been developed in a disorderly manner, which has resulted in lack of space for expansion and for construction of adequate tailings facilities (Veiga et al., 2014a). As a result of the confined space, many processing centers are forced to dispose of tailings directly into the river.

Conflicts between miners, processing center technicians and gold dealers are common, according to Velásquez-López (2010). In addition, the exploitation of gold in the region is undertaken typically by non-formalized miners who engage in partnerships with other artisanal miners, working in groups of 5 -10 people. When a miner does not have their own concession, they end up sharing the ore extracted with the owner of the land. Consequently, in most cases, informality, ignorance, the lack of regularization, and the lack of financial and technical resources are the principal reasons why mining operations are still underdeveloped in southern Ecuador.

3.4. Integrated Assessment of ASGM in Southern Ecuador

A number of studies have been carried out in southern Ecuador over the past four decades, mainly focused on understanding the implications and consequences of mercury use and release into the environment (SMI, 1995; Appleton et al., 1996; Appleton 2001; Tarras-Walhberg et al., 2000,2001; Tarras-Walhberg & Lane, 2003; Betancourt et al., 2005; Velásquez-López, 2010; Velásquez-López et al., 2000,2011; González et al., 2011; Guimarães et al., 2011, Veiga et al., 2014a; Kiefer, 2015, UNIDO, 2016). As described in chapter 2, when the amalgam which contains mercury and gold is burned, the mercury is vaporised and released into the atmosphere. Previous assessment (González-Carrasco et al., 2011) in the region aimed to bring to raise awareness to the authorities, miners, and the communities of the devastating hazards of mercury amalgamation, both in terms of human health and the environment. Lamentably, some of the impacts associated with these mining activities are still unknown and future work in the site is needed, especially in understanding the discharge of mercury-contaminated tailings discharged by the processing plants into the water bodies of the Puyango-Tumbes River Basin. There are significant knowledge gaps among the ASGM community in Ecuador. Steps need to be taken to measure and address the existing problems in ASGM, including long-term education of the miners, technical curriculum, socio-economic issues, environmental, health, infrastructure of the processing plants and conflicts with the communities. The governments need to play their role as well and strengthen partnerships with the miners with the hope of increasing cohesiveness, and to legalize the artisanal mining activities towards a sustainable future. The role of the government as the enforcer of law and regulator of mining activities in the region of Portovelo-Zaruma needs to be more active in order to reduce the environmental impacts. It is especially important to gain the miner’s perspectives regarding which practices have been most useful to them in overcoming the barriers to sustainable mining practices and what barriers remain the most difficult to overcome despite formalization efforts. The information that was gathered at the processing centers during this study was compared with previous studies in southern Ecuador, as illustrated in Table 3.1.

Table 3-1. Previous ASGM assessment in southern Ecuador

Reference	Content
Veiga, (1997)	Who wrote about use and losses of mercury pollution in ASGM in Latin America.
SGAB-Prodeminca, (1998)	Who founded by the Work Bank evaluated the environmental impacts and contamination of water resources in the region of Portovelo-Zaruma and in the Puyango-Tumbes River.
Wahlberg et al., (2000; 2001)	Who described the environmental impacts of small-scale and artisanal gold mining in southern Ecuador and the implications for the management of ASGM operations.
Betancourt et al., (2005)	Who reported the environmental and health impacts of mercury used by ASGM sector in the Puyango-Tumbes River Basin.
Lovitz, (2006)	Who wrote a thesis on overcoming barriers to cleaner ASGM operations in the district of Portovelo-Zaruma and Ponces Enriquez, Ecuador.
Astudillo, (2007)	Who published a Marxist inspired recapitulation of the local mining history in Ecuador.
Velásquez-López et al. (2010, 2011)	Who conducted a detailed study about the process of gold amalgamation and identified strategies to reduce environmental impacts for improve the processing techniques including cyanidation.
Guimarães et al., (2011)	Who conducted a study about the effect of cyanide on mercury methylation in a gold mining district in Portovelo-Zaruma including the measurement of free cyanide in water and sediments samples.
UNEP, (2012)	Who conducted an analysis of formalization approaches in ASGM sector based on previous experience in Ecuador, Mongolia, Peru, Tanzania and Uganda
Adler-Miserendino et al., (2013)	Who highlighted the challenges to confront, measure and regulate cumulative environmental impacts from local ASGM.
Angeloci, (2013)	Who wrote a thesis on myths and realities in artisanal gold mining mercury contamination using the South of Ecuador as a basin for his analysis.
Veiga et al., (2013, 2014a; 2014b)	Who described the processing plants in ASGM worldwide including Portovelo and reviewed barriers to reduce the use of mercury in the ASGM sector.
CIIED, (2014)	Which is a report about technical workshop conducted in Portovelo-Zaruma in December 2013 that brought together researchers from 8 countries with a total of 29 people to discuss about the solutions to reduce ASGM impacts. The idea of implementing trainings centers for artisanal miners was the core of the discussion.
Nichols et al., (2015)	Who described the political tensions between Peru and Ecuador due to the contamination of the Puyango-Tumbes River Basin by the ASGM and the hypothetical process of closure of local processing plants.
Vangsnes, (2015)	Who wrote about a political ecological approach on ASGM in the southern Ecuador.

Chapter 4: Methodological Approach

4.1. Data Collection

This study performed an assessment of 52 artisanal and small-scale gold mining processing centers in the Portovelo-Zaruma region. Furthermore, it shows the current level of expertise and access to technology of both artisanal miners and gold processing center owners. It also illustrates the factors that influence the evolution of gold production techniques at the processing centers, while at the same time highlights the existing challenges and barriers for implementing wide-spread use of cyanide in gold production processes and tailings management in the region of Portovelo-Zaruma. A qualitative approach was adopted to assess the methods used to process gold ores and to understand the source of knowledge employed by the owners of the processing centers and operators in southern Ecuador. Furthermore, partnerships with owners of processing centers, miners, community members, workers at the mine, gold shop owners and local mining consultants also provided valuable information in order to check and triangulate the data obtained in this study. In order to fulfill and address the objectives of this study, structured interviews were conducted with technicians who operates the processing centers. Quantitative data was obtained regarding the technologies employed, chemicals used (e.g. mercury and cyanide) and quantities consumed, the size of each operation, location, number of employees, number of days of operation, plant age (years), type of processing center, equipment and the different methods used to extract gold , gold grades, quantities of ore processed and gold produced, level of tailings management, and costs associated with electricity and costs for the miners to rent the processing centers were estimated based on the field observations and information provided by the processing centers.

A questionnaire was used to collect the necessary information from the owners and engineers of each plant. The assessment of the plants occurred in two periods: 1) in December 2013, during which 52 processing plants were visited (Appendix A and Appendix B), and 2) from May 19th to June 5th, 2015 and from August 21st to August 28th, 2015, during which 20 processing plants were visited (Appendix C and Appendix D) and explored in detail. The visits to each plant took approximately one hour to conclude.

The criteria used to select the processing centers were as follows:

- ✓ Accessibility to the processing centers
- ✓ Availability of the owners of the processing centers to provide information
- ✓ Representability of the centers in terms of technology used and relevance in relation to gold produced in the region.

4.2. Mineralogical Analyses

X-ray diffraction (XRD) is a common technique used for the study of phase changes in solid materials. It is based on the fact that crystals in minerals are composed of atoms arranged in an orderly manner, a piece of information important for the identification and classification of different minerals (Shafer, 2014).

Concentrate and tailing samples from the operation of four processing centers were obtained during the field trip in August 2015, and analyzed by the Department of Earth, Ocean & Atmospheric Sciences at the University of British Columbia. The three concentrate samples were products of gravity concentration using carpeted sluice boxes and flotation processes. A tailings sample were obtained from only one processing center, after cyanidation using Carbon-in-Pulp process (CIP).

In order to identify the main minerals existent in the provided samples, a qualitative analysis was performed. Approximately 30 g of each concentrate sample was pulverized for 6 minutes into very fine powder in order to obtain the optimum grain sizes for the analysis using a corundum automatic mortar. A small portion of the powder was smeared on a glass slide with ethanol and submitted to the X-Ray Diffractometer. Moreover, each of the samples was placed into a sample holder and irradiated with x-rays of a fixed wavelength. The intensity of the diffracted radiation was recorded using a goniometer diffraction patterns (diffractograms) were collected in a step-scanning mode over a range of 3 to 80° 2θ with CoKα radiation on a Bruker D8 Focus Bragg-Brentano diffractometer (Figure 4.1).

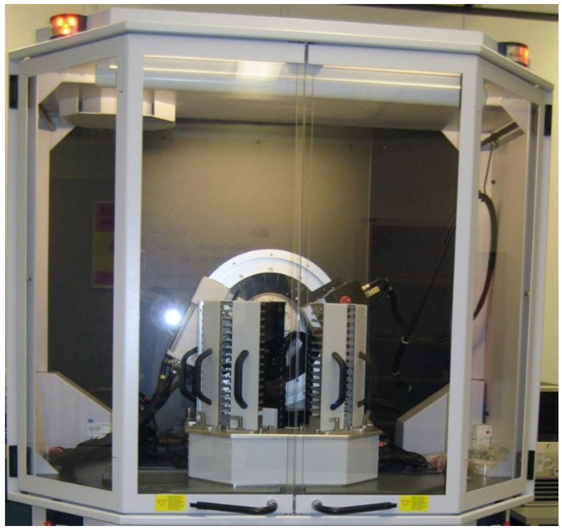

Figure 4.1. Bruker X-Ray diffractometer.

4.3. Data Analysis

The information gathered in this study used observational fieldwork and the document analysis of recent reports and publications in the mining district of Portovelo-Zaruma (Table 3.1). The primary data was collected through the questionnaires given to the owners and engineers of each processing plant and were tabulated in MS Excel. The data resulted in calculations based on two sources of information: 1) the owners and engineers of the processing plants, both through the questionnaire and informal discussions, and 2) own observations visiting the plants, in conjunction with the understanding of the methods used during gold processing in Portovelo-Zaruma. Furthermore, information collected via informal conversations with the actual miners contributed to better precision of my calculations.

Mercury mass balances from UNIDO (2016) were also compared to previous results from Ecuador in 2008 (Velásquez-López et al., 2010) and Colombia in 2010 (Cordy et al., 2011).

Chapter 5: Results and Discussion

5.1. Current Characterization of the Gold Processing Centers

The processing center facilities in Portovelo-Zaruma, according to Velásquez-López (2010), started as a rental service to artisanal and small-scale miners. As observed in the field work investigating the miners, the rationale was that miners with low capital would not need to invest in mineral processing equipment and could therefore rely on the expertise of the operators of the processing plants. Equipment rental has included: crushing, grinding (Chilean mills, ball mills), gravity concentration, amalgamation, flotation, cyanidation tanks including Carbon-in-Pulp (CIP) and Merrill-Crowe, and gold smelting. Some processing centers rent each piece of equipment separately, whereas others offer the whole process of gravity separation and amalgamation. Figure 5.1 shows the different types of processing centers facilities in the region of Portovelo-Zaruma.

In the region of Portovelo-Zaruma, there are three different scenarios for ore processing at the processing centers: 1) processing centers process their own ores exclusively, 2) processing centers rent the equipment for miners to process their own ores, and 3) processing centers process both their own ores and also rent the equipment to miners as well. The third scenario is the most common. In order to extract gold from the ore and to recover the gold, the processing centers offer different services with varying technologies, some more rudimentary and others more advanced. For example, some processing centers concentrate the ore in sluice boxes followed by amalgamation of the concentrates manually by panning or in *chanchas*. Some centers only offer the amalgamation service in *chanchas* to amalgamate the high grade ores, the material retained inside the Chilean mills ("*las ollas*") or, sometimes, the gravity concentrates. Veiga et al. (2014a) found that miners generally extract less than 30% of gold with this method. After consulting miners and processing center owners during this study, it was found that they believed that they were extracting more than 50% of the gold by amalgamation and gravity concentration. Thus gold recovery is not clearly known but it is believed that might be around 30% (Veiga et al., 2014a).

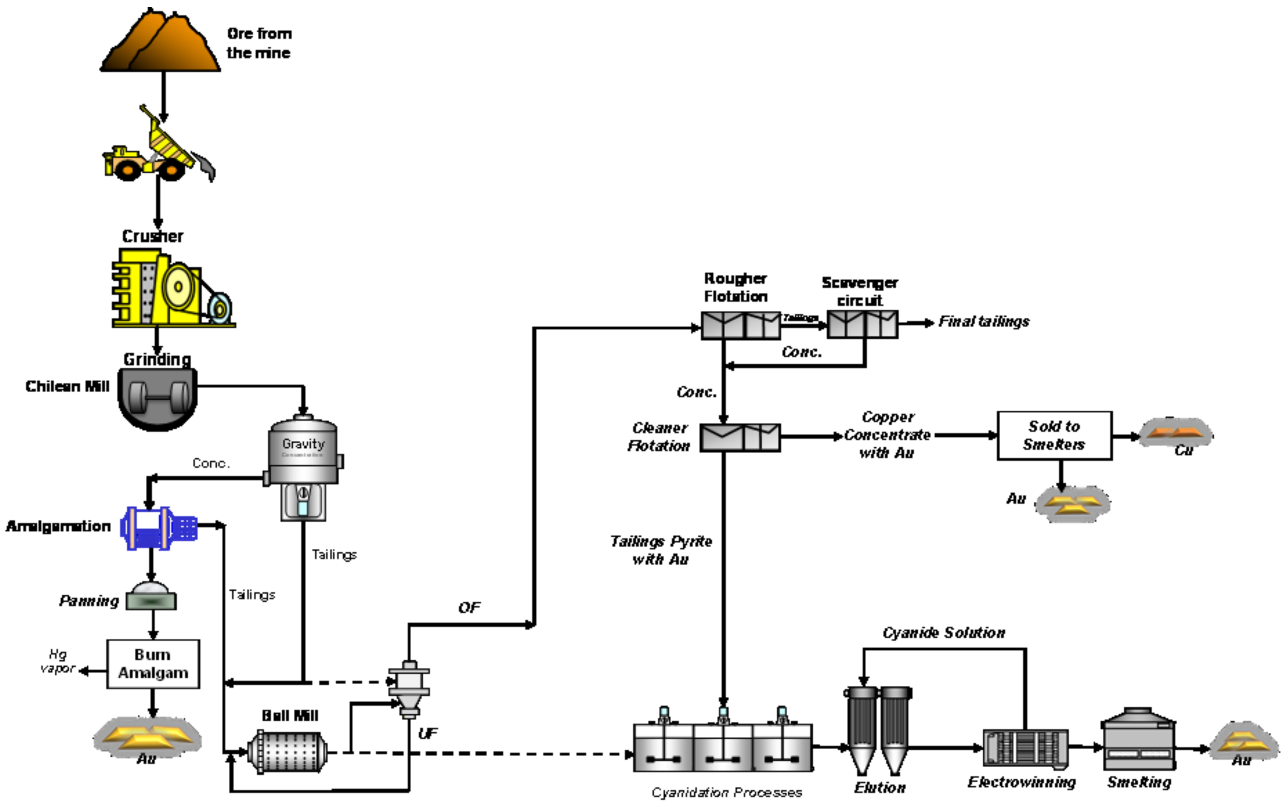

Figure 5.1. Typical flowsheet of the unit operations used by processing centers in Portovelo-Zaruma by A. Gonçalves, 2015.

The processing plants represent an extremely important aspect of gold production in the region, as they are responsible for processing the ore of artisanal miners who do not have the equipment for gold recovery. However, no solutions have been proposed as of yet to address the informality of thousands of artisanal miners who use the processing centers to recover their gold. Processing plants vary widely in Portovelo-Zaruma, as was evidenced by the visits. From the 52 processing centers visited in 2013 and 20 visited in 2015, it was possible to infer that: 1) 15% of all processing centers only process their own ore, 2) 30% of processing centers rent equipment to miners to process their ore, and 3) 55% of processing centers process their own ore and rent the equipment to miners. It is important to point out that amongst the three types of centers described above which were visited and investigated as part of this study, there were large variabilities that included: plant capacity, technical knowledge of engineers and processing plant owners, level of technology used in gold processing, and services offered to miners. The summarized data gathered from the processing centers in 2013 and 2015 is shown in Table 5.1.

Table 5.1. Overall data collected from processing centers in Portovelo-Zaruma*.

	2013	2015
Number of plants visited	52	20
Average plant age (years)	11	13
Number of employees/plant	23	20
Average number of operational days	7	6
Number of Chilean mills/plant	3	6
Number of ball mills/plant	1	1
Number of *chanchas*/plant	2	2
Number of centers using amalgamation (%)	78	65
Number of centers using cyanidation (%)	78	95
Number of centers using Carbon-in-Pulp (CIP) (%)	55	65
Number of centers using Merrill-Crowe process (%)	31	35
Number of centers using flotation (%)	23	25
Number of centers conducting gold refining (%)	70	53
Total operating cost/plant (US$/month)	79,700.61	83,785.44
Electricity costs/plant (US$/month)	5,474.80	6,092.50
Cost to rent equipment (US$/tonne)	15.75	32.46
Cost to rent (CIP) tanks (14-40 m^3)	220.00	267.50
Source of Ore		
Owned mine (%)	33	70
Local miners and from other provinces (%)	71	90
Cyanide		
Destroy cyanide (%)	24	15
Cyanide bought (tonnes/month/plant)	1.56	2.05
Mercury		
Mercury used (kg/month/plant)	6.24	2.40
Average price of mercury (US$/kg)	275	385
Cost to rent chanchas (US$/*chancha*)	2	10
Tailings		
Number of plants which possess tailings ponds (%)	55	65
Gold		
Average ore processed/plant (tonnes/day)	55	62
Average ore processed/plant (tonnes/month)	1,650	1,860
Average ore processed/plant (million/year)	1,722,60	1,941,84
Average gold produced/plant (kg/month)	6.70	5.70

**** Eighteen processing centers in common between 2013 and 2015.***

5.2. Processing Centers: General Data

In 2013, an average of 23 people was employed per center. These values ranged from a low of 1 employee to a high of 120 employees. The average number of employees per center in 2015 was 20, ranging from a low of 3 to a high of 80. Overall, the number of employees in 2015 reduced approximately 13% from 2013. Approximately 40% of the processing center managers had attended university and received an engineering or technology degree with a major in metallurgical engineering, chemical engineering or industrial engineering. On average, the centers had been operating for 13 years, ranging from less than 1 year to 27 years. The newest processing center in the region, which started production in 2013, is located in Santa Marianita in the district of Zaruma and processes approximately 130 tonnes of ore/day with an installed maximum capacity of 250 tonnes of ore/day. On average, the processing centers operated 6 days a week. Most processing centers operated 24 hours a day, with shifts of 8 hours each. Additionally, the processing centers using Chilean mills operated 7 days per week, 24 hours per day. Table 5.2 summarizes the general data of the processing centers in Portovelo-Zaruma.

Table 5.2. General data of processing centers in Portovelo-Zaruma*.

	2013		2015	
	Average	**Range**	**Average**	**Range**
Plant age (years)	11	0-25	13	2-27
Number of Employees/plant	23	1-120	20	3-80
Operational days	6	6-7	6	4-7

**** Eighteen processing centers in common between 2013 and 2015.***

5.3. Different Processes and Equipment Used at Processing Centers

5.3.1. Crushing and Grinding

In order to reduce the size of the ore to between ½ inch - ¾ inches or smaller, the processing centers visited use two different types of crushers: jaw crushers (Figure 5.2) and cone crushers. However, many miners prefer to crush the ore manually using hammers. For grinding, the centers mainly use Chilean mills (Figure 5.3), which are modern versions of the old Muller pans used in North America in the 1850s. In comparison, when the plants process their own ores, they normally use ball mills, which are more efficient. The majority of the existing processing centers in the region wet-grind the ore in Chilean mills.

Figure 5.2. Jaw Crusher used by processing centers in Portovelo-Zaruma. Photo by A. Gonçalves, 2015.

The Chilean mills are 2.5 – 3 m high, 2 m in diameter, and have 2 - 4 cement wheels with a diameter of 1.5 m. The cement wheels usually have a rim of steel. They rotate at approximately 50 rpm on a central spindle and track composed of an 8-cm thick steel plate. Powered by a 20 HP electric motor and operated by a manual feeder, the mills often run 24 hours a day. The ore is crushed to pieces below 6 inches in diameter and manually fed into the mill. The milling capacity of each Chilean mill is approximately 300 to 500 kg/hour. The grinding process occurs with water to create a slurry that ranges from 6–14% solids. The circular path of the wheels grinds the ore while forcing the resulting slurry to go through a 0.2 mm nylon screen. When the material passes through the screen, it overflows to sluice boxes, where the gold is concentrated.

Figure 5.3. Chilean mill used in processing centers in Portovelo-Zaruma. Photo by A. Gonçalves, 2015.

Only one plant was found using ball mills (Figure 5.4) to grind their own ores and/or re-grind the tailings left by the miners. For the most part, ball mill grinding is a service not offered to the miners. In fact, miners prefer the Chilean mills that can be visually monitored over the ball mills because that they believe gold becomes trapped inside and the ball mills would favor the owners of the processing centers. It was observed that the number of Chilean mills used per plant increased in 2015, in comparison with 2013. Overall, however, the changes were small between the two years of study (Table 5.3).

Table 5.3. Equipment used in processing centers in Portovelo-Zaruma*.

	2013		2015	
	Average	Range	Average	Range
Number of jaw crushers	2	1-6	1	1-3
Number of ball mills	1	1-3	1	1-3
Number of Chilean mills	3	1-8	6	1-9
Number of *chanchas*	2	1-10	2	1-7

**** Eighteen processing centers in common between 2013 and 2015.***

The prices charged to miners to rent equipment at the processing centers increased considerably from 2013 to 2015. The average price charged for the services of crushing, grinding, gravity concentration and amalgamation was US$ 15.75 per tonne/ore in 2013 and US$ 32.46 per tonne/ore in 2015, which is an increase of over 100%. According to the processing plant owners, this difference in price is due to miners beginning to leach their own tailings in the last couple of years, using cyanidation in the Merrill-Crowe process, instead of leaving the tailings at the center for the benefit of the owners. Consequently, leaching of the tailings involves an extra cost for the miners (see Table 5.1). Approximately 1.9 million tonnes of ore/a were processed by the 87 processing plants in Portovelo-Zaruma in 2015.

Figure 5.4. Ball mill used in the processing centers in Portovelo-Zaruma. Photo by A. Gonçalves, 2015.

5.3.2. Gravity Concentration

The ground material from the Chilean mill is concentrated in wool-carpeted cement sluice boxes (Figure 5.5), which are 6.8 m long and 0.46 m wide. The sluice boxes are made with a low angle (5 to 10º) and covered with wool carpets to retain fine gold particles. However, this ends up accumulating a large mass of concentrate quickly, and miners must remove the concentrate from the carpets every hour for future panning in a water tub to obtain a final concentrate of 15-20 kg before being amalgamated. The tailings from the sluice-box concentration are then transported to tanks to be treated by cyanidation by the owners of the centers to extract residual gold. Most sluice boxes have two troughs allowing the processor to stop the flow of one so they can make this change. By alternating between troughs, the carpets are cleaned while not interrupting the flow of material. Depending on how many individuals are operating the mill and their procedure, the time between carpet changes can vary greatly, which can have a dramatic effect on gold recovery. Due to the low angle of the sluice box, the carpets become clogged quickly, which then reduces the concentration efficiency. From 8 tonnes of ore milled, approximately 200 –

225 kg of concentrate (or 2.5 - 3% of the mass ore) is recovered, usually with a grade ranging from 10 to 30 g gold/tonne. This low grade is due to the large mass of concentrate. According to Velásquez-López, et al. (2010) and Veiga et al., (2014a) gold extraction using sluice boxes ranges from 40 to 50%, however, it was observed that after panning and amalgamation, miners only take home 20-30% of the gold from their ore, confirming the results found by Velásquez-López (2010). Some processing centers blend tailings from the gravity concentration process with those from amalgamation (Hg-contaminated) to further reprocess in Carbon-in-Pulp tanks (CIP).

Figure 5.5. Chilean Mill with sluice boxes covered with wool carpets, used in processing centers in Portovelo-Zaruma. Photo by A. Gonçalves, 2015.

5.3.3. Amalgamation

In the Portovelo-Zaruma region, mercury is used in two processes: 1) in the whole ore amalgamation using *chanchas* (Figure 5.6) and 2) in the amalgamation of concentrates from Chilean mills and processing using sluice boxes. The hard material left inside the Chilean mills (*las ollas*) is also submitted to this rudimentary amalgamation process. The material not ground by the Chilean mills is removed at the end of the grinding process. To amalgamate this material as well as high grade ores, the centers offer miners the service of amalgamation in *chanchas*, where mercury is mixed with the ore and ground together. This rudimentary process pulverizes mercury, which is then carried with the tailings. Some processing centers, especially in the region of Ponce-Enriquez, are exclusively dedicated to using *chanchas*, as they serve a small number of miners who bring material with a high gold grade (> 30 g/tonne of gold) according to Velásquez-López (2010).

Figure 5.6. *Chanchas* used in processing centers in Portovelo-Zaruma. Photo by A. Gonçalves, 2015.

A *chancha* is a small, horizontal, motor-driven mill, which spins on its lengthwise axis, using steel balls, rods or large stones to grind and amalgamate the gold. Usually, it has at least one access panel that is approximately 40 cm by 30 cm to allow material to be fed into the mill. According to information received by the miners during this study, the *chanchas* receive between 150 to 200 kg of material, 400 to 500 g of mercury and operate for 3.5 to 4 hours at a speed of 60-65 rpm. Depending on the individual miner's personal preference, brown sugar, Coca-Cola, tooth paste and other reagents may be added to the mixture, as many people believe that these reagents will reduce mercury flouring (formation of mercury droplets that cause a loss of coalescence) (Veiga et al., 2006; Veiga et al., 2009).

Other miners prefer to use manual amalgamation in a *batea* to extract gold from sluice box concentrates. As mentioned above, as the sluice is cleaned every hour, the mass of concentrate is substantial, reaching 2.5 to 3% of the initial ore mass. As the gold grade is low (10 to 30 g Au/tonne) and the mass is high, miners use manual panning to concentrate even more of the material. They add mercury and brown sugar in the last step of the panning when the concentrate has the highest grade of gold. In the process of panning, miners end up losing large amounts of gold, which is then left in the tailings for the benefit of the processing center owners. However, as a result from this study, it was observed that some miners have begun to realize this and they prefer to pay the processing center to leach the whole concentrate with cyanide without panning, or to use *chanchas* to amalgamate the concentrate.

After amalgamation in *chanchas*, the material is dumped into two buckets, one smaller bucket inside of a large one that works as an elutriator to remove the heavy minerals from the pulp. The amalgam is then transferred to a piece of cloth and manually squeezed to remove the uncombined mercury (Figure 5.7).

Over the two year period, on average 71.5% of the processing centers visited perform amalgamation in *chanchas*. This is usually done in two circumstances: 1) when the ore is very rich in gold, or 2) to recover the gold of the hard material retained inside of the Chilean mills. This latter is the material rich in quartz that usually becomes retained inside the Chilean mills. The results from the current study have confirmed that amalgamation is the preferred method selected by miners to extract gold from the ore, according to Velásquez-López et al. (2010) and Veiga et al. (2014a). However, it has been indicated that amalgamation has been decreasing in the region in the last couple of years, in part due to the increased use of Merrill-Crowe.

Figure 5.7. **Squeezing excess mercury from an amalgam. (Used with permission of B. Nichols).**

The gold and mercury amalgam with 50-60% mercury is then heated with a propane torch in a rudimentary fume hood until most of the mercury is evaporated, leaving a *doré* (gold and silver) (Figure 5.8), containing small amounts of mercury and other metals. According to Veiga & Hinton (2002) a *doré* has 2 to 5% of mercury, but this depends on the efficiency of the burning process. When amalgams are burned in bonfires, as observed in Sudan and Zimbabwe, the final *doré* can contain up to 20% of non-evaporated mercury (Veiga et al., 2006).

Figure 5.8. A ball of amalgam. Photo by A. Gonçalves, 2015.

In Portovelo-Zaruma, some miners use a retort to evaporate and condense mercury from the amalgams, which reduces the exposure to vaporous mercury. The amalgam is wrapped in paper towel or aluminum foil and burned in a retort. However, the majority of artisanal miners prefer to burn the amalgam in a shovel or tray in the open air, exposing themselves and others to toxic mercury vapor (Figure 5.9). As mentioned on chapter 2, this is the major source of atmospheric mercury emissions in the region of Portovelo-Zaruma and also the primary pathway of mercury contamination to the miners and surrounding community.

Figure 5.9. Miners burning amalgams in the open air, releasing atmospheric mercury emissions. (Used with permission by Velásquez-López).

5.3.4. Mercury Losses

Mercury is used by both miners and owners of processing centers to amalgamate gold from the whole ore amalgamation in *chanchas* and concentrate amalgamation using Chilean mills and sluice box processing. Miners selected this method because it is the easiest way for them to make money in a short time and also because the duration of the cyanidation is longer than amalgamation. They also believe that the processing centers owners can possibly steal their gold, since cyanidation processes work in a closed circuit. During informal conversations with the miners, it was observed that the large majority have no knowledge about how much gold they were extracting from the *chancha* process. Consequently, the miners sometime add more mercury than is needed to amalgamate the gold, which was also observed by Velásquez-López (2010).

In 2013, a mercury mass balance of 11 processing centers was performed in the *chanchas* process in the region of Portovelo-Zaruma by UNIDO (2016). Whole ore amalgamation was selected, as it is the main source of mercury losses in ASGM (Veiga et al., 2014a). It is important to stress that when concentrates are manually amalgamated alone, the mercury losses assessed by Velásquez-López et al. (2010) are only 1.4% of the original mercury introduced in the process. According to UNIDO (2016), the average mercury losses found in tailings accounted for 13.6% ± 11.9%, ranging from 1.05% to over 33%. Average mercury losses from the burning of gold and mercury amalgams reached 18.6% ± 11.7%, ranging from a minimum of 6% to a maximum of over 45%. It was estimated by the UNIDO study that on average, the ratio of mercury lost to gold produced in 2013 was 2.1 ± 0.8. In comparison, a similar study by Velásquez-López in 2008 (Velásquez-López, 2010) found higher maximums and ranges of mercury losses in tailings and from amalgam burning than 2013 study, with percentages of 21.7 ± 9.0% and 24.8 ± 15.2%, respectively.

The results from UNIDO (2016) study show that the average ratio of mercury lost to gold produced in a 2013 study was approximately double (4.3 ± 5.1) than the Velásquez-López study (2008). Although the standard deviation was also higher. The differences in results between the two studies could possibly be explained by variations in the grade of the whole ore or concentrates from sluicing. Furthermore, Velásquez-López (2010) showed larger average quantities of mercury added compared to 2013 study (356.3 vs 255.3 g), which also culminated in a larger percentage of total mercury lost (47.7 vs 32.2%).

In Colombia, a similar study (n = 15) investigating mercury losses was conducted by Cordy et al. (2011) using *cocos,* ball mills similar to *chanchas.* It was observed that the amount of mercury added in *cocos* was an average of 78.1 g/*coco,* which is also less than the 255 g/*chancha* in the Portovelo UNIDO (2016) study. The results from Cordy's study (2011) show that the amount of mercury lost in the tailings varied between 25.9 and 81.8% and the losses through evaporation were between 0.5 to 6.2% of the initial mercury added in the amalgamation process. Additionally, the average ratio of mercury lost to gold produced was approximately 15. The amalgamation of whole ore in small ball mills has also been observed in Indonesia, with mercury losses similar to those found by Cordy et al. (2011) in Colombia (Veiga et al., 2014a).

Table 5.4 compares the mercury balance results from Velásquez's study in Portovelo, Ecuador in 2008 (Velásquez-López, 2010), Cordy et al. in Antioquia, Colombia in 2010 (Cordy et al., 2011) and from Portovelo-Zaruma in 2013 (UNIDO, 2016). The results suggest that the smaller amount of *doré* (gold) produced, the greater amount of mercury is lost. The average ratio of mercury consumed to gold produced in Antioquia, Colombia is many times larger than what was found in Ecuador (26.9 vs 2.1 to 4.3).

Table 5.4. Comparison of mercury balance results from Velásquez-López (2010) in Ecuador (surveyed in 2008), Cordy et al. (2011) in Colombia (surveyed in 2010), and UNIDO (2016) study in Ecuador (surveyed in 2013).

Year of Survey	Sample type and number of samples	Average Hg used (g)	% Hg recovered	% Hg lost in tailings	% Hg lost through amalgam burning	Total % Hg lost	Ratio of Hg lost to Au produced
2013*	Whole Ore *Chancha* (**Ecuador**): n = 11	255.3 ± 242.9	67.8 ± 19.1	13.6 ± 11.9	18.6 ± 11.7	32.2 ± 19.1	2.1 ± 0.8
2010**	Whole Ore *Chancha* (**Ecuador**): n = 11	356.3 ± 170.9	52.3 ± 12.7	21.7 ± 9.0	24.8 ± 15.2	47.7 ± 12.7	4.3 ± 5.1
2011**	Whole Ore Cocos **(Colombia):** n = 15	78.1 ± 21.2	51.0 ± 14.7	45.5 ± 13.8	3.4 ± 2.2	49.0 ± 14.7	26.9 ± 21.2

* UNIDO (2016) - average Hg used in g/chancha
** Velásquez-López (2010) - average Hg used in g/chancha
*** (Cordy et al. (2011) - average Hg used in g/coco

Closer analysis suggests that the higher average amount of mercury lost in tailings in Colombia in comparison with Ecuador (45.5% versus 13.6-18.2%, respectively) may be due to the use of *cocos* in Antioquia. The time spent ore grinding in Antioquia is between 4 to 5 hours (Veiga et al, 2014), while in Ecuador it is approximately 3 hours. Another factor which could cause higher mercury losses found by Cordy et al. (2011) is the smaller size of the *cocos*, which may end up pulverizing more mercury than the c*hanchas* used in Ecuador, resulting in higher quantities being lost with the tailings.

5.3.5. Assessment of Mercury Used at the Processing Centers

In 2008, it was estimated that approximately 1.5 tonnes/a of metallic mercury were released into the environment from processing centers in Portovelo-Zaruma, from which 70% was evaporated during the burning of gold and mercury amalgams and 30% released into the Puyango-Tumbes River bodies as mercury-contaminated tailings including gold and other heavy metals (Velásquez-López, et al., 2010). According to Meech et al. (1998), when the amalgam is burned, it is vaporised and likely to precipitate nearby. It also known that metallic mercury can be oxidized and transformed into methylmercury in aquatic environments (Hyman, 2004).

From a total of 87 plants operating in 2013, 62 plants were using mercury. The total amount of mercury used by these plants was estimated at 4.64 tonnes/a. Based on the mass balance of *chanchas* conducted in 2013 (UNIDO, 2016) (which is the method that causes more mercury loss than amalgamation of concentrates), an average of 13.6 % of Hg was lost with the tailings (Table 5.9), which amounted to 631 kg/a. As 18.6% of the mercury used was lost by evaporation, this would amount to 863 kg/a. The total Hg released to the environment was 1.5 tonnes/a in 2013. From the mercury used, 67.8% of the total amount was recycled, to be used again for further amalgamation.

In 2015, estimation of mercury use was reduced to 2.4 kg/month/plant (Table 5.1), which amounted to 28.8 kg/plant/year or a total of 1.79 tonnes/a. Using the mass balance of 2013, the amount of Hg lost to the tailings was 243 kg/a. The amount lost by evaporation was 333 kg/a. Therefore, the total Hg lost to the environment was 576 kg of Hg in 2015.

In the first scenario of 2013, where 631 kg of Hg/a were lost to the tailings, this result corroborates the estimate presented by Guimarães et al. (2011), who based their calculations on mercury balance data provided by Velásquez-López, et al. (2010). However, in the second scenario, the estimate in 2015 constitutes an apparent reduction in mercury use by the plants of almost two-thirds between 2013 and 2015, which is principally based on three possible explanations: 1) the Ecuadorian Government wanted to crack down on Hg use due to implementation of legislation intended to ensure compliance with the Minamata Convention, which hopes to regulate the sale and use of mercury, 2) the use of cyanidation has increased, due to the understanding that cyanide allows for increased gold production, and 3) fewer miners are still using *chanchas*, because the high gold grade material is getting more and more scarce.

Although the miners understand the health risks associated with mercury use, it is still the preferred method to extract gold, as it is relatively inexpensive, highly accessible and easy to use. Even though there have been numerous studies and attempts to address the problem, it seems that efforts have not been sufficient to reach the miners in an effective matter. Approximately 70% of the processing center managers and owners reported that they have a basic understanding of the environmental and health-related impacts associated with the use of mercury and cyanide; however, most are generally unaware of the magnitude of the problem. At the same time, they were aware of existing methods to reduce mercury vapour exposure. Furthermore, they are concerned that the government does not provide alternatives to promote education to introduce new technologies.

Over the last two decades, several training initiatives have been set up and well-implemented in southern Ecuador to spread awareness and disseminate information regarding the problems and environmental consequences associated with ASGM activities in the region (CIIED, 2014; UNIDO, 2016). In this study, it was observed during the conversation with the managers and processing centers owners that the training initiatives have helped increase their understanding of the socio-economic and environmental implications related to mercury use and the implementation of new processing technologies, however more needs to be done. Very little attention has been focussed on reaching out to the large majority of artisanal miners. This is due to the remoteness of mining sites and the difficulty in providing follow-up after an initial meeting. Furthermore, there is a lack of cooperation and cohesion between national and local mining institutions, which have varying degrees of contact with the artisanal miners.

Most of the training workshops have only been conducted over the course of 1 or 2 days, which is a very short period of time to propagate all of the information related to the application of new gold processing technologies. Furthermore, a broadened educational framework needs to be implemented in order to fully address the health and environmental risks associated with the use of mercury and cyanide in ASGM operations. The Ecuadorian Government has been discussing the idea of creating an institutionalized technical-level program of mining education, but to date nothing has happened.

In October 2013, the Ecuadorian government signed the "Minamata Convention on Mercury", with the objective of protecting human health and the environment from the harmful effects of mercury emissions and releases by the processing centers in southern Ecuador. The government confirmed its commitment to control the use of mercury in mining activities and is working towards the elimination of Hg at processing centers.

As of June 2015, the Ecuadorian Government has banned the use of mercury in artisanal mining in the region of Portovelo-Zaruma. Consequently, this prohibition is forcing miners to burn the gold and mercury amalgams at home, exposing all family members to the harmful vapours. Even in the 1990s, the International Agency for Small-Scale Mining (SMI, 1995) showed that approximately 50% of the miners working in Portovelo were burning the amalgam in their own residences. Therefore, it appears that miners without alternatives provided by the government will continue using the same rudimentary techniques. As artisanal miners do not have the economic resources to run their own operations, they are forced to work according to conditions established by the processing center owners.

Another important aspect is the price of mercury, which has been increasing significantly in ASGM operations over the last 20 years. The international price of mercury has increased exorbitantly from US$ 4.93/kg in 2003 to US$ 55.2/kg in 2011 to US$ 103.7/kg in 2014 (Metal-Pages, 2014; USGS, 2009). According to Veiga et al. (2014a), the price of mercury at ASGM sites is double the international price. In Portovelo-Zaruma, the price of mercury had increased to between US$ 220 - 330/kg in 2013. In June 2015, when mercury use was banned by the Ecuadorian Government, the black market price increased to over US$ 440/kg. Currently, miners pay an average of US$ 330/kg for mercury in Portovelo-Zaruma. Veiga & Marshall (2016) for instance, observed that the price for mercury in others artisanal and small-scale gold mining in Brazil, Colombia and Peru as high as US$ 350/kg.

It is clear from this study that recent initiatives implemented by the Ecuadorian Government to reduce mercury use in ASGM operations in southern Ecuador are resulting in many miners and processing centers using alternative methods to extract gold. Consequently, due to the restrictions regarding mercury, less Hg is being used in the *chanchas* at processing centers and cyanidation processes are increasingly implemented to extract the gold.

5.3.6. Mineralogical Analysis

The results from the XRD qualitative analysis are shown on Table 5.5. The interpretation of the crystalline phases shows mainly the presence of sulfides including arsenopyrite (FeAsS), galena (PbS), pyrite (FeS2), pyrrhotite (Fe1-x S), chalcopyrite (CuFeS2), bornite (Cu5FeS4) and sphalerite (ZnS). For more detailed information about the X-Ray diffractograms, please refer to the Appendix E. The result obtained in the XRD analysis corroborates with the mineralogical characteristics of the district of Portovelo-Zaruma reported by Vikentyev et al. (2005) with a high presence of sulfides such as arsenopyrite, chalcopyrite, galena, muscovite and pyrrohotite. Furthermore, the results from the processing centers also found the presence of clinochlore, kaolinite and sphalerite. It is important to notice that the results obtained were based on the samples received from the processing centers at Portovelo-Zaruma, and during informal conversation with the processing center owners, it was observed that the large majority have absolutely no knowledge whatsoever about the mineralogical characteristics of the mined ore. Furthermore, almost 50% of the ore processed at the gold processing plants in the region of Portovelo-Zaruma comes from different locations and provinces in southern Ecuador, where the ore is rich in arsenic, lead and other heavy metals, which is found in sulfide deposits, where it is present as arsenopyrite, a common component of gold deposits (Straskraba & Moran, 2006).

Table 5.5. XRD qualitative analysis results from four processing centers in Portovelo-Zaruma in 2015, analyzed at the Department of Earth, Ocean & Atmospheric Sciences at University of British Columbia, (2016).

Sample ID	Patterns		
	Majority	Traces	Minority
*1	pyrite quartz	arsenopyrite muscovite	clinochlore chalcopyrite
*2	chalcopyrite quartz	sphalerite galena	sphalerite pyrrhotite
*3	chalcopyrite quartz	sphalerite pyrite	kaolinite muscovite
*4	sphalerite quartz	chalcopyrite pyrite	galena quartz

*No specific names are given for the processing centers due to confidentiality clauses.

5.3.7. Gold Flotation

Gold flotation is a relatively new process being used in Portovelo-Zaruma over the past 15 years. Peruvian engineers introduced this technology to processing centers in Ecuador to better concentrate fine gold and copper minerals from tailings (Figure 5.10). The introduction of this process in the region has brought important economic and environmental benefits to the region, as mining pollution has decreased and gold concentrates (which sometimes also contain both copper minerals and silver) are now being sold to smelters in Peru and China for 65 - 80% of the international market price and no longer amalgamated or leached with cyanide. According to Veiga et al. (2014a), the introduction of gold flotation in Portovelo-Zaruma has also attracted foreign investors from Peru, Colombia, Canada and USA, which in recent years has culminated in at least 40 small processing centers using this technology to take advantage of residual gold left behind in tailings from artisanal miners, or from ore mined by the processing center owners.

At the processing centers which use flotation to concentrate gold, silver and copper, the concentrate grades were determined from values reported by the plant managers and also via personal analyses. As one can observe from the results outlined in Table 5.6, the majority of the information given to us by the processing centers was corroborated by this study analyses. However, in a few cases, the differences are significant, based on a lack of knowledge and experience by engineers at the plants to properly perform the flotation process and correctly assess the end grade results. As a consequence, it was observed that the flotation process still presents challenges to the metallurgical engineers employed at processing centers in the region.

Table 5.6. Concentrate grades (in g/tonne for gold and silver and percentages for copper) produced in the flotation process at Portovelo-Zaruma processing centers in 2015, including both reported values by plant managers and the results analyzed at Met-Solve Analytical in Vancouver, Canada (2016).

Location of processing centers	Concentrated gold (g/tonne)		Concentrated silver (g/tonne)		Concentrated copper (%)	
	Reported	Analyzed	Reported	Analyzed	Reported	Analyzed
*Portovelo-Zaruma	11	29.50	750	825	20	19.84
*Portovelo-Zaruma	40	230.40	878	458	20	19.13
*Portovelo-Zaruma	55	52.60	120	109	23	22.20
*Portovelo-Zaruma	32	80.70	790	1104	26	19.13

* No specific names are given for the processing centers due to confidentiality clauses.

A

B

Figure 5.10 A and B. Flotation of gold and copper minerals at a processing center in Portovelo-Zaruma. Photo by A. Gonçalves, 2015.

5.3.8. Cyanidation

Cyanidation is one of the most common methods used in Portovelo-Zaruma to extract gold from gravity concentrates or gravity concentration tailings. In the past, this method was conducted using vat leaching, which is a crude way to percolate tailings in a cyanide solution (Velásquez-López, 2010). Currently, all processing centers in the region use agitation tanks, which are more expensive but much more efficient than vat leaching. The free cyanide in an alkaline solution (pH 10-11) reacts with exposed gold attached to the particles of other minerals, which is then solubilized forming a strong cyanide complex ($Au(CN)_2^-$). The reaction is controlled by the oxidizing agent, which means that the oxygen in solution speeds up the reaction:

$$4\,Au + 8CN^- + O_2 + 2H_2O = 4Au(CN)_2^- + 4OH^-$$

Unfortunately, some miners believe that by adding more cyanide the reaction will be faster. In fact, more cyanide is only needed when more oxidizing agent is added as part of the free cyanide complex, forming cyanate, which does not leach the gold with the same efficiency as cyanide.

There are two types of cyanidation circuit processes used in Portovelo-Zaruma: 1) Carbon-in-Pulp (CIP), and 2) Merrill-Crowe. Cyanidation is a better option for the miners, since the amalgamation of concentrates usually extracts less than 30% of the gold; with cyanidation, gold recovery is more than 85%. Although, the use of cyanidation has been a lucrative advance in technology for improving gold recovery.

It is known in the region that many processing centers routinely dump their final cyanidation tailings into local rivers (Veiga et al., 2014a), causing massive environmental contamination. According to (Guimarães et al., 2011) it was estimated that over 880,000 tonnes of tailings and mining waste entered the Puyango River on a yearly basis, which contained approximately 650 kg of mercury and 6000 tonnes of cyanide, in conjunction with high concentrations of other heavy metals.

5.3.9. Carbon-in-Pulp

The Carbon-in-Pulp (CIP) process is the preferred method used in Portovelo-Zaruma by the owners of processing centers who treat their own tailings. The CIP process consists of adding activated carbon directly to the steel leaching tanks in conjunction with 15-20 tonnes of tailings (Figure 5.11). The agitation system consists of impellers of up to 15 HP that create a rotational speed of 130 rpm. Normally, most of the the processing centers visited have series of 3 to 8 tanks ranging in size from 30 to 40 m^3 in diameter, where the pulp is transferred from one tank to another in series. Activated carbon moves in a counter flow direction.

During the leaching step, the gold cyanide complex formed is adsorbed on activated carbon and removed from the leaching systems without filtration. The pH is kept between 10 and 11 and controlled by pH strips or sometimes with pH meters. The pulp density is controlled with a Marcy scale. According to the managers of the plants, the tanks normally work with 30% of solids in the pulp. The amount of cyanide (NaCN) added depends on the type of material being processed. Most plants use a NaCN concentration of between 2 to 3 g/L. The residence time of the cyanide added in the tanks ranges from 12-72 hours. After 12 hours of leaching, 20 to 30 kg of activated carbon/tonne of material is added to the tanks. The carbon stays in contact with the cyanide solution for 12 more hours.

When no gold is detected in the solution, the operators open a valve to drain the pulp on a rotating drum with a 2 mm screen to retain the relatively coarse activated carbon (Figure 5.12). The carbon is then sent to the desorption (elution) circuit. As the formation of mercury-cyanide complexes is slower than the gold-cyanide complex during the leaching of Hg-contaminated tailings, only 3.72% of the Hg in the tailings is leached and removed by activated carbon. The remaining Hg-cyanide complexes that stay in the pulp, as well as the metallic Hg not dissolved by the cyanide solution, are apparently routinely discharged into the local rivers.

Figure 5.11. Cyanidation with agitated tanks at a processing center in Portovelo-Zaruma. Photo by A. Gonçalves, 2015.

Figure 5.12. Rotating screen drum used in the CIP process in Portovelo-Zaruma. Photo by A. Gonçalves, 2015.

The elution (gold desorption from activated carbon) circuit (Figure 5.13) works with a hot solution (80-95 °C) 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 (Figure 5.14) to deposit gold onto cathodes. After electro-deposition of gold, the solution returns to the elution towers made of stainless steel. In the electrowinning process, the gold solution is added to a cell with stainless steel wool electrodes using 2-6 V and 300-1500 A. The voltage and current used are different among the processing centers. The elution towers at processing centers in Portovelo-Zaruma usually work with 700 to 800 kg of gold-loaded activated carbon. Therefore, the processing centers need to accumulate this amount of carbon before using the elution process. As this typically takes more than one month, it is not convenient for some artisanal miners, who prefer amalgamation of gravity concentration or using the Merrill Crowe process to produce gold faster (Velásquez-López, 2010). After elution, the used activated carbon (AC) is partially cleaned using nitric acid.

Figure 5.13. Desorption circuit at a processing center in Portovelo-Zaruma. Photo by A. Gonçalves, 2015.

Figure 5.14. Electrowinning circuit at a processing center in Portovelo-Zaruma. Photo by A. Gonçalves, 2015.

5.3.10. Merril-Crowe

When miners want to process their own tailings using cyanidation, some processing centers are able to provide the Merrill-Crowe process for a fee. This process normally uses a high concentration of sodium cyanide NaCN (1 to 5 g/L) with the cyanide consumption ranging from 1.5 to 5 kg of NaCN per tonne of tailings, depending on the amount of copper minerals in the ore. The processing centers that rent this process to miners usually ask where the ore comes from, in order to determine the amount of cyanide to be used in the process.

A 14 m^3 cyanidation tank for the Merrill-Crowe process typically handles 6 to 7 tonnes of material and the process takes from 5 to 6 days. This study found that the cost for the miners to rent this process is approximately US$ 260 per batch. After 12 hours, the agitation is halted and the pulp is allowed to settle for approximately 6 hours. Some plants have filters to clarify the solution before gold precipitation with zinc, but most of them use the settling process. The "clear" solution is then siphoned before sending it to PVC pipes (12 cm wide x 50 cm large) filled with zinc shavings (Figure 5.15). Sometimes it is possible to observe turbidity in the cyanide solution, which causes low efficiency in the zinc precipitation process. This cycle is repeated 5 to 6 times until the miners no longer see gold being precipitated on zinc. After gold precipitation (cementation), the solution of zinc cyanide and free cyanide is re-circulated back to the agitation tanks.

Gold precipitation occurs according to the following reaction (Marsden & House, 2006):

$$\boldsymbol{2Au(CN)_2^- + Zn \rightarrow 2Au + Zn(CN)_4^{2-}}$$

According to Velásquez-López (2010), silver and mercury and eventually copper from sulphide minerals dissolved in cyanide are also reduced by metallic zinc. The zinc precipitation process must be conducted in oxygen-free conditions and with clear solution, as gold can be re-dissolved in the cyanide solution (Marsden & House, 2006). In fact, as much as 10% of the total gold may still be in the final solution, so further recovery is possible. This gold loss could be significantly reduced if filters were used on the tanks (Velásquez-López et al., 2010). When concrete tanks are used to leach Hg-contaminated tailings, mercury droplets fall and are trapped at the bottom of the tank. Miners at the end of the process scoop up the material with visible droplets of mercury retained at the bottom and throw it away, frequently in the river.

According to Velásquez-López (2010) and Veiga et al. (2014a), the Merrill-Crowe process generates significant environmental and health impacts due to two main reasons: 1) the tailings carry heavy metal-cyanide complexes, and 2) when the zinc shavings are loaded with gold (visibly becomes brown) (Figure 5.15), miners evaporate the zinc in a furnace at temperatures above 900°C. The zinc and mercury and other metals (e.g. lead) end up contaminating the atmosphere over a large area. This operation, for security reasons, is usually performed in urban areas. After burning the zinc off, the precious material is washed with nitric acid (HNO_3) to dissolve the silver and excess zinc, and the gold is melted.

A

B

Figure 5.15. A and B. Zinc shavings full of gold during the Merrill-Crowe process at a processing center in Portovelo-Zaruma. Photo by A. Gonçalves, 2015.

5.3.11. Assesement of Cyanide Used at the Processing Centers

The amount of NaCN used in each processing center was calculated based on the amount of ore processed/day, the type of cyanidation process selected by the miner(s) and the processing center. In 2013, it was estimated that each plant used on average 1.56 tonnes/month of sodium cyanide (NaCN), which amounted to an average of 18.7 tonnes/a/plant. In 2015, there was an increase of approximately 31% in comparison to 2013, with each plant using on average 2.05 tonnes/month of NaCN, totalling 24.6 tonnes/a/plant.

This large difference in consumption of sodium cyanide in the past 2-3 years can be explained by a significant increase in the use of cyanidation processes by the processing centers in Portovelo-Zaruma. Furthermore, the amount of tailings processing centers receive from other areas in Ecuador has increased significantly in recent years. Considering that 95% of the plants, or 83 out of 87, use cyanidation to process the gold, this would amount to an estimated yearly consumption of NaCN of approximately 1550 and 2040 tonnes for 2013 and 2015, respectively.

Guimarães et al. (2011) had previously reported annual releases from processing centers in Portovelo-Zaruma of approximately 6000 tonnes/a of sodium cyanide into the local river system. The current estimates are between approximately 65-75% less than that estimated by Guimarães et al. (2011), which could be due to two possibilities: 1) our calculations were quite conservative, based on low average estimates of total NaCN consumed by the plants, and 2) that Guimarães et al. (2011) overestimated the numbers and based their assumptions on limited data.

After cyanidation, the final tailings, which in many cases still have unrecovered gold, are either kept at the processing center for further recovery in the future, transported to the central tailings facility called El Tablon in Portovelo, or dumped directly into the rivers that form the Puyango River. The results from this study have shown that only 20% of the 52 processing plants visited ended up destroying the used cyanide before discharge.

Between June and July 2015, the price of a 50 kg barrel of sodium cyanide (Figure 5.16) increased from US$ 150 to $ 450. This occurred due to Ecuadorian legislation prohibiting the use of mercury. During this time, APROPLASMIN became the only authorized supplier for all of the processing centers. The distribution of sodium cyanide was tightly controlled, which culminated in an inconsistent supply chain. This, in turn, forced some processing centers to shut down their operations when access to NaCN was unavailable. In consequence, plants have had to manage and control their operations more efficiently in order to avoid work stoppages. Currently, the price has now normalized to a certain degree, with a 50 kg barrel of NaCN selling for approximately US$ 220.

Figure 5.16. A 50 kg barrel of cyanide used by the processing centers in Portovelo-Zaruma.

5.3.12. Smelting and Refining the Gold

The final stage of gold production is refining of the gold *doré*. The majority of the processing centers in Portovelo-Zaruma use borax ($Na_2B_4O_7 \cdot 10H_2O$) for the first smelting step (Figure 5.17). Miners add borax, soda ash and the *doré* to a crucible to introduce some impurities to the slag. These impurities can include iron oxides and silicates, among others. The smelting process is conducted either with a propane blow torch or in a gas furnace (Figure 5.18). Gold and silver recovered by electrowinning on a steel wool cathode are also placed in a crucible with borax and melted. Typically, this procedure takes 24 hours, and only authorized personnel is allowed to participate in this process. The melted gold bullion is then solidified in an iron mold and weighed. Some miners refine the gold after this process, whereas others sell the gold bullion with silver to the gold shops. The chemical refining method is the most popular procedure in the region and it follows these steps:

1. The gold bar (Figure 5.19) is melted and poured from a certain height into a bucket with water to form small gold balls, which are easier to leach.

2. The balls are leached with nitric acid. Silver, copper and other residual base metals are leached, forming a blue solution, leaving behind > 99 % pure gold, which is melted and casted in a mold to form a bar.
3. The gold bar is further leached with nitric acid to dissolve some surficial copper.
4. The gold bar is then sold to gold shops.
5. Then table salt (NaCl) is added to the blue nitric solution left behind in plastic bowls. White precipitates of silver chloride are formed immediately. The solution is then filtered with paper filters and the final solution discharged into the drainage.
6. A paste of silver chloride is mixed with steel wool and ferric chloride is formed, with metallic silver being precipitated.
7. Silver is then melted and sold to gold shops.

The refining processing for the gold is mostly carried out in Portovelo-Zaruma.

Figure 5.17. Borax used for smelting the gold. Photo by A. Gonçalves, 2015.

Figure 5.18. Gold smelting at processing centers in Portovelo-Zaruma. Photo by A. Gonçalves, 2015.

Figure 5.19. Gold bar at a processing center in Portovelo-Zaruma. Photo by A. Gonçalves, 2015.

5.3.13. Tailings Management

Over the past 15 years, the use of cyanide in processing centers has increased considerably. All processing centers in Portovelo-Zaruma can easily purchase sodium cyanide without need of a permit. Veiga et al. (2014a) observed that the lack of cyanide management is one of the main sources of pollution in the region. Most of the plants do not have appropriate training to handle cyanide. Additionally, the local medical system has no knowledge of how to treat people poisoned by cyanide ingestion or inhalation.

Cyanide in neutral or acidic pH generates HCN gas, which is extremely toxic and can be fatal (Eisler & Wiemeyer, 2004).

Some plants oxidize the residual cyanide in the tailings (slurry) in a tank for many days using hydrogen peroxide, until the level of total cyanide in solution reaches 1 mg/L (ppm). Nearly all the processing centers in Portovelo-Zaruma are located close to or beside the Calera, Amarillo and Pindo Rivers that form the Puyango-Tumbes River below the towns of Portovelo and Zaruma. This close proximity to the rivers gives the processing centers easy access to water, but based on local geography ends up limiting the size of their operations. Processing plants are often built right next to each other in narrow valleys, leaving little room for tailings reservoirs. Instead, they choose to build small tailings ponds capable of only holding between 1 to 5 days of tailings. The ponds are filled with tailings during the day and then emptied at night. In many plants, tailings ponds were half or totally empty every morning. These simple ponds are sometimes lined with plastic canvas and are only 1 or 2 meters from the edge of the river. This method of tailings disposal into the river systems is very common. During rain showers, the ponds overflow their banks, especially during the raining season, covering the surrounding area with tailings that then drain into the river.

It was observed by Tarras-Wahlberg et al. (2000) and Appleton et al. (2001) that since the early 1990s, artisanal miners have disposed of cyanide and mercury-contaminated tailings into the Puyango-Tumbes watershed, which flows down into Peru before entering the Pacific Ocean. The Ecuadorian Government has collaborated with local governments, APROPLASMIN, the University of British Columbia and the National Institute of Metallurgical Mining Geological Research (INIGEMM), with the proposal to design and build a communal tailings facility (CTF) named El Tablon. The tailing facility is located east of the Puyango River and 2.5 km south of Portovelo. The project began in 2002 and has now been completed. Two dams, each 560 meters high, were constructed at the western and eastern ends of a valley and the bottom third was lined with geo-lining (Nichols et al., 2015).

In addition, currently, the majority of the processing centers do not have the capacity to accumulate large quantities of tailings in their own reservoirs. In this case, when they do have enough material, they truck their tailings to the central tailings facility at El Tablon. Until August 2015, this service was free of charge, but as of 2016 the plants will start paying a nominal fee. A pipeline along the Amarillo and Calera Rivers was designed to transport the tailings from the processing centers to El Tablon for storage. This was intended to be a temporary measure until an Industrial Processing Park could be created, where the Government hopes that all of the processing plants can be relocated. There is no data on how many tonnes of tailings are currently being taken on a daily, weekly or monthly basis to El Tablon.

As shown in Table 5.1, 55% of processing centers visited (52) in 2013 possessed some kind of tailings reservoirs (Figure 5.20), while in 2015 it was 65% of 20 processing centers. The tailings from cyanidation tanks are deposited in tailing reservoirs, which include mercury-laden slurries with high concentrations of other heavy metals. It is important to note that, on average, only approximately 20% of the centers applied hydrogen peroxide (H_2O_2) to destroy cyanide before discharging into the adjacent river. Furthermore, it was found that only two of the processing centers that destroy cyanide end up re-using the water to be recirculated into the grinding circuit.

Recently, one of the oldest processing centers located in Portovelo invested over US$10 million in the construction of a flotation circuit and six tailings ponds. The capacity of the new tailings pond is 229,000 m^3, with a projected capacity of 400,000 m^3. In this plant, the water used throughout the cyanidation processes is treated in the detoxification plant to neutralize the cyanide, using hydrogen peroxide (H_2O_2). The treated water is then recirculated into the process before being disposed into the Puyango-Tumbes River. The water discharged in the river is monitored by an external laboratory and the results are continuously sent to an Ecuadorian governmental agency, ARCOM (Regulatory Agency and Mining Control), as part of their compliance in neutralizing waste waters. However, this kind of processing center is a rare exception, not the rule. It is apparent from this study that most of the processing centers in Portovelo-Zaruma routinely dump their tailings into local water bodies, as they do not have either the infrastructure or environmental conscience to dispose of contaminants in a responsible manner.

The volume of tailings ponds among the visited processing centers displayed tremendous variability, ranging from 850 m^3 to 220,000 m^3. On average, each processing center had 3 tailings ponds. Most processing plants lack the capacity, space and incentive to manage their tailings. Additionally, because so many processing plants in Portovelo are located close to or beside a river so that they have easy access to all the water they need for processing, the size of their operations is limited (Veiga et al., 2014a).

Figure 5.20. Tailings ponds at Processing Centers in Portovelo-Zaruma. Photo by A. Gonçalves, 2015

In Ecuador, existing environmental regulations clearly stipulate how mining and mineral processing should be performed. However, poor enforcement by local and national agencies facilitates artisanal miners and processing centers to discharge contaminated tailings generated by amalgamation and cyanidation directly into local rivers (Veiga et al., 2014). Not only is there an urgent need to address aquatic and atmospheric pollution caused by gold processing in the Portovelo-Zaruma region, but also how areas and populations downriver in southwestern Ecuador and Peru are affected, which has become the key issue in an ongoing trans-boundary environmental conflict.

5.4. Gold Extraction of Processing Centers

Results indicate that miners typically select a processing center based on their own preference, depending on the costs, equipment, accommodations (where the miners sometimes sleep), and personal acquaintances, among other things. In Portovelo-Zaruma, gold is processed using one or a combination of different methods (Table 5.7). The principal ore extraction methods utilized in Portovelo-Zaruma are as follows: 1) Whole ore amalgamation in *chanchas*, 2) Grinding, concentration and amalgamation of the concentrates in Chilean mills, and 3) Cyanidation of gravity concentration tailings or gravity concentrates.

Table 5.7. Percentages of processing centers visited using each process*.

	2013	2015
Amalgamation (%)	78	65
Cyanidation (%)	78	95
CIP process (%)	55	65
Merrill-Crowe (%)	31	35
Flotation (%)	23	25
Gold Refining (%)	70	53

Note: n = 52 in 2013; n = 20 in 2015.
**** Eighteen PC in common between 2013 and 2015.***

Overall, the results of this study show that that use of cyanidation increased about approximately 22% in the region of Portovelo-Zaruma, especially over the last 5 years. One of the reasons for this is that the miners have learned the advantage of using cyanidation versus amalgamation. Another reason is that the processing centers make most of their income by reprocessing tailings from different provinces in southern Ecuador, where amalgamation is the primary method preferred by miners. Processing center owners are also investing more in flotation and cyanidation with Carbon-in-Pulp processes, although it is important to point out that the implementation of these processes is expensive. Therefore, as one can observe in Table 5.8 the increases in 2015 relative to 2013 are relatively small.

5.5. Gold Prodution of Processing Centers

The amount of gold ore processed in Portovelo-Zaruma can vary greatly from plant to plant. This variability is significant because of the different types and sizes of processing centers established in the region. Another aspect that contributes to this variability is the percentage of non-local ore that a given plant may receive for processing (up to 20% in some cases), which originates from different mine sites and provinces in southern Ecuador.

Studies from Velásquez-López, et al. (2010) and Veiga et al. (2014a) have shown that only 5% of processing centers in Portovelo-Zaruma process more than 100 tonnes of ore/day. However, the results from this study show that there was an increase in the number of centers with a capacity of over 100 tonnes/day, from 5% in 2013 to 20% in 2015 (Table 58). Consequently, the average amount of ore processed per plant increased from 55 to 62 tonnes/day between 2013 and 2015 (Table 5.1). Therefore, the estimated total amount of ore processed in the region increased by approximately 13% over the two-year period, based on calculations of 4785 tonnes/day of ore treated in 2013 and 5394 tonnes/day of ore in 2015 (Table 5.8). These results are corroborated by figures outlined in the CIIED report (2014), where it was calculated that all processing centers in Portovelo-Zaruma processed almost 5000 tonnes/day of ore in 2013.

Table 5.8. Daily ore processed in Portovelo-Zaruma*.

	2013	2015
< 10 tonnes/day (%)	10	10
10 to 50 tonnes/day (%)	60	50
50 to 100 tonnes/day (%)	25	20
> 100 tonnes/day (%)	5	20
Average ore processed/plant (tonnes/day)	55	62
Average ore processed/plant (tonnes/month)	1,650	1,860
Ore processed tonnes/day	4785	5394
Average gold produced/plant (kg/month)	6.70	5.70

Note: n = 52 in 2013; n = 20 in 2015

**** Eighteen PC in common between 2013 and 2015.***

In this study, gold produced in the region of Portovelo-Zaruma was estimated based on the information reported by the processing centers. In 2013, from the 52 processing centers visited, it was estimated that an average of 6.7 kg of gold/plant/month was being produced, while in 2015, the average gold produced had reduced to 5.7 kg of gold/plant/month, based on estimates made at 20 plants (Table 3.8). Based on these averages, total gold production per annum for the 87 plants would be approximately 7 tonnes in 2013 and 6 tonnes in 2015.

According to several studies (Veiga et al., 2009; Velásquez-López et al., 2010; Veiga et al., 2014a), the average gold production in Portovelo-Zaruma was estimated at 9 tonnes/a. However, the difference between the results from previous studies and the numbers reported in this study could be due to a number of possibilities: 1) the information reported from processing centers were conservative estimates, as the owners did not want to reveal their true production, 2) not all processing centers in the region (87) were visited in this study, which could include centers with higher annual production, and 3) the estimates from previous studies were markedly high, based on limited and perhaps inconsistent information.

Overall, the grade of the head material processed by the visited processing centers from 2013 and 2015 ranged from 0.6 to 30 g/tonne Au. In 2015, the average gold recovery reported from cyanidation processes was 83%, ranging from 50% to 98%. It is important to note that the processing centers report gold recoveries based on results they obtain from cyanidation tests performed in the laboratory. The laboratory tests are considered to represent 100% of extraction, which are then used as a basis of comparison for the plant results. Unfortunately, this kind of biased comparison makes it difficult to assess the actual gold recovery from the cyanidation processes.

5.6. Electricity and Operating Costs of Processing Centers

On average, it was estimated that 26% of the monthly costs at processing centers in Portovelo-Zaruma are due to electricity, which is used to run all the equipment, including jaw crushers, cone crushers, Chilean mills, ball mills, *chanchas*, pumps, agitators and illumination. It was estimated that processing centers have an average demand-installed capacity of 105 kW, based on the use of three Chilean mills, two *chanchas* and two jaw crushers.

In 2013, the average electricity cost per processing center for just crushing and grinding was estimated at US$ 19,008/plant/day, with an average consumption cost per plant of 45 kWh/tonne. Assuming that a plant processed on average 55 tonnes/day in 2013 and 62 tonnes/day in 2015, then the electricity consumption would be 215,325 and 242,730 kWh/day for 2013 and 2015, respectively. Using an average of US$ 0.09/kWh, then the current average electric energy cost for the 87 plants in Portovelo-Zaruma is approximately US$ 262,000/a.

5.7. Profitability of Processing Centers

In 2013, although profitability of the processing centers was not specifically analyzed, 96% of the plants reported that their operations were economically viable.

In 2015, profitability was estimated at 20 processing centers, using the following formula:

Profitability = (gold production * current gold value) – operating costs

In the above, current gold value was defined as the rate as of April 2016 (US$ 39,067 per gram). However, miners in Portovelo sell the gold at gold shops for an average price of US$ 35.16 per gram.

In 2015, using an average operating cost of US$ 83,785.44/month/plant obtained in Table 5.1, then all 87 processing centers would have an average annual profit of US$ 1,298,783/plant/a or US$ 3,600/plant/day.

From the 15 processing centers which reported their monthly gold production, an average was estimated at 5.06 kg/plant/month, which would generate a revenue of approximately US$ 6000/day/plant. Considering on average operating cost of US$ 3,146/day/plant, then the estimated profit would be approximately US$ 2,854/plant/day which is relatively close to the US$ 3,600 plant/day calculated here.

Chapter 6: Environmental Concerns

6.1. Mercury Use

Mercury is used in two processes in ASGM operations in Portovelo-Zaruma, including whole ore amalgamation in *chanchas* and concentrate amalgamation using Chilean mills and sluice box processing. Through informal conversations with the miners, it was observed that the large majority have no knowledge about the mineralogical characteristics of the mined ore or how much gold they will be extracting from the *chancha* process. Consequently, the miners sometimes add more mercury than is needed to amalgamate the gold, which worsens the amount of contamination affecting the miners, the fluvial environment and the atmosphere.

In 2015, it was estimated that approximately 1.79 tonnes/a of metallic mercury was used by processing centers in Portovelo-Zaruma, from which 576 kg was released to the environment, including 333 kg evaporated during the burning of gold and mercury amalgams and 243 kg released into water bodies as Hg-contaminated tailings.

In 2013, approximately 71% of processing centers in Portovelo-Zaruma were using mercury to process the ore. Because *chanchas* are both the preferred method of processing and the method that results in the greatest mercury loss, a significant amount of mercury (13.6%) was lost with the tailings UNIDO (2016). These numbers point to a significant volume of mercury being released to the environment. In 2015, the estimation of mercury use reduced, which in turn results in less mercury released to the environment. These results corroborate the estimates presented by Guimarães et al. (2011), who based their calculations on mercury balance data provided by Velásquez-López et al. (2010).

6.2. Mercury Use - Risk Characterization

A recent assessment of tailings management by INIGEMM (2013, unpublished) has shown that a large number of plants in the El Pache district of Portovelo-Zaruma have tailings with high THg concentrations varying between 2801 and 43,400 mg/kg. If discharged into the Puyango-Tumbes River basin, the mercury, in different forms, such as metallic and Hg-cyanide complexes, would ultimately accumulate in soils and sediments and become bioavailable upon methylation for uptake by aquatic organisms. It is important to point out that the CCME (Canadian Council of Ministers of the Environment) guidelines for total mercury concentrations in sediment (Freshwater PEL (Probable Effect Level) - Sediment Quality Guidelines for the Protection of Aquatic Life, 2006) and soil (Agricultural Standard - Soil Quality Guidelines for the Protection of Environmental and Human Health, 2006) are 0.5 and 6.6 mg/kg, respectively.

6.3. Mercury Use - Understanding Risks and Disseminating Information

Although the miners are aware of the health risks associated with mercury use, it is still the preferred method to extract gold. Approximately 70% of the processing center managers and owners reported that they have a basic understanding of the environmental and health-related impacts associated with the use of mercury and cyanide, however, most are generally unaware of the magnitude of the problem and the prevalence of mercury contamination in the environment. At the same time, they were aware of some methods to reduce mercury vapour exposure, but were not practicing them. Furthermore, they were concerned that the government did not provide alternatives to promote education to introduce new technologies.

Several training initiatives have been implemented in ASGM operations over the past decade in southern Ecuador as an opportunity to teach miners, local communities and processing center owners about sustainable mining practices with workshops. Although the training initiatives have helped the miners and processing center owners understand of social and environmental impacts related to mercury use and the implementation of new processing technologies, more needs to be done to ensure the techniques presented are actually used for processing.

6.4. Mercury Use - Information Refinement

In October 2013, the Ecuadorian government signed the “Minamata Convention on Mercury”, with the objective of protecting human health and the environment from the harmful effects of mercury emissions and releases by the processing centers in southern

Ecuador. The government confirmed its commitment to control the use of mercury in mining activities and is working towards the elimination of Hg at processing centers.

For the last 25 years, mercury use and the reduction of mercury released into the environment has been an important topic among institutions working with ASGM. As of June 2015, the Ecuadorian Government has banned the use of mercury in artisanal mining in the region of Portovelo-Zaruma. Although this seems like a positive step, it is forcing miners to burn the gold and mercury amalgams in their homes, exposing family members and neighbours to the toxic vapours. This was also common practice in the 1990s (SMI, 1995), before modern technology was available for them to use. Thus, miners without alternatives provided by the government will continue using the same rudimentary techniques, but in their private homes.

Although mercury use continues, it is clear that recent initiatives implemented by the Ecuadorian Government to reduce mercury use in ASGM operations in southern Ecuador are resulting in many miners and processing centers employing alternative methods to extract gold. Consequently, due to the restrictions regarding mercury use resulting from the Minamata Convention, less mercury is being used in the *chanchas* at processing centers and cyanidation processes are increasingly implemented to extract the gold.

6.5. Tailings Management - Suggested Solutions

The objective of tailings management is to confine the mine tailings and provide for their safe, long-term disposal. Tailings are stored in engineered structures called tailings impoundment areas, which can be created through the use of dams, berms, and natural features of the mine site such as valleys, hillsides, or depressions.

Responsible tailings management needs to consider the specific characteristics of tailings. For example, gold processing centers must take into account the presence of sulphide minerals, as well as reagents used in the gold mining process, including cyanide. All mining sites that use cyanide for metals recovery should have a comprehensive and well-maintained cyanide management plan, which must include descriptions of how cyanide-containing solutions and slurries are to be handled, stored, contained, monitored and destroyed.

It is essential that tailings facilities be designed for site-specific environmental conditions, ore type, geochemistry, topography and other constraints. However, all tailings management options are designed to minimize interactions between the tailings and the local environment to prevent acid generation, metal leaching and contamination of surface water and groundwater. Therefore, proper tailings management is able to mitigate deleterious effects on vegetation, wildlife and aquatic life, as well as direct and indirect human health impacts.

Currently, there are 240 mine concessions and 87 processing centers operating in the Portovelo-Zaruma region. Each of the plants processes gold using a combination of mercury amalgamation and/or cyanidation, resulting in an estimated 0.576 tonnes of mercury and 2,040 tonnes of cyanide being released each year, some of which end up in tailings reservoirs. The processing plants are located in a hilly region with a scarcity of flat areas, thus the mining facilities and some tailings reservoirs are built directly on the river banks. In 2015, it was estimated that only 65% of the processing centers possessed tailings facilities. Due to poor construction, inadequate or complete lack of storage facilities, mismanagement and lack of environmental stewardship, most of the tailings from the small reservoirs end up in the Puyango-Tumbes River, amounting to an estimated 1.6 million tonnes of tailings enriched with cyanide, mercury and other heavy metals. Due to strong metal-binding properties of cyanide complexes, transport of mercury (Hg) and other heavy metals are carried far downstream from ASGM processing plants.

6.6. Tailings Management - Analysis Phase

As mentioned above, for the years 2013 and 2015, an estimated 631 and 243 kg/a, respectively, of total mercury used by 62 out of 87 processing centers in Portovelo-Zaruma was lost with the tailings, most of which is apparently dumped into the Puyango-Tumbes River. Additionally, for 2013 and 2015, there was an estimated average consumption of 18.7 and 24.6 tonnes/plant/month, respectively, of sodium cyanide (NaCN) used in cyanidation processes by 83 of the 87 plants. This amounted to the annual generation of 1550 and 2040 tonnes for 2013 and 2015, respectively, of NaCN tailings that have been largely discharged into the local river system.

Guimarães et al. (2011) had reported significant annual releases of NaCN into the local river system. Estimations based on the data presented in the preceding chapters places the annual release of NaCN between 65-75% lower than Guimarães et al. (2011). This discrepancy is likely due to an under-estimation by Guimarães et al. (2011) of the NaCN consumed by plants, different methodologies used to measure the numbers, or even the source of the ore.

6.7. Tailings Management - Risk Characterization

After cyanidation, the final tailings are either kept at the processing center, transported to El Tablon in Portovelo, or dumped directly into the river. The results from this study have shown that only 20% of the 52 processing plants visited end up destroying the used cyanide before discharge.

Currently, the majority of the processing centers do not have the capacity to keep large quantities of tailings in their own reservoirs. A pipeline along the Amarillo and Calera Rivers was designed to transport the tailings from processing centers to a constructed central tailings facility called El Tablon for storage; however, this project has not been finalized. This was intended to be a temporary measure until an Industrial Processing Park could be created, where the Ecuadorian Government hopes that all of the processing plants can be relocated. In the interim, processing centers are trucking their tailings to El Tablon.

6.8. Tailings Management - Information Refinement

In Ecuador, existing environmental regulations clearly stipulate how mining and mineral processing should be performed. However, poor enforcement by local and national agencies and lack of options by artisanal miners and processing centers facilitates the discharge of contaminated tailings generated by amalgamation and cyanidation directly into local rivers. Not only is there an urgent need to address aquatic and atmospheric pollution caused by gold processing in the Portovelo-Zaruma region, but also investigate how areas and populations downriver in southwestern Ecuador and Peru are affected, which has become the key issue in an ongoing trans-boundary environmental conflict.

Chapter 7: Conclusion

This research was undertaken to assess different approaches in use to extract and process gold from artisanal and small-scale gold mining in southern Ecuador and to understand the source of knowledge employed by the processing plants.

The following conclusions were derived from this study:

- In Portovelo-Zaruma, as of 2015, there were 240 mining concessions with approximately 1,000 miners working in groups of 5 -10 people.
- The gravity method and cyanidation processes are the principal methods used in the Portovelo-Zaruma mining district.
- Approximately 1.7 million tonnes of ore/annum were processed by the 87 plants in 2013.
- Approximately 1.9 million tonnes of ore/annum were processed by the 87 plants in Portovelo-Zaruma in 2015.
- Approximately 1.6 million tonnes/annum of tailings were produced by the 87 processing centers.
    - The plants lack the capacity, space and incentive to manage their tailings.
- In 2015, approximately 6.0 tonnes of gold/annum were produced by all of the 87 processing centers.
- In 2013, it was estimated that each plant used on average 1.56 tonnes/month of sodium cyanide (NaCN), which amounted to an average of 18.7 tonnes/annum.
- In 2015, there was an increase of NaCN use of approximately 31% in comparison to 2013. Each plant uses on average 2.05 tonnes/month of NaCN, totalling 24.6 tonnes/a/plant.

- Considering that 95% of the plants, or 83 out of 87, are using cyanidation to process ore or gravity separation tailings, this would amount to an estimated yearly consumption of NaCN of approximately 1550 and 2040 tonnes for 2013 and 2015, respectively.
- Only 20% of the 52 processing plants visited ended up destroying the cyanide from tailings before discharging it into the adjacent river.

- The increased use of cyanide is in reaction to 1) prohibition of use of mercury in ASGM in Ecuador (June 2015), and 2) more knowledge of the processing centers and miners that cyanidation extracts more gold than amalgamation.

- Processing centers in Portovelo-Zaruma also receive large amounts of tailings from other provinces of Ecuador to be processed, which has increased significantly in recent years.

- In 2013, 78% of the plants were using a total of 4.64 tonnes of Hg/a being used. In 2015, this was reduced to 65% or 2.4 tonnes of Hg/a used.

- Based on the mass balance of *chanchas* conducted in 2013 (UNIDO, 2016), (which is the method that causes more mercury loss than amalgamation of concentrates), an average of 13.6 % of Hg was lost with the tailings, which amounted to 631 kg/a. As 18.6% of the mercury used was lost by evaporation, this would amount to 863 kg/a. The total Hg released to the environment was 1.5 tonnes/a in 2013. From the mercury used, 67.8% of the total amount was recycled, to be used again for further amalgamation

- Using the percentages obtained in the mass balance of 2013, the amount of Hg lost to the tailings was 243 kg/a in 2015 and the amount lost by evaporation was 333 kg/a. Therefore, the total Hg lost to the environment was 576 kg of Hg in 2015.
  - The reduction of mercury used and lost by the plants compared with 2013, is mainly based on three possible reasons:
    - 1) the Ecuadorian Government wanted to crack down on Hg use due to implementation of legislation intended to ensure compliance with

the Minamata Convention, which hopes to regulate the sale and use of mercury,

- 2) the the use of cyanidation has increased, due to the understanding that cyanide allows for increased gold production, and
- 3) fewer miners are still using *chanchas*, because the high gold grade material is getting more scarce.

- The implementation of gold processing technologies that do not involve the use of mercury is absolutely necessary to reduce the negative health impacts associated with the burning of gold and mercury amalgams, as well as the environmental contamination associated with the release of mercury-laden tailings into aquatic systems.
- However, flotation methods for obtaining copper concentrates is still difficult to implement in Portovelo-Zaruma, due to limited technical expertise of metallurgical engineers employed in the region.
- Miners still accept low levels of gold recovery, as it is apparent that they do not fully understand the processes of gold extraction and recovery and they have gold in their hands in a short time.
- Although the miners understand the health risks associated with mercury use, it is still the preferred method to extract gold, as it is relatively inexpensive, highly accessible and easy to use.
    - Approximately 70% of the processing center managers and owners reported that they have a basic understanding of the environmental and health-related impacts associated with the use of mercury and cyanide, however, most are generally unaware of the magnitude of the problem.
    - At the same time, they were aware of existing methods to reduce mercury vapour exposure.
    - Furthermore, they are concerned that the government does not provide alternatives to promote education to introduce new technologies.

- There is a strong evidence that processing centers are still discharging soluble mercury-cyanide complexes into the Puyango-Tumbes watershed.
    - It is fundamental to assist the processing centers to better manage their tailings, in order to mitigate further environmental contamination.
- More training is needed for the artisanal miners in Portovelo-Zaruma to better understand the dangers of mercury use, as well as the implementation of more advanced processing technologies to improve gold recovery and reduce environmental impacts.

Chapter 8: Originality of the Research

This thesis was created to better understand the current artisanal and small-scale gold mining practices and methods employed at processing plants in the region of Portovelo-Zaruma in Ecuador. The characterization of the plants provided valuable information on the level of expertise and access to technology by both miners and processing centers owners and the most common practices in use to extract and recover gold. Even though there is a considerable amount of literature available on this subject, this thesis is the first time the following have been done:

- An integrated assessment of 52 artisanal and small-scale gold mining processing centers to identify the positive and negative lessons learned by different stakeholders in the mining district of Portovelo-Zaruma.
- The amount of gold produced and gold recovery by the processing center was evaluated and discussed.
- Different operating costs for artisanal and small-scale mining were assessed and analyzed.
- The profitability of the processing centers has been measured.
- Detailed information about regents and methods used by each plants was assessed in individual plants.
- Suggestions were made to improve the implementation of training programs which work to achieve cleaner production of gold and contribute to sustainable development of the mining communities in Ecuador.

Hopefully, these new contributions to the field will expand to other mining regions all over Ecuador and help to stop the use of mercury in ASGM.

Chapter 9: Opportunities for Future Research

Artisanal and small-scale gold mining has been a source of investigation over the last four decades in the mining district of Portovelo-Zaruma, with the aim to mitigate the negative effects of the destructive gold mining operations in the region. Based on the observations obtained from the study present, further research is needed:

- Future assessments should investigate the differences in processing plants that utilize Carbon-in-Pulp from those that use Merrill Crowe, in order to evaluate the quality of effluents in terms of cyanide consumption, Hg releases, and the types and quantities of metals in effluents. Additionally, it would be worthwhile to determine cyanide consumption and environmental impacts in terms of different types of ore, as some are rich in arsenic, copper and other metals that interfere directly in the process.
- Assessments of gold recovery in different processes observed in the region are badly needed. Currently, only anecdotal information is available regarding gold recovery from "*chanchas*", manual amalgamation and different types of cyanidation. In order to convince the processing center owners to adopt cleaner techniques, it is important to provide them with information about the efficiency of their current methods.
- It is important to conduct a geographically representative assessment of artisanal gold ore extraction sites in the headwaters of the Puyango-Tumbes River Basin and evaluate the occupational hazards associated with the use of primitive and rudimentary mining methods, including risks of subsidence, suffocation due to poor ventilation, landslides, flooding, and other types of accidents in the mines.
- It is crucial to conduct a detailed assessment of the direct impacts associated with inhalation of mercury vapors from the smelting of gold *doré* and burning of

amalgams in open pans on targeted individuals, and especially for vulnerable populations, including children and pregnant women.

- Additionally, it is essential to do a full assessment of the barriers impeding completion of pipelines from processing centers in Portovelo-Zaruma to the El Tablon tailings dam facility recently constructed in the region. Furthermore, solutions regarding tailings management practices need to be found in order to mitigate environmental contamination in local waterways.

- Finally, an assessment of the ore and tailings supply chain associated with the hierarchical nature of the business model for processing centers needs to be conducted in order to help reduce mercury use and restructure the power balance between processing center owners and artisanal miners.

References

Adler-Miserendino, R. (2012). Tracing mercury pollution in aquatic systems: implications for public health. PhD. Thesis, John Hopkins University.199 p. Retrieved from http://pqdtopen.proquest.com/doc/1432373790.html?FMT=AIon 04/22/2016.

Adler Miserendino, R., Bergquist, B.A., Adler, S.E., Guimarães, J.R.D., Lees, P.S.J., Niquen, W., Velasquez-López, P.C., Veiga, M.M. (2013). Challenges to measuring, monitoring, and addressing the cumulative impacts of artisanal and small-scale gold mining in Ecuador. *Resources Policy* **38(4):** 713–722. DOI:10.1016/j.resourpol.2013.03.007.

Angeloci, S.G. (2013). Myths and realities in artisanal gold mining mercury contamination. MASc. thesis. Department of Mining Engineering, University of British Columbia, 180 pp. https://open.library.ubc.ca/cIRcle/collections/ubctheses/24/items/1.0071961 05/12/2014.

Appleton, J. D., Carrasco, M., Maldonado, R., and H, Orbea (1996). Assessment of mercury contamination in the Ponce Enriquez artisanal gold mining area, Ecuador. Nottingham, British Geological Survey: 49.

Appleton, J.D., Williams, T.M., Orbea, H., Carrasco, M. (2001). Fluvial contamination associated with artisanal gold mining in the Ponce Enriquez, Portovelo-Zaruma and Nambija areas, Ecuador. *Water Air and Soil Pollution* 131(1): 19-39.

Astudillo, C. (2007). El sudor del sol. Hstoria de la mineria orense. Ediciones la tierra. Ecuador, 190p.

Betancourt O., Narváez A., Roulet M. (2005). Small-scale gold mining in the Puyango river basin, southern Ecuador: a study of environmental impacts and human exposures. *Ecohealth* 2(4): 323-332. Retrieved from http://link.springer.com/article/10.1007/s10393-005-8462-4 on 05/06/2014.

Björnberg, A., Hakanson, L., Lundbergh, K., (1988). A theory on the mechanisms of regulating the bioavailability of mercury in natural waters. *Environmental Pollution* 49: 53-61.

Botz, M.M. (1999). Overview of Cyanide Treatment Methods. *Mining Environmental Management*, Mining Journal Ltd., London, UK, pp. 28-30, May 2001. Retrieved from http://www.botz.com/MEMCyanideTreatment.pdf on 07/06/2016.

Bose-O'Reilly, S., Lettmeier, B., Matteucci-Gothe, R., Beinhoff, C., Siebert, U., Drasch, G. (2008). Mercury as a serious health hazard for children in gold mining areas. *Environmental Research* 107: 89–97. Retrieved from http://ehp.niehs.nih.gov/1307864/ on 05/07/2016.

Branfireun, B.A., Roulet, N.T., Kelly, C.A., Rudd, J.W.M. (1999). In situ sulphate stimulation of mercury methylation in a boreal peatland: toward a link between acid rain and methylmercury contamination in remote environments. *Global Biogeochemical Cycles* **13:** 743-750. DOI: 10.1029/1999GB900033.

Buxton, A. (2013). Responding to the challenge of artisanal and small-scale mining - How can knowledge networks help? London: IIED.
Retrieved from http://www.ddiglobal.org/login/resources/responding-to-the-challenge-of-asm-how-can-knowledge-networks-help.pdf on 09/12/2015.

Carmouze, J.P., Lucotte, M, Boudou, A. (2001). Mercury in the Amazon: Importance of Human and Environment, Health Hazards. Synthesis and Recommendations. IRD Editions; Institut de Recherche Pour le Developpement, Paris, 40 p.

Castilhos, Z.C., Rodrigues-Filho, S., Rodrigues, A.P.C., Villas-Bôas, R.C., Siegel, S., Veiga, M.M., Beinhoff, C. (2006). Mercury contamination in fish from gold mining areas in Indonesia and human health risk assessment. *Science Total Environment* 368: 320-325.

Chen, M.A. 2007. Rethinking the informal economy: Linkages with the formal economy and the formal regulatory environment. UN/DESA. United Nations Department of Economic and Social Affairs. Research Paper, 46. 14p. Retrieved from http://www.un.org/esa/desa/papers/2007/wp46_2007.pdf on 21/01/2015

CIIEID ICIIED (2014). Implementing Training Centres for Small-Scale Mining. Report to CIIEID ICIIED Canadian International Institute for Extractive Industries and Development, 63p.

Clarckson, T.W. (1997). The toxicology of mercury. *Critical Reviews in Clinical Laboratory Sciences* 34: 369-403. DOI: 10.3109/10408369708998098.

Clark, R.M., Hakim, S. (Eds). (2014). Securing Water and Wastewater Systems, Protecting Critical Infrastructure 2, DOI: 10.1007/978-3-319-01092-2_1. @ Springer International Publishing Switzerland.

Coles, C.A., Cochrane, K. (2006). Mercury cyanide contamination of groundwater from gold mining and prospects for removal. In: Proc. 59th Canadian Geotechnical Conference and 7th Joint CGS-IAH Groundwater Speciality Conference, pp. 1118-1122. Available at http://www.engr.mun.ca/wccoles/Publications/0227-231.pdf.

Collins, N.; Lawson, L. (2014). Investigating approaches to working with artisanal and small-scale miners (ASM): A compendium of strategies and reports from the field. IM4DC Action Research Report, 124p. Available at http://im4dc.org/wp-content/uploads/2013/09/Collins-ASM-FR-Completed-Report.pdf.

Colombo, M.J.; Ha, J.; Reinfelder, J.M.; Barkay, T.; Nathan, Y. (2013). Anaerobic oxidation of Hg (0) and methylmercury formation by Desulfovibrio desulfuricans ND132. Geochimica et Cosmochimica Acta. V (112), pp 166-177. DOI: 10.1016/j.gca.2013.02.001.

Cordy, P.; Veiga, M.M.; Salih, I.; Al-Saadi, S.; Console, S.; Garcia, O.; Mesa, L.A.; Velásquez-López, P.C.; Roeser, M. (2011). Mercury contamination from artisanal gold mining in Antioquia, Colombia: The world's highest per capita mercury pollution. *Science of the Total Environment* 410–411: 154–160. DOI: 10.1016/j.scitotenv.2011.09.006.

Cordy, P., Veiga, M.M., Crawford, B., Garcia, O., Gonzalez, V., Moraga, D., Roeser, M., Wip, D., (2013). Characterization, mapping and mitigation of mercury vapour emissions from artisanal mining gold shops. Environ. Res. 125, 82–91.

Counter, S.A., Buchanan, L.H., Ortega, F., Laurell, G. (2002). Elevated blood mercury and neurological observations in children of the Ecuadorian gold mines. *Journal of Toxicology and Environmental Health, Part A:* 65: 149-163.

Counter, S.A., Buchanan, L.H., Ortega, F. (2006). Neurocognitive screening of mercury-exposed children of Andean gold miners. *The International Journal of Occupational and Environmental Health* 12: 209–14.

Davies, G.R. (2014). A toxic free future: Is there a role for alternatives to mercury in small-scale gold mining? Futures (62): 113-119. Retrieved from http://www.sciencedirect.com/science/article/pii/S0016328713001638 on 10/06/16

Dellinger, J., Dellinger, M., & Yauck, J.S. (2012). Mercury Exposure in Vulnerable Populations: Guidelines for Fish Consumption. Mercury in the Environment: Pattern and Process 86: 289–287. 300. DOI:10.1525/california/9780520271630.001.0001.

Dillard, K., 2012. Artisanal Gold Mining Threatens Riverine Communities in Guyana. New Security Beat, In: http://www.newsecuritybeat.org/2012/08/artisanalgold-mining-threatens-riverine-communities-in-guyana/#.UzCxRPldUgI (Accessed March 21, 2016).

Drake, P. L., Rojas, M., Reh, C. M., Charles, A. M., & Jenkins, F. M. (2001). Occupational exposure to airborne mercury during gold mining operations near El Callao, Venezuela.*International Archives of Environmental Health, 74*, 206–212.

Eisler, R., Wiemeyer, N.S. (2004). Cyanide hazards to plant and animal from gold mining and related water Issues. *Reviews of Environmental Contamination and Toxicology* 183: 21-54.

Gibb, H.; O'Leary, K.G. (2014). Mercury Exposure and Health Impacts among Individuals in the Artisanal and Small-Scale Gold Mining Community: A Comprehensive Review. *Enviromental Health Perspectives*. Vol. 122 (7), pp.667-672.

González-Carrasco, V., Velasquez-Lopez, P.C., Olivero-Verbel, J., Pájaro-Castro, N. (2011). Air mercury contamination in the gold mining town of Portovelo, Ecuador. *Bulletin of Environmental Contamination and Toxicology* 87(3): 250-253. DOI 10.1007/s00128-011-0345-5.

Grandjean, P.; Satoh, H.; Murata, K.; Eto, K. (2010). Adverse Effects of Methylmercury: Enviromental Health Research Implications. *Enviromental Health Perspectives* 118(8) pp. 1137-1145.

Grimaldi, M.; Guédron, S.; Grimaldi, C. (2015). Impact of Gold Mining on Mercury Contamination and Soil Degradation in Amazonian Ecosystems of French Guiana. © CAB International 2015. CPI Group (UK) pp.95-107.

Guimarães J.R.D., Forti M.C. (1999). Mercury in human and environmental samples from two lakes in Amapá, Brazilian Amazon. *Ambio: A Journal of the Human Environment* 28(4): 296-301.

Guimarães, J.R.D., Betancourt O., Miranda M.R., Barriga R., Cueva E., Betancourt S. (2011). Long-range effect of cyanide on mercury methylation in a gold mining area in southern Ecuador. *Science of the Total Environment*, *409*(23): 5026–33. doi:10.1016/j.scitotenv.2011.08.021

Guiza, L., Aristizabal, J. (2013). Mercury and gold mining in Colombia: a failed state. Universitas Scientiarum Univ. Sci. 2013, 18(1): 33-49.

Habashi, F. 1987. One hundred years of cyanidation. *CIM Bulletin* 80(905): 108-114.

Hentschel, T., Hruschka, F., Priester, M. (2002). Global report on artisanal & small scale mining. Mining, Minerals and Sustainable Development (MMSD), 67.

Hentschel, T.; Hruschka, F.; Priester, M. (2003). Artisanal and small-scale mining challenges and opportunities. London: IIED 1 84369 470.

Hilson, G. (2002). Small-scale mining and its socioeconomic impact in developing countries. *Natural Resources Forum* 26 (1): 3–13.

Hinton, J.J., Veiga, M.M., Veiga, A.T.C. (2003). Clean artisanal gold mining: a utopian approach? *Journal Cleaner Production* 11(2): 99–115.

Hyman, M. (2004). The impact of mercury on human health and the environment. *Alternative Therapies* 10: 70-75. Retrieved from http://search.proquest.com/openview/0bfe1f39b34922035a121e9d77f7636a/1?pq-origsite=gscholar on 09/18/2015

ICMC (2014). International Cyanide Management Code (ICMI) for the manufacture, transport and use of cyanide in the production of gold. Environmental & Health Effects. *ICMC*. Retrieved from: http://www.cyanidecode.org/cyanide-facts/environmental-health-effects

International Labor Organization (1999). *Social and Labor Issues in Small-Scale Mines*; Sectoral Activities Program, International Labor Organization, International Labor Office: Geneva, 17-22 May, 1999. International Labour Office.

IPCS (2003). International Programme on Chemical Safety. World Health Organization. Concise International Chemical Assessment Document 50: Elemental mercury and inorganic mercury compounds: human health aspects. Geneva, Switzerland. http://www.who.int/ipcs/publications/cicad/cicads

Jønsson, J.B.; Charles, E.; Kalvig, P. (2013). Toxic mercury versus appropriate technology: Artisanal gold miner's retort aversion. *Resources Policy* 38: 60-67.

Jones H.R. (1971). Mercury pollution control. New Jersey: Noyes Data Co.

Kessler, R. (2013). The Minamata Convention on Mercury. A first Step toward protecting Future Generations. *Enviromental Health Perpectives* 121 (10): A305-A309.

Kiefer, A.M.; Drace, K.; Seney, C.S.; Veiga, M.M. (2015). Challenges associated with using retorts to limit mercury exposure in artisanal and small-scale gold mining: case studies from Mozambique, Ecuador, and Guyana. In: Trace Materials in Air, Soil, and Water; ACS Symposium Series; American Chemical Society, 2015; Vol. 1210, pp 51–77.

Korte, F.; Spiteller, M.; Coulston, F. (2000). The cyanide leaching gold recovery process is a nonsustainable technology with unacceptable impacts on ecosystems and humans: the disaster in Romania. Ecotoxicology Environment, 46:241–245.

Lane, K., (2004). Unlucky strike: gold and labor in Zaruma, Ecuador 1699-1820. *Colonial Latin America Review* 13: 65-84.

La Republica, 2013a. La minería informal tiene el 20% de la producción de oro del Perú. http://www.larepublica.pe/26-08-2013/la-mineria-informal-tiene-el-20-de-la-produccion-de-oro-del-peru

Logsdon, M.J., Hagelstein, K., Mudder, T.I. 1999. *The Management of Cyanide in Gold Extraction*. ICME Publications, Ottawa.

Lovitz, S.B. (2006). Scales of responsible gold mining: overcoming barriers to cleaner artisanal mining in southern Ecuador. MSc thesis. University of Vermont. 145 p. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.507.131&rep=rep1&type=pdf on 01/03/2015

Malm, O., Branches, F.J.P., Akagi, H., Castro, M.B., Pfeiffer, W.C., Harada, M. (1995). Mercury and methylmercury in fish and human hair from the Tapajós river basin, Brazil. *Science of the Total Environment* 175: 141–50. DOI: 10.1016/0048-9697(95)04910-X

Marsden, J., House, C. (2006). The chemistry of gold extraction. Vol. 2: 81-89.

Meech, J.A., Veiga, M.M. (1997). Emissions and stability of mercury in the Amazon. *Canadian Metallurgical Quarterly* 36(4): 231-239.

Meech, J.A., Veiga, M.M., Tromans, D. (1998). Reactivity of mercury from gold mining activities in darkwater ecosystems. *Ambio* 27: 92-98.

MRNNR e; Ministerio de Recursos Naturales Non-Renovables, 2013. Ecuador Tiene 1349 Labores Minerales Artesanales. Retrieved from: from http://190.11.28.23/en/inicio/destacados/959-ecuador-tiene-1349-labores-mineras-artesanales.html.(Accessed January 3, 2016).

Nichols, B., Veiga, M., Van Zyl, D., Xavier, A.M. (2015). Closure of artisanal small scale gold mine processing plants in Ecuador. *Journal of Management and Sustainability* 5(2): 41-47.

Paredes, A. (1980). Oro y sangre en Portovelo. El imperialismo en el Ecuador. Ecuador. 240 p.

Pirrone, N., Cinnirella, S., Feng, X., Finkelman, R.B., Friedli, H.R., Leaner, J., Mukherjee, A.B., Stracher, G.B., Streets, D.B., Telmer, K. (2010). Global mercury emissions to the atmosphere from anthropogenic and natural sources. *Atmospheric Chemistry and Physics*, 10(13): 5951–5964. doi:10.5194/acp-10-5951-2010

Priester, M., Hentschel, T. (1992). Small-scale gold mining: processing techniques in developing countries. GTZ/GATE, Vieweg, Eschborn, Germany, 96 p.

PRODEMINCA, (1999). Monitoreo ambiental de las areas mineras en el sur del Ecuador. Proyecto de desarrollo minero y control ambiental, Quito, Ecuador. 214 p.

Puño, N. (2014). Securing Water and Wastewater Systems. doi:10.1007/978-3-319-01092-2

Risher, J. (2003). World Health Organization, United Nations Environment Programme, International Labour Organisation, Inter-Organization Programme for the Sound Management of Chemicals, International Program on Chemical Safety, 2003. Elemental mercury and inorganic mercury compounds: human health aspects. World Health Organization, Geneva.

Sandoval, F., (2001). (SSMD) Small-scale mining in Ecuador. Mining, Minerals and Sustainable Development. England 75, 27pp.

Shafer, Z. (2014). Use of X-ray diffraction to identify and quantify soil swelling potential. ProQuest Dissertations & Theses Global.

Straskraba, V., Moran, R.E (2006). Environmental occurrence and impacts of arsenic at gold mining sites in the Western United States. Int. J. Mine Water, 9(1-4): pp 181-191.

Seccatore, J. (2012). An estimation of the artisanal small-scale production of gold in the world. Report for Codex Engineering Services, Via Lungomare, Italy.

Seccatore J., Veiga M.M., Origliasso, C., Marin, T., Tomi, G.D. (2014). An estimation of the artisanal small-scale production of gold in the world. *Science of the Total Environment* 496: 662-667.

SGAB-Prodeminca (1998). Monitoreo ambiental de las áreas mineras en el sur de ecuador, 1996-1998: Proyecto de desarrollo minero y control ambiental, subcomponente 3.1. Quito: Swedish Environmental Systems. Report SES No:R-Ec-E-9.46/3.1-9810-069.

SMI, (1995). Environment Protection in Ecuadorian Gold Mining. *International Agency for Small-Scale Mining Bulletin* 8: February 1995.

Siegel, S., Veiga, M.M. 2010. The myth of alternative livelihoods: artisanal mining, gold and poverty. Int. J. Env. & Poll. 41, 3/4. 272-288.

Swain, E.B., Jakus, P.M., Rice, G., Lupi, F., Maxson, P.A., Pacyna, J.M., Veiga, M.M. (2007). Socioeconomic consequences of mercury use and pollution. *Ambio* 36(1): 45–61.

Tarras-Wahlberg, N.H., Flachier, A., Lane, S., Fredriksoon, G., Lundberg, G., Sangfords, O. (2000). Environmental impact of small-scale and artisanal gold mining in southern Ecuador. Implications for the settings of environmental standards and for the management of small scale mining operations. Royal Swedish Academy of Sciences. *Ambio* 29(8): 484–91.

Tarras-Wahlberg, N.H., Flachier, A., Lane, S., Sangfors, O. (2001). Environmental impacts and metal exposure of aquatic ecosystems in rivers contaminated by small scale gold mining: The Puyango river basin, southern Ecuador. *Science of the Total Environment* 278(1): 239-261.

Tarras-Wahlberg, N.H., Lane, S. (2003). Suspended sediment yield and metal contamination in a river catchment affected by El Niño events and gold mining activities: The Puyango River Basin, southern Ecuador. *Hydrological Processes* 17:3101-3123.

Tassel, F., Rubio, J., Misra, M., Jena, B.C. (1997). Removal of mercury from gold cyanide solution by dissolved air flotation. Minerals Engineering 10: 803-811.

Telmer, K., Veiga, M.M. (2008). World emissions of mercury from small scale artisanal gold mining and the knowledge gaps about them. In: Pirrone N. Mason R. editors, Mercury fate and transport in the global atmosphere: measurements models and policy implications. UNEP United Nations Environmental Program. Geneve, Switzerland. 96-129.

UNEP- United Nations Environment Program (2013). *Global Mercury Assessment 2013: Sources, Emissions, Releases and Environmental Transport* (pp. 1–44). Geneva, Switzerland. http://www.unep.org/hazardoussubstances/Portals/9/Mercury/Documents/ASGM/PROTOCOLS%20FOR%20ENVIRONMENTAL%20ASSESSMENT%20REVISION%2018-FINAL%20BOOK%20sb.pdf

United Nations Environment Program (2013). Mercury: Time to act (Vol. 1, pp. 483–483). doi:10.1038/ngeo275

UNEP – United Nations Environment Programme (2012). Case Study Ecuador. Analysis of formalization approaches in the artisanal and small-scale gold mining sector based on experiences in Ecuador, Mongolia, Peru, Tanzania and Uganda. (pp. 1-44). Geneva, Switzerland.

UNIDO – The United Nations Industrial Development Organization (2016). Implemeting Integrated Measures for Miniminzing Mercury Releases from Gold Mining in Ecuador. June 2016. 366p.

Van P. Straaten, (2000). Human Exposure of mercury due to small-scale gold mining in Northern Tanzania Sci. Total Environ., 259 (2000), pp 45-53.

Vangsnes, G.F. (2015). Towards a political ecological approach on small-scale gold mining in southern Ecuador. 34 p.

Veiga, M.M., Meech, J.A., Hypolito, R., 1995. Educational measures to address Hg pollution from gold mining activities in the Amazon. Ambio 24 (4), 216–220.

Veiga, M.M. (1997). Introducing new technologies for abatement of global mercury pollution in Latin America. Rio de Janeiro, Brazil. UNIDO/UBC/CETEM , 94p.

Veiga, M.M., Meech, J.A. (1999). Reduction of mercury emissions from gold mining activities and remedial procedures for polluted sites. In: Environmental Impacts of Mining Activities. Chapter 10. Azcue, J.M. (Ed). Springer-Verlag, Berlin. 143-162.

Veiga, M.M., Hinton, J.J. (2002). Abandoned artisanal gold mines in the Brazilian Amazon: a legacy of mercury pollution. *Natural Resources Forum (Genova)* 26(1): 15–26.

Veiga, M.M., Baker, R. (2004). Protocols for environmental and health assessment of mercury released by artisanal and small-scale gold miners. Published by GEF/UNDP/UNIDO Global Mercury Project. Vienna. 289p. ISBN 92-1-106429-5.

Veiga, M.M., Bermudez, D., Pacheco-Ferreira, H., Pedroso, L.R.M., Gunson, A.J., Berrios, G., Vos, L., Huidobro, P., Roeser, M. (2005). Mercury Pollution from Artisanal Gold Mining in Block B, El Callao, Bolívar State, Venezuela. In: Dynamics of Mercury Pollution on Regional and Global Scales, Atmospheric Processes and Human Exposures around the World. p. 421-450. Pirrone, N., Mahaffey, K.R. (Eds) ISBN: 0-387-24493-X, July 2005, Springer, Norwell, MA, USA (chapter in book)

Veiga, M.M., Maxson, P.A., Hylander, L.D. (2006). Origin and consumption of mercury in small-scale gold mining. *Journal Cleaner Production* 14: 436-447.

Veiga, M.M., Nunes D., Klein, B., Shandro, J., Velásquez- López, C., Souza, R.N. (2009). Replacing mercury use in artisanal gold mining: preliminary tests of mill-leaching. *Journal of Cleaner Production* 17: 1373-1381.

Veiga, M. M., Angeloci, G., Hitch, M., & Colon Velásquez-López, P. (2014a). Processing centres in artisanal gold mining. *Journal of Cleaner Production* 64: 535-544. http://dx.doi.org/10.1016/j.jclepro.2013.08.015.

Veiga, M.M., Angeloci-Santos, G., Meech, J.A. (2014b). Review of barriers to reduce mercury use in artisanal gold mining. *The Extractive Industries and Society* 1(2): 351-361.

Veiga, M.M., Angeloci-Santos, G., Ñiquen, W., Saccatore, J., 2015. Reducing mercury pollution by training Peruvian Artisanal Gold Miners. J. Cleaner Prod. 94.

Velásquez- López, C., Veiga, M.M. (2007). Review of mercury and cyanide uses in the artisanal gold mining sector in Ecuador. Report to UNIDO United Nations Industrial Development Organization, 70 p.

Velázquez-López, P.C. (2010). Mercury in artisanal and small scale gold mining: identifying strategies to reduce environmental contamination in southern Ecuador. PhD thesis. The University of British Columbia. 200 p.

Velásquez-López, P.C., Veiga, M.M., Hall, K. (2010). Mercury balance in amalgamation in artisanal and small-scale mining: findings ways to reduce environmental pollution in Portovelo-Zaruma, Ecuador. *Journal of Cleaner Production* 18(3): 226-232. DOI:10.1016/j.jclepro.2009.10.010

Velásquez-López P.C., Veiga, M.M., Klein, B., Shandro, J.A., Hall, K. (2011). Cyanidation of mercury-rich tailings in artisanal and small-scale gold mining: identifying strategies to manage environmental risks in Southern Ecuador. *Journal of Cleaner Production:* 19: 1125–33.

Vikentyev, I., Banda, R., Tsepin, A., Prokofiev, V., Vikentyeva, O. (1998). Mineralogy and formation conditions of Portvelo-Zaruma gold sulphide deposit, Ecuador. Geochemistry, Mineralogy and Petrology, Bulgarian Academy of Science. Sofia, 43, 154.

Vikentyev, I.; Banda, R.; Tsepin, A.; Proofiev, V.; Vikentyeva, O. (2005). Mineralogy and formation conditions of Portovelo-Zaruma gold-sulphide vein deposit, Ecuador. *Geochemistry, Mineralogy and Petrology* 43: 148-154.

Watras, C.J., Bloom, N.S. (1992). Mercury and methylmercury in individual zooplankton: implication for bioaccumulation. *Limnology and Oceanography* 37: 1313-18. DOI: 10.4319/lo.1992.37.6.13130.

WHO (2000). World Health Organization. Chapter 6.9 Mercury, Air Quality Guidelines. WHO Regional Office for Europe, Copenhagen, Denmark.

WHO (2004). World Health Organization. *Hydrogen Cyanide and Cyanides: Human Health Aspects*: 1–73. Retrieved from http://www.who.int/ipcs/publications/cicad/en/cicad61.pdf

WHO (2007). World Health Organization. Exposure to mercury. Public Health and Environment. Geneva, Switzerland.

Appendices

Appendix A. Processing Centers Visited in Portovelo-Zaruma - 2013

NUMERO	PLANTA_DE	TITULAR	UBICACIËN	X (WGS 1984 UTM Zone 17S)	Y (WGS 1 UTM Zone
1	AGUILAR	FREDDY FABIAN AGUILAR ESPINOZA	EL SALADO	651189	958639
2	ALTO VIZCAYA	CESAR ARNALDO ROMERO CARRION	STA. MARIANI	653103	959456
3	AMERLAND	AMERLAND S.A.	BOTONEROS	652647	959681
4	BOTONEROS	ANGEL VICENTE GAONA ALVAREZ	BOTONEROS	652891	959671
5	BUZA	CIA. SANTA FE MINING S.A.	BOTONEROS	649810	959794
6	CAZADEROS	ENRIQUE GILBERTO CABRERA PASTOR	VIA A BUSA	651510	959136
7	CELICA	EDUARDO UBERTO LOAYZA ESPINOZA	CELICA	651901	959632
8	CENTENARIO	ANGEL VICENTE SALINAS PEDALOZA	EL SALADO	651051	958875
9	CHILINGOS	JUAN RAMON ESPINOSA MACAS	LA FLORIDA	652490	958843
10	CORONEL HERRERA	DARIO CORONEL JIMENEZ - WILSON JAPON HERRERA	EL PACHE	652089	958983
11	EL CARMELO	FAUSTO MATAMOROS ACARO-NORMAN MATAMOROS ACARO	EL PACHE	651988	959040
12	EL PACHE	EMPRESA MINERA EMICOR CIA. LTDA.	EL PACHE	652111	959041
13	EL PUMA	ANGEL ENRIQUE PONTON JARAMILLO	EL PACHE	651961	959073
14	ESPINOZA 1	ASOCIACION DE CUENTAS DE PARTICIPACION ESPINOZA-1	EL SALADO	650018	958581
15	FAYUMA	JUAN JOSE TINOCO CHICA	EL PACHE	652330	958987
16	FEIJOO	JOSE GUIDO FEIJOO ARMIJOS	EL PACHE	652040	958966
17	GAVIOR	GALO VICENTE ORTIZ PEÐAFIEL	EL SALADO	651700	958792
18	GERAIS	OLGA DEL CARMEN BUELE SALAMEA	EL PACHE	652058	958992
19	GUILLERMO ROMERO	ANGEL AGUILAR ATIENCIE - WILSON SARMIENTO	EL PACHE	651887	959087
20	HERMANOS FRANCO	RUTILO MANUEL FRANCO TORRES -ERASMO RUPERTO FRANCO TORRES	EL PACHE	652120	958959
21	ISRAEL	VICENTE RODRIGO ORTEGA MORALES	CURIPAMBA	651208	958628
22	ISRAEL 1	VICENTE RODRIGO ORTEGA MORALES	EL SALADO	651188	958630
23	ISRAEL 2	TITO WASHINGTON PEÐAHERRETA ESPINOSA	LA FLORIDA	653013	958876
24	JESUS DEL GRAN PODER	FEIJOO ARMIJOS JOSE GUIDO	EL PACHE	652105	958957
25	JESUS DEL GRAN PODER	FRANKLIN MOTOCHE GONZALEZ Y OTROS.	PUENTE NEG	651887	958846
26	LA FORTUNA	JOSE GUSTAVO QUEZADA CAPELO	EL PACHE	651998	959032
27	LA FORTUNA	JOSE MAURICIO FERNANDEZ DIAZ	ARCAPAMBA	654100	959698
28	LA FORTUNA 2	JOSE GUSTAVO QUEZADA CAPELO	EL PACHE	652023	959012
29	LA ORQUIDEA	NERY OSWALDO GRANDA JARAMILLO	EL PACHE	652053	958995
30	LA ORQUIDEA	FREDDY ENRIQUE SALAZAR	VIA A BUSA	650601	959615
31	LEON	JORGE ALFREDO LEON ASANZA	EL SALADO	651118	958608
32	LOS AGAPITOS	JOSE GERARDO VALAREZO RIVERA	EL PACHE	652084	958973
33	MATAMOROS	WILSON CRISTOBAL TORRES CEVALLOS Y OTROS	EL PACHE	652117	958962
34	MINANCA	COMPAÐ=A MINANCA-MINERA NANGUIPA COMPAÐ=A ANONIMA	PUENTE NEG	652130	958815
35	MINAS NUEVAS 1	CASTILLO AGUILAR ERNESTO DANILO	MINAS NUEV/	651450	959983
36	MIRANDA 1	SAMANIEGO ASANZA IRLANDA DEL CARMEN	EL PACHE	651884	959095
37	MISORO	JOHANA ALEXANDRA CHUICO PINTO	EL PACHE	652072	958846
38	MULUNCAY	COMPAÐIA MINERA DEL PACIFICO NOROESTE S.A. MINPANOREST	BOTONEROS	651983	959708
39	MULUNCAY	MIGUEL ANGEL AVELINO ESPINOZA CABRERA	MULUNCAY	653952	959884
40	OROMET	COMPAÐ=A OROMET CIA. LTDA	EL SALADO	651118	958608
41	ORQUIDEA DE LOS ANDES	COMPAÐ=A MINESADCO S.A	EL PACHE	652120	958915
42	PARAISO 1	VELEZ ROMERO KLEBER GONZALO	EL SALADO	651092	958610
43	PILLACELA	CLOTARIO DE JESUS AGUILAR AGUILAR	EL PACHE	651999	959069
44	PITAYA	COSME DE JESUS APOLO AGUIAR	VIA A BUSA	650105	959751
45	PORTOVELO	FLORES ROJAS ANDRES PORFIRIO	LA FLORIDA	652480	958843
46	PORTOVELO 1	ANDRES PORFIRIO FLORES ROJAS	EL SALADO	651195	958667
47	PROSARESA	PROSARESA PROCESADORA DE ARENAS S.A.	PUENTE NEG	651892	958841

NUMERO	PLANTA_DE	TITULAR	UBICACIËN	X (WGS 1984 UTM Zone 17S)	Y (WGS 1 UTM Zone
48	REINA DEL CISNE	JUAN JOSE ESPINOZA MALDONADO	BOTONEROS	652339	960258
49	REINA DEL CISNE	DANIEL ALBERTO MARTINEZ LOAYZA	EL SALADO	651282	958630
50	REINA DEL CISNE II	EMILIO MODESTO ROMERO AÐASCO	EL PACHE	651992	959062
51	REINA DEL CISNE III	ROLANDO DE JESUS BLACIO AGUILAR	STA. MARIANI	653226	959783
52	ROMERO GUZMAN	JOSE MIGUEL ROMERO LOAYZA	EL PACHE	652105	958968
53	SAGRADO CORAZON	MILTON IVAN AGUILAR LOAYZA	ARCAPAMBA	654018	959696
54	SAN ANTONIO	JORGE ANTONIO TUTIVEN MATAMOROS	EL PACHE	652049	958915
55	SAN ANTONIO DE PADUA	MIGUEL ANGEL ESPINOZA VALAREZO	LA FLORIDA	653081	958877
56	SAN JORGE	JOSE FRANCISCO MERIZALDE ENCALDA	VIA A BUSA	651723	959117
57	SAN JOSE	ANGEL JORGE BLACIO TINOCO	EL SALADO	651054	958591
58	SAN LUIS	SEGUNDO MANUEL ALEJANDRO ZHINGUE GUZMAN	EL PACHE	651979	959068
59	SANTA MARIANITA	CARLOS MANUEL BUELE SALAMEA -SILVILIO UBITICIO TORRES	EL PACHE	652106	958917
60	SANTA MONICA	MIGUEL ANGEL ABAD RUIZ	EL PACHE	651786	959001
61	SEÐOR DE LA DIVINA JUSTI(	JOSE MARIA LOPEZ ROMAN	EL PACHE	652074	958991
62	SODIREC (BIRA)	SODIREC S.A.	VIA A BUSA	650550	959370
63	SVETLANA	COMPAÐ═A GOLDEN VALLEY PLANTAS S.A.	EL PACHE	652000	958950
64	TOCADULOMO	NELSON RODRIGO DURAN CHUCHUCA	EL PACHE	652090	958958
65	TORATA	CLOTARIO DE JESUS AGUILAR AGUILAR	EL PACHE	651922	959080
66	TOTIS	TITO WASHINTON PEÐAHERRETA ESPINOZA	EL SALADO	651149	958611
67	VIRGEN DE LA NUBE	GEORGE HUMBERTO VASQUEZ VASQUEZ	EL SALADO	651234	958646
68	VIVANCO	JOSE MARIA EDDY VIVANCO VIVANCO	EL PACHE	652074	958979
69	EL BRILLANTE	JOS ORLANDO ROMERO	EL PACHE	652113	958979
70	MAFRE	SEGUNDO ANGEL MARÝN GOMEZ	EL SALADO	651746	958791
71	MINALTA	EDDY FEIJOO	BUZA	651453	959752

Appendix B. Questionnaire of the Processing Centers in Ecuador – 2013

The University of British Columbia
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Questionnaire of the Processing Centers in Ecuador - 2013

Preguntas para los OPERADORES de Molinos

Encuesta de los Centros de Procesamiento en Ecuador

Encuestador (Interviewer): ______________________________ **Fecha (Date):** ____________

Nombre del Centro (Processing Center Name) ____________ **Poblado (Town):** ______________

Propietario (Owner's Name): ____

Correo electrónico (email):____

Localidad (Locality): ____

Tipo Molino Chileno (Chilean Mill Processing Center) _________**or Tipo *Chancha* (*Chancha* Processing Center)**

____________________**Molino de Bolas**____________________

Cantidad equipos (How many):

- Cantidad de Molinos Chilenos (How many Chilean Mill)?_____________ Cantidad de ruedas_____
- Cantidad de trituradoras (Number of jaw crushers)?___________o no tengo_____________
- Cantidad de *Chanchas* (How many chanchas)? ______________________________
- Numero de Molino de Bolas ______________________________
- Numero de Empleados (Number of employees)? ______________________________

Procesamiento de Mineral (Ore Processing):

1. Cuánto cobra por el uso del equipo (What do you charge to use your equipment)? $_____/hora o $______/toneladas
   $_____________/sacos ____________________________ % de Oro
2. Costos operativos mensuales (What are your monthly operating costs) ____________________
3. ____ (mano de obra, eléctrico, etc)
4. [For OWNER] Energia Electrica (Electricity) ______________________________ kwh/mes
5. Otros ____(diesel galones)/mes
6. [For OWNER]Energia Electrica (Electricity) ______________________________$/mes

7. Otros ____$/mes
8. Recircula agua?SI______________________o NO______________________
9. Euipo de alquiler (Rentalequipment):SI ________________o NO________________
10. Merrill-Crowe (Do you rent a Merrill-Crowe)? __________ Cuanto cobra por proceso (forhowmuch)? _________$/proceso
Chanchas?__________________Cuanto cobra por saco (for how much)? ________________$/batch
11. Carbon en pulpa?_______Cuanto cobra por proceso (for how much)? ____________________$/dia
12. De donde proviene el mineral (Where does the ore come from)?
13. Mina propia (Own Mine)_______% o Mina Local (Local Mine) ________% o Ponce ___________% u otra _________%
14. [For OWNER] Que cantidad de mineral es procesado (How much ore is processed here):
15. Compraria usted mineral conociendo la ley de oro (Would you buy ore and process it based on the results of a chemical analysis)? ____
16. Vende usted el relave? SI________________o NO____________________, yo lo proceso.
17. Realiza la remolienda en molinos de bolas? SI__________oNO________________________
18. [For OWNER]Tiene proceso de flotacion (flotation)? SI________ o NO__________Si tiene, cantidad de concentrado que vende por mes (if yes, how much do you sell)?____________________________ /tonne
19. Que reactivos utiliza en la flotacion (which reagents do you use in flotation?
20. Hace usted la flotacion de relaves? SI__________________ o de mineral? SI________________
21. A quien vende el concentrado (To whom do you sell the concentrate)?____________________
22. A cuanto vende el concentrado (how much do you sell the concentrate)?________________$/tonne

Cianuracion (Cyanidation):

1. Realiza proceso de cianuracion de mineral?SI__________o de relaves?_______o no lo hago?_________
2. Cuantos tanques de cianuracion tiene?________________ capacidad________________m³
3. **[For OWNER]**Cuanto cianuro compra mensual?_____________kilos/mes
4. Que otros reactivos utiliza?____
5. Controla el pH en la cianuracion? SI____________o NO__________, como?________________
6. Que pH utiliza para el proceso?____
7. Cuanto de cal utiliza mensualmente?______________________________kilos/mes
8. **[For OWNER]** Que proceso de cianuracion :

Merrill-Crowe?____________ cuanto de zinc compra al mes?____________ kilos/mes, costo zinc ______________$/lb
CIP?________cuanto de carbon activado compra al mes?_______________kilos /mes, costo carbón __________$/ton
Vat-leaching?____

9. Tiempo de cianuracion por proceso?________________________________horas
10. Tiene equipo de elusion de carbon? SI____________________o NO________________
11. Tiene proceso de refinacion de oro?SI____________________o NO________________
12. Cuanto de plata produce al mes?____________________________________kilos
13. Donde deposita los relaves de cianuracion?______________________________
14. Dimension (m3) de zona de deposito de relaves?__________________________m³
15. Hace degradacion de cianuro?SI______________________o NO______________, como?____

Mercurio (Mercury):

1. Usted provee el mercurio (Do you supply mercury)? ______________________________
2. Cuantos kilogramos de mercurio provee al mes (How many kg of mercury do you provide per month)? ____________kg

3. Donde compra el mercurio(Where did you buy Hg)? ____
4. Usted recupera el mercurio (Do yourecyclethemercury)?Si_____en Retorta (Yes, I use retorts) __________________No.
5. Usted reusa el mercurio que recupera (Do you reuse the recycled mercury)?SI _________o NO___________________
6. Cuanto cuesta el mercurio (How much does the mercury cost)? ____$/kg?
7. Es caro (Ismercuryexpensive)?SI_________________________o NO____
8. Alguien le ha enseñado como usar el mercurio para extraer oro (Has anyone come hereto show youhowto use mercurytoextractgold)?____________________ encaso de SI quien (if yes Who)?______________________________

Oro (Gold)

1. Que cantidad de concentrado recupera del canalon al dia (How much concéntrate from sluice box)?___________sacos, peso/saco____
2. A cuanto vende el gramo de oro (How much do you sell it for per gram)? _____________________________________ $/g
3. Donde vende el oro (Where do you sell your gold)? ____
4. Cuanto mineral de relaverecoge al mes (How much tailings do you collect each month)? __________________________
5. Cuanto oro produce al mes ____Kg/mes

Socio- Economico (Socio-economic)

1. Que actividad hacia antes de la mineria (What did you do before mining)? _______________________________________
2. Tieneotro empleo o actividad economica (Do you have another work)? ____
3. Quisiera estar en la mineria toda su vida (Would you like to mine for the rest of your working life)____________________
4. Hay alguna otra ocupacion que le gustaria desempeñar?SI____o NO____Cual? (or is there something else you think you might do? What)? ____
5. Cree que el proceso afecta su salud (Are you concerned about your health)? ___________________________________
6. Usted cree que su proceso contamina el rio? ____ como?____
7. Si hubiese alguna otra tecnologia disponible sin usar mercurio la usaria (If the technology was available would you process your ore without mercury)? ____
8. Es rentable la operacion? _____________________porque?____
9. Para que ahorra (Why are you saving)? ____
10. Como ahorra su dinero (How do yousave)?____
11. Usted es el dueño de la planta (Do youownthisplant)? ____
    a. En caso de SI pidió prestado dinero (If so, have you borrowed money to purchase it)? ___________________
12. Le gustaria iniciar su negocio propio (Would you like to start your own business)? ________________________Que tipo de negocio (What)? ____
13. Tiene conocimiento para iniciar un negocio propio (Do you have the knowledge or the skills to run a business)? ____
14. Que tipo de educacion le ayudaria para mejorar su trabajo (What education would help you at your job)?_____________
15. Usted pagaria para estudiar (Would you pay for education if it is available)? ___________________________________
16. Que nivel de instruccion tiene?____
17. Conoce la función que Inigemm cumple?_____________________comente su respuesta________________________
18. Esta satisfecho con la función de Aproplasmin____
19. Que opina de la construcción del relave?____
20. Esta de acuerdo con la reubicación en el parque?____

Comentarios del Encuestador (Surveyer Comments)

Appendix C. Processing Centers Visited in Portovelo-Zaruma - 2015

Processing Center	Informant
ALTO VISCAYA	Manager of the plant
CAZADEROS	Manager of the plant
BIRA	Manager of the plant
EL PUMA	Foreman
EMICOR	Manager of the plant
FEIJOO	Foreman
GERAIS	Administrator of the plant
JESUS DEL GRAN PODER	Foreman
LA ORQUIDEA	Owner
LEON	Manager of the plant
LOS AGAPITOS	Manager of the plant
MAFRE	Plant Manager
MISORO	Administrator of the plant
OROMET	Foreman
PARAISO 1	Manager of the plant
PORTOVELO 1	Manager of the plant
ROMERO GUZMAN	Owner
SAN LUIS	Foreman
SEÑOR DE LA DIVINA JUSTICIA	Administrator of the Plant
VIRGEN DE LA NUBE	Foreman

Appendix D. Questionnaire of the Processing Centers in Ecuador – 2015

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Planta de Beneficio: ___________________________ **Localidad:** ________________

Entrevistador: _______________________________**Propietario:**_________________

A. GENERAL

1. Cuantos años tiene la planta ____
2. Cuantas personas trabajan en la planta de procesamiento ________________________
3. Cuantos dias trabajan a la semana y cuantas horas? ____________________________
4. Procesan unicamente su material o rentan el equipo para procesar el material de otros? ( ) procesan su propio material ( ) rentan el equipo $_______________________
5. Cual es el gasto mensual de la planta ?____
6. Cuanto gastan en energia electrica mensualmente?_____________________________
7. Tienes Laboratorio? ( ) SI ( ) NO
8. Vendes concentrado? ( ) SI ( ) NO Para donde? _________________________
9. Concentrado: Oro__________Plata___________Cobre___________Otros __________

B: INFORMACION SOBRE EL PRODUCTO:

10. De donde obtienen las rocas: Portovelo:________________ El Pache: __________ Zaruma: _____________________________Otros:_______________________________
11. Cuantos gramos de oro por tonelada tiene el material que procesan? ________(g/tonne)
12. Cuanto material procesan por dia? ____
13. Cuál es el porcentaje de recuperación? _____________________________________ %
14. Cuál es la producción de oro mensual? ______________________________________
15. A quien venden el oro? ____
16. Cuanto les pagan por gramo? ____
17. Utilizan Mercurio? ( ) SI ( ) NO Cuanto?_______________________________
18. Destruyen el Cianuro? ( ) SI ( ) NO
19. Reutilizan el agua de las relaberas? ( ) SI ( ) NO
20. Mejoras: ____

QUESTIONNAIRE FOR OWNERS AND MINERS (IN ENGLISH)

Processing Center Name ____________________________ Locality: ___________

Interviewer: ____________________Owner's name: __________________________

A. GENERAL

21. How old is the processing center? ____
22. Number of Employees? ____
23. How many days per week and how many hours per day do you work? _________________
24. Do you only process your own material or do you rent to other people as well? ( ) Process their own ore ( ) Rent equipment $____
25. What is the monthly cost of the processing center? _______________________________
26. How much do you spend on electricity monthly? _________________________________
27. Do you have laboratory? ( ) YES ( ) NO
28. Do you sell concentrate? ( ) YES ( ) NO Where to? _____________________
29. Concentrate: Gold________Silver_______Copper_____ Others __________________

B: GOLD INFORMATION:

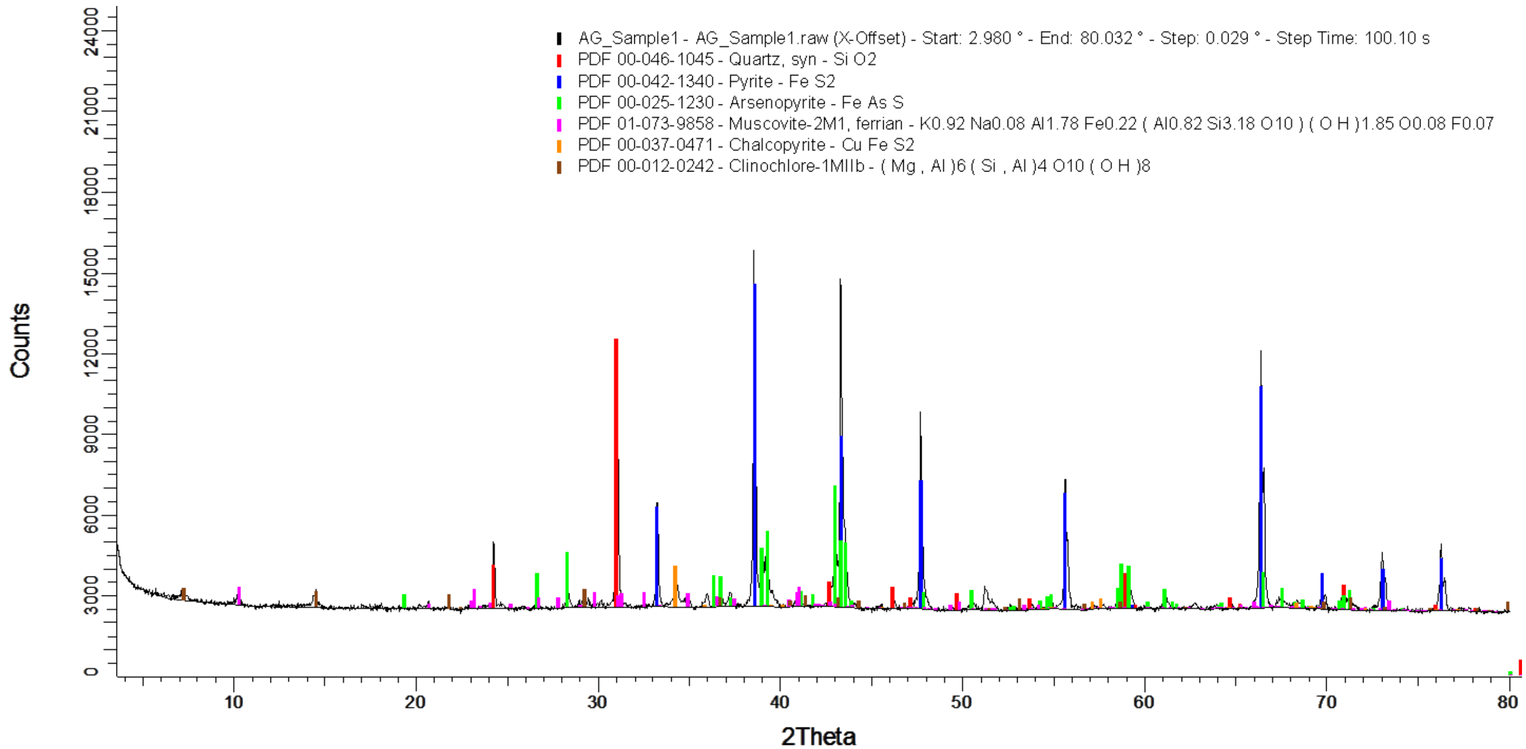
30. Where does the ore come from? Portovelo:____________El Pache: _______________

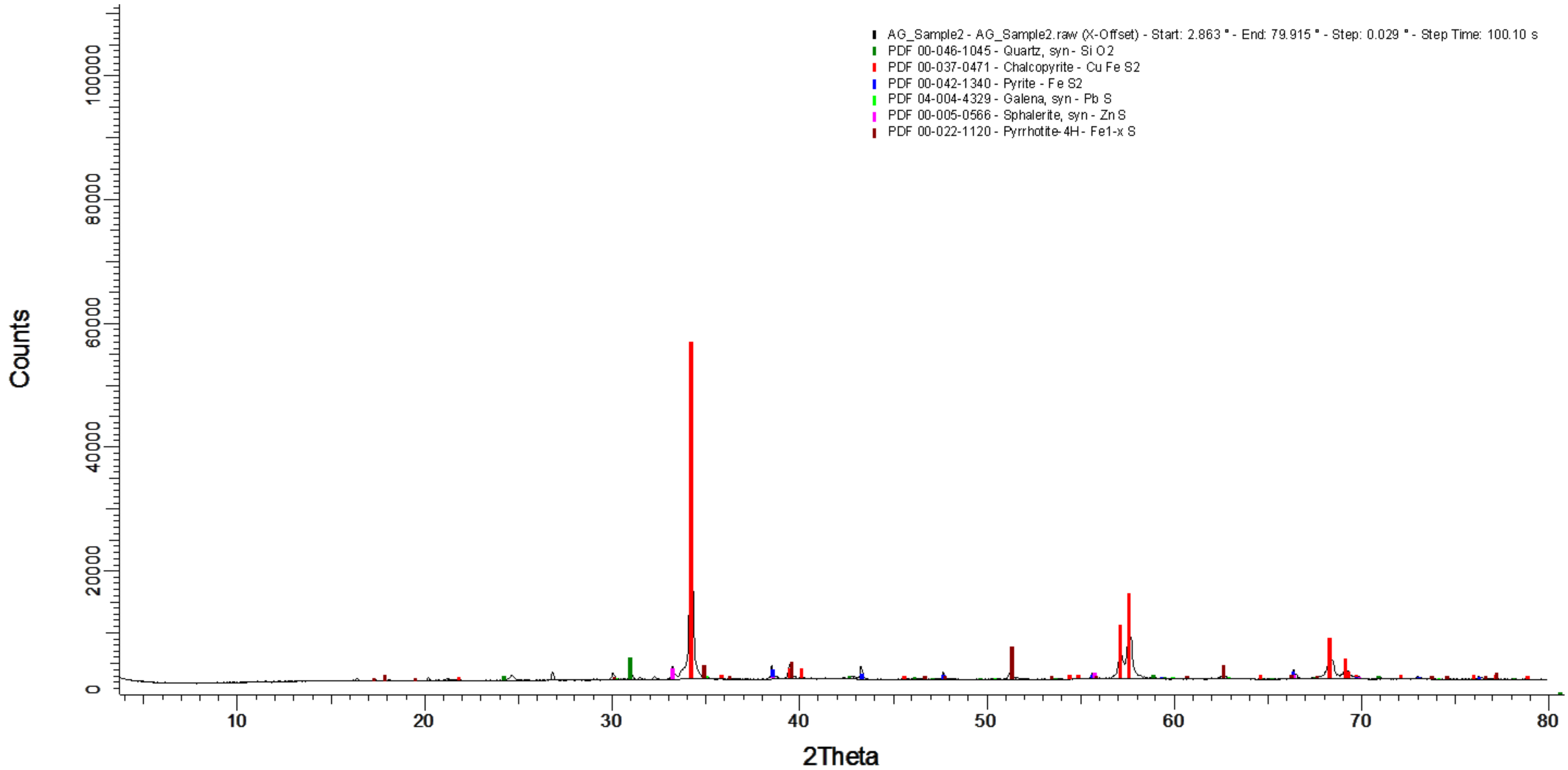
Zaruma: __________________________Other: ___________________________________

31. What is the grade? ____(g/tonne)
32. How much ore is processed per day?_______________________________________
33. What is the gold recovery? ____%
34. What is the monthly gold production? _____________________________________
35. Who do you sell the gold to? ____
36. How much do you get for a gram of gold? __________________________________
37. Do you use Mercury? ( ) YES ( ) NO How much? _______________________
38. Do you destroy the cyanide? ( ) YES ( ) NO
39. Do you recirculate the water? ( ) YES ( ) NO
40. Improvements: ____

COMMINUTION	#	Brand	Supplier	Size 1	Size 2	Capacity	
Trituradora de Mandibula							
Molino de bolas							
Molino chileno							
Chanchas							
CLASSIFICATION	**#**	**Brand**	**Supplier**	**Type**	**Mesh**	**Capacity**	
Zarandas							
Hidrociclones							
Filtros							
CONCENTRATION	**#**	**Type**	**Pression**	**Capacity**			
Falcon							
Knelson							
LEACHING	**#**	**Total Vol**	**Pulp Vol**	**Duration**	**Cyanide**	**Cal**	**pH**
Tanques de agitacion							
SEPARATION	**#**	**Type 1**	**Capacity 1**	**Type 2**	**Capacity 2**		
Drum Screen							
CONCENTRATION	**#**	**Total Vol**	**Pulp Vol**	**Carbon Amount**	**Duration**		
Carbon en Pulp							
Carbon en Leach							
TAILINGS	**#**	**Vol 1**	**Vol 2**	**Vol 3**	**Community Tail**	**Cost**	
Tailings Ponds							

Appendix E: XRD Analysis Results

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PDF 00-046-1045 - Quartz, syn - Si O2
PDF 00-037-0471 - Chalcopyrite - Cu Fe S2
PDF 00-042-1340 - Pyrite - Fe S2
PDF 04-004-4329 - Galena, syn - Pb S
PDF 00-005-0566 - Sphalerite, syn - Zn S
PDF 00-022-1120 - Pyrrhotite-4H - Fe1-x S
Counts
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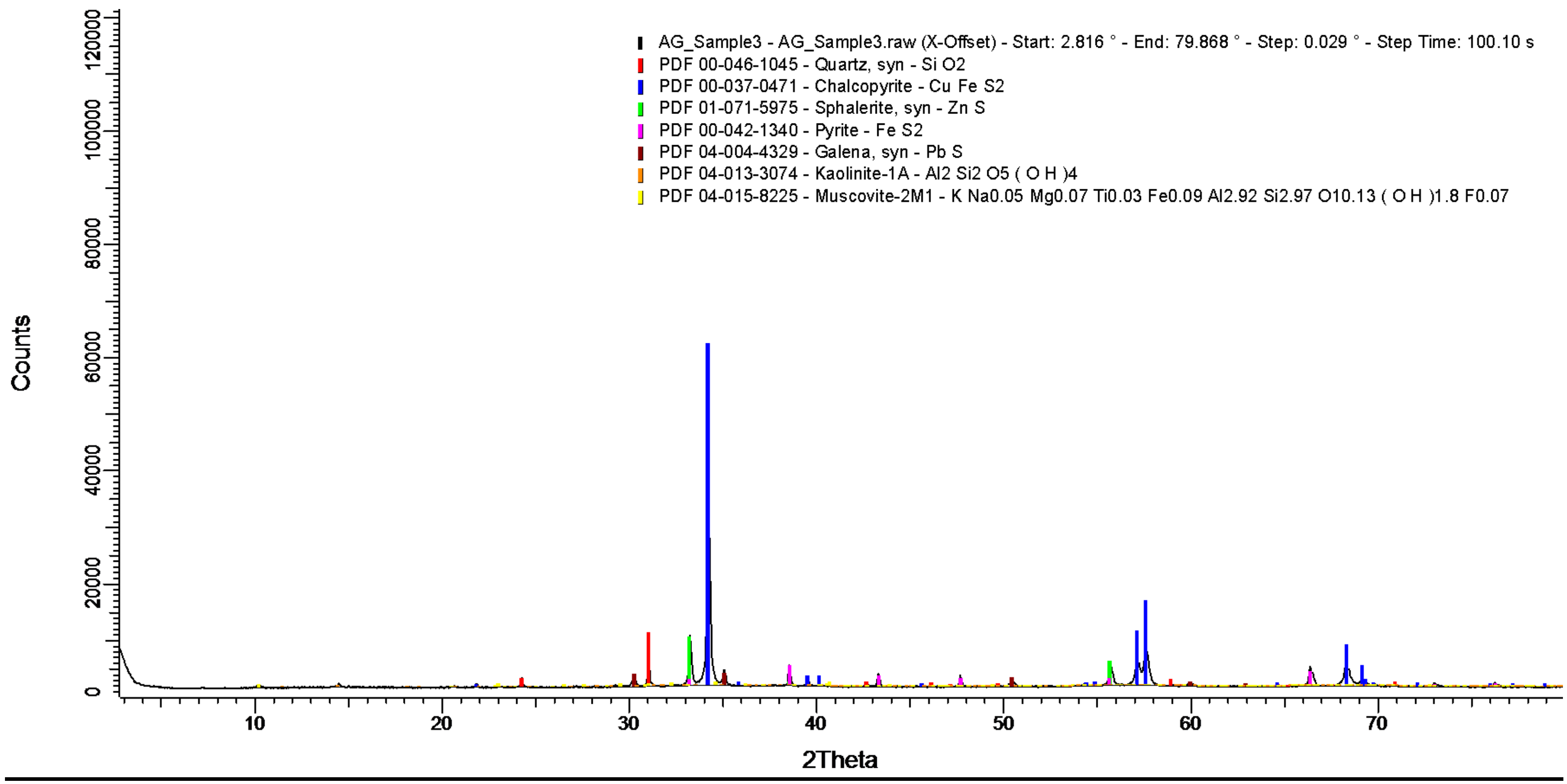
40000
60000
80000
100000
10
20
30
40
50
60
70
80
2Theta


AG_Sample3 - AG_Sample3.raw (X-Offset) - Start: 2.816 ° - End: 79.868 ° - Step: 0.029 ° - Step Time: 100.10 s
PDF 00-046-1045 - Quartz, syn - Si O2
PDF 00-037-0471 - Chalcopyrite - Cu Fe S2
PDF 01-071-5975 - Sphalerite, syn - Zn S
PDF 00-042-1340 - Pyrite - Fe S2
PDF 04-004-4329 - Galena, syn - Pb S
PDF 04-013-3074 - Kaolinite-1A - Al2 Si2 O5 (O H)4
PDF 04-015-8225 - Muscovite-2M1 - K Na0.05 Mg0.07 Ti0.03 Fe0.09 Al2.92 Si2.97 O10.13 (O H)1.8 F0.07
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80000
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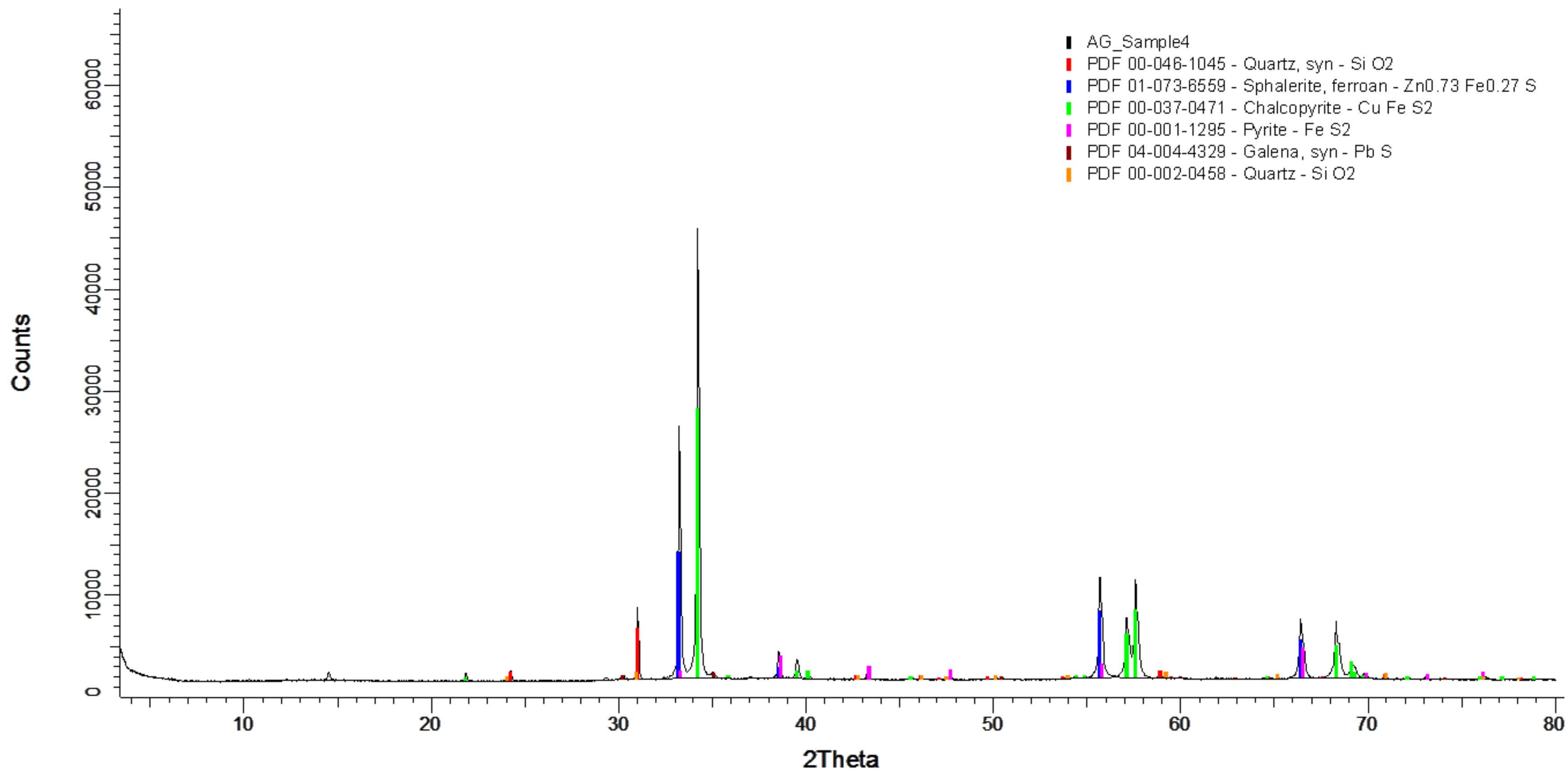
120000
10
20
30
40
50
60
70
2Theta


AG_Sample4
PDF 00-046-1045 - Quartz, syn - Si O2
PDF 01-073-6559 - Sphalerite, ferroan - Zn0.73 Fe0.27 S
PDF 00-037-0471 - Chalcopyrite - Cu Fe S2
PDF 00-001-1295 - Pyrite - Fe S2
PDF 04-004-4329 - Galena, syn - Pb S
PDF 00-002-0458 - Quartz - Si O2
Counts
2Theta
0
10000
20000
30000
40000
50000
60000
10
20
30
40
50
60
70
80