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Mercury flow analysis in artisanal and small-scale gold mining operations in the Philippines

Myline D. MACABUHAY, Arlene GALVEZ, Jimbea LUCINO, Evelyn CUBELO, Jashaf Shamir LORENZO, Teddy MONROY and Richard C. GUTIERREZ

BAN Toxics, Unit 6C Perseveranda Townhomes II, Maningning St.,Sikatuna Village, Quezon City, Philippines.Quezon City 1101 Philippines
e-mail: myline@bantoxics.org

Abstract

Artisanal and small-scale gold mining (ASGM) is the largest emission and release source of mercury in the Philippines. In 2008, the Philippine Department of Environment and Natural Resources (DENR), using an inventory toolkit provided by the United Nations Environment Program (UNEP), estimated 113 tons of mercury emissions and releases by the sector annually. However, the UNEP toolkit provides significant uncertainties due to the use of default input and distribution factors that may not reflect actual domestic use and release patterns. This study provides concrete quantitative information based on actual measurements of mercury flows in ASGM operations in three communities in the Philippines. Results of the study show that miners use an average of 19.2 g mercury to process 1.0 g of gold. However, the amount used may range from 1.5 to 149.0 g per extraction process. Still, this average is six times higher than the default input factor prescribed in the UNEP toolkit. The study also found that most of the mercury that enters the environment goes to both the water and soil, due to the improper management of mercury-contaminated mine wastes. The results of the study have implications on the development of programs geared at addressing mercury pollution from ASGM operations, and can inform the initial steps in the preparation of the country's Minamata Initial Assessment (MIA) and National Action Plan (NAP) for ASGM. Finally, the study recommends further collection of measurement data from operations in other provinces in the country to make the analysis more robust.

Keyword : amalgam, mercury flows, artisanal and small-scale gold mining, ASGM, Philippines, UNEP

Introduction

Mercury and mercury compounds are highly toxic with adverse effects to humans, ecosystems and wildlife (Bernhoft, 2012; Rice et al. 2014; Neathery and Miller, 1975). While initially seen as an acute, localized hazard, mercury pollution is now acknowledged as a global problem, capable of putting populations distant from the point source of emissions or releases at risk from its toxic effects (United Nations Environmental Programme, 2013). It is one of the top ten chemicals of major public health concern listed by the World Health Organization (2016).

Mercury is unique among heavy metals for possessing a vapor pressure of 0.001201 Torr at 20°C (Stone et al., 2007). This means that the saturation concentration of mercury in the air increases dramatically with increasing temperature. Once released, mercury is distributed to the environment through air-surface exchange with soil, freshwater and vegetation, as well as exchanges between soil-vegetation and water-vegetation (Bernhoft, 2012; Wang, 2004). Its persistent nature stems from its ability to be converted from one form to another, such as in the case of the formation of organic methylmercury (Ullrich et al., 2001). Considered to be its most toxic form, methylmercury can bioaccumulate in living organisms and biomagnify through the food chain (Chasar et al., 2009). These transport and transformation mechanisms allow mercury to drift long distances and contaminate global food supplies at levels which present major risks to human health.

There is no known safe level of exposure to mercury (Bose-O'Reilly et al., 2010). Studies have found that about 80% of inhaled mercury vapor is retained in the body and dissolved in circulating red blood cells (Morgan et al., 2002). Elemental mercury vapors are well-absorbed through the lungs, carried throughout the body, and are capable of crossing the blood-brain and placental barriers (Park and Zhen, 2012). Exposure to high concentrations of this toxic substance via inhalation may result to pneumonia, bronchitis, chest pain, dyspnea, cough, stomatitis, gingivitis, excessive salivation and diarrhea (Baxter et al., 2000). On the other hand, chronic exposure to low doses of mercury, such as when eating methylmercury-containing food and food products, can impact the central nervous system, causing tremors, behavioral changes and abnormal reflexes (Baxter et al., 2000). Severe injury to organ systems, including the kidneys, liver, brain, heart and colon can also be experienced (Baxter et al., 2000). The methylmercury poisoning incident in Minamata, Japan, which was discovered in the 1950s, is a prime example of how anthropogenic sources of mercury threaten the well-being of people and communities, with the damage significantly resonating to succeeding generations.

Because of its impacts on human health, the identification and reduction of mercury in the environment and its bioaccumulation has become an urgent issue. The critical findings of the 2002 Global Mercury Assessment report of the United Nations Environment Programme (UNEP) led to the development and adoption of a legally-binding, global treaty on mercury that started in 2009. The Minamata Convention on Mercury aims "to protect human health and the environment from the anthropogenic emissions and releases of mercury compounds" by controlling the life-cycle stages of mercury (Selin, 2014).

In order to manage mercury in an environmentally sound manner, it is crucial to account for emissions and releases especially in a sector known to contribute significantly to mercury pollution. While the UNEP inventory toolkit is a good starting point, the results described contain many uncertainties due to the use of default input factors that may not reflect actual use and release patterns in the mining areas. In addition, investigations on the extent of illegal mercury trade in the Philippines and in the Asian region reveal large volumes of mercury supply traded in the sector, implying that the inventory underestimates the mercury used in the artisanal and small-scale gold mining (ASGM) (Gutierrez et al., 2017). In this study, we provide concrete quantitative information regarding mercury emissions and releases in ASGM operations in the Philippines collected on site, which can serve as a basis for implementing strategic mercury management in the country. Results of this study can also inform and update the input factors in the UNEP inventory toolkit, which, in its latest version, already allows for varying input factors depending on site information. The substance flow analysis (SFA) for mercury used in the sector was developed by (1) describing the stages and processes involved in ASGM operations, and (2) taking actual measurements of mercury input, emissions and releases.

Present status of ASGM in the Philippines

The use of mercury in ASGM communities in the Philippines is prevalent and can be traced back to the late 80s and 90s when mercury amalgamation was widely practiced at the height of the gold rush (BAN Toxics, 2010). Widespread poverty in the rural areas, the growing demand for gold, and the inability to formalize due to legal and technical hurdles have all contributed to push small-scale miners to produce more gold within the fastest time possible, thereby making mercury amalgamation an attractive option especially for those engaged in subsistence mining. Furthermore, many of the miners handling the chemical do so with lack of knowledge of the substances and basic protective equipment.

Republic Act No. 7076, otherwise known as "The Peoples' Small-scale Mining Act of 1991", defines small-scale mining as "mining activities which rely heavily on manual labor using simple implements and methods and do not use explosives or heavy mining equipment". It involves mining operations that have an annual production of not more than 50,000 metric tons of ores. Around 500,000 individuals and their families in more than 30 different provinces in the Philippines rely on ASGM as a main source of livelihood (Philippine Extractive Industries Initiative, 2015). However, a substantial portion of these operations are considered informal due to their failure to acquire the appropriate licenses and permits. Despite this status, the sector's contribution to the total gold production in the country is substantial. Available data from the Mines and Geosciences Bureau (MGB) show that total gold production from 2005 to 2014 averaged 30,733 kg annually, of which 63% came from ASGM (National Tax Research Center, 2015).

The continued use of mercury in the sector has led to various health and environmental effects, however, only a few are documented and/or published in literature (e.g. Murao et al. 2002a; Murao et al. 2002b). A study by Appleton et al. (2006) reported the heavy contamination of the Naboc River in Mindanao in the 1990s, caused by nearby ASGM operations, which have affected soil quality, crops and aquatic life in the area. Soil in rice paddy fields contained an average of 24 mg/kg of mercury, exceeding the safety thresholds of the UK and Canadian soil quality standards. In addition, aquatic life in the area has also been tested to contain alarming levels of mercury, with fish containing an average of 220 μg/kg of methylmercury. The same study reported that 38% of the local inhabitants were classified as intoxicated with mercury.

In 2008, the Philippine Department of Environment and Natural Resources (DENR) conducted an inventory of mercury sources and uses using a toolkit provided by UNEP. The study found the significant contribution of the ASGM sector to mercury loading, both as a direct source of emissions and releases to the environment (air, water, land) and as an indirect source through the improper disposal of mercury-contaminated wastes. The inventory estimated that approximately 113 tons of mercury is produced annually from the sector, 60% of which goes to the atmosphere (DENR, 2008).

Materials and methods

Site selection

Three provinces with ASGM communities were surveyed in this study, namely: Camarines Norte, Compostella Valley and South Cotabato. A total of 52 operations were included (Camarines Norte: 18, Compostella Valley: 27, South Cotabato: 7). Convenience sampling was done by selecting those operations that are easily accessible to the researchers, due to the informal nature of the mining activities. Descriptions of the mining communities are provided in the succeeding sections, whereas Figure 1 shows the municipalities where the surveyed operations are located.

Camarines Norte

ASGM in Camarines Norte is concentrated in the municipalities of Jose Panganiban, Labo and Paracale. This gold mining district is recognized as one of the country's oldest and richest gold mining sites: a significant portion of the country's gold production comes from the area. Although mining has been a major source of income for centuries, the industry has failed to bring people out of poverty. For instance, gold-rich municipalities like Paracale are still dependent on internal revenue allotment from the national

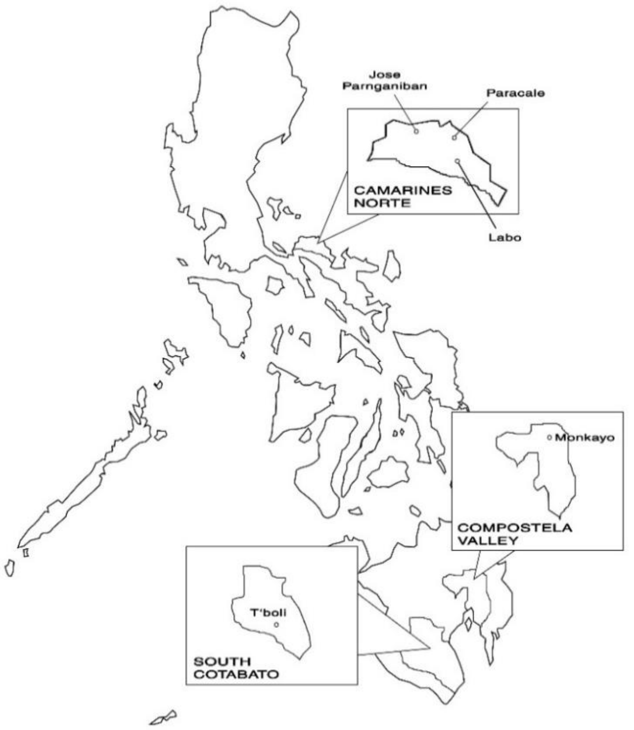

Fig. 1 ASGM municipalities in the Philippines where the surveyed operations are located

government (Soltes, 2012).

ASGM is essentially a poverty-driven activity, and many of Camarines Norte's poorer citizens have turned to mining in the hopes of a better future (Tantengco, 2014). With the limited opportunities present to these communities, child labor has become a growing problem. Although laws prohibiting child labor exist, children are sent to mines because families are left with no alternative to earn money for their daily subsistence (Saludez, 2016).

Mt. Diwata, Monkayo, Compostella Valley

Located in the southeastern region of the country, the discovery of gold in 1982 has since triggered a gold rush to the 5,000-ha Mt. Diwata (also called Mt. Diwalwal) in the municipality of Monkayo, Compostella Valley. The DENR has claimed that the area contains the largest gold deposits in the world, with an estimated USD1.8 billion worth of gold reserves (Blacksmith Institute, 2017). Current ore grades hover under 10.0 g per ton, although it used to be 10 to 100 times higher, indicating that the deposits are becoming exhausted (Andoy, personal communication).

Essentially a mining camp, Mt. Diwata has transformed into a full-fledged settlement village that hosts generations of mining families (Patino, 2016). Although the official census lists the total number of residents at 42,000 people, the population increases alongside the increase in gold prices. The area has also earned notoriety as a lawless village, with frequent violent and lethal clashes between frontiersmen fighting over gold (Aljibe, 2012). In addition, a study conducted in 2014 revealed that child labor is present in one out of five households in the area (Capistrano, 2014)

T'boli, South Cotabato

T'boli is one of the gold-rich municipalities in the province of South Cotabato. The 21-ha People's Mine in the town is the only small-scale mining site in the country that is fully monitored and regulated by the local government (Lacorte, 2014). Discovered in the late 1980s, exploration estimates of the gold and copper reserves in a single town in South Cotabato reached at least 2.5 million tons, a number indicative of the province's abundant mineral resources.

T'boli's progressive mining policies are credited for helping turn the town into a first-class municipality, with an annual income of at least USD 1 million. Miners are expected to contribute to local government coffer, while the local government ensures the safety of the mining areas as well as the promotion of scientific technology for the sustainability of the industry. The government's thrust to formalize small-scale mining in the town has reaped positive results, with the provincial government already pushing for the industry's expansion. Despite these efforts, however, child labor and high poverty incidence issues still exist in the area (Estabillo, 2012).

Substance flow analysis

SFA has been used in many studies on mercury (e.g. Civancik and Yetis 2015; Cain et al., 2007; Sundseth et al., 2011). The methodology consists of three main steps applied to ASGM operations: system definition, flow quantification and interpretation of results (Voet et al., 1995). The system boundary was limited from the cradle-to-gate stages of mining operations, i.e., the extraction of ore, transportation and the concentration/ processing stages. On the other hand, the pathways considered are divided into two groups: mercury flows in consumption, discharges and removal, and flows in environmental media (Huang et al., 2014). Mercury flows in imports, exports, production and other processes are excluded.

SFA is based on the mass balance principle and links the sources to pathways and final sinks of a substance (Brunner and Rechberger, 2004). For this study, actual mass balance measurements were conducted in selected ASGM operations by directly measuring the amount of mercury added and recovered in each step of the gold extraction process. Recovery of mercury was done either through panning, settling of mercury at the bottom of a catch basin, or squeezing of excess mercury using a cloth or a repurposed umbrella. Any remaining water was removed using a sponge. The calculated difference between the mercury input and the amount recovered is considered equivalent to the mercury loss in the system, which can either be emissions to air or releases in water or land with the tailings (In local ASGM sites, "tailings"

Table 1 Summary of mercury flows in an ASGM operation in Camarines Norte, Compostella Valley and South Cotabato, Philippines.

	ASGM Site			Average
	Camarines Norte	Compostella Valley	South Cotabato	
No. of operations surveyed	18	27	7	—
Amalgam, g	4.5	3.0	3.1	3.5
Gold, g	1.9	1.0	1.4	1.4
Mercury emissions[a], g	2.6 (4%)	1.9 (27%)	1.7 (12%)	2.1
Mercury releases[b], g	70.6 (96%)	5.2 (73%)	12.8 (88%)	29.5
Total emissions and releases, g	73.3	7.2	14.5	31.7
Ave Hg:Au[c]	34.3	10.7	12.6	19.2
Max Hg:Au	149.0	33.8	37.2	73.3
Min Hg:Au	1.5	2.9	1.8	2.1

[a] Weight loss after smelting of amalgam

[b] Difference between mercury added to the mill and mercury recovered after milling

[c] Amount of mercury (g) used to extract 1.0 g of gold

refer to either (1) gangue, which is disposed immediately or (2) sluice tailings, which are collected in small “tailings” ponds to be processed later or to be sold to processing plants).

Results

Stages in ASGM operation and associated mercury flows

One of the methods employed in ASGM communities in Camarines Norte, South Cotabato and Compostella Valley is tunnel mining. Tunnel mining refers to either drift mining or shaft mining. The former is an underground mine driven horizontally into the ore seam. A shaft mine, on the other hand, is an underground mine with a vertical shaft as the main entry point. Tunnel mining in the country consists of three main stages, namely, excavation, extraction and processing.

Excavation starts with prospecting, where miners physically search for mineral specimens. The process involves collecting rock and soil samples, and in the case of mining communities in the Philippines, utilizes indigenous sampling methods similar with assay sampling using either a pan or a shovel to determine the presence of gold. Once prospective mining sites are identified and the amount of gold that can be potentially extracted deemed economically profitable, the construction of mining sites will commence. This involves clearing the area of trees, rocks and other items that may be considered obstructive to operations. Mining bases are usually made from wood, with the trees cut from the clearing operations sometimes converted into timber. Tunnels are also dug using a variety of tools that range from hand-held tools to explosives, although small-scale miners are legally prohibited from using the latter.

Once the ores are extracted, they are brought to a separate mining facility which houses grinding/ milling machine/s in the form of rod mills. Rod mills are cylindrical rotating shells or drums which are mounted on bearings and filled with a grinding medium such as steel rods of up to 40% by volume (Veiga et al., 2006). The mill is powered either by electricity or diesel and its running time depends on several factors. In Mt. Diwata, miners use banks of four drums welded together in sets of two rows, for a total of eight drums. They refer to the entire plant as one ‘mill’ and one milling event as a ‘trip’. They usually process one bag of ore (weighing around 50 to 70 kgs) in a single trip. On the other hand, mills in T’boli, South Cotabato are usually comprised of 30 small drums arrayed on long paired axes turned by a single motor, with each drum containing only a shovelful of ore.

The rotating action of the mills causes the steel rods to fall back into the cylinder, thereby grinding the materials inside. Once the gold ores are reduced into fine particles, liquid mercury is placed in the drum. The mill is again operated for at least an hour, at which time the mercury is assumed to have captured the gold liberated during milling. In Camarines Norte, miners add lime juice along with mercury, to maintain acceptable pH levels and to ensure the least amount of gold loss (Wells, 1936). The addition of mercury in the milling process is referred to as whole ore amalgamation.

Measurement

Results of the mass balance measurements reveal that the amount of mercury used per gram of gold (Hg:Au) in the surveyed ASGM operations vary, from as little as 1.5 to as much as 149.0 (Table 1). The average mercury to gold ratio is 19.2, but shows difference for the three sites: i.e. approximately 10.7 for Compostella Valley; 34.3 for Camarines Norte; and 12.0 for South Cotabato, respectively.

Most small-scale miners in the Philippines believe that the addition of mercury during milling facilitates more efficient capture of the liberated gold particles. However, this assumption is erroneous and economically detrimental, as the constant pounding in the cylinder causes a large part of the mercury to be broken down into very small droplets with sizes of less than a millimeter. This milled mercury is called mercury flour due to the fine grain size of the droplets, and can host large amounts of gold. The continuous breaking off of mercury particles weaken their affinity to each other, causing them to be eventually lost in the slurry and transported downstream of mining operations (Pantoja and Alvarez, 2000; Alpers et al., 2005). In addition, remediation of affected areas poses a challenge for land management (Alpers and Hunerlach, 2000).

The milled ore is placed in a storage tank or a large pan to retrieve the mercury containing the liberated gold. The amalgam is then squeezed using either a fine piece of cloth or a repurposed umbrella. This separation of the amalgam from the slurry results in the production of mine tailings. The amount of mercury subsequently lost to the tailings was determined by measuring the amount of mercury input in the system and the amount of mercury recovered after milling. Analysis of the two flows shows that 73 to 96% of the mercury used in an ASGM operation in the country is lost in the tailings. Based on observation, the variation largely depends not only on the miner's ability to capture and to collect the remaining mercury, but also on the length of time he or she is willing to devote to such exercise. The release of mercury to the environment through the tailings raises environmental and health risks since most operations do not practice appropriate tailings management to prevent contamination. For instance, several operations release their tailings directly into rivers and waterways, spreading the contamination beyond the point source of pollution.

On the other hand, the amalgam undergoes smelting, where mercury is vaporized and released into the air, leaving behind the sponge gold. Approximately 4 to 27% of the total mercury input in the operation is directly released into the atmosphere during this stage, and is potentially inhaled by miner workers and nearby residents. Small-scale miners from developing countries such as the Philippines work without any kind of protection such as gloves, masks or technical systems to avoid the release of mercury vapor and subsequent exposure (Baeuml et al., 2011). A study conducted by Drasch et al. (2001) found that workers from Mt. Diwata showed severe symptoms related to mercury intoxication.

The remaining mercury-contaminated mine tailings can also be processed in mineral processing plants, where they undergo cyanide heap leaching. Heap leaching is a low-cost process that extracts gold by dissolving the metal content from the feed material. Most of the feed material in the ASGM communities surveyed are tailings from milling operations using mercury, with only a small percentage of plants processing ore directly. In the worst case, the combination of mercury processing and cyanide heap leaching can be considered lethal, as it provides an additional pathway for mercury in the environment. Cyanide reacts with mercury to produce soluble chemical compounds that are easily transported with water, thereby spreading contamination to large areas (Coles and Cochrane, 2006). It also converts mercury to a form which makes it easier to enter the food chain and bioaccumulate. Mercury-cyano compounds contaminate groundwater and drinking water, and removal to an acceptable level can only be achieved at an exorbitant cost.

Table 2 Comparison of the input and distribution factors of the UNEP toolkit inventory and this study

	Default input factor, kg Hg/ kg Au	Output distribution factors		
		Air	Water	Land
This study	19.2	0.14	0.86[a]	
UNEP toolkit inventory[b]	3.0	0.25	0.4	0.35

[a] Distribution between water and land needs to be studied further

[b] Input factors for whole ore amalgamation

Hence, the amalgamation method of gold processing, including the cyanide process, contributes largely to mercury pollution through:

- Discharge of mercury together with other wastes into inadequate tailings ponds, or worse, thrown away directly into rivers and waterways;
- Release of vaporized mercury into the atmosphere when the amalgam is smelted and refined; and
- Creation of soluble mercury-cyano compounds which makes it easier for mercury to enter the food chain and bioaccumulate.

Comparison with the UNEP inventory

A comparison of the UNEP mercury inventory toolkit and the mercury emissions and releases reported in this study is shown in Table 2. The input and distribution factors for ASGM in the former and this study are drastically different. Whereas the UNEP toolkit assigned a default Hg:Au ratio of 3.0, the study documented the amount of mercury used in ASGM communities in the Philippines to be more than six times higher. Hence, the UNEP toolkit can result in significant uncertainty in the total contribution of the sector to mercury pollution.

In addition, the distribution of the mercury that enters the environment in the two studies are different, with this study highlighting the significant mercury loading to water and soil media due to mercury-contaminated tailings. This has implications on the development of programs geared at addressing mercury pollution from ASGM operations, which should be looking at preventative practices or putting additional emphasis on the management of mine wastes. While the study only surveyed three mining communities in the country, these represent the biggest ASGM sites in the Philippines in terms of contiguous land area and operations. As such, the use of actual measurements in these areas has improved the reliability of the results and reflects the specific circumstances in the country.

Conclusions

We have developed SFA for mercury using measurements of actual mercury input, emissions and releases from 52 mining operations in three communities in the Philippines. The average amount of mercury used to extract 1.0 g of gold is 19.2 g. However, this may range from as little as 1.5 g to 149.0 g, depending on the preferences and capabilities of the miners and operators. Most miners handle mercury with very little understanding of the substance and with no personal protective equipment (PPEs), which increases their risks to health effects associated with mercury exposure. Moreover, the study also found that most of the mercury that enters the environment goes to either the water and soil through the improper management of mercury-contaminated mine wastes. This new set of data can be used to refine the existing methodology for mercury inventory for the ASGM sector. More importantly, these can form the initial steps in the preparation of the country's MIA and NAP for ASGM. These updated numbers can likewise help paint a clearer picture of the illegal mercury trade flowing into the sector and inform enforcement strategies. Finally, further collection of measurement data from the operations in other provinces in the country is recommended to make the information more robust.

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