A Collaborative Training Program to Assess Mercury Pollution from Gold Shops in Guyana’s Artisanal and Small-Scale Gold Mining Sector

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Received: 6 June 2020; Accepted: 30 June 2020; Published: 6 July 2020

Abstract: A three-phase, 11-day training program designed to monitor elemental mercury (Hg⁰) emissions originating from gold shops was conducted in Georgetown and Bartica, Guyana, during May of 2019. The first phase consisted of interactive lectures and discussions on mercury use in artisanal and small-scale gold mining throughout Guyana, the region, and the world. In addition, specific training in the theory and use of analytical instrumentation to quantify Hg⁰ pollution associated with the processing of amalgams and sponge gold occurred. Trainees participated in the mapping of smelting facilities in Georgetown where, outside of one gold shop, Hg⁰ concentrations exceeded 100,000 ng/m³. During the second phase of training, a subset of trainees traveled to Bartica, where they mapped the town center to identify point sources of Hg⁰ pollution, all of which corresponded to the location of shops where amalgams and sponge gold were heated and purchased. Once mapped, Hg⁰ concentrations were measured during the smelting of gold inside the Guyana Gold Board (GGB) facility and two privately-owned gold shops. Maximum Hg⁰ concentrations at the GGB facility did not exceed 98,700 ng/m³ during the measurement period, while maximum concentrations at the two privately owned shops were measured as 527,500 ng/m³ and 302,200 ng/m³. With guidance from the training team, trainees were responsible for the collection and interpretation of all data. The third phase of the training involved the collaborative production of a report summarizing the findings from the training. This work represents the first formal training opportunity for the assessment of Hg⁰ concentrations in and around gold shops in Guyana, and provides baseline data to assist the government of Guyana to generate air quality standards for Hg⁰ emissions.

Keywords: mercury; artisanal and small-scale gold mining; amalgam; Minamata Convention on Mercury; gold shop

1. Introduction

1.1. The Mercury Problem in Artisanal and Small-Scale Gold Mining

In 2014, it was estimated that 16 million artisanal and small-scale gold miners annually produced 380–450 tonnes (t) of gold, representing ≈17–20% of global gold production [1]. Although the estimated
number of miners may change on the basis of global gold prices and other factors, it is undeniable that artisanal and small-scale gold mining (ASGM) plays an important role not only in global gold production, but also as a meaningful source of employment throughout the developing world [1–10]. In spite of its socioeconomic importance, ASGM can severely impact both environmental and human health through deforestation [11,12], habitat loss [13,14], social issues [15,16], and work-related injuries [17,18]. ASGM is also closely associated with mercury pollution derived from ore processing [19–27] and is now the leading source of anthropogenic mercury emissions on the planet [28,29].

Although ASGM practices are diverse and dependent upon the ore being processed, the technologies available, and the region in which mining is occurring, the majority of ASGM is conducted using elemental mercury (Hg\(^0\)) at some stage of the process. Amalgamation with Hg\(^0\) concentrates gold, separating it from unwanted minerals. Subsequent heating of the amalgam evaporates the Hg\(^0\), revealing the sponge gold that can then be sold. During these processes, Hg\(^0\) is lost to both the tailings and the atmosphere. Mercury is used because it is inexpensive, readily available, requires no special training, acts quickly, and can be used independently. Miners often believe that the money they earn from mining outweighs the health risks associated with the Hg\(^0\) vapor—an acute and chronic toxin [30–33]. This issue is inadvertently supported by the fact that Hg\(^0\) vapor is not detectable by the human senses, and physiological changes associated with chronic mercury poisoning develop slowly, leading many miners to believe that the health effects of mercury are not severe. Further, the behavior of Hg\(^0\) in the environment compounds the threat to human health. Hg\(^0\) is both a mobile and persistent pollutant; once Hg\(^0\) enters the global mercury cycle, it can be converted into inorganic mercury (Hg\(^{2+}\)) and ultimately methyl mercury (CH\(_3\)Hg\(^+\)), which is readily bioaccumulated and biomagnified [34,35].

1.2. ASGM in Guyana

ASGM in Guyana has a long history, largely beginning with a gold rush in the mid 19th century that led to people leaving agricultural work on the coast for mining activities in the interior [36]. Guyanese miners, locally known as pork-knockers for their habit of carrying large barrels of dried pork into the interior for sustenance, were initially forced to follow bodies of water and only mine near-surface gold due to the inaccessibility of the jungle. As the transport of mechanized equipment inland has become more manageable, miners adopted new technologies that allowed them to access new deposits while improving throughput of material. While river dredging and hard-rock mining both occur in Guyana, the majority of ore is extracted using land dredges.

Ore extraction and processing is relatively uniform across Guyana and employs hydraulic mining. The mining claim is cleared, and the overburden is removed using heavy equipment. A mining team then uses water monitors to wash gold-containing soil, clay, sediment, etc. to the bottom of the pit, where the resulting slurry is subsequently pumped out of the pit to be concentrated on a sluice box. The vast majority of mining operations concentrate gold on carpet material that lines the sluice box. After an appropriate amount of material has been collected, the miners “wash down” and amalgamate the concentrate. The Hg\(^0\)-contaminated tailings are discarded, and the amalgam is heated on site, revealing the sponge gold. Miners bring the sponge gold to a business that purchases gold, where it is reheated in an attempt to drive off residual Hg\(^0\) prior to sale.

All gold extracted in Guyana is required to be sold to the state, and as such miners bring their sponge gold to either one of the Guyana Gold Board (GGB) locations in Georgetown or Bartica, or to one of the eight private gold dealers licensed by the GGB. A gold dealer is licensed to buy on behalf of the GGB and export. Miners may also bring their sponge gold to one of several gold traders licensed by the GGMC that can purchase gold and resell it within Guyana [37,38]. Although Guyanese miners can easily smelt and sell gold to licensed dealers and traders, some miners choose to sell to unlicensed gold buyers. These private shops may offer a higher price for gold than the GGB, or may provide miners with other incentives such as supplies or the ability to work the shopkeepers claim [39]. Although all gold buyers are required by law to sell the gold to the GGB, there is an ongoing issue with unlicensed
gold buyers illegally smuggling gold out of Guyana. In 2016, the Minister of Natural Resources estimated that ≈15,000 ounces (Ozs) of gold were smuggled out of the country each week [40–42].

In this report, the term “gold shop” will refer to any private business that purchases gold, legally or illegally. Gold shops are not unique to Guyana and are found in many Central and South American countries with ASGM. These shops are often located in residential and populated business areas, and are known point sources for Hg\(^0\) pollution [43–47]. Unlike GGB facilities that have adequate ventilation systems to remove adventitious Hg\(^0\) during the smelting process, the vast majority of gold shops do not. These shops not only reheat or smelt sponge gold, but miners sometimes burn entire amalgams, releasing large quantities of Hg\(^0\) vapor into the shop and immediate surroundings. During burning, Hg\(^0\) concentrations in the air often exceed levels that represent an immediate threat to human health [48,49].

1.3. ASGM and the Minamata Convention on Mercury

The Minamata Convention on Mercury is an international treaty designed specifically to decrease the use of Hg\(^0\) and Hg-containing compounds, thus reducing anthropogenic emissions of the toxic metal [29,50,51]. Due to the sheer magnitude of emissions related to ASGM, Article 7 and the corresponding Annex C of the convention requires nations to reduce and, where feasible, eliminate both the use of Hg\(^0\) and Hg\(^0\) emissions that result from mining and processing activities. The treaty requires each signatory nation with ASGM to produce a detailed national action plan (NAP) highlighting efforts to curtail Hg\(^0\) use. Countries are specifically tasked with setting their own goals and reduction targets, while developing a baseline estimate of the amount of Hg\(^0\) used in ASGM activities. The NAP identifies actions to eliminate worst practices such as whole-ore amalgamation, cyanidation of Hg-contaminated tailings, and burning of amalgams in residential areas. In addition, nations are required to outline steps to formalize mining, and develop a public health strategy to address Hg\(^0\) exposure in communities, particularly targeting vulnerable populations. While continued monitoring of Hg\(^0\) emissions from ASGM activities is not specifically required after the filing of the NAP, reports on progress towards the nation’s goals are required every three years.

Hg\(^0\) use is only one component of a complex and varied mining culture, and efforts to limit Hg pollution are occasionally equated with attempts to eliminate ASGM, and thus the livelihood of miners. Successful implementation of the Minamata Convention will require experts from the social and natural sciences, education, engineering, health professions, and private business to work together to find solutions to complex issues arising at the interface of the environment and society [4,50,52–58]. A recent systematic review highlighted the importance of both education and collaboration in addressing Hg-related issues in ASGM communities [58]. The convention recognizes this as well, and there are numerous mechanisms for collaboration between signatory nations and other parties.

1.4. Training Program for Monitoring of Hg\(^0\) in Air in ASGM Communities

A recent collaboration between the Guyana Geology and Mines Commission (GGMC) and Mercer University identified the need to further develop governmental competencies in both the collection and interpretation of scientific data in the field. The data collected and interpreted by the GGMC could be used both in the development of Guyana’s NAP and subsequent assessment of progress towards meeting national goals. The collaboration relies on the experience of the GGMC in addressing the technical aspects and environmental ramifications of Guyanese mining, and Mercer’s experience in conducting environmental analyses of Hg\(^0\) emissions to air in ASGM communities. The GGMC, particularly the Mineral Processing Unit and the Environmental Division, have extensive experience in field work, mining camp safety assessment, and data collection. While the GGMC has instrumentation that allows them to monitor Hg\(^0\) emissions in the field, they recognize that newer methods and instrumentation are available that would aid in both environmental assessment and limiting exposure of GGMC workers to Hg\(^0\) contamination while conducting this assessment.
Monitoring Hg\(^0\) at mining sites in Guyana is complicated; the vast amount of mining consists of concentrate amalgamation, with the amalgam being burned at the mining site only once per week. Oftentimes, the burning of the amalgam is conducted in private to avoid theft and potential violence as a result of disclosing the location of productive, remote mining sites. Measuring Hg\(^0\) vapor in these environments is also complicated by the fact that many of these sites are deforested and open, leading to the rapid dispersal of Hg\(^0\) in the atmosphere. However, the reheating of sponge gold and the smelting of gold at gold shops in populated, urban environments generates high concentrations of Hg\(^0\) that can be measured with more accuracy [43,46]. As the open burning of amalgams and sponge gold, particularly burning activities in residential areas, are considered “actions to eliminate” under the Minamata Convention, it was decided that initial training would be conducted in ASGM communities with a number of gold shops. The monitoring of these shops is under the purview of the GGMC, and as such, it was decided that training using multiple portable atomic spectrometers for the detection of Hg\(^0\) in the atmosphere would benefit the GGMC. Additional hand-held X-ray fluorescence analyzer training to determine heavy metal concentrations in soils and tailings would also occur. Herein, we present an overview of the training that took place, as well as the findings of the environmental assessment resulting from the training.

2. Materials and Methods

Soils and tailings were screened using an Olympus Vanta C Handheld X-ray fluorescence analyzer (XRF) with a field stand kit. Samples were analyzed using the manufacturer’s GeoChem(2) method. The GeoChem(2) method utilizes a fundamental parameters calculation method [59–63]. Mercury concentrations in air were determined using four commercially available atomic absorption spectrometers: one Mercury Instruments Mercury Tracker 3000 IP (MTIP), one Mercury Instruments VM-3000 (VM-3000), and two Lumex RA-915 M (Lumex) spectrometers. The MTIP and VM-3000, calibrated by the manufacturer, measure ranges of 0–2,000,000 ng/m\(^3\), have sensitivities of 0.1 µg/m\(^3\), and have response times of 1 s. The Lumex employs Zeeman correction and has a significantly lower detection limit (0.5 ng/m\(^3\)). Both Lumex spectrometers were calibrated by the manufacturer prior to use. Areas with concentrations exceeding 50,000 ng/m\(^3\) were actively avoided due to the instrument’s calibration limits [64]. Concentrations occasionally exceeded 50,000 ng/m\(^3\) due to shifting winds or unexpected activity within gold shops.

Concentrations of Hg\(^0\) within gold shops and ventilated exhaust from gold shops on the streets and sidewalks were determined exclusively with the MTIP. When concentrations exceeded 1,500,000 ng/m\(^3\), the MTIP was removed to an area of low concentrations of Hg\(^0\) (<50 ng/m\(^3\)) and operated until measured concentrations decreased to less than 1000 ng/m\(^3\).

All maps were generated from data collected by the Lumex less than 42,307 ng/m\(^3\) to ensure that measurements remained on the calibration curves of both instruments. The mapping protocol has been previously described in the literature [65]. The Lumex was operated using the manufacturer’s RAPID software and synced with a Garmin Oregon GPS unit. Both the Lumex and the GPS unit collected a sample every second. Upon the completion of data collection, all data were imported into Microsoft Excel, and the position was linked to concentration via time. Occasionally, a data point was generated with only position or concentration; these data were eliminated. Maximum Hg\(^0\) values assigned to each unique set of coordinates were mapped.

Concentrations of Hg\(^0\) in and around gold shops routinely exceeded the detection limit of the Lumex instrument. At high concentrations of Hg\(^0\), the Lumex detector can become saturated, leading to the measurement of concentrations as less than 0 ng/m\(^3\) until the re-establishment of a normalized baseline occurs. To avoid this, the MTIP was paired with the Lumex mapping teams to avoid areas where concentrations exceeded the detection limit. Any negative concentrations measured during monitoring were not mapped.

During training, heat maps were initially produced using Google Fusion Tables to rapidly plot the data; however, the heat map functionality of Google Fusion Tables was retired in December 2019.
To that end, training and maps in this manuscript were generated using QGIS ("QGIS Development Team (2020). QGIS Geographic Information System. Open Source Geospatial Foundation Project. http://qgis.osgeo.org").

3. Results and Discussion

3.1. Overview of Training

Training was conducted 15–30 May 2019 in Georgetown and Bartica, Guyana. The training was divided into three phases, informally referred to as “discuss, do, and disseminate” (Figure 1). At the request of the GGMC, the initial “discuss” phase took place in Georgetown and included 47 participants from government, academia, non-governmental organizations (NGOs), and miners’ organizations. The goal was to provide an overview of the project in addition to a foundation for subsequent training on instrumentation and data interpretation. Training in the field during this phase was intended for participants to learn how each instrument operated and could be used to generate maps depicting Hg \(^0\) vapor concentrations associated with gold shops in Georgetown.

The second “do” phase served as an eight-day training session in Bartica, where 22 select trainees from phase one were further trained to collect data using the Lumex and MTIP, map the data, and interpret the maps. Additional monitoring of emissions from gold shops was also conducted.

Finally, the third and final “disseminate” phase consisted of work done after completion of the formal training. Representatives from the GGMC were enlisted to formalize the findings of the training in a final report. The report was generated and reviewed by both collaborating institutions, with the goal of incorporating the peer-reviewed literature to support the justification of the project, the results of the training, and conclusions drawn from the results.

Figure 1. Overview of content and training activities.
3.2. Phase I: Training in Georgetown

The “discuss” component of training was conducted 15–17 May in Georgetown, Guyana. Participants were selected by the GGMC and included representatives from the Environmental Division and Mineral Processing Unit of the GGMC, the Guyana Environmental Protection Agency (EPA), the Ministry of Natural Resources, the Ministry of Public Health, the University of Guyana, and the Guyana Gold Board. Additional representatives from the National Mining Syndicate, the Guyana Gold and Diamond Miners Association, and the Guyana Women Miners’ Organization were present, as were representatives from Conservation International Guyana and other NGOs.

The first day was dedicated to a non-scientific project “kickoff”. Representatives from Mercer University, the Ministry of National Resources, and the GGMC provided a project overview to the participants, as well as the role of each organization in the project. The remainder of the first day was dedicated to an introductory lecture discussing global ASGM practices, Guyanese ASGM practices, Hg\textsubscript{0} use in ASGM, and an overview of the Minamata Convention on Mercury. A second lecture was then given, discussing the environmental fate of Hg\textsubscript{0} from ASGM including the global mercury cycle and the health effects of Hg\textsubscript{0}. After the second lecture, a group discussion was moderated that engaged participants to offer their own observations on Hg\textsubscript{0} use in Guyana, particularly as to how it related to the mining process. During this conversation, chemical hygiene and safe storage of Hg\textsubscript{0} was discussed.

It was unequivocally stated by both governmental representatives and miners alike that Hg\textsubscript{0} needed to be replaced in the ASGM process; however, currently there is no suitable replacement for Hg\textsubscript{0} in Guyana. This is not unique to Guyana. Hg\textsubscript{0} is inexpensive, readily available, requires no formal training for use, and can be used by an individual miner. Although mercury-free technologies and techniques have been developed for use in ASGM, none have been widely adopted [10,66–68].

The second day of training was more technical in nature, with detailed discussions related to the chemistry of artisanal and small-scale mining, mineral processing engineering, and analytical techniques for monitoring Hg\textsubscript{0} in the environment (Table 1). Because of the varied backgrounds of participants, care was taken to address each topic from an accessible perspective; while technical data was disseminated, it was placed in appropriate context for the audience, knowing that the second phase in Bartica would allow for additional technical training. Content was delivered through PowerPoint lectures, round-table discussions, and hands-on introduction to the instrumentation.

| Topic                                                                 | Content Delivery                        |
|----------------------------------------------------------------------|-----------------------------------------|
| Introduction to the chemical properties of Hg\textsubscript{0}       | Lecture                                 |
| Mercury in the environment: Myths vs. Realities                      | Lecture, discussion                      |
| Mercury Pollution from ASGM: processing ore vs. processing amalgams  | Lecture, discussion                      |
| Monitoring Hg\textsubscript{0} pollution in the environment          | Lecture, discussion                      |
| Human health effects of Hg\textsubscript{0}: safety in the field     | Lecture, discussion                      |
| Techniques for soil analysis: XRF screening of metals in the field,  | Lecture, discussion, hands-on training   |
| laboratory analysis                                                 |                                         |
| Techniques for monitoring Hg in the air: Hg\textsubscript{0} vs. total gaseous mercury (TGM) | Lecture, discussion, hands-on training |
| Case study on Peruvian ASGM mercury emissions: science vs. policy    | Lecture, discussion                      |
| Introduction to operating principles of XRF and portable spectrometers| Lecture                                |
| Closing discussion: Hg\textsubscript{0} use in Guyana                | Discussion                              |

On day two, discussions were moderated on Hg\textsubscript{0} use from miners’ perspectives. These included how the burning of amalgams in the field and in gold shops directly affect human and environmental health. The lectures and discussions were placed into the context of the Minamata Convention on Mercury, particularly the potential effects of the treaty on mercury use in Guyana in the future. A case study of a recent joint project between Mercer University and the Peruvian Ministerio del Ambiente
(MINAM, Ministry of the Environment) was presented and discussed, including the results of mapping activities conducted in ASGM communities in the Peruvian Amazon. Hg\textsuperscript{0} pollution originating from Peruvian gold shops was placed in the context of existing Peruvian air quality standards, which limit air concentrations to 2000 ng/m\textsuperscript{3} of total gaseous mercury (TGM) over a 24 h period [69,70]. During the collaborative assessment of the Peruvian ASGM communities, Hg\textsuperscript{0} concentrations exceeding 2,000,000 ng/m\textsuperscript{3} were measured on the street outside these gold shops. As Hg\textsuperscript{0} is a component of TGM, the measured values clearly exceeded the legal limit for Hg\textsuperscript{0} emissions to air by many orders of magnitude. However, because the technical norms at the time required that TGM be measured, the Hg\textsuperscript{0} concentrations collected during the study period were inadequate to demonstrate that the air quality standards were exceeded. The work conducted by Mercer and MINAM led to the modification of Peruvian code to allow for the use of a conversion factor converting data collected by cold vapor atomic absorption spectroscopy (CV-AAS) with Zeeman correction into an estimate of TGM concentrations. Following the presentation of the case study, the current lack of a Guyanese Hg\textsuperscript{0} emission standard was discussed with respect to the Peruvian case study.

To accommodate the large crowd, all four portable atomic absorption spectrometers and the handheld XRF were displayed. Trainees were split into multiple groups and allowed to handle each unit, examine how the unit was operated, and previewed the software, prior to rotating to the next instrument. For the VM-3000 and the MTIP, an amalgam (parad shivling, [71]) in a glass container was placed in front of each unit and opened so that trainees could see the concomitant increase of Hg\textsuperscript{0} as measured by the instruments. Upon completing the demonstration, short clips of a YouTube video made at Mercer University allowing for the indirect visualization of Hg\textsuperscript{0} vapor using a UV lamp and a thin-layer chromatography plate imbued with a fluorescent dye were shown to the participants [71,72]. On the basis of feedback and recommendations from the audience, especially representatives from the miners’ organizations, we are currently modifying the video to directly engage the ASGM community.

Field Training in Georgetown

The final day of training was dedicated to using the MTIP and Lumex spectrometers to rapidly assess Hg\textsuperscript{0} concentrations from gold shops in Georgetown. The trainees were split into two groups, one in the morning and one in the afternoon; both groups followed the same path through the city. As there has yet to be a comprehensive survey of gold shops in the city, this activity was largely based upon the knowledge of gold shops by GGMC employees. The Lumex spectrometers and MTIP were carried while walking through the city, and trainers demonstrated appropriate procedures and methods for data collection. Instruments were then handed to volunteer trainees, and they were assisted in collecting data by the trainers. During monitoring, two sites with elevated Hg\textsuperscript{0} concentrations were located, both associated with gold shops (Figure 2). Concentrations of Hg\textsuperscript{0} outside of both shops exceeded 10,000 ng/m\textsuperscript{3}, with one shop exceeding 100,000 ng/m\textsuperscript{3} as measured by the MTIP.

The data were quickly processed and mapped using Google Heat Maps so that participants could see the sources of Hg\textsuperscript{0} contamination. The quantitative heat map generated through QGIS can be found in Figure 2. While participants had already been instructed on how both chronic and acute exposure to Hg\textsuperscript{0} can lead to a variety of long term or instantaneous health issues, a discussion after mapping allowed trainees to revisit the relationship between Hg\textsuperscript{0} concentrations and health effects (Table 2).
Figure 2. Map generated of elemental mercury (Hg⁰) concentrations during phase one of training in Georgetown, Guyana.

| [Hg³⁺] (ng/m³) | Agency | Description/Potential Health Effects | Reference |
|----------------|--------|--------------------------------------|-----------|
| 200            | ATSDR ᵃ | Minimum risk level (MRL)              | [73]      |
| 1000           | ATSDR ᵃ | Recommended action level, residential setting | [74]      |
| 2000           | Government of Peru | Air quality standards, Total gaseous mercury (TGM), not to exceed value over 24 h. | [69,75] |
| 10,000         | ATSDR ᵃ | Isolation of residential setting (evacuation, restricted access, etc.) | [74]      |
| 20,000         | WHO ᵇ | Chronic exposure greater than or equal to this value can result in damage to the central nervous system | [30]      |
| 25,000         | ACGIH ᶜ | Threshold limit value (TLV)           | [76]      |
| 50,000         | NIOSH ᵈ | Recommended exposure limit (REL), 10 h time-weighted average | [76]      |
| 100,000        | NIOSH ᵈ/OSHA ʷ | Acceptable ceiling concentration | [78]      |
| 670,000        | USEPA ᶠ | Acute exposure guideline limit (AEGL) 2; 1 h, irreversible, serious, and/or long-lasting health effects may occur | [77]      |
| 2,200,000      | USEPA ᶠ | Acute exposure guideline limit (AEGL) 3; 4 h, life-threatening effects or death | [77]      |
| 3,100,000      | USEPA ᶠ | Acute exposure guideline limit (AEGL) 2; 10 min, irreversible, serious, and/or long-lasting health effects may occur | [77]      |
| 10,000,000     | NIOSH ᵈ | Immediately dangerous to life or health (IDLH) | [78]      |

ᵃ Agency for Toxic Substances and Disease Registry; ᵇ World Health Organization; ᶜ American Conference of Governmental Industrial Hygienists; ᵈ National Institute for Occupational Safety and Health; ʷ Occupational Safety and Health Administration; ᶠ United States Environmental Protection Agency.
Oftentimes, gold shops serve as a residence for the owner and his/her family, and as such environmental, residential, and industrial standards were highlighted. Reviewing these benchmark concentrations was particularly important when considering the fact that Guyana currently has no Hg emissions standards (Hg<sub>0</sub> or TGM); therefore, the data collected by the participants were put into context using international standards.

Due to a lack of ventilation, concentrations in gold shops during burning often exceed these values, and exposure to Hg<sub>0</sub> vapor during burning can contribute to severe lung damage or death [31,47–49,79–81]. Two published cases of lung damage occurring during the processing of amalgams, one specific to a Guyanese miner, were discussed [48,49]. Trainees were reminded that the maps generated during this process were a snapshot in time; the data collected served as a record that Hg<sub>0</sub> was being emitted at these locations, but Hg<sub>0</sub> emissions from these sites could not be determined or even estimated using these protocols. As a screening protocol, this method is both rapid and effective.

To contrast the difference between Hg<sub>0</sub> concentrations emitted from Georgetown gold shops and the local GGB smelting facility, air concentrations surrounding the facility were monitored with a Lumex, and the VM-3000 was set up inside GGB and monitored for ≈4 h during burning operations. Concentrations on the street outside of the facility never exceeded 200 ng/m<sup>3</sup>, and Hg<sub>0</sub> concentrations never exceeded 2800 ng/m<sup>3</sup> during smelting. A discussion was held regarding the value of screening a large area using the mapping protocol vs. fixed-point measurements at a gold shop. Trainees correctly concluded that both were useful techniques, but the data collected had very different uses and applications. For example, while mapping allows for the screening of an entire neighborhood or community, it only reflects the concentrations of Hg<sub>0</sub> over short time periods and only when the spectrometer is present. Fixed-position monitoring provides a time-weighted average over a longer time period, and thus is more reflective of Hg<sub>0</sub> concentrations in a given environment. However, individual fixed-position systems do not provide an overview of concentrations throughout a neighborhood or community.

3.3. Phase II: Training in Bartica

Training sessions in Bartica were built upon course material discussed during the Georgetown session, with the understanding that participants would be required to use all instrumentation in a real-world setting during the “do” phase. Training in Bartica occurred from 20–30 May, with a cohort of 18 persons (16 GGMC and 2 EPA) being trained throughout. Four additional persons representing NGOs and miners’ unions attended training on select days. Although there was a three-day break from formal training for the observance of Guyanese Independence Day, trainers and trainees collected data throughout the entire training period.

Prior to departure from Georgetown, Mercer University and the GGMC agreed that successful completion of training would require (1) collection of data with the Lumex, VM-3000, and MTIP; (2) organization of data collected using the GPS-linked Lumex using a spreadsheet program; (3) generation of a map plotting [Hg<sub>0</sub>] vs location using QGIS and/or Google Heat Maps; and (4) interpretation of the maps and [Hg<sub>0</sub>] collected in the field using the MTIP. Progress in these areas were assessed by both Mercer University collaborators and select GGMC employees. Training would also occur on the collection of data in gold shops using the stationary VM-3000. However, many of the gold shops were small, and it was difficult for more than one person to be in a gold shop at a time. To this end, data were collected but training in fixed-position monitoring was not mandated for all participants. Similarly, using the XRF was not required for trainees, and therefore data collected during the training were not presented in this report.

A brief but general overview of the lectures in Guyana was conducted on the first day. Because Hg<sub>0</sub> vapor is both highly toxic and invisible, safety training specific to field work was conducted first. Trainees and trainers operating the MTIP were supplied with half-face masks with the appropriate filter for Hg<sub>0</sub> vapor, and taught how to fit and use the masks properly. The MTIP has a long wand that allows for early detection of elevated concentrations of Hg<sub>0</sub> vapor; the MTIP protects both the operator
and the more sensitive Lumex, which is prone to memory effects at higher concentrations. In spite of the potential danger of H\textsubscript{g}\textsuperscript{0}, perhaps the most dangerous component of monitoring H\textsubscript{g}\textsuperscript{0} emissions is traffic. Operators become so engrossed in what they are doing (or so distracted by conversation) they can accidentally walk into traffic. To this end, each portable spectrometer was operated by a team of three people. In the case of the Lumex, one carries the instrument and is responsible for directing the intake wand; another carries the computer and monitors data collection; and a third watches out for obstacles and safety hazards, ensures the connection is maintained between the Lumex and the computer, and ensures that an adequate pace is maintained throughout the monitoring period.

After safety training, pacing for walking with the instruments was practiced. The Lumex with a GPS unit records data in 1-s intervals. Walking too quickly decreases the number of readings per GPS coordinate and may disrupt the flow of air entering the Lumex. Both moving the Lumex and swinging the intake hose too quickly effectively alter the path length of the instrument. In our experience, this results in the recording of artificially low concentrations in contaminated areas near gold shops, although the effect is not noticeable in areas where only low, natural background levels of H\textsubscript{g}\textsuperscript{0} are found. Teams were also instructed to monitor the weather. As training was occurring during the rainy season, teams were instructed to preemptively save their data, shut down the instruments, and place them in plastic bags to be immediately brought back to their storage location.

After the initial training was completed, the 18 trainees and the trainers were divided into 4 teams distributed amongst the 3 portable spectrometers and the XRF. By the end of the training, five teams were active, with one team resting while the others worked. The majority of data collection occurred between 8:00 a.m. and 4:00 p.m. Each day, the data collected were downloaded to a computer, organized, and mapped using QGIS. As with data collection, these processes were initially demonstrated by the trainers but ultimately conducted by trainees.

3.3.1. Mapping of Central Bartica

Although maps were generated each day, the data collection process was slow, and even with two Lumex instruments it was impossible to map all of Bartica in one day. In addition, because of the number of trainees and the nature of the mapping protocol, it was necessary to walk the same paths through the town repeatedly. Although maps were generated at the end of each day, on the last day of the training period, all location vs. data collected were combined into a single spreadsheet. The maximum values of H\textsubscript{g}\textsuperscript{0} concentrations that fell on the Lumex calibration curve at each unique location were mapped (Figure 3).

The map clearly identified gold shops emitting H\textsubscript{g}\textsuperscript{0}. Unlike previous work conducted in Peru and Ecuador, the concentrations determined on the street using the Lumex were significantly lower, with the exception of one occasion wherein the MTIP never exceeded 100,000 ng/m\textsuperscript{3}. This is attributed to the fact that many of the gold shops were considerably set back from the street and sidewalks, were often vented with high chimneys, and were not operating as frequently as in other ASGM communities. Numerous gold shop owners stated that business had been slowed by heavy rains and flooding in the interior that limited transportation to Bartica, while a few commented that the number of gold shops significantly decreased the amount of gold purchased at any one shop.
3.3.2. Monitoring Hg\(_0\) Concentrations During Burning/Smelting Operations at Gold Shops

Concentrations of Hg\(_0\) inside two gold shops and at the Bartica branch of the GGB were recorded during the smelting of sponge gold using the VM-3000. Data collection at both gold shops was only allowed under the condition of anonymity. Due to the small size of the rooms in which burning occurred and the fact that there was no set timetable to burn gold, we made efforts to ensure that the monitoring did not compromise the safety of the instrument operators or gold shop employees. To this end, the VM-3000 was set to measure Hg\(_0\) concentrations every second, and the data were stored to the onboard computer. As there is a finite amount of storage space on the VM-3000, at certain intervals, we downloaded data to a laptop computer. At all locations, the unit was placed on the floor of the room, 1–2 m from the opening of the fume hood where gold was smelted. Ideally, the spectrometer intake would be located at approximately face level to determine Hg\(_0\) concentrations in locations where employees would be breathing; however, the unit would have been a tripping hazard in the confined spaces of the rooms.

The GGB facility in Bartica was evaluated the day before monitoring, and the facility office area was found to have Hg\(_0\) of less than 1000 ng/m\(^3\) as measured by the MTIP prior to burning. The burning room itself, which had been used \(\approx 40\) min prior, still had the ventilation system running and had a concentration of < 2000 ng/m\(^3\). The following day, the VM-3000 was set up, and data recording commenced. The results of the study are found in Figure 4. The maximum concentration at floor level was determined to be 98,700 ng/m\(^3\) during the study period, in which sponge gold was smelted once. Over the 7 h and 24 min of monitoring, the average Hg\(_0\) concentration was 9590 ng/m\(^3\). These Hg\(_0\)
concentrations were significantly higher than the Hg concentrations measured at the GGB facility in Georgetown, which had recently installed a modern ventilation and capture system. Guyana currently has no laws related to ceiling indoor Hg\(^0\) concentrations in industrial environs, nor a time-weighted average for employee exposure. This was an initial assessment of [Hg\(^0\)] in this GGB facility. As only one smelting episode was recorded on one day, it is impossible to draw long-term conclusions from the data presented here. It is possible that the Occupational Safety and Health Administration permissible exposure limit (OSHA PEL) of 100,000 ng/m\(^3\) is exceeded during burning at the face of the fume hood. The same holds true for the National Institute for Occupational Safety and Health recommended exposure limit (NIOSH REL) of 50,000 ng/m\(^3\) (TWA) over an 8-h workday. However, employees in the room were equipped with appropriate personal protective equipment including laboratory coats and half-face masks, and on the basis of the collected data it is clear that the GGB sites evaluated during this study had significantly less Hg\(^0\) contamination than the gold shops assessed. Future monitoring should be designed to monitor Hg\(^0\) at approximate human face level. In addition, while no Hg\(^0\) measured outside was directly attributed to the GGB Bartica facility, future assessment should include monitoring of the effluent emitted directly from the facility’s ventilation system to determine the concentrations of Hg\(^0\) emitted during burning.

![Graph](image)

**Figure 4.** Hg\(^0\) concentrations recorded during the smelting of sponge gold in the Guyana Gold Board (GGB) processing facility in Bartica, Guyana.

A gold shop had been identified during the prior day’s measurements as having significantly elevated concentrations of Hg\(^0\) at the front opening. The owners openly allowed the shop and connected waiting area to be assessed for Hg\(^0\) concentrations. They stated that their ventilation system was installed by a private contractor and cost $2500 (USD). Concentrations in the waiting room exceeded 50,000 ng/m\(^3\), as measured by the MTIP, and the burn room was highly fluxional, with
concentrations ranging between 100,000 ng/m$^3$ and 200,000 ng/m$^3$. The owners reported that business had been slow, and they had not burned in three days.

The following morning, the owners contacted us and stated that they would be receiving sponge gold and would be smelting the next day. They granted permission to set up the VM-3000, but stated that we could not be at the location during smelting. As such, it was impossible to link the activities in the gold shop to Hg$^0$ concentrations, but it was ascertained that multiple pieces of sponge gold were reheated, and the owners combined and smelted the gold during the observation period. The results can be found in Figure 5.

![Figure 5. Hg$^0$ concentrations recorded at a gold shop in Bartica, Guyana.](image)

The maximum concentration of Hg$^0$ as measured during burning was 527,500 ng/m$^3$, with an average concentration of 58,400 ng/m$^3$ over the $\pm$5-h monitoring period. It is clear that concentrations of Hg$^0$ in this gold shop exceeded safe levels; however, it should be noted that this gold shop had a ventilation system that passed air from the fume hood through a 55-gallon drum filled with water, and the vast majority of Hg$^0$ was removed from the room. The owners claimed that the system captured Hg$^0$ but had never recovered it. Concentrations during burning at the exhaust exceeded 2,000,000 ng/m$^3$, the detection limit of the MTIP. Other gold shops had a variety of these ventilation/capture systems, but all seem to be custom-made and unique. This may lead to future issues in monitoring the effectiveness of these systems should an emissions standard be developed.

Because the mapping process was highly visible, with dozens of trainees and trainers walking on the streets with unwieldy instrumentation, we were approached by numerous citizens, miners, and gold buyers who were interested in what we were doing. One gold shop owner reported that their neighbors were complaining that their shop was venting into the courtyard behind the building into an area where a young child was sleeping. As a result, the gold shop was assessed and Hg$^0$ concentrations...
were determined during the smelting of sponge gold into a single ingot. The second gold shop was located on the ground floor of a two-story building that also served as a residence and a business unrelated to mining. Behind the building was a courtyard and another residence. Earlier in the day, the owner placed a 90° angle bend at the top of the exhaust pipe, which extended above the roof of the building. The intent was to direct the vented gas away from the courtyard and toward the street. The monitoring of the smelting can be found in Figure 6. Similar to the previous informal gold shop, concentrations over the brief monitoring exceeded the OSHA PEL with a maximum concentration of 302,200 ng/m³.

The gold shop contained a single fume hood that vented through the wall behind it. A pipe extended through the wall and was directed toward the ground and into a box containing a fan. The two-story exhaust pipe extended up from this box. During smelting, concentrations rapidly exceeded 650,000 ng/m³ within 30 cm from the pipe/box junctures; the MTIP was removed from this area immediately to prevent contamination. However, 1 m away, concentrations were less than 25,000 ng/m³, and were less than 5000 ng/m³ within 3 m at the entrance of the courtyard. Meanwhile, an unsuspecting Lumex team who had stopped mapping for the day and was waiting on the opposite side of the street ≈25 m from the front of the building recorded a rapid increase to >25,000 ng/m³ and immediately left the area. During monitoring, it seemed as though the 90° bend on the exhaust pipe served to redirect the Hg⁰ vapor onto the street and away from the building. It is important to note that this system may not effectively move the Hg⁰ away from the residence, and the vapor may have been carried away from the gold shop during the observation time by the prevailing wind from the river.

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**Figure 6.** Hg⁰ concentrations recorded at a gold shop in Bartica, Guyana.
3.3.3. The Relationship Between Gold Shops and Hg<sub>0</sub> Contamination in Bartica

Not surprisingly, all Hg<sub>0</sub> vapor contamination in Bartica was found to originate at gold shops during phase 2 of training, and all elevated concentrations can be traced back to either (1) Hg<sub>0</sub> contamination from previous smelting activities in gold shops, (2) the burning of amalgams, (3) the reheating of processed amalgams, or (4) smelting of gold. There are seven GGB licensed gold dealers in Bartica [82] and over 30 gold shops, although some were not actively burning during the training period. In spite of the large number of gold shops, Hg<sub>0</sub> concentrations in public areas such as streets and sidewalks were considerably lower when compared to previous work mapping conducted in Peru.

There are numerous reasons that the maps generated in Bartica display relatively less Hg<sub>0</sub> than in other communities. As previously mentioned, less burning occurred during the rainy season due to flooding. As a result, it was less likely to find that gold shops were open throughout the entire day. During training many gold shops were closed from ≈2:00–4:00 p.m., as were many other stores. In addition, many stores closed when rain came. Gold shop owners that chose to close their shops may reduce the amount of Hg<sub>0</sub> emanating from the shop, thus decreasing the likelihood that Hg<sub>0</sub> would be detected if a Lumex team passed. Many Guyanese gold shops were also set back further from the street and sidewalk than Peruvian shops, and most gold shops had burning stations located in the back of the business away from the street. Unlike gold shops or burning facilities in Peru, there were no gold shops in Bartica that vented directly onto the street through horizontal piping. Many shops in Guyana had vertical exhaust stacks that may lead to greater dilution of Hg<sub>0</sub> vapor than those in other ASGM communities. However, as highlighted at the second gold shop, the effect of tall chimneys on Hg<sub>0</sub> emissions from gold shops may lead to wider distribution of Hg<sub>0</sub> pollution and affect mapping and identification activities. Finally, certain gold shops in Guyana had conditioned air that led to exterior windows and doors being closed, whereas in Peru, the front of most shops were open. The closing of shops to maintain a cool temperature may lead to higher concentrations of Hg<sub>0</sub> trapped inside the burning area. The effect of tall chimneys and air conditioning should be investigated at a later date.

Previous work in Ecuador and Peru had demonstrated that although Hg<sub>0</sub> concentrations may vary from day to day, that mapping could always be used to determine the locations of gold shops. It became apparent during training that this was not to be the case in Bartica; there were mercury emissions not noted at a given location one day, and yet mercury emissions appeared on another day of training (Figure 7). Therefore, the mapping technique presented to trainees is noted as an effective screening tool for identifying gold shops that is limited because it only records concentrations at a given time. For this reason, trainees were routinely told that mapping represented a “snapshot in time”. Trainees were reminded that mapping cannot be carried out over a single day, but must be comprised of data collected over multiple days.

3.4. Phase III: Analysis and Dissemination of Results

During joint planning sessions between Mercer and the GGMC, a GGMC representative stated that although employees were capable of collecting data in the field, a potential area for growth could be interpretation of the data collected and the generation of the final report. While all 18 full-time trainees (1) were instructed in Guyana and Bartica; (2) participated in the collection of data using the Lumex, MTIP, and XRF; (3) mapped at least one day’s worth of collected data using Microsoft Excel and quantum geographic information system (QGIS); (4) interpreted the map and referenced it with their observations in the field; and (5) assisted or were presented with the final findings of the mapping work, it was logistically infeasible to engage all trainees and trainers in the production and review of the final report. As a result of this conversation, selected GGMC employees participated in the final interpretation of data and writing of the report. These trainees were selected because of their dedication to the collection and interpretation of data. These trainees were ultimately able to generate maps independent of trainers, and as such, were identified as potentially being able to lead future internal training for the GGMC. On the final day of training, trainees assisted in the generation of the total map and participated in a discussion related to the findings of the program.
mapping cannot be carried out over a single day, but must be comprised of data collected over multiple days.

Upon the generation of the drafted report, the trainees were asked to bridge the scientific findings with their experiences during the training. In addition, they were asked to place the technical and scientific findings in the context of Guyanese mining practices.

4. Conclusions and Future Directions

A three-phase training program was established from a collaboration between a U.S. university and the GGMC. The first phase of the training encompassed the use of Hg\(^0\) in ASGM in the context of science, the environment, and policy, in particular the Minamata Convention. Participants were introduced to a suite of analytical instrumentation to assess Hg\(^0\) contamination originating from gold shops in the capital city of Georgetown. During the second phase of training in Bartica, data were collected and mapped that quantified Hg\(^0\) pollution at gold shops. In addition, concentrations of Hg\(^0\) were measured inside the Guyana Gold Board facilities. During monitoring periods, GGB facilities remained under the OSHA PEL guideline of 100,000 ng/m\(^3\), but the gold shops produced Hg\(^0\) concentrations that exceeded the PEL. Furthermore, these gold shops were found to vent concentrations of Hg\(^0\) exceeding 1,000,000 ng/m\(^3\), with one shop exceeding 2,000,000 ng/m\(^3\), the detection limit of the MTIP. During the third and final phase of the project, select representatives from the GGMC were asked to assist in the preparation of a final report, reinforcing learned concepts and requiring further interpretation of the results.

Because the GGMC has identified the need for the development of standards for the emission of Hg\(^0\), the data collected during this training may serve as a baseline for deciding emissions limits and may assist in the generation of national air quality standards. A delicate balance must be reached between profits from gold mining and protecting human and environmental health. The reality is that existing laws in other countries may not apply to areas of high contamination such as gold shops. This program also identifies sources of Hg\(^0\) to the atmosphere, but it does not provide insight into the ultimate fate of this Hg\(^0\). The maps generated indicate that Hg\(^0\) is rapidly diluted once it leaves the gold shop. The reality is that this Hg\(^0\) must go somewhere, entering the atmosphere and/or depositing on the ground or surface of buildings, and thus would be inaccessible to the sampling probes of the spectrometers. Whether Hg\(^0\) from these gold shops is deposited locally, regionally, or globally has yet to be determined. In other areas, inexpensive passive air samplers have been used to quantify Hg\(^0\) in the air over extended periods of time [83–86]. Future mapping that incorporates data from passive air

Figure 7. Panels (A, B) are daily maps generated by trainees. No burning activity (panel (A)) may not be reflective of gold shop activity. When sponge gold or amalgams are heated in the same location in subsequent days, Hg\(^0\) is clearly visible on the map (panel (B)).
samplers may add to our understanding of the fate of Hg\(^0\) emitted from gold shops. This is a global challenge, and as such, will be faced not only by Guyana but by all signatory nations of the Minamata Convention with ASGM activities.

**Author Contributions:** Conceptualization: A.M.K.; investigation: S.T.B., L.L.B., S.S.A., S.T.T., T.E.G., G.K.M., A.V.E., K.M.H., D.C.L., and A.M.K.; methodology: S.T.B., K.M.H., D.C.L., C.S.S., and A.M.K.; project administration: L.L.B. and A.M.K.; resources: A.M.K.; supervision: L.L.B., S.S.A., and A.M.K.; visualization: S.T.B., G.K.M., A.V.E., and A.M.K.; writing—original draft: S.T.B., L.L.B., S.S.A., S.T.T., T.E.G., D.C.L., C.S.S., and A.M.K.; writing—review and editing: S.T.B., L.L.B., S.S.A., S.T.T., T.E.G., D.C.L., C.S.S., and A.M.K. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Acknowledgments:** The authors acknowledge Guyana’s Ministry of Natural Resources, the Guyana Geology and Mines Commission, and the Mercer on Mission program for financial and logistical support for this project. Madison Ayers, Hailey Christian, Alaina Dawson, Owen House, Kayla Kelley, Alina McCue, Kyle Powell, and Sutton Scarboro are acknowledged for assisting with in-country data collection and training.

**Conflicts of Interest:** The authors declare no conflict of interest.

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