



Mercury emissions from Peruvian gold shops: Potential ramifications for Minamata compliance in artisanal and small-scale gold mining communities



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ABSTRACT:

Ratification of the Minamata Convention on Mercury has led to the establishment of Peruvian regulations limiting mercury concentrations in air to 2000 ng/m³ over a 24-hr measurement period. As a result, three communities in Madre de Dios, Peru were mapped during October 2017 to determine Hg⁰ vapor concentrations in the air. The town of Tres Islas exhibited Hg⁰ concentrations less than 200 ng/m³: the minimum risk level defined by the Agency for Toxic Substances and Disease Registry. These low concentrations were reflective of a town in the region with limited exposure to artisanal and small-scale gold mining (ASGM). However, the ASGM communities of Laberinto and Delta One exhibited concentrations of Hg⁰ vapor that exceeded 2,000,000 ng/m³ surrounding active gold shops, where amalgams and processed amalgams were heated with open flames. Laberinto was reevaluated in May 2018 during which time Hg⁰ levels on the sidewalks in front of gold shops again exceeded 2,000,000 ng/m³. Within the scope of this paper a rapid mapping technique allows for the detection of sources of Hg⁰ pollution and identifies neighborhoods that require intervention to decrease Hg⁰ emissions. In addition, this work highlights the difficulties of measuring total gaseous mercury in ASGM communities with gold shops according to the Peruvian law.

1. Introduction

Artisanal and small-scale gold mining (ASGM) is recognized as the leading source of anthropogenic mercury emissions on the planet (Global Mercury Assessment, 2013; U.N., 2019). Miners use liquid elemental mercury (Hg⁰) to amalgamate gold from crushed rock and river sediments, separating it from gangue minerals and concentrating it in the solid amalgam. Hg⁰ can be discharged into the tailings and the surrounding environment during whole-ore amalgamation; if the ore is concentrated via gravity or some other means prior to amalgamation, less Hg⁰ is used which decreases contamination to the tailings (de Lacerda and Salomons, 1998; Veiga et al., 2014; Hilson and Vieira, 2007; Hilson, 2006; Velásquez-López et al., 2010; Esdale and Chalker, 2018; Zolnikov and Ramirez Ortiz, 2018). Regardless of the amalgamation process, the amalgam contains ~40–60% Hg⁰ by mass and is

subsequently “burned” (heated) to evaporate the Hg⁰ revealing the processed amalgam, often referred to as a *doré* or sponge gold (Kiefer et al., 2014, 2015). The gold amalgam is often burned at the processing plant in open air. While inexpensive retorts are available that collect the distilled Hg⁰ during the burning process, miners infrequently use them, and Hg⁰ vapor is often discharged directly into the atmosphere (Kiefer et al., 2015; Jönsson et al., 2013).

The processed amalgam, which may still contain up to 5% by mass Hg⁰ (Velásquez-López et al., 2010; Veiga and Hinton, 2002), is then sold to a gold shop in an urban area, where it is then reheated to remove the majority of Hg⁰ (Wip et al., 2011; Cordy et al., 2011, 2013; García et al., 2015). Less frequently, miners will burn the amalgam in the gold shop using the gold shop's equipment (Wip et al., 2011). During these processes Hg⁰ vapor is directly emitted into the gold shop or exhausted onto the street using rudimentary ventilation systems, often at

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concentrations determined to be dangerous to human and environmental health (de Lacerda and Salomons, 1998; Wip et al., 2011; Cordy et al., 2011, 2013; García et al., 2015; Hacon et al., 1995, 1997, 2000; Malm et al., 1995, 1997, 1998; Lacerda et al., 1995, 2004; Santa Rosa et al., 2000; Ashe, 2012; Malm, 1998; Akagi and Naganuma, 2000; Akagi et al., 1995; Cleary et al., 1994; Pfeiffer et al., 1991; Bastos et al., 2004; Sousa et al., 2011; Rozane and Marins, 2000; Branches et al., 1993; Sousa and Veiga, 2009; Drake et al., 2001; Lauthartte et al., 2018).

Hg^0 vapor is a potent chronic and acute neurotoxin and nephrotoxin (Risher, 2003; Eisler, 2003; Fernandes Azevedo et al., 2012; Clarkson and Magos, 2006). While there is no safe concentration of Hg^0 vapor in the air, the United States Agency for Toxic Substances and Disease Registry (ATSDR) defines the minimum risk level for Hg^0 vapor to be 200 ng/m³, with recommended action levels in residential settings of 1000 ng/m³ for normal exposure and 10,000 ng/m³ for isolation of residents (ATSDR, 2015). Chronic exposure to Hg^0 vapor has been linked to kidney problems and micromercurialism (fatigue, memory loss, tremors). Risher notes that effects on the central nervous system (CNS) can occur over years of exposure to concentrations equal to or greater than 20,000 ng/m³ (Risher, 2003). The National Institute for Occupational Safety and Health (NIOSH) sets an 8-h time-weighted average (TWA) of exposure at 50,000 ng/m³, and the Occupational Safety and Health Administration (OSHA) sets a permissible exposure limit ceiling of 100,000 ng/m³ (CDC, 2015; OSHA Annotated PELS). Exposure to higher concentrations of Hg^0 vapor, including concentrations emitted during the processing of amalgams, adversely affects the lungs and have led to illness and even death. (de Lacerda and Salomons, 1998; Eisler, 2003; Lilis et al., 1985; Levin et al., 1988; Milne et al., 1970). Milne and coworkers estimate that exposure to concentrations exceeding 1,000,000 ng/m³ may result in mercurial pneumonitis, a life threatening disease similar to metal fume fever (Milne et al., 1970). The United States Environmental Protection Agency Acute Exposure Guideline Levels (AEGLs) for Hg^0 states that concentrations exceeding 2,200,000 ng/m³ represent life-threatening conditions over a 4-h period (USEPA, 2014). Concentrations in gold shops routinely exceed these values (Hacon et al., 1997; Drake et al., 2001).

Hg^0 from ASGM activities enters the global mercury cycle, where it can be transported across the world and converted into both inorganic and CH_3Hg^+ (Obrist et al., 2018; Driscoll et al., 2013). As a result, mercury pollution originating from ASGM is a global issue and is specifically targeted in Article 7 and the corresponding Annex C of the Minamata Convention on Mercury. The Convention is an international treaty designed to address the use of Hg, anthropogenic emissions of Hg to the environment, as well as to mitigate the threat it poses to the environmental and human health (UNEP, 2013; Mercury Convention texts, 2019). The Convention requires that each signatory nation with ASGM and related processing activities must develop a national action plan (NAP) that outlines steps to reduce the use of Hg^0 and corresponding emissions to the environment with the ultimate goal of replacing Hg^0 altogether. As a component of the NAP, each nation outlines its actions to eliminate the open burning of amalgams and processed amalgams, as well as the burning of amalgams in residential areas. Within the plan are actions to specifically address vulnerable populations, particularly children, women of childbearing age, and pregnant women. While the plan requires a baseline estimate of the amount of Hg^0 used and mercury-involved gold mining practices employed throughout the country, the NAP does not explicitly require the monitoring of mercury emissions in ASGM communities. However, the Convention requires a report every three years after the submission of the NAP, making it difficult for participating nations to demonstrate the effectiveness of Hg^0 reduction programs without gathering data to determine an initial baseline of mercury in the environment. In addition, the Convention requires the development of strategies to identify and assess sites contaminated by mercury (Article 12), and states that all parties should endeavor to improve representative monitoring of

mercury and mercury compounds in the environment (Article 19).

Because of these mandates, the government of Peru recently passed legislation requiring total gaseous (TGM) mercury emissions to not exceed 2000 ng/m³ (*Aprueban Estándares de Calidad Ambiental (ECA)*, 2019). TGM is the sum of Hg^0 vapor, reactive gaseous mercury (RGM), and particle-bound mercury (P_{Hg}). The Ministerio del Ambiente (MINAM, Ministry of the Environment) of Peru was tasked with determining if Hg levels in the atmosphere associated with ASGM activities in urban and residential communities were within these limits. MINAM initiated a collaborative investigation with Mercer University that involved 1) the rapid and preliminary screening of Hg^0 concentrations in the air associated with the heating of amalgams and the reheating of processed amalgams in gold shops; 2) identification of potentially vulnerable populations affected by gold shop emissions; 3) an introductory training session for MINAM personnel on the basics of monitoring Hg^0 in the atmosphere; and 4) an initial assessment of the effectiveness of existing Peruvian regulations for monitoring Hg concentrations in ASGM communities. The work presented herein represents the first assessment of Hg^0 emissions originating from Peruvian gold shops and describes how these emissions relate to recently enacted national legislation governing Hg^0 emissions.

1.1. Site selection

The Peruvian Department of Madre de Dios was selected for study because it has significant ASGM activity employing Hg^0 and has received world-wide attention related to deforestation and loss of biodiversity resulting from mining activities (Ashe, 2012; Caballero Espejo et al., 2018; Cortés-McPherson, 2019; Martinez et al., 2018; Yard et al., 2012; Swenson et al., 2011). Madre de Dios is ~85,000 km² of primarily Amazon lowland rain forest, characterized by daily temperatures exceeding 30 °C and high humidity. Data was collected in October 2017 (beginning of the rainy season) and May 2018 (dry season). While rainfall can occur at anytime throughout the region, data was not collected during rainfall. Prevailing winds during the study periods were from the North and East; however, as measurements were taken in residential and business areas, wind directions varied considerably.

MINAM selected the communities of Tres Islas, Delta One, and Laberinto to be mapped and assessed for airborne mercury contamination during October 2017 (Fig. 1). Tres Islas (-12.546583333333, -69.3754) is an indigenous community of approximately 120 families selected to serve as an example of a mining-free community. While mining does occur in the area, there are no permanent gold shops or processing sites in the community center. Delta One (-12.78955 -70.520433333333) is a remote and active ASGM community located between the Colorado and Puquiri rivers consisting of restaurants, gold shops, and other businesses catering to miners. The community has a fluxional population, with many migrants from the Andes who have turned to ASGM for employment. Laberinto (-12.718333333333, -69.58905) is an ASGM community similar to Delta One, but located in close proximity to Puerto Maldonado, the capital of the Madre de Dios Region. Laberinto was selected by collaborators to undergo further mapping in May of 2018 due to its proximity to Puerto Maldonado and the support of the municipal government.

2. Experimental

Mercury concentrations in air were determined using two commercially available atomic absorption spectrometers tuned to 253.7 nm, the Mercury Tracker IP (MTIP) and Lumex RA-915 M (Lumex). The MTIP, calibrated by the manufacturer, measures ranges of 0–2,000,000 ng/m³, has a sensitivity of 0.1 $\mu\text{g}/\text{m}^3$, and a response time of 1 s. Because of its robustness in the field, the MTIP precedes the more sensitive Lumex, which employs Zeeman correction, has a significantly lower detection limit (0.5 ng/m³), and is prone to memory effects at



Fig. 1. Sites Assessed in the Department of Madre de Dios with respect to the city of Puerto Maldonado.

higher concentrations of mercury. The Lumex was calibrated by the manufacturer prior to both trips (0–46,336 ng/m³ for analysis during October, 0–38,959 ng/m³ during May). While the manual states that the instrument has an effective range of 2–200,000 ng/m³, areas with concentrations exceeding 50,000 ng/m³ were actively avoided due to the instrument's calibration limits (Ohio Lumex Co. and Inc, 2011). Concentrations outside of gold shops occasionally exceeded 50,000 ng/m³ due to shifting winds or unexpected activity within gold shops. Concentrations of Hg⁰ within gold shops and ventilated exhaust from gold shops on the streets and sidewalks were determined exclusively with the MTIP. When concentrations exceeded 2,000,000 ng/m³, the MTIP was relocated to a predetermined location with low concentrations of Hg (< 50 ng/m³) and operated until the MTIP's Hg⁰ concentrations decreased to less than 1000 ng/m³.

All maps were generated from data collected by the Lumex and at concentrations less than 35,000 ng/m³ to ensure that measurements remained on both calibration curves. The Lumex was connected to a computer running the manufacturer's RAPID software and was set to take a sample every second. The computer clock was synchronized with a Garmin Oregon GPS Unit that recorded latitude and longitude every second. The Lumex and GPS unit were physically attached to one another and carried slowly down the streets and sidewalks behind the MTIP. Mercury concentrations were saved through the Rapid Software onto a hard drive, and the GPS data was downloaded using Garmin BaseCamp. All data were imported into Microsoft Excel, where the position was linked to concentration via time. Infrequently, a data point was collected with only position or concentration, and these data were eliminated. Using Excel, mercury concentration values were sorted by unique GPS coordinates and a maximum value assigned to each coordinate. Because of the high concentrations of Hg⁰ in the air in Laberinto the Lumex detector occasionally became saturated. As a result, the detector was unable to measure Hg⁰ concentrations until the establishment of a new baseline, leading to Hg⁰ concentrations lower than 0 ng/m³. As a screening technique, no data was removed prior to mapping; however, maximum values were mapped as opposed to

average values at each unique latitude and longitude to avoid the effect of the (–) values. Maps were generated using QGIS ("QGIS Development Team (2019). QGIS Geographic Information System. Open Source Geospatial Foundation Project. <http://qgis.osgeo.org>".)

3. Results and discussion

Initial Assessment of Tres Islas, Delta One, and Laberinto. In October 2017, preliminary assessment of three communities in Madre de Dios were conducted to determine mercury concentrations in air due to ASGM activities, in particular emissions from gold shops. Tres Islas, Delta One, and Laberinto were mapped for airborne mercury contamination. All mercury concentrations measured over 1000 ng/m³ were associated with gold shops. The initial data collected demonstrated that communities with active gold shops showed elevated Hg⁰ concentrations in the air.

Tres Islas has no active mining operations or gold shops in the community and as expected, had low concentrations of Hg⁰. Concentrations of Hg⁰ in Tres Islas never exceeded 50.65 ng/m³ (Fig. 2). The highest concentrations were found at a small shop near the dock on the Madre de Dios river. Upon discussing this relative increase in concentration with both the shop keeper and a local government official, it was determined that burning occurred behind the store "several weeks" prior to the data collection, and mercury used to be sold at this store. This explains the modest increase in mercury concentrations at this location that contrasts with the consistent measurements of 10–20 ng/m³ throughout the rest of the community. This evidence indicates that even slightly elevated concentrations of mercury in the atmosphere from mining activities can be detected through this methodology. It also demonstrates that although Hg⁰ is volatile in the environment, it is also persistent over a measurable period of time.

Delta One is an ASGM community with active gold shops. The map in Fig. 3 represents data collected over 1 h and 54 min of walking through residential areas ending in the marketplace. Data collected from the Lumex recorded mercury concentrations exceeding 30,000 ng/m³

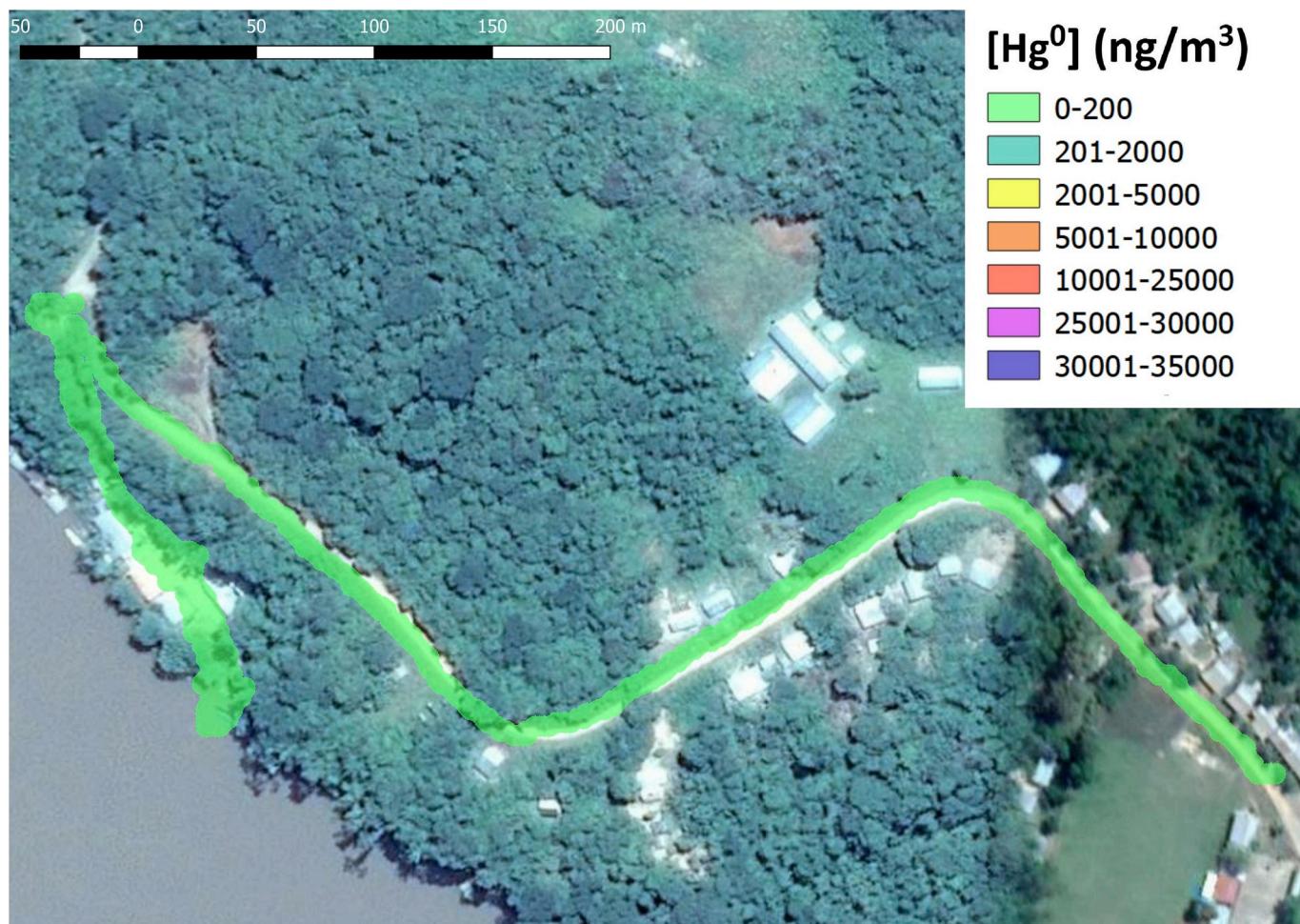


Fig. 2. Map of $[Hg^0]$ vs GPS location at the indigenous community of Tres Islas, October.

m^3 on the street. Concentrations exceeding $2,000,000\text{ ng}/m^3$ were measured on the sidewalk and the road near gold shops of Delta One. These gold shops burn amalgams and reheat processed amalgams brought from numerous independent mines that are located throughout the region. Overall, Delta One exemplifies a small town that attracts business of ASGM miners around the region, and in doing so concentrates mercury pollution in residential and business areas.

Laberinto contains gold shops that move throughout the town depending on the severity of the rainy season. Due to mining operations nearby, mining-related businesses have boomed. The proximity of the town to the city of Puerto Maldonado ($< 1\text{ h}$ by car) allows for rapid and easy access to mining equipment and services. The initial assessment of Laberinto revealed that gold shop owners used different methods for burning and capturing/ventilating mercury vapors (Fig. 4). Measurements from the MTIP ranged from $400,000\text{--}500,000\text{ ng}/m^3$ inside a gold shop with no amalgam burning, and exceeded $2,000,000\text{ ng}/m^3$ at the front of two shops during and immediately after burning. The initial mapping was limited to a small subsection of the town containing the gold shops. During this initial visit, the map for Laberinto was generated and shared with politicians in the town who were dubious about 1) the health effects of mercury and 2) the extent of contamination throughout the town; this map was intended to be a momentary snapshot highlighting the effects of gold shops on mercury contamination in the town, with mapped concentrations exceeding $28,000\text{ ng}/m^3$. The town's highest concentrations were located by the market and business district containing the gold shops. It is clear from the data collected that the elevated mercury concentrations originate at the gold shops. In spite of these elevated levels, areas surrounding the

market area, schools, residencies, and the town center consistently show lower concentrations. This indicates that the high concentrations of Hg^0 produced by the gold shops are dispersed and diluted in the air over relatively short distances. Future work should be directed to determine the ultimate fate of Hg^0 originating at these shops in order to assess the local, regional and global impact of these emissions.

Laberinto and Delta One had comparable levels of mercury in the atmosphere, all centered around working gold shops. When compared and contrasted to the neighboring community of Tres Islas, concentrations of mercury were found to be orders of magnitude greater in areas with gold shops. Somewhat surprisingly, residential areas distant from these shops show similar concentrations to the residential areas of Tres Islas, indicating that the mercury emitted from gold shops is rapidly diluted in the air and dispersed. Because of a positive interaction with community leaders, Laberinto was selected as a site for future monitoring and assessment of existing mercury ventilation systems.

3.1. Mapping of Laberinto for Hg^0 emissions (May 2018)

To ensure that the rapid assessment of Laberinto conducted in October of 2017 was reflective of mercury concentrations throughout the community, additional mapping was conducted from May 16th-May 23rd of 2018. The map in Fig. 5 represents the maximum concentration of Hg^0 recorded at each GPS coordinate measured over 4 days with the Lumex.

Again, the highest concentrations of Hg^0 in Laberinto are found in the market area containing all known gold shops. Concentrations in this area have consistently high levels of mercury vapor, with

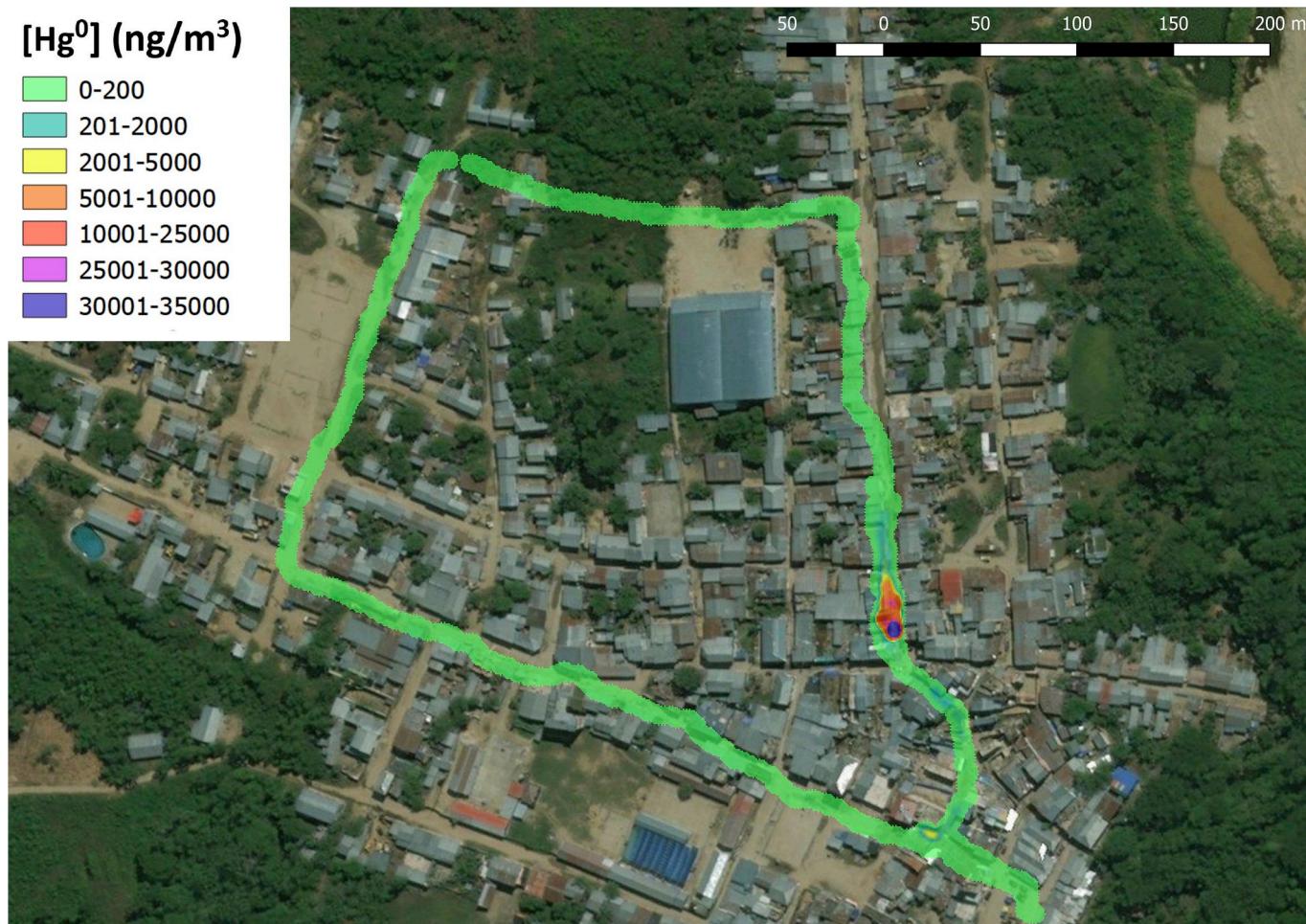


Fig. 3. Map of $[Hg^0]$ vs GPS location at the ASGM community of Delta One, October.

concentrations routinely exceeding $2,000,000 \text{ ng/m}^3$ on sidewalks outside of gold shops where we observed the burning of amalgams and reheating of processed amalgams. It was observed that this area has the highest population of people on the streets of the community between 7:00 AM and 6:00 PM. There are residences within this zone, including gold shop owners that reside directly above their businesses with their families.

Over the course of data collection concentrations over $70,000 \text{ ng/m}^3$ were measured with the Lumex in areas around the gold shops; however, mapping only includes data collected that fall within the range of the calibration curve of the instrument (below $35,000 \text{ ng/m}^3$). The mercury concentrations released routinely exceeded the upper limit of the calibration of the Lumex, and the MTIP was used as both a precautionary tool as well as a measuring device. Readings of over $2,000,000 \text{ ng/m}^3$ were measured in this area, exceeding the upper limit of the calibration of the MTIP. Shops located near gold shops also had high levels of Hg^0 contamination.

Concentrations of Hg^0 exceeding 2000 ng/m^3 were recorded at the local preschool. As there are no point sources of mercury at the school or in surrounding areas, it is inferred that mercury emissions may come from a closed gold shop nearby. This gold shop was active in both October of 2017 and March of 2018, but was closed by May of 2018. Certain gold shops in Laberinto move based on seasonal changes. During the rainy season, the river rises and floods low-lying areas. As a result, gold shops relocate to higher elevations to continue to work. During the dry season, this gold shop registered concentrations exceeding $15,000 \text{ ng/m}^3$ measured by the MTIP when the steel security door was closed and locked. We are currently unaware of other gold

shops that remain closed in the dry season, and the maps produced in May of 2018 show no evidence of other closed gold shops as point sources of mercury contamination.

We were unable to gain access to the shuttered gold shop, but we were able to measure concentrations within 30 cm of a different gold shop's door prior to and immediately after opening. Prior to the opening of the door, mercury concentrations ranged between 0 and 5000 ng/m^3 . Immediately after the door was opened, mercury concentrations exceeded $200,000 \text{ ng/m}^3$ and remained highly fluxional for approximately 10 min. Within 10 min of opening, concentrations ranged between 0 and $20,000 \text{ ng/m}^3$. The increase in concentration directly after the opening of gold shops is attributed to the buildup of Hg^0 vapor inside the shop while the doors are closed. Many shops had visible liquid Hg^0 on the floors and on/around ventilation systems (Fig. 6C); when the doors and windows of the gold shop were closed, the trapped mercury evaporated and approached equilibrium, resulting in highly elevated concentrations of Hg^0 .

3.2. Ventilation of gold shops in Laberinto

The number of gold shops that actively burn amalgams and/or reheat processed amalgams in Laberinto is dependent upon the season. Each gold shop observed during this study has either a locally fabricated mercury capture system (MCS) and/or a ventilation system in place where the amalgam is burned. It is important to note that Hg^0 is colorless and odorless, and local fabricators lack the technology to test these systems to determine if they work efficiently. Varying greatly in design and effectiveness, most are constructed from easily accessible

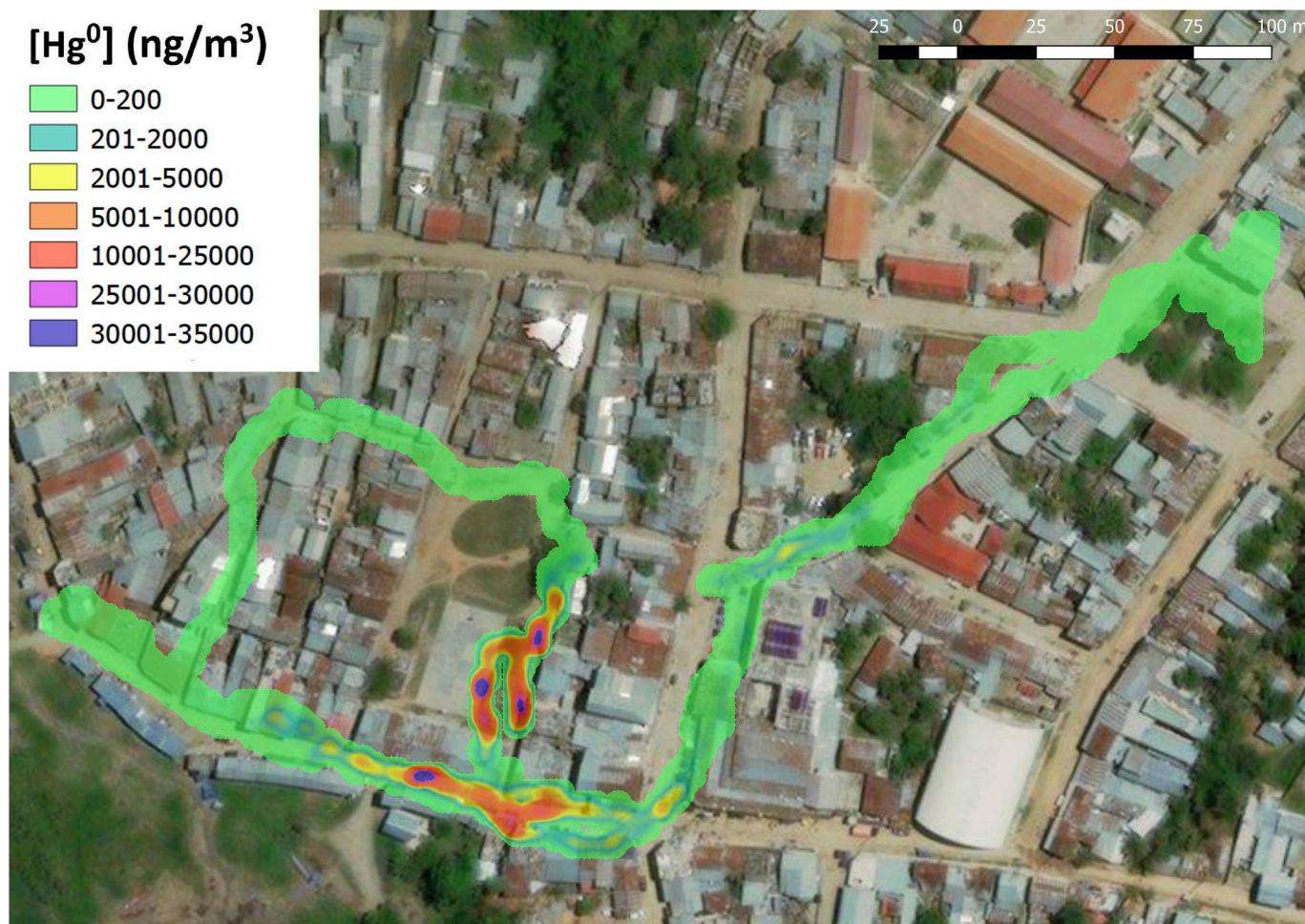


Fig. 4. Preliminary mapping of $[Hg^0]$ vs GPS location in Laberinto, October.

materials and objects and contain pipes that redirect the vapors to different areas. Occasionally, these pipes travel through or terminate in closed rooms, concentrating mercury in these areas. Some ultimately vent directly onto the street. In each case, the ventilation systems or MCSs were designed to move Hg^0 vapors away from the individual burning the amalgams.

One active gold shop contained two separate burning stations connected via metal piping that joined PVC piping. In general, burning stations consist of a steel cuboid container topped with a square pyramidal roof that is connected to duct work (Fig. 6A). The shared metal pipe was directed through a metal cistern containing water to cool the vapor, and then continued through the wall into a separate room where the blacksmith forge fan was located that exhausted the air into PVC piping and ultimately through an exterior wall and onto the street (Fig. 6B and D). A third system was vented directly through the wall and over a steel vessel containing cooling water and into PVC piping that exited through the aforementioned pipe exiting the exterior wall.

Although the units were capable of condensing mercury, we were unable to estimate the efficiency of the systems because there was so much Hg^0 condensed on the piping, the floor, and the condensation tanks that it was unsafe to work in the confined space for extended periods of time (Fig. 6C). The concentrations in the condenser room exceeded 600,000 ng/m³ with the door closed while burning occurred. On a separate occasion, additional measurements were taken after the heating of processed amalgams. Six minutes after burning and with the door to the condenser room open, Hg^0 concentrations measured between 27,000 and 170,000 ng/m³. Inside the shop, Hg^0 concentrations were over 300,000 ng/m³. At the burning site and the final exhaust

point, concentrations exceeded 2,000,000 ng/m³.

The gold shop operators live above the gold shop with their family; entrance to the apartment was made through the ventilation room (Fig. 6b), and the living space was directly above where the system vented onto the street. When the system was turned on but there was no active burning, concentrations surrounding the vent exceeded 2,000,000 ng/m³. During burning concentrations greatly exceeded the upper limit of the calibration of the instrument. The apartment located upstairs had a concentration after burning of greater than 60,000 ng/m³.

At another smaller gold shop, a ventilation system was set up that transported mercury vapor during heating using a vacuum cleaner (Fig. 7). The burning station was vented directly into PVC tubing connected to the metal wand of a vacuum cleaner. The vacuum cleaner itself was placed underneath the burning station. Concentrations of Hg^0 in the gold shop exceeded 400,000 ng/m³ when the system was not in operation feet away from the burning station. Passing liquid mercury through a standard vacuum cleaner is exceptionally dangerous, as the system aerosolizes the mercury making it easier to inhale (Alby-Laurent et al., 2016; Bonhomme et al., 1996; Scheepers et al., 2014). In this particular case, the mercury is vaporized prior to reaching the vacuum cleaner, and the unit vents below the burning station ensures that the mercury vapor not trapped in the system is ventilated directly into the room with the miner and the gold shop worker. No efforts were made to measure Hg^0 emissions with this system during burning due to danger of inhalation imposed in this environment.

In one particular case, a ventilation system in a gold shop expelled Hg^0 vapor into a separate room that served as access to a residence

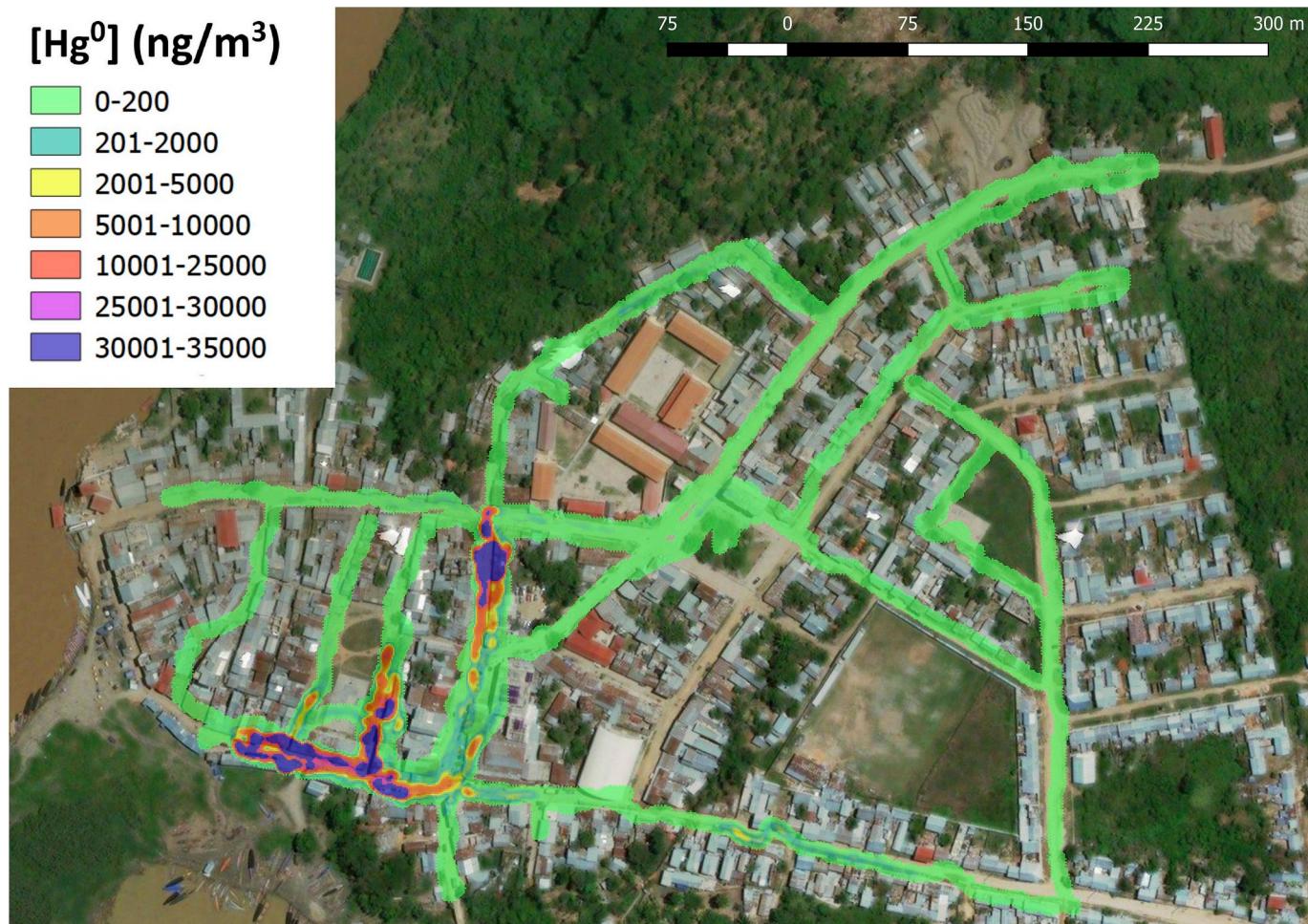


Fig. 5. Map of $[\text{Hg}^0]$ vs GPS location in Laberinto over 4 days, May.



Fig. 6. Laberinto Gold Shop. A) Two burning stations connected to a water cooling tank. B) On the other side of the wall, metal piping is connected to PVC. Concentrations exceeded $600,000 \text{ ng}/\text{m}^3$ in this room. Note the child sitting on the stairs in the upper left. C) Hg^0 is condensed on metal components around the ventilation system. D) Vapor is directly vented onto street. The wooden support beams shown are the porch of a residence.



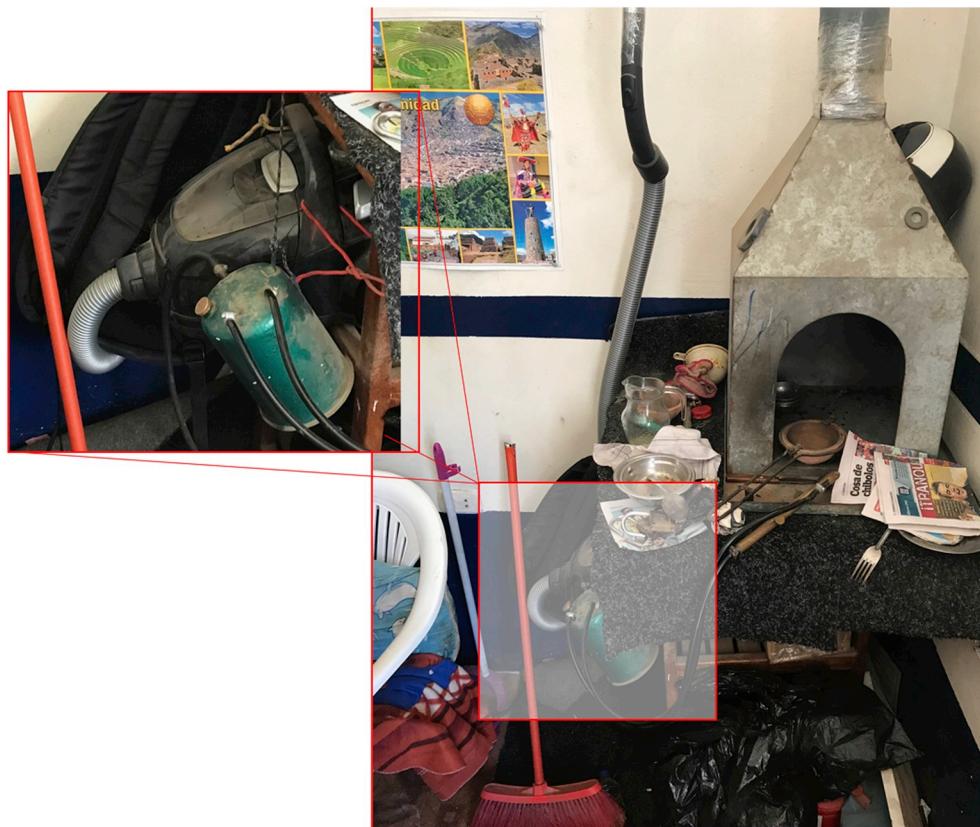


Fig. 7. Laberinto Gold Shop using vacuum cleaner ventilation system.

above the shop (Fig. 6b). These observations are of particular concern as children, pregnant women, and women of child-bearing age are particularly vulnerable to the effects of mercury. As a component of the NAP, countries must provide strategies to minimize exposure of both children and women to mercury used during ASGM activities. During the assessment of gold shops in Laberinto it was common to see children and infants inside and immediately outside of gold shops. This is not unique to Laberinto, and was observed in Delta One, Huaypetue, and other ASGM communities. Many gold shop employees are female, and their children play, complete school assignments, and spend time with their families in the gold shop. Children live in surrounding buildings and occasionally in residences directly connected to gold shops.

3.3. Comparison of results to prior air studies in ASGM communities

The measurement of mercury contamination originating from gold shops and other ASGM activities has been previously conducted. Initial work in these areas measured TGM and utilized field sampling techniques and analysis within a laboratory using cold-vapor atomic absorption spectrometers (CV-AAS). Malm reports an average Hg concentration of 2800 ng/m³ near areas where reburning occurs. He also reports occupational exposure in gold shops averaging 71,400 ng/m³ during the reheating of sponge gold, and concentrations exceeding 15,000, 000 ng/m³ when burning amalgams in the field with no retort (Malm, 1998). Undoubtedly, the burning of amalgams in enclosed gold shops with limited ventilation produces higher concentrations. Drake et al. similarly monitored air concentrations during the burning of amalgams in Venezuela, determining that in one case TGM concentrations exceeded 6,000,000 ng/m³ (Drake et al., 2001). Lin and coworkers sampled air, collected Hg⁰ via amalgamation, and analyzed the sample using Cold Atomic Fluorometry and documented Hg⁰ concentrations ranging between 1,950,000 and 3,050,000 ng/m³ in areas where amalgams were heated (Lin et al., 1997). Perhaps the highest

concentrations of Hg⁰ recorded in an ASGM community occurred in Alta Floresta, a municipality in the Brazilian Amazon. Total atmospheric Hg was measured inside four gold shops to determine occupational exposure of the workers, with concentrations ranging from 70,000–40,600,000 ng/m³ (Hacon et al., 1997). While these methods of determining TGM concentrations are both effective and established, they require a fixed position and do not provide researchers with real-time determination of mercury concentrations.

Hg⁰ concentrations can be determined using a Lumex RA-915+ for low to moderate levels of Hg⁰ contamination and a Gold-film Mercury Analyzer such as the Jerome 431X for levels up to 1,000,000 ng/m³ (Wip et al., 2011; Cordy et al., 2011, 2013; García et al., 2015; González-Carrasco et al., 2011). In 2011, Cordy and coworkers reported concentrations in Antioquia, Colombia ranging from 5000 ng/m³ – 200,000 ng/m³ in gold shops (Cordy et al., 2011). The authors report that amalgams are frequently burned in the open air; however, in one gold shop with a mercury abatement system exhausted air with Hg⁰ concentrations of 100,000 ng/m³. In 2013 Cordy and coworkers reported the mapping of urban areas in Colombia and Chile with gold shops, highlighting average concentrations ranging between 0 and 10,000 ng/m³ (Cordy et al., 2013). A Lumex RA-915+ was linked to a GPS unit, and data was collected driving in a vehicle attempting to maintain a speed of ~20 km/h, although speeds were dependent upon local traffic conditions. The authors state that the data were corrected to adjust for transit time through the sampling tube. We found that when using the Lumex RA-915M in a vehicle the data collected were routinely lower than when measured via walking. In some cases concentrations remained below 200 ng/m³, when walking with the spectrometer in a similar area recorded concentrations exceeding the upper limit of the calibration of the instrument. In addition, walking allows for measuring on narrow streets; some gold shops were found in areas that were difficult to drive past.

Unlike previous work, the maps presented in this paper reference

the maximum concentration at a given position as opposed to the average concentration. The Lumex RA-915M is prone to memory effects in areas of high Hg⁰ concentration that may result in negative values for [Hg⁰]. Inclusion of these values into the average results in lower values of Hg⁰ than what was being recorded. In addition, the aforementioned Peruvian air standard sets a TGM maximum concentration limit over 24 h, requiring a maximum concentration value as opposed to an average ([Aprueban Estándares de Calidad Ambiental \(ECA\), 2019](#)).

3.4. Gold shops and existing mercury pollution regulations in Peru

In 2017, the Decreto Supremo N° 003-2017-MINAM, translated to “Environmental Quality Standards for Air and Established Complementary Provisions”, updated existing air standards for a number of pollutants and set a standard for TGM for the first time ([Aprueban Estándares de Calidad Ambiental \(ECA\), 2019](#)). The air quality standards establish the concentration level of a pollutant in the ambient air which is recommended to avoid risks to human health and are applied nationally regardless of the source of the pollutant. For mercury the document sets the air standard of TGM at any time over a 24-h monitoring period to not exceed 2000 ng/m³. The Peruvian Technical Norm NTP 900.068 (NTP) dictates how sampling and analysis of TGM is conducted, specifying that TGM be measured using Cold Vapor Atomic Fluorescence Spectroscopy (CVAFS) or Cold Vapor Atomic Absorption Spectroscopy (CVAAS) using gold traps for pre-concentration ([Monitoreo de Calidad Ambiental, 2016](#)). Interestingly, the NTP allows for the measurement of gaseous Hg⁰ concentrations using CVAAS with Zeeman correction with ambient air as a carrier gas. This method does not measure TGM, but because Hg⁰ is the major component of TGM greatly exceeding both RGM and P_{Hg} it is assumed that [Hg⁰] approximates TGM. These norms are only applicable to environmental sampling and do not apply to concentrations of TGM within residences and businesses.

The high concentrations of Hg⁰ vapor released during ASGM practices complicates monitoring of TGM in ASGM communities in accordance with the NTP. The NTP was modeled after norms implemented in Europe, in countries with no recent history of ASGM activities. The methods were tested in four European sites where values ranged from less than 2 ng/m³ to concentrations found in industrial areas; the 24-h average measured during the testing of the method never exceeded a daily average of 300 ng/m³ of TGM, with the four sites averaging 1.9, 3.6, 1.5, and 32 ng/m³ over the course of monitoring. Based on the maps generated during this work, the concentration of Hg⁰ near gold shops exceeded the daily average measured during the testing of the method by orders of magnitude. In addition, while the law states that the amount of TGM may not exceed 2000 ng/m³ during a 24-h period, the concentrations of TGM in ASGM communities are highly variable depending on time of day and mining activity. The NTP states that the measurements were taken between 30 s and 30 min during the field trials cited in the norm. The time at which samples are collected and analyzed may be important in enforcing the law in Peru.

Decreto Supremo N° 003-2017-MINAM requires the determination of TGM, not Hg⁰, and as such, CV-AAS instruments with Zeeman correction like the Lumex RA-915M could not be used to enforce the regulation ([Aprueban Estándares de Calidad Ambiental \(ECA\), 2019](#)). Nonetheless, the ease of use, portability, and relatively low cost of the Lumex makes it an effective unit for monitoring Hg⁰ pollution in remote ASGM communities. The findings of this study led to a discussion with MINAM regarding how to make CV-AAS with Zeeman correction acceptable for conducting assessments in ASGM communities. In December of 2019, an Air Monitoring Protocol was passed providing a correction factor for operators to estimate TGM from data determined by CV-AAS with Zeeman correction ([Decreto Supremo N° 10-2019-MINAM](#)). These instruments were already included in the adopted NTP ([Monitoreo De Calidad Ambiental, 2016](#)). Attention should be paid

when monitoring in ASGM communities using portable CV-AAS spectrometers with Zeeman correction, since the upper limit of the calibration of instruments like the Lumex is often exceeded at Hg⁰ concentrations found near gold shops by orders of magnitude.

Finally, this work demonstrates the complexities of drawing conclusions about mercury concentrations at fixed positions in ASGM communities. It may be possible to conduct stationary monitoring at multiple sites throughout a community without exceeding the permissible standard, while hot spots may exist in close proximity that greatly exceed the standard. Distinct from stationary monitoring, mapping allows for the rapid detection of emission sources that can be used to inform site selection for formal, 24-hour monitoring. Mapping the community prior to conducting formal monitoring may allow Peru to collect data that is more reflective of mercury pollution in the community.

3.5. Future directions

The data collected and maps presented here contribute to the technical discussion of how to viably apply the existing norms for specific cases in ASGM communities. Concentrations of Hg⁰ in and around Peruvian gold shops indicates the potential health threat to miners, gold shop owners and their families, as well as members of the community as a whole. In addition to providing feedback on areas with high contamination and estimating TGM from Hg⁰ concentrations for further analysis, this mapping technique may be useful in enforcing existing and future norms.

The recently approved “National Plan for the Application of the Minamata Convention on Mercury” (Decreto Supremo N° 004-2019-MINAM) outlines Peru’s approach to implementing all aspects of the Convention ([Decreto Supremo N° 004-2019](#)). Activities 15.1 and 15.2 include the outline of a prevention program to protect those at risk from mercury exposure in compliance with Article 16 of the Minamata Convention. This will require the establishment of a health occupational standard based on scientific information that protects vulnerable and exposed populations. This standard will be applied to areas where amalgams are burned and where processed amalgams are preheated. This national legislation should not be confused with the aforementioned NAP, which deals only with ASGM. Based on the results of the present study, the NAP should assure that gold shops are not located in residential or commercial areas.

Although the total phaseout of Hg⁰ use should be the ultimate goal of every nation with significant ASGM, the reality is that for many miners there are currently few alternatives. Future work should be dedicated to determining the validity of passive air samplers in ASGM communities, particularly in and around gold shops. These air samplers are inexpensive, reusable, and easily transportable. They can be analyzed using conventional analytical instrumentation and offer a viable alternative to using expensive instrumentation in the field ([McLagan et al., 2016, 2018](#)). Recently, they have been used to map the area around a former Hg mine in Italy and estimate Hg emissions in the study area ([McLagan et al., 2019](#)). It is clear that continued progress towards Hg-free ore processing technologies ([Veiga et al., 2009, 2018; Drace et al., 2012; Appel and Na-Oy, 2014; Vieira, 2006](#)) and training ([Sousa and Veiga, 2009; Stocklin-Weinberg et al., 2019; Artisanal Gold Council, 2019; Veiga and Marshall, 2017](#)) is essential.

4. Conclusions

Concentrations of Hg⁰ in ASGM communities with gold shops exceed safe limits of mercury exposure in public areas, residential areas, homes, and the shops themselves. A simple technique to rapidly identify point sources of Hg⁰ pollution was developed and employed to generate maps of Hg⁰ pollution. The maps generated through this study have confirmed that enforcement of Peruvian mercury emission limits and the norms required to determine compliance with the law is

complicated by the nature of gold shop Hg⁰ emissions. Hg⁰ emitted by these gold shops is rapidly dispersed in the environment, and location of the 24-hr measurement site may effect the viability of the assessment. The results of this work have contributed to the elaboration of the Peruvian air quality protocol for mercury monitoring as Hg⁰, and to the development of a correction factor to estimate TGM in accordance with the existing regulation.

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References

- Agagi, H., Naganuma, A., 2000. Human exposure to mercury and the accumulation of methylmercury that is associated with gold mining in the Amazon basin, Brazil. *J. Health Sci.* 46, 323–328. <https://doi.org/10.1248/jhs.46.323>.
- Agagi, H., Malm, O., Branches, F.J.P., Kinjo, Y., Kashima, Y., Guimaraes, J.R.D., Oliveira, R.B., Haraguchi, K., Pfeiffer, W.C., Takizawa, Y., Kato, H., 1995. Human exposure to mercury due to goldmining in the tapajos river basin, Amazon, Brazil: speciation of mercury in human hair, blood and urine. In: Porcella, D.B., Huckabee, J.W., Wheatley, B. (Eds.), *Mercury as a Global Pollutant: Proceedings of the Third International Conference Held in Whistler, British Columbia, July 10–14, 1994*. Springer Netherlands, Dordrecht, pp. 85–94. https://doi.org/10.1007/978-94-011-0153-0_10.
- Alby-Laurent, F., Honoré-Goldman, N., Cavau, A., Bellon, N., Allali, S., Abadie, V., 2016. Intoxication accidentelle au mercure chez l'enfant. *Arch. Pediatr.* 23, 1161–1164. <https://doi.org/10.1016/j.arcped.2016.08.008>.
- Appel, P.W.U., Na-Oy, L.D., 2014. Mercury-free gold extraction using borax for small-scale gold miners. *J. Environ. Prot.* 493–499. <https://doi.org/10.4236/jep.2014.560502>.
- Aprueban Estándares de Calidad Ambiental (ECA) para Aire y establecen Disposiciones Complementarias, SINIA | Sistema Nacional de Información Ambiental (n.d.). <https://sinia.minam.gob.pe/normas/aprueban-estandares-calidad-ambiental-eca-aire-establecen-disposiciones>, Accessed date: 15 April 2019.
- Ashe, K., 2012. Elevated mercury concentrations in humans of Madre de Dios, Peru. *PLoS One* 7, e33305. <https://doi.org/10.1371/journal.pone.0033305>.
- ATSDR, Toxicological profile: mercury (n.d.). <http://www.atsdr.cdc.gov/toxprofiles/tp.asp?id=115&tid=24>, Accessed date: 26 June 2015.
- Bastos, W.R., de Freitas Fonseca, M., Pinto, F.N., de Freitas Rebelo, M., Silva dos Santos, S., Glória da Silveira, E., Torres, J.P.M., Malm, O., Pfeiffer, W.C., 2004. Mercury persistence in indoor environments in the Amazon Region, Brazil. *Environ. Res.* 96, 235–238. <https://doi.org/10.1016/j.envres.2004.01.008>.
- Bonhomme, C., Gladyszczak-Kholer, J., Cadou, A., Illef, D., Kadi, Z., 1996. Mercury poisoning by vacuum-cleaner aerosol. *The Lancet* 347, 115. [https://doi.org/10.1016/S0140-6736\(96\)90239-1](https://doi.org/10.1016/S0140-6736(96)90239-1).
- Branches, F.J.P., Erickson, T.B., Aks, S.E., Hryhorczuk, D.O., 1993. The price of gold: mercury exposure in the amazonian rain forest. *J. Toxicol. Clin. Toxicol.* 31, 295–306. <https://doi.org/10.3109/15563659309000396>.
- CDC, Immediately dangerous to life or health concentrations (IDLH): mercury compounds [except (organo) alkyls] (as Hg) - NIOSH publications and products (n.d.). <http://www.cdc.gov/niosh/idlh/7439976.html>, Accessed date: 26 June 2015.
- Caballero Espejo, J., Messinger, M., Román-Dañobeytía, F., Ascorra, C., Fernandez, L.E., Silman, M., 2018. Deforestation and forest degradation due to gold mining in the Peruvian Amazon: a 34-year perspective. *Remote Sens.* 10, 1903. <https://doi.org/10.3390/rs10121903>.
- Clarkson, T.W., Magos, L., 2006. The toxicology of mercury and its chemical compounds. *Crit. Rev. Toxicol.* 36, 609–662. <https://doi.org/10.1080/10408440600845619>.
- Cleary, D., Thornton, I., Brown, N., Kazantzis, G., Delves, T., Worthington, S., 1994. Mercury in Brazil. *Nature* 369, 613–614. <https://doi.org/10.1038/369613b0>.
- 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. *Sci. Total Environ.* 410–411, 154–160. <https://doi.org/10.1016/j.scitotenv.2011.09.006>.
- Cordy, P., Veiga, 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. <https://doi.org/10.1016/j.envres.2012.10.015>.
- Cortés-McPherson, D., 2019. Expansion of small-scale gold mining in Madre de Dios: 'capital interests' and the emergence of a new elite of entrepreneurs in the Peruvian Amazon. *Extract. Indust. Soc.* 6, 382–389. <https://doi.org/10.1016/j.exsis.2019.01.002>.
- de Lacerda, L.D., Salomons, W., 1998. *Mercury from Gold and Silver Mining: A Chemical Time Bomb?* Springer Berlin Heidelberg.
- Decreto Supremo N° 004-2019-MINAM (n.d.). <https://www.gob.pe/institucion/minam/normas-legales/273839-004-2019-minam>, Accessed date: 22 April 2019.
- Decreto Supremo N° 10-2019-MINAM, Accessed date: 12 December 2019.
- Drace, K., Kiefer, A.M., Veiga, M.M., Williams, M.K., Ascari, B., Knapper, K.A., Logan, K.M., Breslin, V.M., Skidmore, A., Bolt, D.A., Geist, G., Reidy, L., Cizdziel, J.V., 2012. Mercury-free, small-scale artisanal gold mining in Mozambique: utilization of magnets to isolate gold at clean tech mine. *J. Clean. Prod.* 32, 88–95. <https://doi.org/10.1016/j.jclepro.2012.03.022>.
- Drake, P.L., Rojas, M., Reh, C.M., Mueller, C.A., Jenkins, F.M., 2001. Occupational exposure to airborne mercury during gold mining operations near El Callao, Venezuela. *Int. Arch. Occup. Environ. Health* 74, 206–212.
- Driscoll, C.T., Mason, R.P., Chan, H.M., Jacob, D.J., Pirrone, N., 2013. Mercury as a global pollutant: sources, pathways, and effects. *Environ. Sci. Technol.* 47, 4967–4983. <https://doi.org/10.1021/es305071v>.
- Eisler, R., 2003. Health risks of gold miners: a synoptic review. *Environ. Geochem. Health* 25, 325–345.
- Esdaile, L.J., Chalker, J.M., 2018. The mercury problem in artisanal and small-scale gold mining. *Chem. Eur. J.* 24, 6905–6916. <https://doi.org/10.1002/chem.201704840>.
- Fernandes Azevedo, B., Barros Furieri, L., Peçanha, F.M., Wiggers, G.A., Frizera Vassallo, P., Ronacher Simões, M., Fiorini, J., Rossi de Batista, P., Fioretti, M., Rossoni, L., Stefanon, I., Alonso, M.J., Salaises, M., Valentim Vassallo, D., 2012. Toxic effects of mercury on the cardiovascular and central nervous systems. *Biomed Res. Int.* <https://doi.org/10.1155/2012/949048>.
- García, O., Veiga, M.M., Cordy, P., Stescún, O.E., Molina, J.M., Roeser, M., 2015. Artisanal gold mining in Antioquia, Colombia: a successful case of mercury reduction. *J. Clean. Prod.* 90, 244–252. <https://doi.org/10.1016/j.jclepro.2014.11.032>.
- Global Mercury Assessment 2013: Sources, Emissions, Releases and Environmental Transport. United Nations Pubns, Geneva. <http://www.unep.org/PDF/PressReleases/GlobalMercuryAssessment2013.pdf>, Accessed date: 25 June 2015.
- 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. *Bull. Environ. Contam. Toxicol.* 87, 250–253. <https://doi.org/10.1007/s00128-011-0345-5>.
- Hacon, S., Artaxo, P., Gerab, F., Yamasoe, M.A., Campos, R.C., Conti, L.F., Lacerda, L.D.D., 1995. Atmospheric mercury and trace elements in the region of Alta Floresta in the Amazon basin. *Water Air Soil Pollut.* 80, 273–283. <https://doi.org/10.1007/BF01189677>.
- Hacon, S., Rochedo, E.R., Campos, R., Rosales, G., Lacerda, L.D., 1997. Risk assessment of mercury in Alta Floresta. Amazon basin - Brazil. *Water, Air, Soil Pollut.* 97, 91–105. <https://doi.org/10.1023/A:1018367313384>.
- Hacon, S., Yokoo, E., Valente, J., Campos, R.C., da Silva, V.A., de Menezes, A.C.C., de Moraes, L.P., Ignotti, E., 2000. Exposure to mercury in pregnant women from Alta floresta—amazon basin, Brazil. *Environ. Res.* 84, 204–210. <https://doi.org/10.1006/enrs.2000.4115>.
- Hilson, G., 2006. Abatement of mercury pollution in the small-scale gold mining industry: restructuring the policy and research agendas. *Sci. Total Environ.* 362, 1–14. <https://doi.org/10.1016/j.scitotenv.2005.09.065>.
- Hilson, G., Vieira, R., 2007. Challenges with minimising mercury pollution in the small-scale gold mining sector: experiences from the Guianas. *Int. J. Environ. Health Res.* 17, 429–441. <https://doi.org/10.1080/09603120701633396>.
- Jönsson, J.B., Charles, E., Kalvig, P., 2013. Toxic mercury versus appropriate technology: artisanal gold miners' retort aversion. *Resour. Policy* 38, 60–67. <https://doi.org/10.1016/j.resourpol.2012.09.001>.
- Kiefer, A.M., Drace, K., Gottlieb, S., Coursey, S., Veiga, M.M., da Cruz Marrumbe, P.N., Arlete, M., Chapo, Jose, 2014. Evaluation of mercury content in amalgams from

- Munhena mine, Mozambique. *J. Clean. Prod.* 84, 783–785. <https://doi.org/10.1016/j.jclepro.2013.09.039>.
- Kiefer, Adam M., Drace, Kevin, Seney, Caryn S., Veiga, Marcello 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. American Chemical Society, pp. 51–77. <https://doi.org/10.1021/bk-2015-1210.ch003>, Accessed date: 25 February 2016.
- Lacerda, L.D., Malm, O., Guimarães, J.R.D., Salomons, W., Wilken, R.D., 1995. Mercury and the new gold rush in the south. In: Salomons, P.D.W., Stigliani, P.D.W.M. (Eds.), Biogeodynamics of Pollutants in Soils and Sediments. Springer Berlin Heidelberg, pp. 213–245. http://link.springer.com/chapter/10.1007/978-3-642-79418-6_10, Accessed date: 4 August 2015.
- Lacerda, L.D., de Souza, M., Ribeiro, M.G., 2004. The effects of land use change on mercury distribution in soils of Alta Floresta, Southern Amazon. *Environ. Pollut.* 129, 247–255. <https://doi.org/10.1016/j.envpol.2003.10.013>.
- Lauthartte, L., Ferreira, D., Mussy, M.H., de Holanda, Í.B.B., Almeida, R., Bastos, W., 2018. Potencial Exposição ao mercúrio atmosférico no ambiente ocupacional de comércios de ouro de Porto Velho. *Rondônia, Química Nova.* 41, 1055. <https://doi.org/10.21577/0100-4042.20170253>.
- Levin, M., Jacobs, J., Polos, P.G., 1988. Acute mercury poisoning and mercurial pneumonitis from gold ore purification. *Chest* 94, 554–556. <https://doi.org/10.1378/chest.94.3.554>.
- Lilis, R., Miller, A., Lerman, Y., 1985. Acute mercury poisoning with severe chronic pulmonary manifestations. *Chest* 88, 306–309.
- Lin, Y., Guo, M., Gan, W., 1997. Mercury pollution from small gold mines in China. *Water, Air, Soil Pollut.* 97, 233–239. <https://doi.org/10.1023/A:1018384822608>.
- Malm, O., 1998. Gold mining as a source of mercury exposure in the Brazilian Amazon. *Environ. Res.* 77, 73–78. <https://doi.org/10.1006/enrs.1998.3828>.
- Malm, O., Castro, M.B., Bastos, W.R., Branches, F.J.P., Guimarães, J.R.D., Zuffo, C.E., Pfeiffer, W.C., 1995. An assessment of Hg pollution in different goldmining areas, Amazon Brazil. *Sci. Total Environ.* 175, 127–140. [https://doi.org/10.1016/0048-9697\(95\)04909-6](https://doi.org/10.1016/0048-9697(95)04909-6).
- Malm, O., Guimarães, J.R.D., Castro, M.B., Bastos, W.R., Viana, J.P., Branches, F.J.P., Silveira, E.G., Pfeiffer, W.C., 1997. Follow-up of mercury levels in fish, human hair and urine in the Madeira and Tapajós basins, Amazon, Brazil. *Water, Air, Soil Pollut.* 97, 45–51. <https://doi.org/10.1023/A:1018340619475>.
- Malm, O., de Freitas Fonseca, M., Hissnauer Miguel, P., Rodrigues Bastos, W., Neves Pinto, F., 1998. Use of epiphyte plants as biomonitoring to map atmospheric mercury in a gold trade center city, Amazon, Brazil. *Sci. Total Environ.* 213, 57–64. [https://doi.org/10.1016/S0048-9697\(98\)00074-6](https://doi.org/10.1016/S0048-9697(98)00074-6).
- Martinez, G., McCord, S.A., Driscoll, C.T., Todorova, S., Wu, S., Araújo, J.F., Vega, C.M., Fernandez, L.E., 2018. Mercury contamination in riverine sediments and fish associated with artisanal and small-scale gold mining in Madre de Dios, Peru. *Int. J. Environ. Res. Public Health* 15, 1584. <https://doi.org/10.3390/ijerph15081584>.
- McLagan, D.S., Mazur, M.E.E., Mitchell, C.P.J., Wania, F., 2016. Passive air sampling of gaseous elemental mercury: a critical review. *Atmos. Chem. Phys.* 16, 3061–3076. <https://doi.org/10.5194/acp-16-3061-2016>.
- McLagan, D.S., Mitchell, C.P.J., Steffen, A., Hung, H., Shin, C., Stupple, G.W., Olson, M.L., Luke, W.T., Kelley, P., Howard, D., Edwards, G.C., Nelson, P.F., Xiao, H., Sheu, G.-R., Dreyer, A., Huang, H., Abdul Hussain, B., Lei, Y.D., Tavshunsky, I., Wania, F., 2018. Global evaluation and calibration of a passive air sampler for gaseous mercury. *Atmos. Chem. Phys.* 18, 5905–5919. <https://doi.org/10.5194/acp-18-5905-2018>.
- McLagan, D.S., Monaci, F., Huang, H., Lei, Y.D., Mitchell, C.P.J., Wania, F., 2019. Characterization and quantification of atmospheric mercury sources using passive air samplers. *J. Geophys. Res.: Atmos.* 124, 2351–2362. <https://doi.org/10.1029/2018JD029373>.
- Mercury Convention texts and annexes (n.d.). <http://www.mercuryconvention.org/Convention/Text/tabid/3426/language/en-US/Default.aspx>, Accessed date: 22 April 2019.
- Milne, J., Christophers, A., Silva, P.D., 1970. Acute mercurial pneumonitis. *Br. J. Ind. Med.* 27, 334–338.
- MONITOREO DE CALIDAD AMBIENTAL, 2016. Calidad del aire. Método normalizado para la determinación del mercurio gaseoso total.
- Obrist, D., Kirk, J.L., Zhang, L., Sunderland, E.M., Jiskra, M., Selin, N.E., 2018. A review of global environmental mercury processes in response to human and natural perturbations: changes of emissions, climate, and land use. *Ambio* 47, 116–140. <https://doi.org/10.1007/s13280-017-1004-9>.
- Ohio Lumex Co, Inc, 2011. RA-915M Mercury Analyzer Operation Manual B0100-00-00-00 OM. Twinsburg, Ohio.
- OSHA Annotated PELs (n.d.). <https://www.osha.gov/dsg/annotated-pels/tablez-2.html>, Accessed date: 26 June 2015.
- Pfeiffer, W.C., Malm, O., Souza, C.M.M., Drude de Lacerda, L., Silveira, E.G., Bastos, W.R., 1991. Mercury in the madeira river ecosystem, rondonia, Brazil, forest. *Ecol. Manag.* 38, 239–245. [https://doi.org/10.1016/0378-1127\(91\)90145-L](https://doi.org/10.1016/0378-1127(91)90145-L).
- 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, Elemental Mercury and Inorganic Mercury Compounds: Human Health Aspects. World Health Organization, Geneva.
- Rozane, J.B. de A., Marins, V., 2000. Sampling techniques for the assessment of anthropogenic vapour and particulate mercury in the Brazilian Amazon atmosphere. *J. Environ. Monit.* 2, 325–328. <https://doi.org/10.1039/b000608o>.
- Santa Rosa, R.M.S., Müller, R.C.S., Alves, C.N., Sarkis, J.E. de S., Bentes, M.H. da S., Brabo, E., de Oliveira, E.S., 2000. Determination of total mercury in workers' urine in gold shops of Itaituba, Pará State, Brazil. *Sci. Total Environ.* 261, 169–176. [https://doi.org/10.1016/S0048-9697\(00\)00641-0](https://doi.org/10.1016/S0048-9697(00)00641-0).
- Scheepers, P.T.J., van Ballegooij-Gevers, M., Jans, H., 2014. Biological monitoring involving children exposed to mercury from a barometer in a private residence. *Toxicol. Lett.* 231, 365–373. <https://doi.org/10.1016/j.toxlet.2014.03.017>.
- Sousa, R.N., Veiga, M.M., 2009. Using performance indicators to evaluate an environmental education program in artisanal gold mining communities in the Brazilian Amazon. *Ambio* 38, 40–46.
- Sousa, R., Veiga, M., Van Zyl, D., Telmer, K., Spiegel, S., Selder, J., 2011. Policies and regulations for Brazil's artisanal gold mining sector: analysis and recommendations. *J. Clean. Prod.* 19, 742–750. <https://doi.org/10.1016/j.jclepro.2010.12.001>.
- Stocklin-Weinberg, R., Veiga, M.M., Marshall, B.G., 2019. Training artisanal miners: a proposed framework with performance evaluation indicators. *Sci. Total Environ.* 660, 1533–1541. <https://doi.org/10.1016/j.scitotenv.2019.01.113>.
- Swenson, J.J., Carter, C.E., Domic, J.-C., Delgado, C.I., 2011. Gold mining in the Peruvian Amazon: global prices, deforestation, and mercury imports. *PLoS One* 6, e18875. <https://doi.org/10.1371/journal.pone.0018875>.
- Training Materials, Artisanal Gold Council (n.d.). <http://www.artisanalgold.org/publications/products/>, Accessed date: 25 August 2019.
- U.N., 2019. Environment, Global Mercury Assessment 2018. UNEP - UN Environment Programme. <http://www.unenvironment.org/resources/publication/global-mercury-assessment-2018>, Accessed date: 29 October 2019.
- U.N.E, 2013. Programme, Minamata convention on mercury: text and annexes. <https://wedocs.unep.org/handle/20.500.11822/8541>, Accessed date: 12 April 2019.
- US EPA, 2014. Mercury Vapor Results - AEGL Program. US EPA. <https://www.epa.gov/aegl/mercury-vapor-results-aegl-program>, Accessed date: 7 April 2019.
- Veiga, M.M., Hinton, J.J., 2002. Abandoned artisanal gold mines in the Brazilian Amazon: a legacy of mercury pollution. *Nat. Resour. Forum* 26, 15–26. <https://doi.org/10.1111/1477-8947.00003>.
- Veiga, M.M., Marshall, B.G., 2017. Teaching artisanal miners about mercury pollution using songs. *Extract. Indust. Soc.* 4, 842–845. <https://doi.org/10.1016/j.ejis.2017.10.006>.
- Veiga, M.M., Nunes, D., Klein, B., Shandro, J.A., Velasquez, P.C., Sousa, R.N., 2009. Mill leaching: a viable substitute for mercury amalgamation in the artisanal gold mining sector? *J. Clean. Prod.* 17, 1373–1381. <https://doi.org/10.1016/j.jclepro.2009.03.012>.
- Veiga, M.M., Angeloci-Santos, G., Meech, J.A., 2014. Review of barriers to reduce mercury use in artisanal gold mining. *Extract. Indust. Soc.* 1, 351–361. <https://doi.org/10.1016/j.ejis.2014.03.004>.
- Veiga, M.M., Masson, P., Perron, D., Laflamme, A.-C., Gagnon, R., Jimenez, G., Marshall, B.G., 2018. An affordable solution for micro-miners in Colombia to process gold ores without mercury. *J. Clean. Prod.* 205, 995–1005. <https://doi.org/10.1016/j.jclepro.2018.09.039>.
- Velásquez-López, P.C., Veiga, M.M., Hall, K., 2010. Mercury balance in amalgamation in artisanal and small-scale gold mining: identifying strategies for reducing environmental pollution in Portovelo-Zaruma, Ecuador. *J. Clean. Prod.* 18, 226–232. <https://doi.org/10.1016/j.jclepro.2009.10.010>.
- Vieira, R., 2006. Mercury-free gold mining technologies: possibilities for adoption in the Guianas. *J. Clean. Prod.* 14, 448–454. <https://doi.org/10.1016/j.jclepro.2004.09.007>.
- Wip, D., Warneke, T., Petersen, A.K., Notholt, J., Temme, C., Kock, H., Cordy, P., 2011. Urban mercury pollution in the city of paramaribo, Suriname. *Air Qual. Atmos. Health* 6, 205–213. <https://doi.org/10.1007/s11869-011-0162-3>.
- Yard, E.E., Horton, J., Schier, J.G., Caldwell, K., Sanchez, C., Lewis, L., Gastañaga, C., 2012. Mercury exposure among artisanal gold miners in Madre de Dios, Peru: a cross-sectional study. *J. Med. Toxicol.* 8, 441–448. <https://doi.org/10.1007/s13181-012-0252-0>.
- Zolnikov, T.R., Ramirez Ortiz, D., 2018. A systematic review on the management and treatment of mercury in artisanal gold mining. *Sci. Total Environ.* 633, 816–824. <https://doi.org/10.1016/j.scitotenv.2018.03.241>.