Journal of Cleaner Production 165 (2017) 836–845

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

Evidence of reduced mercury loss and increased use of cyanidation at gold processing centers in southern Ecuador

Adriana O. Gonçalves, Bruce G. Marshall, Robert J. Kaplan, Jose Moreno-Chavez, Marcello M. Veiga*

Norman B. Keevil Institute of Mining Engineering, University of British Columbia, Vancouver, Canada

ARTICLE INFO

Article history:
Received 13 March 2017
Received in revised form
14 June 2017
Accepted 12 July 2017
Available online 21 July 2017

Keywords:
Artisanal and small-scale gold mining (ASGM)
Mercury pollution
Cyanide
Ecuador

ABSTRACT

Due to the strong price of gold, the number and capacity of gold processing centers in Portovelo-Zaruma in southern Ecuador have increased considerably in recent years. In turn, this has caused increasing environmental pollution of waterbodies with cyanide, mercury and other heavy metals. This paper provides an assessment of gold production methods at 52 processing centers in 2013 and 20 in 2015, including estimations of mercury (Hg) losses and releases, cyanide use and tailings management. Due to an increase in the price of mercury and other government initiatives to reduce and eliminate Hg use, there is evidence of a shift from amalgamation processes to increased employment of cyanidation techniques. It was estimated that the 87 processing centers released 1.9 million tonnes/a of tailings in 2015, including 2033 tonnes/a of cyanide and 222 kg/a of Hg. Furthermore, it was estimated that the burning of gold amalgams released 303 kg/a of Hg to the atmosphere. Although mercury use showed a 60% reduction from 2013 to 2015, while cyanidation processes increased 30% over the same time period, more needs to be done, as 65% of the centers still use Hg amalgamation to extract gold.

Contents

1. Introduction

Artisanal and small-scale gold mining (ASGM) is defined based on the rudimentary processes used in mining and processing gold

* Corresponding author.
E-mail address: veiga@mining.ubc.ca (M.M. Veiga).

http://dx.doi.org/10.1016/j.jclepro.2017.07.097
0959-6526/© 2017 Published by Elsevier Ltd.

ores, which is characteristic of small operations (Veiga, 1997). However, small-scale mining operations are not necessarily always artisanal, as 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., 2014a). Frequently, the terms artisanal and small-scale are used interchangeably, but the term "artisanal" refers only to the rudimentary practices, while "small" denotes the size of the operation. For this study, to avoid misinterpretations, the term ASGM is used to encompass all small-scale processing activities in Ecuador that use rudimentary or semi-conventional techniques to process gold (Au) ores. Artisanal and small-scale gold mining is the primary source of gold production in Ecuador, accounting for 85% of total production (Veiga et al., 2009). Furthermore, in 2015, gold exports accounted for 3.6% of Ecuador's economy and totalled more than $700 million USD (OEC, 2017).

Worldwide, ASGM encompasses approximately 16 million miners that produce between 380 and 450 tonnes of gold annually (Seccatore et al., 2014) and release 1000–1400 tonnes/a of mercury to the environment (UNEP, 2013; Veiga et al., 2014a). When artisanal miners use mercury, it is released to the environment in two ways: 1) together with tailings, which causes fluvial contamination; and 2) mercury vapour, created when gold amalgams are burned in open pans, generating atmospheric pollution. When mercury-enriched tailings are discharged into water bodies, the metallic mercury is deposited in sediments, where it oxidizes under adequate environmental conditions and can be transformed into methylmercury, which has the potential to accumulate in aquatic organisms and biomagnify up the food chain (Meech et al., 1998; Chumchal et al., 2008).

In order to recover remaining gold from amalgamated tailings, cyanide processes are being increasingly implemented by artisanal miners in Ecuador, using mainly the Merrill-Crowe or Carbon-in-Pulp (CIP) process. The CIP process consists of adding activated carbon directly to the steel leaching tanks in conjunction with tailings and agitation. Most of the processing centers that use this technology have a series of 3–8 tanks ranging from 30 to 80 m^3, where the pulp is transferred from one tank to another. In comparison, the Merrill Crowe process is commonly used when miners want to process their own tailings using a cyanidation process. It consists of a 14 m^3 cyanidation tank with a high concentration of NaCN (1–5 g/L), whereby the cyanide consumption ranges from 1.5 to 5 kg NaCN per tonne of tailings, depending on the amount of copper minerals in the ore. After 12 h, the agitation is halted and the pulp settles for about 6 h. Some plants have filters to clarify the solution before gold precipitation with zinc, but most of them use a settling process. The "clear" gold rich solution is then siphoned before sending it to PVC pipes (12 cm wide x 50 cm large) filled with zinc shavings. 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. However, when cyanide mixes with mercury, $Hg(CN)_2$ complexes are formed, which can cause potentially serious health impacts. Due to the high toxicity of this compound, it is believed that mercury cyanide is also very dangerous to the environment, although little is known about how it becomes bioavailable to aquatic life. Despite the fact that mercury accumulation in fish has been reported to be higher in areas where mercury cyanide was dumped into local drainages (McDaniels et al., 2010), the conversion of these complexes to methylmercury are still unclear (Veiga et al., 2014a).

As most of the processing centers in Portovelo-Zaruma have historically been discharging tailings directly into the Puyango-Tumbes River on an indiscriminate basis, the associated pollution has created a sharp conflict over this issue between Peru and Ecuador in recent years (Velásquez-López et al., 2010; Veiga et al., 2014b). To minimize the conflict, characterization of gold processing methodologies utilized by processing centers in southern Ecuador is important to understand the current reality and develop new strategies to alleviate the environmental degradation of mercury and cyanide pollution, as well as avoiding serious health risks associated with mercury use in gold processing. Furthermore, reduction in Hg use by ASGM miners must be accompanied by a shift towards cleaner production methods, while at the same time promoting responsible tailings management.

2. Material and methods

2.1. Study area

The twin towns of Portovelo-Zaruma and their surrounding areas, located in the Province of El Oro, encompass the largest mining district in Ecuador (Fig. 1), followed by Ponce Enriquez in Azuay Province, and Nambija and Guayzimi in Zamora Province (Sandoval, 2001). 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, amalgamating and 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 partnership between miners, their family members and concession owners) a significant 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 et al., 2010). Currently, there are 240 mine concessions and 87 processing centers, of which 78 have a legal operating permit.

2.2. Gold Processing Centers in Portovelo-Zaruma

The gold processing centers in southern Ecuador are known by the local communities as "plantas de beneficio", which typically process ore brought to the centers by local artisanal miners (Fig. 2). In 1990, custom milling emerged in the region, due to some individuals taking advantage of the lack of capital and knowledge of the artisanal miners to offer services to process their ore using mercury amalgamation and more recently, cyanidation. Currently, due to few alternative methods being available, most small-scale and artisanal miners in Ecuador still use the amalgamation method with *chanchas*[1] (Fig. 3) to extract the gold, resulting in extensive environmental degradation (UNIDO, 2016; Veiga et al., 2014b) and acute health impacts.

According to Velásquez-López et al. (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. Additionally, miners also bring mercury-contaminated tailings from the Ponce-Enriquez region to the processing centers in Portovelo-Zaruma

[1] 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.