In-Situ monitoring of mercury and mercury compounds in and around Artisanal and Small-Scale Gold Mining sites

Technical Background Document

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1. Executive Summary

[This section will be developed pending draft final version.]

2. Introduction

1.1. Mercury as a global pollutant

Mercury (Hg) is a persistent global pollutant that can be emitted from both natural and anthropogenic sources (Pirrone et al., 2010; UNEP, 2018). With a residence time of approximately one year in the atmosphere (Bergan et al., 1999; Engstrom et al., 2014), mercury has the capacity to travel thousands of kilometers from emission point sources before depositing in terrestrial or aquatic surfaces (Driscoll et al., 2013; Engstrom et al., 2014). Upon deposition, mercury can potentially be converted to bioavailable forms that can threaten human and environmental health (Basu et al., 2018; Canham et al., 2020; Driscoll et al., 2013; Scheuhammer et al., 2007). Given the global nature of mercury's emission and distribution, and its high-level toxicity to humans and wildlife and environmental persistence, it is critical to understand and monitor the behavior and environmental fate of Hg and to model and predict long-term and large-scale distribution and dispersion patterns to develop effective strategies for reducing the negative environmental and health impacts of this pollutant.

The biochemical cycle of mercury is complex. As Fitzgerald and Lamborg (2003) noted:

> "Mercurial, the metaphor for volatile unpredictable behavior, aptly reflects the complexities of one of the most insidiously interesting and scientifically challenging biogeochemical cycles at the Earth's surface".

All chemical forms of Hg are toxic. The form of most concern is the organic and highly bioavailable form, methylmercury (MeHg) (Hsu-Kim et al., 2013; Ullrich et al., 2001). Primarily produced in aquatic environments through the methylation of elemental mercury by microorganisms, MeHg is a potent neurotoxin that readily accumulates in living organisms and biomagnifies within food webs, becoming enriched in high trophic levels of freshwater and marine ecosystems (e.g., long-lived piscivorous marine and freshwater predators) (Azevedo-Silva et al., 2016; Bastos et al., 2015; Callister & Winfrey, 1986; Eckley & Hintelmann, 2006). As a result, humans and wildlife with diets that consume high trophic level predators are at elevated risk of Hg dietary exposure (AMAP, 2011; Hacon et al., 2020). The potential negative health effects of MeHg exposure have prompted an increased global awareness regarding the consumption of marine and freshwater species that contain high MeHg levels, and in several at-risk populations.

Governments and environmental agencies have imposed regulations (e.g., the 1998 Aarhus Protocol on Heavy Metals, the Clean Air Act, and the EU Regulation Concerning Mercury) to reduce Hg emissions, reduce global exposure risks, and negative impacts on humans and the environment from mercury. The Minamata Convention on Mercury (referred here as "the Convention") was spearheaded by the United Nations Environment Programme (UNEP) to protect human health and the environment from mercury. Much of the Convention's work is focused on addressing Hg throughout its life cycle in several economic sectors.

1.2. Mercury in artisanal and small-scale gold mining

The economic sector with the largest Hg emissions and releases is artisanal and small-scale gold mining (ASGM) (UNEP, 2013, 2018). The ASGM sector is estimated to account for almost 38% of the global total mercury emissions and to be the major contributor to the emissions from South America and Sub-Saharan Africa. Improving the understanding of the dynamics and environmental fate of Hg from ASGM is of significant concern to human and environmental health.

1.3. Monitoring of mercury from artisanal and small-scale gold mining within the framework of the Minamata Convention

The reduction of Hg emissions in the ASGM sector is highlighted as a priority in the Convention, and is specifically addressed in Article 7 and Annex C. Further, three Convention articles highlight the importance of well-designed and implemented strategies to monitor mercury, including those in and around ASGM sites: Articles 7, 19 and 22, which are outlined below.

- **Article 7** addresses Hg released from ASGM that uses mercury amalgamation to extract gold from ore. Countries ("Parties") with ASGM are required to take phases to reduce and/or eliminate the use of mercury, as well as mercury emissions and releases to the environment. Each Party is to inform the Convention whether there is more than an "insignificant" presence in its territory. If so, Parties shall develop and implement a National

Action Plan (NAP) in accordance with Annex C of the Convention. The development of the NAP should be based on Convention's obligations and current technical and scientific understanding of the ASGM sector, including the use of mercury and processing of gold amalgam, its health and environmental effects, as well as social and economic analysis of the ASGM sector.

- **Article 19** addresses research, development, and monitoring. Parties are encouraged to collaborate in the development and improvement of inventories on use, consumption and emissions of mercury and its compounds. Mercury impact assessments (including information on the environmental cycle, transport, and environmental fate) and geographically representative monitoring of levels of mercury and its compounds in vulnerable populations and in environmental media are mentioned as specific areas of work under this article, as well as the development of harmonized methodologies for monitoring ASGM sites,
- **Article 22** addresses the Effectiveness Evaluation (EE) of the Minamata Convention. The Conference of the Parties (COP) is to periodically evaluate the effectiveness of the Convention, and to perform this evaluation based on available scientific, environmental, technical, financial, and economic information. Comparable monitoring data on the presence and movement of mercury and its compounds in the environment, as well as trends in wildlife and vulnerable human populations, are of particular interest to COP in the context of the Effectiveness Evaluation (for more information on EE, see the document "Guidance on monitoring of mercury and mercury compounds to support evaluation of the effectiveness of the Minamata Convention" (UNEP, 2021a).

1.4. Scope and objectives of this technical guidance document

This document is intended to provide technical information to support the practitioners on obtaining monitoring data of mercury and its compounds in and around ASGM sites, to supplement knowledge for the local assessment and management of ASGM related Hg releases by outlining guiding principles for compiling and/or generating monitoring data for understanding the presence, movements, and trends of mercury in and around ASGM sites

The main objectives of this document are to:

1. provide guidance on the design and implementation of monitoring strategies and practices to monitor mercury in terrestrial and aquatic environments in and around areas where ASGM is practiced.

2. provide guidance to practitioners that intend to conduct Hg monitoring programs on relevant data and ancillary information.

3. provide guidance to practitioners who wish to develop new Hg monitoring programs, or improve existing ones, which is consistent with efforts contributing to Effectiveness Evaluation efforts under the Minamata Convention.

This document is targeted for program managers and technical practitioners in civil society and governmental organizations who have interest in the design of monitoring programs to assess mercury pollution in and around ASGM sites. As ASGM expands globally, there is an increasing demand for practical information on how to design and undertake mercury monitoring programs. Reasons for these programs include the generation of information on potential environmental exposures resulting from mercury releases related to ASGM activities, policy evaluation with regulatory requirements on environmental conservation, biodiversity protection or eco- and human health protection, and policy evaluation.

This document discusses Hg monitoring in and around ASGM in soils, surface sediments, and biota. It also discusses Hg monitoring using surface water and the significant challenges related to its use for environmental monitoring in and around ASGM sites. This document does not address Hg monitoring in air or human mercury biomonitoring. Links to guides for these media are provided in a reference section in the annex section below.

Many countries are developing Hg monitoring programs to support national policy implementation (e.g. NAP implementation) and the global effectiveness evaluation under the Convention. Parties are encouraged to collaborate according to Article 19 and are required to develop NAP's according to Annex C if they have reported more than insignificant ASGM activities according to article 7, but the requirement in article 22 concerns the COP, not individual Parties.

The Convention's EE actions (UNEP, 2021a) aim to measure change in key environmental compartments that results from activities under the Convention and addresses the following four overarching policy questions:

(a) Have the Parties taken actions to implement the Minamata Convention?

(b) Have the actions taken resulted in changes in mercury supply, use, emissions and releases into the environment?

(c) Have those changes resulted in changes in levels of mercury in the environment, biotic media and vulnerable populations that can be attributed to the Minamata Convention?

(d) To what extent are existing measures under the Minamata Convention meeting the objective of protecting human health and the environment from mercury

We intend this document mainly to be a useful tool for local practitioners in their efforts to develop evidence-based knowledge on mercury pollution in and around ASGM sites for local, sub-national and national priorities. The Hg monitoring efforts that are discussed in this document do not necessarily need to be part of monitoring activities related to the Convention compliance or effectiveness evaluations but can be useful for this effort. The information generated by these types of monitoring efforts could additionally be useful for the Convention related activities, such as tracking the progress of the implementation of a country's Minamata Convention National Action Plan.

To aid readers place this document within the suite of reference documents developed by UNEP and the Minamata Secretariat, linkages have been made in the text to relevant documents such as *Guidance for Effectiveness Evaluation of the Minamata Convention* (UNEP, 2021a) and the *Guidance for Conducting a Rapid Environmental Mercury Assessment of Artisanal and Small-Scale Gold Mining Sites in the Context of National Action Plans* (UNEP, 2019).

1.5. Structure of the document

This guidance document is structured in six sections, outlined below:

Section 1: Introduction

Provides an overview of mercury as a global pollutant, Hg releases from the ASGM sector, and Hg monitoring of ASGM. The scope and objectives of the document are described.

Section 2: State of knowledge of mercury monitoring data in terrestrial and aquatic environments in and around ASGM sites

Provides an overview of the state of knowledge of ASGM as a major source of mercury pollution, the tracing of ASGM-related mercury in the environment, and discussions of mercury dynamics in aquatic and terrestrial systems, with a focus on tropical environments due to ASGM's high prevalence in these environments. A summary of needs and challenges for in-situ monitoring of ASGM-related mercury is also provided.

Section 3: A proposed framework for in-situ mercury monitoring in and around ASGM sites

Presents a framework for developing in-situ mercury monitoring of areas in and around ASGM sites for the identification of mercury pollution, the measurement of mercury levels, and the assessment of potential environmental health risks in potentially impacted areas.

Section 4: Hg monitoring case study

Presents a case study of a mercury monitoring effort in a region recognized as a major hotspot of ASGM in Latin America: the Amazonian region of Madre de Dios, Peru.

Section 5: Summary and recommendations

Provides a summary of the information presented in the document and discusses the advantages and disadvantages of the approaches and methods. This section also discusses how in-situ environmental Hg monitoring programs for ASGM can be integrated with other environmental Hg monitoring approaches (e.g., remote sensing) and Hg monitoring programs that focus on human health impacts, to increase cost and effort efficiencies, linkages, and insights across monitoring efforts.

Section 6: References

This section provides a list of the bibliographic references cited in this document.

Section 7: Annexes [***Note****: The supplementary material that will be presented in the Annex section has not been finalized, but will/may include:*

a) a lightly edited version of the annotated literature review of peer-reviewed reports of mercury from terrestrial and aquatic ecosystems affected by ASGM (i.e., Project Deliverable 3) *b) annotated reference lists of relevant technical documents on in-situ mercury monitoring (e.g., Standard Operating Procedures (SOPs), technical protocols)*

c) annotated reference lists of programs and projects implementing in-situ mercury monitoring in ASGM sites.]

3. State of knowledge of mercury in terrestrial and aquatic environments in and around ASGM sites

3.1 ASGM as a major source of mercury

Artisanal and small-scale gold mining (ASGM) is the largest economic sector that uses mercury globally, and the largest source of anthropogenic mercury releases to the environment (UNEP, 2018). Monitoring and improving the understanding of the environmental fate of mercury releases from this sector is of particular concern in the context of human and environmental health, particularly in areas where ASGM is prevalent and expanding.

ASGM has acquired significant economic and social importance in many countries due to rising gold prices and widespread poverty. ASGM occurs in over 80 countries and is widespread in South America, sub-Saharan Africa and East and Southeast Asia (Telmer & Veiga, 2009; UNEP, 2018), producing as much as 450 tons of gold annually (Seccatore et al., 2014). It is particularly extensive in rural areas from low- and middle-income countries where gold ore is present and alternative livelihoods are scarce. Between 14 to 19 million people are estimated to be directly engaged in ASGM; another 80 to 100 million people are dependent on the sector for their livelihoods (Steckling et al., 2017).

The total amount of mercury released to the global environment by ASGM, and the proportion of Hg released to different environmental compartments (i.e., air, water, soils, sediments, and biota) remains uncertain (Moreno-Brush et al., 2020). Most estimates point to the ratio of gold to mercury used in amalgam based ASGM as a controlling factor that constrains estimates of Hg use and emissions by the sector. A recent study estimates that the average ratio of Hg releases to gold produced by ASGM is 4.96:1 in Latin America, 1.96:1 in Africa and 1.23:1 in Asia, with these differences attributed to differences in the amalgamation process practiced in each region (Yoshimura et al., 2021). However, it is important to note that by basing estimates of mercury releases on gold production, which itself requires data on mercury use for its determination, a problematic circular reference may be created in the calculation of Hg emissions (Moreno-Brush et al., 2020). Nevertheless, these estimates can be useful to calculate the total social, environmental, and economic cost of ASGM using mercury, and to compare alternate public investment options in the sector.

3.2. Tracking mercury in areas in and around ASGM sites

Significant amounts of mercury are released to the environment by ASGM, primarily through the processes of amalgamation and inappropriate disposal of mine tailings (UNEP, 2018). Mercury amalgamation is currently the most widely used method for extracting gold in ASGM. Miners use elemental (metallic) mercury (Hg^0) for extracting gold particles from alluvial sediments or crushed hard-rock deposits. Amalgamation is typically used with either whole ore, or gravity-concentrated fractions to create a Hg-Au amalgam. Commonly, an amalgam ball is created by miners by placing the amalgam removed from an amalgamation container into a cloth, which is used to sieve out excess liquid mercury. Although there is usually an effort to recapture this surplus mercury, small amounts can be lost to the environment.

To recover the gold fraction from the amalgam ball, miners roasted the ball to evaporate off the mercury. This process emits large amounts of mercury vapor into the air and can be the main route of mercury exposure for miners and people living in areas adjacent to amalgam processing sites (Black et al., 2017). Amalgam roasting frequently first occurs in the field, soon after the amalgam is taken out of the amalgamation container or pool. This first roasting event is where most of the Hg released to the air occurs. Secondary roasting events, frequently occurring in “gold shops”, which are gold buyers roast amalgams offered for purchase again in order to drive off as much of the Hg as possible before weighing). Although this secondary burn typically releases lower quantities of mercury, they frequently happen in urban or semi-urban settings, which can increase the impact of inhalation exposure for nearby people. Although the use of retorts to condense and recover Hg during amalgam roasting has been actively promoted by governments and NGOs to reduce these emissions (Bosse Jønsson et al., 2013; UNEP, 2012), it has been shown that its effective uptake and use by miners is limited (Bosse Jønsson et al., 2013). Another pathway of Hg release is through different phases of the amalgamation process and the direct disposal of mercury-treated tailings into nearby water bodies.

Cyanidation, the use of cyanide to leach gold from gold-bearing material, is also used in ASGM. Cyanide (CN) is used either as an alternative extractive method or used in combination with Hg amalgamation to extract gold from ore, or from tailings previously treated with Hg (Carling et al., 2013; Razanamahandry et al., 2016; Sousa et al., 2010; UNEP, 2021b). The combination of Hg and CN extraction has been shown to produce hazardous Hg-CN complexes which have been associated with increased bioaccumulation of mercury in the environment, negative public health impacts, and long-range transport of mercury in watersheds (Seney et al., 2020). The combined practice of mercury amalgamation and cyanidation has been identified in Appendix C of the Minamata Convention as one of the four worst practices to be eliminated due to the significant risks it poses to environment and human health.

A complete understanding of the dynamics of ASGM-related Hg remains unclear (Moreno-Brush et al., 2020). Although several studies support that high mercury pollution can occur in and around mining and processing sites, and in areas close to gold amalgam refining facilities (Appleton et al., 2006; Cesar et al., 2011; Cordy et al., 2011; Gammons et al., 2006; Guedron et al., 2009; Malm et al., 1995; Pataranawat et al., 2007; Rajaee et al., 2015; van Straaten, 2000), there is more limited evidence regarding the extent of downstream impacts of mercury released by ASGM in aquatic ecosystems. In river systems with presence of ASGM, higher Hg concentrations have been reported in river sections with active mining as compared to sections upstream from mining activities (Diringer et al., 2015; Marshall et al., 2018). Nevertheless, a clear downstream dispersion pattern that can be directly associated with ASGM is not always found. Mercury concentrations in sediments can rapidly decline within short distances from mining sites down to values like those found in unpolluted areas (e.g., Lechler et al. (2000); Roulet, Lucotte, Canuel, et al. (1998); Taylor et al. (2005); van Straaten, (2000)). Moreover, rivers with no history of ASGM can present similar, or even higher, mercury concentrations than rivers with ASGM (e.g., Moreno-Brush et al. 2016; Ouboter et al. 2012).

Tracking the environmental fate of mercury in ASGM sites remains a particular challenge, particularly in tropical areas as the biogeochemistry and dispersal trends of mercury in tropical environments are still poorly understood. A recently published review of this topic concluded that hydrology is the dominant factor controlling the fate of Hg in tropical rivers, and that the geochemical composition and grain-size distribution of sediments are key factors controlling the concentration and distribution of Hg in sediment and soils (Moreno-Brush et al., 2020). These variables can be crucial factors for accurately assessing mercury in aquatic environments, but may not be included in Hg monitoring studies, thus limiting the ability to develop accurate estimates of the extent and fate of mercury in ASGM sites.

Additionally, ASGM activities are not always the only source of mercury in areas in and around ASGM. In some regions, forest soils can have naturally elevated Hg background concentrations, and can be a significant natural source of mercury to aquatic systems (de Oliveira et al., 2001; Roulet, Lucotte, Saint-Aubin, et al., 1998; Roulet & Lucotte, 1995). Forest fires, flooding, deforestation, increased erosion stemming from logging, agriculture - and even ASGM itself - can also increase perturbation and mobilization of Hg-rich surface soils into rivers and lakes (Lacerda et al., 2004; Miserendino et al., 2018; Schudel et al., 2019). The complexity of the Hg cycle can make it difficult to identify and directly assign a specific Hg source to suspected or detected pollution events.

The use of mercury stable isotopes to differentiate Hg sources (for example, between Hg from ASGM and Hg from naturally enriched soils) in ASGM sites is a new and promising approach to more clearly determine Hg sources. As an example, a study looking at Hg in the Amapa region of the Brazilian Amazon used Hg isotope analysis to determine that elevated mercury concentrations downstream from ASGM activities were a result from increased soil erosion, and not from mercury released by ASGM (Miserendino et al., 2018). Another study conducted in Portovelo, Ecuador, used Hg isotopes analysis to determine that ASGM that used both mercury and cyanide was the source of mercury pollution found downstream in the Puyango-Tumbes River on the border of Ecuador and Peru (Marshall et al., 2018; Schudel et al., 2019). Though this technology is still costly and evolving, studies that use stable isotopes have the potential to greatly improve the understanding of the contribution and mobility of mercury released from ASGM. The use of mercury isotope analysis for environmental Hg monitoring programs will be discussed further in Section 3.2.

3.3 Mercury dynamics in aquatic environments

Direct mercury releases from ASGM activities to aquatic environments are primarily elemental metallic mercury (Hg^0) which is a dense, unreactive, insoluble substance, with a very high surface tension and a slow oxidation rate. These characteristics make ASGM-derived Hg^0 in aquatic environments most likely to be present as droplets, and accumulate in bottom sediments close to the sites of direct release (e.g. amalgamation locations). Hg^0 droplets can be stabilized in aquatic sediments by mineral particles as they are progressively buried by overlying material (Dominique et al., 2007). Due to their high density Hg^0 droplets are typically only transported downstream during high flow and flooding events. Hg^0 can undergo oxidation (to Hg^{2+}) and dissolution in oxygenated environments, and in presence of dissolved organic matter (Meech et al., 1998; Melamed et al., 2000; Miller et al., 2002). Due to its high vapor pressure, Hg^0 can undergo evaporation at room temperature (Gao et al., 2006; Miller et al., 2002). Importantly for environmental and human health, Hg can be converted to the highly toxic and bioavailable methylmercury (MeHg) in water bodies if anoxic conditions are present. The production of MeHg has been a long-running concern in areas in and around ASGM (Gerson et al., 2020), due to its capability of entering and magnifying in aquatic food webs and the fact that fish consumption is the dominant pathway for human MeHg dietary exposure. Fish consumption is frequently an important, if not primary, protein source for many populations including riverine and indigenous communities.

Most studies on Hg methylation pathways in aquatic environments have been conducted in boreal and temperate latitudes, with studies in tropical latitudes much less common. Mercury pollution in the tropics is of particular concern because aquatic environments may have more favorable conditions for Hg methylation than in temperate regions (i.e higher ecosystem sensitivity to mercury). Conditions found in tropical environments that increase ecosystem sensitivity to mercury include shallow anoxic warm waters, low pH, low salinity, high prevalence of sulfate-reducing bacteria, and organic-matter-rich sediments (Ullrich et al., 2001). For example, studies from the Brazilian and Bolivian Amazon suggest that floodplain areas and roots zones of floating aquatic plants are important methylation sites due to the elevated concentrations of organic matter that favors the formation of anoxic conditions and generates an increase in bacterial activity (Achá et al., 2011; Guimarães et al., 2000; Lázaro et al., 2016; Roulet et al., 2001).

3.4. Mercury dynamics in terrestrial environments

Soil erosion and surface runoff are the predominant means in the transport of Hg and other heavy metals to aquatic systems (Gabriel & Williamson, 2004; Kerr & Cooke, 2017; Rickson, 2014; Roulet et al., 2000). In temperate and boreal soils, soil Hg distribution is strongly controlled by the content and cycling of organic matter (Grigal, 2003), whereas in soils from the humid tropics, Hg retention and accumulation is governed by soil texture and geochemical composition, specifically by the content of iron oxides (do Valle et al., 2005; Roulet, Lucotte, Saint-Aubin, et al., 1998). In these soils, Hg accumulation in organic surface horizons is strongly limited by the faster soil organic matter turnover due to higher temperature and humidity as compared to temperate and boreal climates (Trumbore, 1993).

In and around ASGM sites, elevated mercury levels in environmental, human and biota samples from downstream environments have often been attributed to upstream ASGM activities. Although it may be reasonable to initially assume that ASGM is the primary source of Hg contamination in areas adjacent to ASGM processing facilities, the sources of Hg in tropical environments with no apparent history of mining can be difficult to identify. Elevated Hg levels in aquatic systems may primarily originate from the erosion of ferralitic forest soils (old, deeply weathered, and leached soils of the humid tropics) rather than from anthropogenic pollution (Fostier et al., 2000; Lacerda et al., 2004, 2012; Roulet et al., 1999; Roulet, Lucotte, Saint-Aubin, et al., 1998). Ferralitic soils are enriched in minerals containing aluminum and iron oxides that efficiently retain and accumulate mercury (de Oliveira et al., 2001; Fadini & Jardim, 2001). In regions with these types of soils, heavy rainfall and discharge events may amplify the export of Hg from ferralitic soils to aquatic systems.

3.5 Conclusions

A review of the scientific literature on mercury assessments and monitoring efforts in and around ASGM sites over the last 20 years conducted by the authors for the purposes of the document, and presented in the Annex, provides two important takeaways regarding factors that are relevant for Hg monitoring efforts, and which may limit the scientific validity, comparability and usefulness of Hg assessment and monitoring efforts.

- **The lack of standardized protocols for sampling and sample processing used in a consistent manner limited spatial and temporal comparability of mercury monitoring efforts.** Although Hg pollution in and around ASGM sites has been widely studied, there remain challenges for comparing between studies that report Hg data because of the wide range of protocols that are used for field sampling and measuring Hg concentrations in the lab. The review highlighted that the inconsistent use of standardized protocols for sample collection, handling, treatment, storage, and sample and data analysis were identified as factors that limit inter-comparability across sites, and from one time to another.

- **The use of methods inappropriate for monitoring goals limits the production of accurate or valid data**. The literature review conducted revealed that in several cases, monitoring programs used approaches and methods unsuitable for assessing the Hg processes of interest.

- **The lack of control sites in monitoring studies limited the ability of monitoring to understand the amount of deviation that a study site has as compared to local background levels of mercury.** Because identifying Hg sources in ASGM impacted systems is often a key goal of monitoring, the use of control sites is important for accurate quantification of Hg enrichment levels in and around ASGM. However, many monitoring programs lack control site data or data on regional Hg baselines. Some studies instead use highly generalized reference values or guidelines published by national and international agencies (e.g., WHO, EU) to compare to collected samples. Because environmental mercury levels can be spatially heterogeneous, the use of control sites and regional Hg background values as comparison values in regional Hg monitoring programs is considered a best practice and would improve the accuracy of quantifying Hg enrichment levels in and around ASGM sites over time (see section 3.2 for more information about control sites).

4. A framework for developing in-situ monitoring plans for mercury in and around ASGM sites

4.1. Introduction

In this section, we outline a framework for in-situ mercury monitoring in and around ASGM sites. This framework uses a simple and straightforward approach for designing and implementing a monitoring program. Depending on the needs and goals of the monitoring effort, not all phases would need to be conducted; however, all the phases described here should be considered. These phases are presented in a sequential order, but in practice some phases would be done in parallel or iteratively during the course of the monitoring effort.

- **Phase 1:** Gathering initial information on the potential mercury use in ASGM
- **Phase 2:** Defining clear goals and objectives of the monitoring program
- **Phase 3:** Development of a stakeholder engagement plan with relevant local communities and Indigenous peoples to create effective communications channels
- **Phase 4:** Identifying and securing initial resources needed for the monitoring program
- **Phase 5:** Designing field sample collection and sample analysis plans that fit time, logistical and budget constraints
- **Phase 6:** Carrying out field sample collection, sample analysis and interpretation of the results to develop basic knowledge of mercury levels in target sites
- **Phase 7:** Communicating the results to stakeholders and interested parties
- **Phase 8:** Considering and conducting high-complexity mercury data analysis to identify and understand sources, processes, and projections based on the previous findings

The phases listed above are based on the *UNEP Guidance for Conducting a Rapid Environmental Mercury Assessment of ASGM Sites* (UNEP, 2019), a useful document that was created to support countries in developing National Action Plans (NAPs) to help reduce or eliminate mercury use in fulfillment of Article 7 of the Minamata Convention on Mercury by providing information on how assessment results may contribute to formulating a public health strategy to help prevent mercury exposures. The *UNEP 2019 Guidance* provides general guidelines to identify potential pathways of human exposure to mercury, evaluate the need for environmental sampling of ASGM sites, develop a mercury sampling plan to rapidly assess mercury levels in the environment, where appropriate, support the formulation of the strategies to prevent exposure of vulnerable populations, as required by the Minamata Convention NAP. It is important to note that this previous guide discusses the planning of a rapid assessment approach designed to quickly understand the extent and severity of mercury contamination risks and set priorities to manage and address those risks effectively given limited resources and capacity, as opposed to a longer-term monitoring effort which is the focus of this document.

4.2. A framework for developing in-situ *monitoring of* mercury in ASGM sites

Developing an effective in-situ monitoring program in and around ASGM can be a challenging endeavor. ASGM is often an informal, and sometimes illegal, activity typically conducted in remote locations. Areas where ASGM is most prevalent are often understudied (particularly in the humid tropics), and can have little or no pre-existing mercury data to develop baseline levels to compare against measured data. Information on the location and size of the mining activity, and details on suspected mercury releases is often lacking. Sample collection activities can occur in remote areas that require complex and costly logistics to secure samples and transport them to a laboratory in a manner that maintains the needed sample integrity for contaminant analysis. In some areas, the safety and security of field teams conducting field sampling and monitoring activities may also be a concern.

Further, a monitoring program requires access to an analytic laboratory with the capacity of measuring mercury in a variety of sample matrices. Depending on the mercury compound being measured (e.g., total mercury, methylmercury) the costs of analysis can range from tens to hundreds of US dollars per sample. Some areas may even lack access to nearby or qualified analytical laboratories, requiring sample transport to laboratories in other regions, or countries, further increasing logistical complexity and costs.

Although the complexity of the task to develop an effective Hg monitoring program for ASGM areas (and to do so within budget) can be daunting, these challenges can be better understood and mitigated through the development of a well-designed monitoring plan that is specifically tailored to the monitoring program's objectives and goals, and informed by the realities of the ASGM region to be monitored. A well-designed plan is critical for obtaining meaningful data and information for assessing mercury in ASGM areas, can help determine the required approach, design,and resources for implementation, and for the development of a clearly defined set of activities for planning, execution and reporting of results.

PHASE 1: GATHERING INITIAL INFORMATION ON THE POTENTIAL MERCURY USE IN ASGM

Phase one activities focus on conducting desk-level scoping to gather available pre-existing information on the location and extent of the suspected mercury release event, and the location and characteristics of the ASGM activities that may be linked to the release event. These actions can include searching, reviewing, and synthesizing available literature (government reports, scientific papers, gray literature), gathering geospatial information from maps and digital mapping platforms for an initial characterization of the Area of Interest (study site). If available, pre-existing information on previous ASGM activities and mercury releases in the study site can be valuable, though there can be challenges for obtaining accurate and reliable information on study areas. The collection of other study sites - related information such as information on travel and ease of access to potential sites for monitoring activities, and an up-to-date security assessment are also useful at this stage.

The following topics and questions can guide practitioners on the selection of information that can be compiled during this phase. This list is meant to provide examples of the types of questions that can be asked and is not intended to be definitive or exhaustive. Practitioners can also develop and include other questions that are relevant to their specific area of interest and contamination event:

- Geographical/Spatial
    - What are the spatial characteristics of the Area of Interest (i.e., location, size, proximity to population centers, water bodies, previous contamination events)?
    - Where does ASGM occur within the study site?
- ASGM mining information
    - Activity status
        - Are ASGM operations active or inactive?
        - How long has ASGM been occurring in the area of interest?
        - How has the extent of ASGM changed during its occurrence?
        - How has the rate of growth of ASGM changed during its occurrence?
    - Mining type
        - What type of ASGM mining is being conducted (e.g., hydraulic alluvial mining, fluvial dredge mining, placer mining using heavy machinery)?
    - Environmental compartment
        - In which type of environment is ASGM conducted (e.g., rivers, lakes, alluvial plains, mountains)?
        - Is there any existing information on ecosystem sensitivity to MeHg transformation, and contamination risks?
- Mercury use in ASGM in the area of interest
    - Is mercury used in the gold extraction process?

    - How much mercury is used and released to the environment?
    - Is there pre-existing information on mercury levels in the study site, or in nearby unaffected areas that could serve as background controls?
- Accessibility and security status
    - How accessible is the area of interest if field monitoring is required?
    - Is the site accessible at all time periods (i.e., limited by season, flood, or monsoon events)?
    - Are there security concerns at the study site, or *in route* to the area of interest?

Some of these questions, such as those related to the past use of mercury, pre-existing assessments of mercury pollution, and other types of site assessments, can also be answered through a comprehensive review of published literature; typically peer-reviewed scientific literature, government reports, assessments done by NGOs and international organizations.

Relevant information regarding the ASGM site and other useful information can also be found in a country's National Action Plan (NAP) document, if available. This can include:

- Amount of mercury used at specific ASGM sites
- Specific ways in which mercury is used at individual ASGM sites, such as whether mercury is vaporized into the open air, or released into the environment under more controlled conditions
- Proximity of communities to ASGM sites, with highest exposures within half of a kilometer of ASGM sites
- Size and potential vulnerability of communities to ASGM sites
- Proximity of water and food resources to ASGM sites
- Proximity to high biodiversity and/or critical wildlife areas

NAPs are available on the Minamata Convention's webpage.

Local informants can also be invaluable to help answer scoping questions, such as those related to current site characteristics and state of ASGM mining activity. Local government authorities, members of civil society organizations (e.g., NGOs, resident groups, indigenous communities), local residents or even the miners themselves can provide important and timely information not available in published reports. Additionally, geospatial information and maps are now more widely available, and can usually be accessed through using publicly available internet-accessible digital mapping platforms that range from the very general (Google Maps, Google Earth) to one that are more specific to mapping deforestation events (Global Forest Watch, Terra-I) to those tailored to identifying ASGM (RAMI, ASMspotter, Project Inambari). For more on these useful tools, refer to the guidance document on remote sensing tools for ASGM assessments (https://www.mapx.org/projects/remote-sensing-for-asgm/) which can helps practitioner understand how to use remote sensing approaches, methods, and tools to detect and monitor ASGM activities.

PHASE 2: DEFINING CLEAR GOALS AND OBJECTIVES OF THE MONITORING PROGRAM

Goals are statements that clearly define what the monitoring effort is expected to achieve during a given period. The monitoring of progress toward goals serves to track and assess the results of the monitoring activities throughout the life of the program. Goals also help guide the decision of what data is required, and how it will be obtained at distinct stages. It is therefore important to clearly define the goals before beginning any monitoring activities, to prioritize them according to the available time and budget. Ideally, a monitoring program's goals should be to develop the principles of the SMART approach: Specific, Measurable, Achievable, Realistic, and Timely. Goals will always need to be informed by well understood time and budget constraints, as it is seldom possible to assess all known ASGM sites, environmental components, or for all potential exposures. Goals and priorities should be revisited and revised frequently throughout the monitoring process to ensure that the effort remains on-track.

The overall goal for these types of monitoring programs is to assess mercury contamination from ASGM activities in specific environmental compartments or media (i.e., soil, sediment, water, and biota). However, it is useful to define goals and objectives more narrowly and tie them to the purpose for the monitoring effort. For example, Hg monitoring conducted in watersheds with nearby population centers could be used to inform policy on developing fish consumption advisories or other protective public health measures to reduce exposure risks for fish consuming populations. Hg monitoring in soils could be conducted to assess the need for mercury remediation in an area that is considered for future agriculture or agroforestry. By explicitly connecting the reason for conducting monitoring (the "Why"), the design of the methods to be used (the "How") will become more apparent.

Monitoring should ideally be done at a consistent spatial and temporal scale, prioritizing environments at sites that are most likely to have the highest mercury contamination levels, highest levels of ecosystem sensitivity (conditions for transformation of mercury to methylmercury), highest potential for mercury exposure risk to communities, highest biodiversity or highest score for providing ecosystem services. Field work to assess site conditions and collect samples for analysis should ideally have as easy and inexpensive logistics as possible to increase the probabilities of subsequent monitoring through time.

PHASE 3: DEVELOPMENT OF A STAKEHOLDER ENGAGEMENT PLAN WITH RELEVANT LOCAL COMMUNITIES AND INDIGENOUS PEOPLES TO CREATE EFFECTIVE COMMUNICATIONS CHANNELS

Phase three involves the intentional creation of relationships with local stakeholders. This goes beyond simple notification of local communities of sampling or *post hoc* presentation of findings. Instead, this phase involves actions that integrate and build local capacity in stakeholders from the beginning of the monitoring effort, through initial scoping and environmental samples to the reporting of findings and a meaningful interpretation tailored to the needs of these communities. Engaging local universities, research institutes, labs, and environmental agencies is also key to provide these actors the opportunity to contribute to the monitoring effort and build their capacity. Unfortunately, this phase is the one that is most frequently underestimated, underbudgeted, or worse, not done at all – usually to the detriment of the program. However, with sufficient awareness, planning and professional respect and empathy for local stakeholders, local engagement is typically mutually beneficial for all parties involved.

Reviews of successful programs have shown that efforts to build local engagement and capacity, promoting feelings of process co-ownership in monitoring programs is frequently a key factor in the overall successful outcome of monitoring programs (Brooks et al., 2013; Sterling et al., 2017). To do this effectively, however, requires resources, time, effort, and skill, and should be included in a monitoring program’s work plan as clearly and concretely as other tasks such as sampling or analysis activities.

Starting the process of creating an engagement plan with local stakeholders may seem challenging, but usually starts like any other planning process: a desk-based assessment. *Stakeholder mapping* allows practitioners to better understand the set of stakeholders involved, how they relate to each other, how they relate to the mercury release event, and how they may relate to the monitoring team and the organization in charge of the monitoring program.

After an initial stakeholder map is developed, a member of the monitoring team should be tasked for leading engagement with key stakeholder groups throughout the monitoring effort. This engagement can be used to exchange initial planning information with local groups, and gauge concerns and receptiveness for upcoming field Hg monitoring activities. But more than just a means of information collection or exchange, local engagement should be seen as a means of building trust and soliciting active participation with local actors and knowledge-holders. Frequently, the principal actors in ASGM areas are the miners themselves, and having these key stakeholders involved in Hg monitoring can better inform the design and execution of the program. Further this outreach can build Hg exposure risk awareness in miner populations and even provoke behavioral change on mercury handling and use. It is especially important to be aware of as many stakeholders as possible, particularly in areas where ASGM may be performed illicitly or under insecure conditions. Generally speaking, care should be taken so as not to alienate local stakeholders, and avoid compromising the quality of the monitoring effort or the safety and security of the monitoring program staff.

A foundational concept of any monitoring program should be a commitment to return the findings of any assessments to local stakeholders, and present them in a manner that they can best understand. Far too many monitoring programs fail to provide monitoring results back to local communities in a timely and comprehensive manner, if at all. This lack of feedback and reporting can be interpreted as a lack of respect and concern for local populations, and can undermine trust in the monitoring program and make future assessments more difficult due to apathy, or worse, active opposition. Common reasons frequently cited for not completing this crucial phase include: a lack of time, funds, or spending authority in final project stages, a perception that local actors may not be interested in the findings, or concerns that certain stakeholders will be displeased by findings, among others. Most, if not all, of these concerns can be preemptively mitigated through sufficient planning, and a firm commitment to interactive and iterative communication with local stakeholders.

PHASE 4: IDENTIFYING AND SECURING INITIAL RESOURCES NEEDED FOR THE MONITORING PROGRAM

Conducting mercury assessments typically require access to specialized equipment and supplies, well trained field workers, and significant investments of time and money. It is important to identify available resources throughout the process of planning and designing a monitoring program, thus ensuring the feasibility of executing the monitoring activities within time, cost, and logistics constraints. The ultimate objective of this phase is to maximize potential benefits and minimize costs given the resources available.

The costs related to sampling methods and supplies for any given monitoring program will depend on the goals of the program, and the data required to inform monitoring assessments and achieve these goals. For example, access to instruments for mercury analysis is often a significant challenge for many countries. Similarly, some sampling sites might require greater field logistics for being in areas of difficult access or in conflict and high-risk areas. Establishing partnerships with government agencies, universities, local organizations, or local communities that have the needed capacities might ease access to needed equipment, supplies and logistics. In the case of mercury analysis, if budget allows it, samples could be analyzed in certified laboratories, either in-country or in a foreign country. Because the reliability of data for a mercury monitoring program depends on a wide range of operating procedures for sample collection and analysis, it is highly recommended that a sustainable monitoring program try to build local technical and analytical capacity that will enhance the prospect for sustainability of the monitoring effort, even if more expensive in the short term.

The following actions should be considered in this phase:

- develop a rough order-of-magnitude estimate of the time and budget required for executing the monitoring program, including field and laboratory work.
- contact responsible authorities and institutions to obtain permission for site access, and the use of data produced on mercury contamination on ASGM area (if any).
- identify affordable and reliable laboratories for sample analysis with recognized QA/QC procedures.
- identify general information about monitoring parameters of interest, potential sampling points, timing, campaigns, analytical procedures, data evaluation procedures.

Once goals and priorities have been established, work to establish the required partnerships has been done, and potential field and laboratory analysis capacities have been identified, a detailed first-cut sampling plan and budget should be developed and compared to available resources. Often, budget constraints can provide significant limits for a monitoring sampling and analysis plan and potentially limit the scope of the monitoring effort. Therefore, both need to be revised and adjusted accordingly.

Although budget limitations are a hard reality, it is important to highlight the need to maintain a high standard of technical quality and rigor for sampling and sample analysis conducted in monitoring efforts at any scale. Cost cutting measures that violate scientifically valid sampling principles, or allow for sub-standard sample collection, transport, treatment and/or contaminant analysis will compromise the quality and the usefulness of the data for characterizing and assessing mercury in ASGM sites and reduce its usefulness for informed effective evaluation and decisions making.

Though listed here as a discrete phase, budget and resources management is a *continuous* process that needs to be done *iteratively* throughout the life of the monitoring program. Timely data on the amount and rate of resources used would need to be collected and analyzed in order to ensure sufficient resources for the completion of the monitoring tasks and accomplishment of the program's goals.

PHASE 5: DESIGNING FIELD SAMPLE COLLECTION AND SAMPLE ANALYSIS PLANS THAT FIT TIME, LOGISTICAL AND BUDGET CONSTRAINTS

A well-designed field sampling and laboratory sample analysis plan will determine the quality of the data obtained and to the overall cost of a monitoring program. Hence, the importance of carefully planning and designing the sampling plan, including pilot testing to refine work protocols and logistics, and training personnel to ensure accurate measurements and robust data quality, is critical. Below we present a series of actions for the design and development of a robust sampling and analysis plans for mercury monitoring in areas in and around ASGM.

- *5.A. Development of detailed work plans, timelines, and budgets*
- *5.B. Selection of sampling environments and sites*
- *5.C. Determination of site sampling frequency*
- *5.D. Selection of sampling media*
- *5.E. Sampling design, size, and representativeness*
- ***5.F.** Building capacity to collect samples for mercury analysis*

The following sections describe each of these activities in detail and discuss its relationship to the goals of Hg monitoring in and around ASGM sites.

5.A. Development of detailed work plans, timelines, and budgets

The development of a field monitoring program requires more detailed work planning, timeline development and budgeting than the initial scoping level time and budget estimates developed in phase 4.

The development of a work plan with enough detail for creating realistic timelines and budgets, frequently requires the use of methods such as a Work Breakdown Structure (WBS) (Norman, 2005). A work breakdown structure is a deliverable-oriented hierarchical decomposition of the work to be executed by the monitoring team to accomplish program objectives and create the required monitoring deliverables (PMI, 2021). The monitoring program design team should invest the time and effort to specify and evaluate each action in the monitoring plan for need, complexity, appropriateness, sequencing, dependencies, and cost. Unneeded actions should be challenged, underspecified actions should be described, overly complex activities should be disaggregated, and hidden operational dependencies should be revealed and mitigated to avoid bottlenecks. Once vetted, actions should be listed in a time sequential manner to develop project level timelines, as well as more detailed granular operation timelines for key operational objectives and deliverables.

Detailed budgets should be developed by disaggregating the rough scoping-level budget estimates developed in phase 4 by the monitoring actions listed in the WBS-based work plan described above. Individual activity costs should be estimated using the best available information. Cost estimates must be sufficiently detailed and accurate, to be able to conduct meaningful comparisons between alternative approaches and methodologies. Overall program costs are estimated by the summing individual activity costs which are tied to specific work actions that are specified in time. Given that each activity should have a well-defined start date and a duration period, it should be possible to calculate how much money will be spent, by any particular activity, at any moment of the monitoring program.

5.B. Selection of sampling environments and sites

The selection of sampling environments, sites, and media within a monitoring area of interest is a key part of developing a viable monitoring plan. *Sampling environments* are defined here as the environmental compartments located in and around the monitoring study area that will be sampled. *Sampling sites* are specific locations within a given sampling environment where samples will be collected. *Sampling media* is the environmental matrix (e.g., soil, air, biota) that will be sampled at a given site with a given environment.

A review of Hg assessment studies in and around ASGM areas found that most studies/monitoring efforts sampled only from a single environment and a single environmental media in the areas of interest (Annex). Sampling from only one environmental compartment is considered insufficient for developing a comprehensive understanding of the behavior, mobility, and fate of mercury in the environment. As such, data should ideally be acquired from two or more media that include both abiotic and biotic samples for a more complete assessment of the study site.

5.B.1. Selecting sampling environments

There are two main types of environments that can be sampled: aquatic and terrestrial. There are three aquatic environments relevant for ASGM monitoring: freshwater, coastal and marine ecosystems. These environments include lotic ecosystems (flowing waters such as rivers and streams), lentic ecosystems (standing water habitats such as lakes and ponds), and several types of wetlands ecosystems. The terrestrial environments for ASGM-Hg monitoring include forest, grassland, desert, tundra, and mountain/alpine ecosystems. As ASGM is found in all terrestrial environments, except in permafrost Arctic/Antarctic environments, any of these can be the focus of monitoring efforts.

Selection of the sampling environment(s) will depend on a combination of factors such as the monitoring program’s objectives, site accessibility, and available resources. As a practical matter, if resources are limited, priority should be given to sampling in aquatic environments (with a preference to lentic systems over lotic systems due to greater ease of representational sampling) with aquatic biota (with a preference to non-migratory high-trophic level fish) as the sampling media. Due to their position in aquatic food webs and the tendency of methylmercury to biomagnify up food webs, predatory fish species tend to integrate the signal of bioavailable mercury present in a given aquatic ecosystem. Hg levels will tend higher in top predatory (high-trophic level) fish, meaning that the mercury analysis for these samples is unlikely to require costly low-level (parts-per-billion range) or ultra-low level (parts-per-trillion range) mercury measurement.

5.B.2. Selecting sampling sites

Practitioners should carefully select the sampling sites prior to engaging in field measurements and sample collection. An effective monitoring program ideally should sample both the sites to be monitored in suspected contaminated areas and in control sites, which can be described as ‘monitoring sites that are identical in all respects to the site being assessed (sometimes called the test site) except for the disturbance[1]. The use of local mercury baseline levels as control data, as opposed to regional/global-scale baselines or published mercury reference levels, will result in more accurate quantifications of Hg enrichment in areas in and around ASGM. When selecting control sites, care should be taken to ensure that they are comparable in as many aspects as possible to the monitoring sites except for the presence of mercury from ASGM (e.g., altitude, weather, vegetation). A first cut for site selection would identify a list of potentially contaminated and control sites in and around the area of interest, with a careful registration of each site's geospatial coordinates. This list would then be sorted using selection factors related to monitoring program's objectives, resource constraints and site characteristics (e.g., risk of human and wildlife exposure, site accessibility, safety).

5.C. Determination of site sampling frequency

An important decision related to site selection involves the determination of sampling frequency, which is the number of times that sampling will occur within a given time period (e.g. month, season, year, decade). This is critical to develop temporal trend data on mercury levels. Given that one of the main goals of a mercury monitoring program, as opposed to one-time rapid mercury assessment, is that mercury levels are measured over time to develop time series information that can help answer questions regarding changes in contaminant levels resulting from ASGM activity, inter-seasonal variations, or to evaluate the effectiveness of an policy or enforcement action.

Reliable observations of long-term trends in monitoring data require that sampling frequencies be related to the average annual variability of the environmental compartment to be sampled. For example, the optimal sampling frequency for tropical river ecosystems with strong seasonal variability in precipitation would be different than in lakes that are fed by the outflows from hydroelectric dams. Climate variation is typically an important factor for deciding site sampling frequency. In another example, temporal variations in tropical environments are driven by seasonal rainfall variability rather than by changes in temperature, as in temperate environments. This means that when sampling in tropical rivers, large (sometimes extreme) temporal variations in river discharge between wet and dry seasons can result in high fluctuations in the amount of suspended matter loads. Given that mercury transport in rivers is strongly governed by suspended matter loads, ideally sample collection should be done both in dry and rain seasons to account

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[1] Australian and New Zealand Environment and Conservation Council (ANZECC) & Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ), 2000

for this variation. In this case, if sampling at a higher frequency was not possible, sampling bias errors could be reduced by sampling in a consistent manner in time (e.g., sampling on a similar date every year) allowing the data to be compared across years and develop a time trend. Understanding these aspects will also help to select the appropriate sampling media that would be collected at a given sampling site within a given sampling environment.

5.D. Selection of sampling media

After sampling environments and sites have been selected, the next phase is to choose the sampling media, which may include biota, soil, sediment, and surface water. This section presents general aspects to consider for the selection of the most adequate environmental media to monitor mercury in and around ASGM sites. For this task, it is useful to understand the cycling of mercury in the environment, how mercury behaves in each media, as well as the advantages and disadvantages of monitoring ASGM-related mercury in each of them.

Figure 1. Diagram of the Hg cycling, showing order of magnitude of mercury concentrations in different compartments [this figure is under development and it is intended to help practitioners understand in which compartments it is more relevant and easier to monitor mercury levels]

As in the case of the sampling environments, data should ideally be acquired from two or more media for a comprehensive monitoring program. Given constraints, priority should be given to sampling biota, sediments and soils in and around ASGM sites where mercury is used, or expected to be used, and in sensitive ecosystems. *Sensitive ecosystems* are defined as those ecosystems with characteristics that favor the production and bioaccumulation of methylmercury that could represent an exposure route for vulnerable populations and wildlife.

It should be noted that this guidance document focuses on mercury monitoring in aquatic and terrestrial environments using biota, sediment, soil, and water as sampling media. Although mercury monitoring in air is not discussed in this document, generally speaking it is important for air monitoring to be included in mercury monitoring in and around ASGM sites due to the significant amounts of Hg that can be emitted to the atmosphere during gold extraction and processing in ASGM. Information on how to conduct atmospheric mercury monitoring using a tiered approach, and the relevancy for monitoring mercury in air to understand the findings in other media is presented in Chapter 3 of the Convention's EE Guidance (UNEP, 2021a). Likewise, although human mercury biomonitoring is also not addressed in this guidance; it should also be considered as a component in a comprehensive mercury monitoring program. Information on developing a human mercury monitoring program is presented in Chapter 5 of the Convention’s EE Guidance (UNEP 2021a) and technical information documents published by the World Health Organization such as Guidance for Identifying Populations at Risk from Mercury Exposure (UNEP, 2008).

5.D.1 Biota and wildlife

Biota is the most examined medium for mercury levels in areas in and around ASGM sites due to the ability of methylmercury (MeHg) to bioaccumulate in living organisms and biomagnify along food webs. Because MeHg is primarily produced in aquatic systems, and fish consumption is the main exposure route for humans, research efforts and public attention have focused on the monitoring of Hg exposure in fish and high-trophic-level fish-eating wildlife species, such as birds and mammals. MeHg can cause a range of neurochemical, behavioral, hormonal, and reproductive adverse effects to fish, mammals, and birds at environmentally relevant exposure levels (Basu et al., 2005, 2006; Clarkson & Magos, 2006; Scheuhammer et al., 2007; Wiener et al., 2003; Wolfe et al., 1998). Long-term biomonitoring programs with standardized sampling protocols used for tracking temporal trends are still infrequent and are mostly conducted in temperate and boreal areas (see Part A-Section 2 in Supplementary Material of the Main Guidance). In the tropics, systematic studies of mercury levels in wildlife and the effects of mercury exposure have been particularly understudied despite the high priority placed on conservation of tropical ecosystems.

5.D.1.1 Bioindicators

The selection of bioindicators for biota should be made based on the characteristics of the species to qualify as a good bioindicator within the constraints of the monitoring program. It is important that the species selected and tissue used for Hg measurement is appropriate for the characterization of temporal and spatial mercury trends, and serves to link mercury source to exposure to wildlife and human communities. Biomonitoring efforts should focus on commonly consumed local plant and/or animal species that could reveal an exposure pathway to wildlife (or human) populations. These samples could also serve to indirectly provide useful information on Hg contamination in surrounding abiotic media such as sediment and water.

For wildlife monitoring, Hg levels in fish, birds and mammals can be especially useful as bioindicators because they provide information that can be directly associated with Hg exposure to human and other wildlife health. However, monitoring these taxa can be costly and logistically complex since sampling may need to be done at a species or genus level (depending on the taxa) with sufficient sample size for representativity. Factors such as rarity, conservation status and species-specific behavioral strategies (e.g., migration, lunar phobia) may also complicate sampling and make reaching minimum sample sizes for quantitative and meaningful results difficult. If soft tissue is to be sampled (as in the case of fish and mollusks), a consistent cold chain transport would be required for sample integrity, which may be a logistical challenge in some remote areas.

If these challenges are significant, monitoring programs may also want to consider using other taxa as bioindicators, such as aquatic invertebrates, to characterize Hg in study sites. For example, dragonflies (order *Odonata)* can be useful and low-cost bioindicators for mercury in aquatic ecosystems. Dragonfly larvae are aggressive predators that can live for years underwater eating insects, and even small fish, and accumulate Hg that can serve to provide insight into the mercury loads in the streams in which they live (Eagles-Smith et al., 2020). Dragonflies larvae are easier and more economical to sample than fish, with lower transport costs to the laboratory. Samples can be air dried or kept in alcohol until the arrival to the lab. Because of the lower costs and complexity, the use of dragonflies can be used as a scoping-level biota indicator to identify if other organisms such as fish and fish-eating wildlife are at risk of Hg toxicity. They can also be a useful and interesting tool for identifying sensitive or vulnerable ecosystems that would require more in-depth monitoring using other complementary abiotic and abiotic sampling matrices.

Vegetation can also be a useful indicator to assess Hg contamination in and around ASGM. For example, paddy rice (*Oryza sativa*) is a commonly consumed species that has recently been identified as one that biomagnifies methylmercury present in the soils and suspended sediments transported by irrigation waters. There is a growing concern that rice consumption may represent a significant pathway to methylmercury exposure in populations that have high rice consumption. Another example that focuses instead on non-consumable vegetation, uses soil litter vegetation under the canopies of intact, mature forests as indicator of airborne mercury deposition resulting from ASGM mercury amalgam roasting. Recent studies have reported that mature forests can act as scrubbers that capture available atmospheric mercury with their leaves and direct it down into the leaf litter below and subsequently into the top layers of forest soils. In this way, leaf, and leaf litter in forests around ASGM sites can be used as bioindicators to indicate the magnitude and extent of mercury pollution around ASGM sites and provide stable sampling points for long term monitoring (Gerson et al., 2022).

5.D.1.2 Sample matrix

The selection of the sampling tissue will strongly depend on the study taxa and on available field resources and laboratory capacity. The type of tissue collected from the sample specimen should be chosen based on available information on the percentage of methylmercury that is typically present in the tissue. The most commonly used tissues in animal monitoring are muscle, blood, fur, eggshells, and feathers since they primarily contain methylmercury. For example, the scientific literature indicates that about 90% of the total mercury that is present in bird feathers and blood is methylmercury (Rimmer et al., 2005; Thompson & Furness, 1989). This is significant because this means that these samples can be analyzed for total mercury concentration instead of methylmercury concentration.

The analytical methods for measuring total mercury (THg) are simpler and more cost-effective than those for MeHg. THg measurement data can then be extrapolated to MeHg concentrations. For plant studies that aim to assess mercury levels in agricultural products, the sample matrices are the parts of the plant that are edible, since these would be the route of exposure (e.g., rice grains, fruits, nuts). The same logic regarding MeHg fraction in helping to decide a sample tissue can be applied to plant tissues as well.

5.D.1.3 Monitoring sites

The selection of monitoring sites for mercury biomonitoring should be done based on the ecosystem sensitivity to mercury. As mentioned above in section 2.3, sensitive ecosystems are ecosystems (typically aquatic) that have certain conditions that can promote the production of methylmercury. Further details on mercury biomonitoring and ecosystem sensitivity is found in the Convention EE Guidance, section 4.3 and 4.4.

5.D.1.4 Sampling techniques

Biota sampling strategies and techniques will depend on whether the aim is to collect flora or fauna samples, and within those groups, the species and tissues of interest. Field protocols for biota sampling are available for all tissue types (see Part A-Section 2 in Supplementary Material of the EE Guidance). Although the collection of samples from individual species is ideal, composite samples can be considered if resources are limited. Composite samples are made of tissue from the same species, and from individuals with similar characterics such as body size and sex).

Sampling efforts should be informed by the knowledge and participation of local stakeholders to increase knowledge, sampling efficiency, and increase buying and a sense of ownership of the monitoring effort by local communities. For example, in the case of sampling fish, consulting with local fishers who are familiar with target species and its behavior, seasonality and habitat may provide higher-quality information, increase sampling success and efficiency, and reduce sampling costs. There are numerous opportunities for this sort of collaborative interaction with local stakeholders, and we encourage practitioners to explore these options in their design and execution of sample collection.

5.D.1.5 Sample storage and preservation

Soft, perishable tissue should be kept in a cold chain (frozen or, at minimum, at 4°C) until arrival at the laboratory. Once in the lab, samples can be analyzed in a wet or dry form. If the sample is to be analyzed dry, the water content must be calculated as Hg concentrations in soft tissue are usually reported on a wet weight basis. Among drying methods, freeze drying is preferred as it preserves the mercury in the samples and produces a shelf-stable sample that does not require refrigeration. Non-perishable tissue such as hair, fur, and feathers, do not require refrigeration.

5.D.1.6 Ancillary measurements

The minimum requirements of ancillary measurements for animal samples should include scientific species name, common name, body size, body weight, sex, reproductive stage, when possible and feeding habit. Features of the ecology of the species, such as migratory behavior, should also be recorded. Moreover, if samples are acquired in local markets, information on the sampling location should be provided. Ancillary data for flora samples should include scientific and common species name, as well as size and growth stage. This information is important to be recorded and can be especially useful if ecotoxicological assessments are done at a later date since Hg measurements could be associated with ecological characteristics.

5.D.2: Soils

Soils are an important factor in interpreting the results of mercury analysis of other types of samples in a particular location. Depending on the characteristics of the soils, these can serve as a source and a medium for accumulating mercury either from direct releases or by deposition from the atmosphere (Gerson et al., 2022). Soil erosion and surface runoff are the predominant components in the transport of mercury from terrestrial systems to aquatic systems. Further details on the accumulation of Hg in soils, including the relevance for the monitoring are presented in Section 2.4.

5.D.2.1 Sampling techniques

Adequate soil sampling is fundamental for monitoring mercury in terrestrial environments. The sampling technique to be applied depends on the objective and resources of the monitoring program, as well as on the characteristics of the soil in the sampling location. Soil sampling can be done using shovels, spoons, hand augers, soil probes, core samplers, among others.

It is important to develop and use a standardized sampling design that is used in a consistent manner throughout the life of the monitoring effort. Ideally, sampling should be done at different distances from Hg point sources, and at different depths to monitor long-term horizontal and vertical mobility of mercury. If sampling is to be conducted at a single depth, it should be clearly defined whether samples are to be taken from the humus (organic) cover or the mineral soil (which itself can be divided in the topsoil and the subsoil). Clearly defining the boundaries of each soil layer is also important for sample collection. A review of several Hg monitoring studies revealed that many soil Hg studies often report collecting samples from the “topsoil” but varied on the depth that the upper layer of the soil covers that was actually sampled hampering comparability.

Figure 2: Commonly used soil samplers. Shovels (top), soil auger (bottom). Sources (in clockwise order from the top left): Flickr, StockLib, Kim et al. (2012), Flickr.

Because mercury is primarily bound to fine-grained particles (silt-clay fractions), sieving samples through either on-site or upon arrival to the lab for fractionation (i.e., sort particles into size categories) is recommended. Sieving in the field provides the advantage of reducing the amount of sample material to be transported (thus reducing transportation costs). Ideally mercury concentrations should be analyzed within different grain-size fractions to identify the fractions with a higher adsorption capacity. However, if this is not possible, fine-grained soils should be prioritized. If Hg analysis will only be conducted in the fine-grained fraction, samples in the field can go through a first fast sieving process (using a non-metal sieve) to discard large particles (gravel) and keep only the sand-lime-silt fraction. Once in the lab, samples are sieved a second time to separate the sand from the silt-clay fraction. The boundary between grain-size particles is arbitrary. According to the Unified Soil Classification System (USCS), gravel and sand are separated by a sieve with an opening of 4.75 mm, whereas sand and silt are separated using a sieve with an opening of 0.075 mm. The British standard sets the boundary between gravel and sand at 2 mm and the boundary between sand and silt at 0.063 mm.

5.D.2.2 Sample storage and preservation

Soil samples should be kept in plastic bags with a hermetic seal with all air removed and placed in cold containers (4°C) and in the dark until the analysis. If the sampling is conducted close to ASGM processing sites and there is the possibility of having metallic mercury in the samples, then samples should be kept in tight containers. A possibility is to use vacuum bags. Vacuum storage will also avoid oxidation of the samples. Once in the lab, if Hg analysis is conducted in wet samples, a subsample needs to be taken for determining water content by oven-drying to constant weight at 105°C for at least 24 hours. Mercury concentrations in soil are reported on a dry weight basis. If sample drying is required, freeze drying (lyophilization) is the preferred method followed by air drying. Oven drying is the least preferred method but can be done below 40°C and only for samples not collected in or close to ASGM processing sites where there are higher probabilities of presence of metallic mercury. As elemental Hg evaporates at room temperatures, some elemental Hg present in the samples could get lost during the drying process.

5.D.2.3 Ancillary measurements

Mercury concentration variations in soils are explained by the input of Hg to the soil and the chemical and mineralogical soil properties. In addition to measuring Hg concentrations, soil samples should be analyzed for pH, cation exchange capacity (CEC), organic matter, clay, silt, sand and iron and aluminum oxide contents. Because soils can help to predict the behavior of mercury in the study site and help interpret available mercury data in other media of the same location, it is recommended to identify and report the soil type or types present in the study area. Examples of international soil classification systems are the FAO World Reference Base for Soil Resources (WRB) and the USDA soil taxonomy system. Other ancillary data that can be recorded include visual characteristics such as color (yellow or red color indicate, for example, presence of iron oxides as in the case of ferralitic tropical soils), texture (e.g., muddy, or sandy), land cover (e.g., forest soil or disturbed soil), and sampling depth.

5.D.3 Surface sediments

Sediments are the main sink and source of mercury and other heavy metals in aquatic systems, and have a critical role in the mobility, bioavailability, and fate of these elements in the environment. The adsorption, mobility, bioavailability, and environmental fate of mercury in sediments depend on the chemical form in which mercury is present, the sediment geochemical properties (e.g., texture and content of organic matter, clay minerals and oxides) and the water properties (e.g., pH, salinity, redox conditions, dissolved oxygen). As in soils, Hg in sediments is found enriched in fine-grained particles, i.e., silt and clays (<0.075 or 0.063 mm), due to their high surface area and higher content of clay minerals, aluminosilicates, oxyhydroxides and fine organic matter compared to coarse sediments.

5.D.3.1 Sampling techniques

There are several approaches and methods available for sediment sampling. Selecting the correct approach will depend on the objectives of the monitoring program, available budget, characteristics of the target water body (still-water vs running-water ecosystems or shallow vs deep water ecosystems), and the texture of the sediments in the water body (e.g., lime and clay vs sand). In still-water (lentic) environments, such as lakes and ponds, sampling focuses on bottom sediments, which are accepted as a sink as well as a source of contaminants in the aquatic environment. In running-water (lotic) environments, bottom sediments are easier to collect in slow-flow stretches. In high-flow rivers, like tropical rivers, sampling of suspended sediments would be more adequate for monitoring ASGM-related mercury, as it is transported primarily bound to fine-grained sediments. During high discharge events, fine-grained particles in bottom sediments are resuspended and transported downstream as suspended particulate matter. As a result, bottom sediments of fast-flowing rivers may lack fine-grained sediments and be mostly composed of sand.

In still-water environments, grabs and manual dredges are the most popular techniques for bottom sediment sampling. They are versatile, easy to handle and relatively economical. Samples should be collected from the grabs using non-metal spatulas or spoons by removing the first 3 to 5 cm from the middle of the grab. Heavier grab alternatives must be considered for fast-water environments as bottom sediments can be tricky to collect with lightweight grabs as high flow rates may hinder the grab reaching the bottom of the river or stream. Also, bottom sediments in fast-water environments may lack fine-grained material to which mercury is bound to. A more economical and easier alternative for sediment sampling in fast-water environments are riverbank sediments, which can be collected manually using scoops or spoons. In rivers that transport high loads of suspended sediments (such as tropical whitewater rivers), sampling suspended particulate matter (<0.45 um) should be considered (see surface water sampling section).

Independently of the type of water body and the applied sampling technique, sediment sampling should focus mainly on the fine-grained fractions (see section D.2.1 soils).

Figure 3: Commonly used surface sediment samplers.

5.D.3.2 Sample storage and preservation

The storage and preservation approaches and methodologies for sediments are the same as those applied for soil samples (see section 5.D.2.2).

5.D.3.3 Ancillary measurements

Ancillary data that can help with interpretation of mercury sediment data are the same as those for soils (see section 5.D.2.3 soils). Mercury enrichment in aquatic food webs can be limited in the absence of fine-grained, organic-rich sediments to which Hg preferentially partitions and in anoxic conditions which may facilitate Hg methylation. Although requiring high-sensitivity analytical methods, other ancillary data that can help to interpret mercury sediment data, especially when studying or monitoring lentic sediments, are the concentrations of conservative lithogenic elements, such as titanium (Ti) and zirconium (Zr), which are considered to be geochemically stable and conservative in most geochemical environments, and can provide insights into the changes in the weathering regime of a catchment, as well as of the source of Hg in lake sediments (Boës et al., 2011; Koinig et al., 2003). Carbon-to-nitrogen (C/N) ratios can also be used as an indicator of organic matter sources (Meyers & Ishiwatari, 1993).

5.D.4 Surface water

Water is an environmental compartment frequently considered as a monitoring medium for mercury pollution in and around ASGM areas driven mainly by concerns of Hg contamination of drinking water. However, it is important to highlight that drinking water consumption is not found to be an important pathway of mercury exposure to humans due to low concentrations in water as compared with concentrations in fish. Hg in water is present primarily as Hg^{2+} (a non-bioavailable form of mercury), rather than as methylmercury. Hence, Hg present in water and ingested would have very low absorption and pose a low risk to humans or wildlife. Further, the generally low Hg concentrations in water require more sensitive measurement instruments and/or require the use of preconcentration techniques that could make the sampling and analysis more complicated and expensive. Because of these factors, water monitoring is not considered an effective environmental compartment for monitoring mercury in areas in and around ASGM. If a decision to monitor mercury in water is made, we highlight considerations for sampling in this medium below.

Mercury in water samples is inherently unstable. If inadequate measures are applied, mercury losses can occur due to adsorption on the container's interior wall or through volatilization. Cross-contamination can also easily occur. The accurate analytical determination of mercury concentrations at low levels is also a significant challenge because mercury in water occurs both in the particulate (particle size >0.45 um) and dissolved phase (particle size <0.45 um). The latter is considered to be the bioavailable fraction. Hence, water samples require filtering using membrane filters. As mentioned above, samples also require sensitive (and expensive) analytical instrumentation capable of detecting concentrations at nanogram level. All these factors contribute to the determination that water is a highly challenging, and unsuitable environmental media for monitoring mercury in and around ASGM sites.

In river and lake water, mercury is associated with suspended particulate matter (SPM). In lakes, mercury settles to the lake bottom along with the sediments, whereas in rivers, the variability of Hg concentrations reflects differences in suspended matter loading. The latter is particularly evident during high discharge and rainfall events in fast-moving fluvial systems in which suspended particulate matter is dominated by mineral particles. A thorough understanding of mercury binding to SPM is critical for understanding the behavior and environmental fate of mercury in areas in and around ASGM, and for assessing the risk for entering and accumulating in aquatic food webs.

5.D.4.1 Sampling techniques

To monitor mercury in water in and around ASGM sites, the use of samplers with a simple operation, long-shelf life and low cost should be prioritized. The easiest way to collect a water sample is with a flask or bottle. Sampling should be conducted consistently, always at the same depth, and with the same sampling protocol. For analyzing dissolved mercury in water, samples should be filtered using membrane filters of 0.45 um after preconditioning the filters using a small amount of sample, ideally on-site or within 24 hours after the collection. For analyzing total mercury in water, samples should be filtered as described above, and the filters should be kept to also be analyzed for mercury content. The total concentration of mercury in water will be the sum of dissolved mercury in water, and mercury bound to particulate suspended matter.

Figure 4 : Commonly use surface water samplers

Figure 5: Figure showing the water sampling process for dissolved and total mercury. [this figure is under development]

5.D.4.2 Sample storage and preservation

Mercury in solution is known to be unstable during storage. Factors that affect the stability of mercury include: the form in which the mercury is present in the solution (speciation), the container material and the preservation techniques. There is currently no consensus on the material of the containers that should be used to store aqueous samples for environmental mercury analysis.

U.S. EPA standard methods suggest samples should be treated with a preservative in glass, high-density polyethylene (HDPE) or fluoropolymer bottles upon collection or within 48 hours of collection. Studies using Teflon, quartz and glass containers have reported mercury losses. In academic research, polypropylene tubes are often used for mercury water analysis. In any case, to minimize adsorption and cross-contamination, sampling should always be conducted using new containers as reused flasks are a major source of mercury cross-contamination. From the moment of sampling to the moment of the analysis, all samples should be kept in dark conditions and in a cold chain of 4°C.

Regarding sample preparation, there is also no consensus for the best preservation method for water samples. The currently accepted method in the Contract Laboratory Program (CLP) Inorganic Statement-Of-Work (SOW) of the U.S. Environmental Protection Agency (EPA) for the preservation of mercury samples requires a stabilization with 2% nitric acid (HNO_3) with an allowed holding time of 26 days prior analysis. Nevertheless, there are reports that acidification of water samples is unsuitable for preserving samples for mercury analysis. A variety of chemical reactions can take place inside the sample containers. Some of these reactions may produce elemental mercury Hg^0 which can get lost by permeation and diffusion through the wall of containers or volatilize through the threads of the bottle cap. To avoid this, the USEPA Method 1631 recommends stabilizing the samples using 1% of a solution of bromine chloride (ultrapure grade). Stabilizing the water sample with potassium permanganate-persulfate is also an option. The addition of these oxidizers ensures removal of all Hg^0 by transforming it into the more stable Hg^{2+}.

5.D.4.3 Ancillary measurements

The dynamic of mercury in aquatic systems is controlled by the chemistry of water, dissolved organic matter and suspended matter composition. Therefore, ancillary data required to be collected for mercury analysis in water include: (1) physicochemical water parameters such as pH, conductivity, temperature, and dissolved oxygen, (2) concentration of organic carbon (total organic carbon (TOC), particulate organic carbon (POC) and/or dissolved organic carbon (DOC)), and (3) concentration of suspended particulate matter. The capability of reactive Hg^{2+} to bind to DOC is particularly important in waters with high ratios of mercury to DOC such as tropical blackwater rivers. Monitoring programs including sampling in running waters should also record the water flow, discharge rates and climatic conditions such as rainfall, especially when working in tropical systems.

5.E. Sampling design, size, and representativeness

To ensure robust data quality, the sampling program should develop and use a standardized sampling design (i.e., systematic, stratified, or random), sample collection protocol (for example, always in the middle of the river channel) and a minimum sample number that is required to be collected to achieve statistical power. Information on the minimum sample material to be collected should be provided by the laboratory that will receive and analyze the samples.

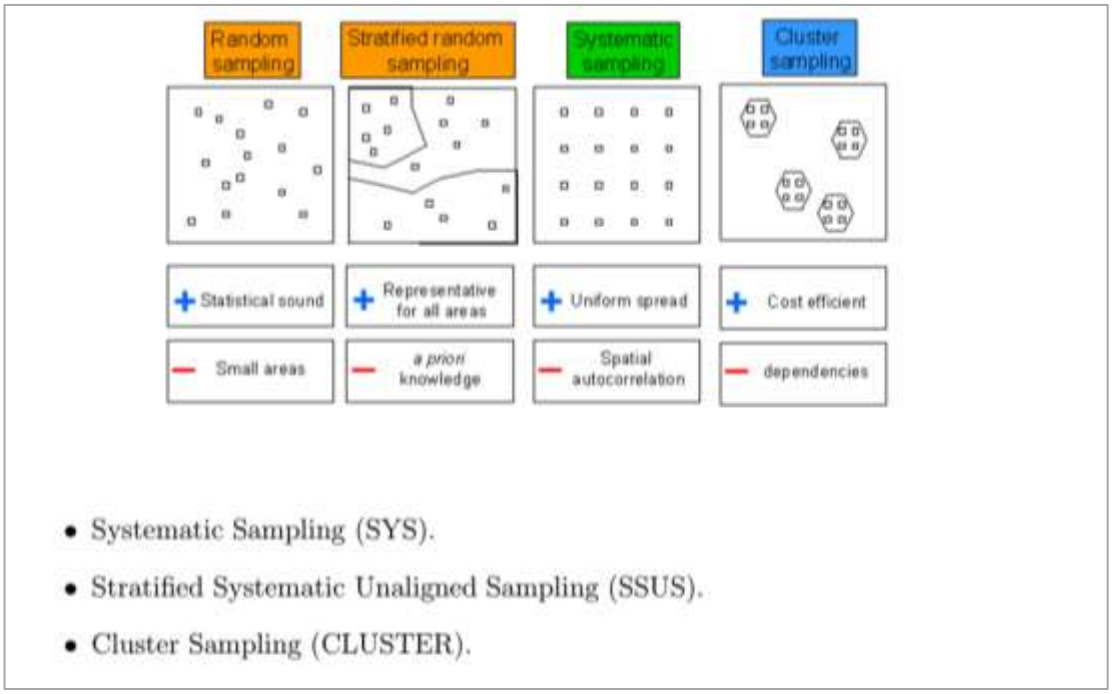


Figure 6: Sampling approaches and major advantages and disadvantages (Banko 1998).

In and around ASGM areas, sampling locations are chosen based on their location relative to extraction sites and workplaces or known Hg-contaminated sites. In rivers, for example, sampling is done upstream and downstream from ASGM operations. Upstream or adjacent streams with similar characteristics to the monitoring sites should be sampled as controls. If access to control sites is not possible, comparison with previously reported Hg values in the study area and/or similar ecosystems may also provide useful insights.

5.F. Building capacity for effective sample collection for mercury analysis

Successful field work for sample collection requires trained skilled field workers to achieve effective site inspection, sampling collection and on-site measurements. For example, in soil studies, if information on soil characterization is not available, at least one person with sufficient scientific knowledge to do this task would be required. Including local people as active participants in monitoring programs may contribute to significantly increasing the quantity and quality of information obtained. Stakeholders and local communities in sensitive or affected areas can also provide useful information based on traditional knowledge.

PHASE 6: CARRYING OUT FIELD SAMPLE COLLECTION, SAMPLE ANALYSIS AND INTERPRETATION OF THE RESULTS TO DEVELOP BASIC KNOWLEDGE OF MERCURY LEVELS IN TARGET SITES

Once field sampling has been conducted (phase 5), it is important to ensure reliable mercury data by following appropriate sample handling and transportation protocols (see sections on sample storage and preservation in phase 5 section D), using appropriate analytical protocols for the mercury sample analysis. It is important to send samples to a laboratory with sufficient experience with the needed analyses using the targeted sample matrices, and one that has verifiable quality control / quality assurance credentials. Once Hg sample measurement data have been generated, the use of an appropriate statistical data analysis protocol is a crucial phase to interpret the data and produce useful findings.

Analytical techniques for mercury analysis

There are a variety of analytical techniques for analyzing total mercury and mercury compounds in environmental samples (Bank, 2012). Among the most frequently used techniques for total mercury determination are cold-vapor atomic absorption spectrometry (CV-AAS), cold-vapor atomic fluorescence spectrometry (CV-AFS) and direct thermal decomposition atomic absorption spectrometry (DTD-AAS). Other techniques used for analyzing Hg include the multi-element analyzers inductively coupled plasma techniques such as inductively coupled plasma mass spectrometry (ICP-MS) and inductively coupled plasma atomic emission spectrometry (ICP-AES) or inductively coupled plasma optical emission spectrometry (ICP-OES).

Analytical advantages and limitations

The selection of a suitable analytical technique will depend on the detection limits needed to produce meaningful data, in this case the selected sample matrix, the available sample amount, and the potential interferences specific to the method play an important role as well (Bank, 2012). CV-AAS is the traditional and still one of the most used techniques for the determination of total mercury, with a great number of methods that can be used with it in a variety of sample matrices (see Table 1). The traditional models allow measurements in the range of part-per-million and part-per-billion, although the new models can reach the part-per-trillion level. CV-AFS is a high-sensitive and high-selective technique that allows measuring Hg concentrations at the part-per-trillion and sub-part-per-trillion levels. In the case of the DTD-AAS the detection limit is typically around the part-per-billion; however, there are new commercial options that can measure down to the part-per-trillion level.

CV-AAS, CV-AFS and DTD-AAS are all suitable for determining total Hg in solid and liquid matrices. However, CV-AAS and CV-AFS detect Hg in solution for which solid samples (e.g., sediments, fish tissue and plant material) need to be acid digested prior analysis to extract the mercury from the sample matrix. DTD-AAS has the advantage that it does not require sample preparation prior analysis. Furthermore, it does not generate acid waste or require expensive high-purity gasses for its operation; it can be operated even with compressed air.

In the context of Hg monitoring in and around ASGM areas, TDA-AAS offers a fast (analysis time of about 6 minutes), accurate and cost-effective mercury analysis. However, if working with samples containing high Hg concentrations (above 1000 ng absolute Hg), the sample should be digested and diluted even for the TDA-AAS technique. ICP-MS can detect Hg concentrations; however, it is significantly much more expensive than the other analytical techniques. ICP-AES or ICP-OES is not recommended for trace element analysis or samples with relatively low concentrations due to low sensitivity.

The cost for the laboratory analysis per sample can vary greatly and will depend on the analytical technique, cost of materials, labor, instrument time and administrative costs and the number of samples to be analyzed. For example, the cost of analyzing a sediment sample by DTD-AAS which does not require prior sample preparation should be significantly lower than analyzing the same sample by CV-AAS or ICP-MS which requires previous acid-digestion of the sample and has a higher cost of consumable and maintenance.

Table 1. Selected methods for the analysis of total mercury (modified from Bank, 2012)

Analyte	Matrix	Detector	Reference or EPA method	Typical MDL
Total Hg	Water	CVAAS	EPA Method 245.1	5-10 ng/L
Total Hg	Water	CVAFS	EPA Method 245.7	0.5-5 ng/L
Total Hg	Water	CVAFS	EPA Method 1631	0.1-0.3 ng/L
Total Hg	Water	ICP-MS	EPA Method 200.8	10 ng/L
Total Hg	Water	ICP-AES	EPA Method 200.7	200 ng/L
Total Hg	Sediment	CVAAS	EPA Method 245.5	5-10 ng/g
Total Hg	Sediment	CVAAS	EPA Method 7471	10-50 ng/g
Total Hg	Sediment	DTDAAS	EPA Method 7473	5-10 ng/g
Total Hg	Sediment	CVAFS	EPA Method 1631 appendix	0.5-1 ng/g
Total Hg	Tissue	CVAAS	EPA Method 245.6	5-10 ng/g
Total Hg	Tissue	DTDAAS	EPA Method 7473	5-10 ng/g
Total Hg	Tissue	CVAFS	EPA Method 1631 appendix	0.5-1 ng/g
Total Hg	Blood	ICP-MS	Palmer et al. (2006)	0.17 ug/L
Total Hg	Blood	FI-AAS	Palmer et al. (2006)	0.6 ug/L

AAS = atomic absorption spectrometry; CVAAS = cold vapor atomic absorption spectrometry; CVAFS = cold-vapor atomic fluorescence spectrometry; FI = flow injection; ICP-AES = inductively coupled plasma atomic emission spectrometry; ICP-MS = inductively coupled plasma mass spectrometry; MDL =method detection limit; DTD = direct thermal decomposition.

Quality assurance (QA) and quality control (QC)

QA and QC are two major aspects of the quality management system and ensure the high-level of confidence of the results produced by a laboratory. Appropriate QA procedures enables a laboratory to show that it has reliable and well-maintained facilities and equipment to conduct the chemical analysis, follow standard operating procedures (SOPs) and has trained staff to perform the analysis and process the data. Good QC procedures include running blanks, replicates, internal standard, and reference materials with each set of samples and gives the laboratory the confidence of producing accurate and reliable data.

Data analysis, interpretation and reporting

The Hg results obtained from the sample analysis, combined with available ancillary data, should be analyzed, interpreted and reported according to the research hypothesis and objectives of the monitoring plan. When analyzing the data, the correct use of statistical procedures is critical to produce reliable data and draw reasonable conclusions. Alternatives of statistical procedures are beyond the scope of this guidance. Practitioners should consult guides on environmental statistics testing to ensure proper data interpretation.

The results obtained from the study sites should be compared against those from control sites or regional background values. If these are not available, the results can be evaluated using international environmental quality guidelines/criteria based on background or reference values (e.g., WHO, USEPA, EU). This will ease the accurate quantification of the enrichment of Hg levels in the study environment and to evaluate the link to ASGM activities. Long-term monitoring data can be processed to assess changes in mercury concentrations over time. A risk assessment can also be conducted to assess the probability and consequences of Hg contamination. In the reporting stage, it is important to communicate the results of the monitoring program in a summarized form (e.g., tables or graphics) that enables decision makers to easily and quickly understand the findings.

PHASE 7: COMMUNICATING THE RESULTS TO STAKEHOLDERS AND INTERESTED PARTIES

The effective communication of the results of monitoring efforts to stakeholders, decision-makers and interested audiences should be considered a fundamental phase of any monitoring effort. By effectively conveying findings to key audiences in a timely manner, the monitoring team can provide information that can be used to better inform decisions by government and civil society actors, engender public engagement and awareness, inform relevant subject matter and technical experts, and empower potentially impacted vulnerable population with information about Hg in their environment.

The goal of any communication effort should be to increase understanding of key messages in targeted audiences. This basic tenet is applicable for technical reports directed at specialists, non-technical research briefs directed at policy audiences and the public, or media summaries intended to inform reporters and subsequently, the public. To do this effectively, particularly regarding an issue as potentially impactful as mercury pollution, requires considered thought and planning. The goals of this effort should be to identify, include, reach and inform all key audiences in a timely manner, and in a way that each audience understands the findings and can use the information to better inform their decisions. A brief description of some communication tools that could be employed during the communication phase of a monitoring effort is provided below.

Technical Reports

Technical reports should provide, at minimum, a detailed description of the goals and objectives of the monitoring effort, sufficient background information to provide context, a clear and detailed description of all methods used, concise reporting of the measurements and results, and a section that interprets the results to develop a set of findings and conclusions. Technical reports are usually considered mandatory elements of monitoring efforts as they provide the most detailed description of the new information developed through the monitoring effort. Audiences for technical reports typically include managers, technical personnel, academics, subject matter experts in NGOs and government agencies, and technically specialized members of the press and the public.

Although they contain the most detail of a given monitoring effort, technical reports may not be the best tool for communicating findings to non-technical audiences such as policy makers, the press, special audiences, and the public. To reach these other audiences, other tools should be considered to inform them more effectively.

Research Briefs

A research brief presents a summary of a technical report, a published, peer-reviewed article, or of a body of published work. It provides key technical details of the work in a short format, but is written using language that is less technical and more “user-friendly”, and includes visual elements (images, infographics, implied diagrams/graphs to increase comprehension in non-technical readers.

Audiences for research briefs can include: policy specialists, decision-makers, journalists, and interested members of civil society and the public. Because research briefs are more “user-friendly”, they can have more impact across stakeholder groups and the public than highly technical reports. Given its greater reach and readership, care should be given to ensure that the information provided by the research brief accurately reflects the information in a corresponding technical document.

Media Summaries

Media summaries are a version of a research brief that specifically addresses the particular needs of journalists that may be interested in covering the results of the monitoring effort. Given the importance of having journalists accurately understand the facts and findings of a monitoring effort so that they can better inform the public, an intentional effort by the monitoring team to provide key information points for journalists can increase reporting fidelity, accuracy, and timeliness. Journalists typically work under tight deadlines and have limited time or funds to travel to field sites for extensive reporting. Given these realities, it greatly benefits the managers of monitoring efforts to provide ”key points” that concisely summarize key elements of the problem statement, the findings, and its significance to impacted populations or environments, and potential next phases or policy responses. The use of media summaries can significantly reduce the chances of a spokesperson being misquoted, or for the monitoring findings to be incorrectly reported or interpreted.

Communication for special audiences

There may be instances where certain key audiences are not best informed by the communication tools discussed above and may require the use of specialized communication approaches. Examples include: non-literate population groups, non-technically literate indigenous communities, student populations, etc. Efforts should be made to develop communication tools that best inform these audiences in a timely manner. The use of non-traditional and creative approaches may need to be employed, such as short live-action or animated videos, posters, or infographics written in native languages, radio shows, podcasts, or social media storytelling.

In summary, it is ultimately the responsibility of the monitoring program to effectively communicate its findings and their significance to stakeholders and other key audiences. By the use of an intentional, structured approach to identify key audiences, and the use of communication tools that best address the characteristics, interests and needs of each audience, monitoring efforts can better ensure that the information developed will improve awareness and knowledge, and better inform decision-making in a timely and meaningful way

PHASE 8: CONSIDERING AND CONDUCTING HIGH-COMPLEXITY MERCURY DATA ANALYSIS TO IDENTIFY AND UNDERSTAND SOURCES, PROCESSES, AND PROJECTIONS BASED ON THE PREVIOUS FINDINGS

The activities listed in this phase require practitioners to have knowledge about and access to advanced analytical and mathematical approaches and techniques for processing high-resolution mercury data to identify mercury sources, understand processes, test hypotheses and project future environmental scenarios. These activities typically also require greater economic resources and specialized staff and may require greater timelines for producing findings. However, these activities can provide powerful insights into the dynamics and impacts of mercury in a study site and produce important information that can be used to project future risks to human and environmental health.

Here we provide a short list of examples of activities that fall under this category. There are others that fall under this category, but the ones listed below are those that could be useful in the monitoring of mercury in ASGM sites. These include: the identification of mercury sources using mercury isotopes, the characterization of mercury bioavailability, the characterization of mercury biomagnification, historical analysis of environmental mercury deposition and modelling of mercury dynamics in the environment.

Identification of mercury sources using isotopes

Stable mercury isotope analysis is a tool that has been used for tracing Hg sources (both natural and anthropogenic) and biogeochemical processes in the environment and can potentially serve as a tool to identify specific Hg sources and their contributions in aquatic systems downstream from ASGM activities. Identifying the sources of Hg is widely sought information in areas in and around ASGM. In addition to improving understanding of Hg transport dynamics in soils and aquatic systems, source attribution is a tool frequently requested by environmental managers to understand the relative fraction of natural (background) mercury and mercury released by informal/illegal ASGM operations mechanisms. Large-scale studies using this novel analytical technique are necessary to look for possible solutions for the reduction of Hg cycling in the ecosystem.

Characterization of mercury bioavailability

Bioavailability is the extent of absorption of a substance by a living organism. In the case of mercury, it is the extent to which mercury (usually as methylmercury) is taken up by animals or plants. Bioavailability is an essential factor to consider when monitoring the relationship between the changes of mercury concentrations and accumulation in biota. Mercury bioavailability, its transformation and effects depend on a combination of factors but mostly of its concentration and speciation. Few mercury speciation studies have been conducted in areas with ASGM. The available literature reports that Hg in ASGM-contaminated sites is present as metallic mercury (elemental Hg or gold-amalgam Hg droplets), whereas in non-mining sites and downstream ecosystems Hg is mostly present as Hg^{2+} bound to organic matter (Cesar et al., 2011; Pinedo-Hernández et al., 2015). In processing sites, Hg bound to organic matter is also found but in low proportions.

Characterization of mercury biomagnification

Mercury concentration data can be combined with stable isotope data of carbon and nitrogen to track mercury biomagnification. Stable isotope signatures of carbon and nitrogen ($^{13}C/^{12}C$, $^{15}N/^{14}N$) reconstruct the interaction between trophic levels by tracing the carbon flow in the food web. The $^{15}N/^{14}N$ isotopic ratio is used to estimate the trophic level of an organism, whereas the $^{13}C/^{12}C$ is used to estimate the relative contribution to the diet of potentially primary sources (Kelly & Rocky, 2000). In the context of Hg monitoring in areas in and around ASGM, carbon and nitrogen stable isotope analysis can help provide more accurate information on the trophic structure and biomagnification factor of the aquatic and invertebrate food webs that govern the movement of MeHg through the ecosystem.

Historical analysis of environmental mercury deposition

Soil and sediment cores have been used widely as environmental archives to reconstruct Hg deposition history. Long-range atmospheric Hg deposition has, for example, been recorded in sediment, peat, and ice cores in areas distant from Hg emissions sources. For use in areas in and around ASGM, soil or sediment cores can be taken from ecosystems located at different distances in the watershed or airshed from Hg:Au amalgam processing sites (e.g., gold shops) to investigate atmospheric Hg deposition and accumulation patterns.

Figure 7: Lake sediment core sampling. Madre de Dios, Peru.

Modelling of mercury dynamics in the environment

Data generated in phase 6 and, if possible, in phase 7 can be used as an input for spatially explicit and non-spatially explicit mathematical models that can help improve the understanding of the behavior of mercury in the environment, and predict future scenarios of mercury accumulation, deposition, transport or transfer between two or more different media.

For example, the analysis of remote sensing imagery can provide an alternative approach to monitoring the concentration and transport of suspended particulate matter in river systems (Umar et al., 2018). While there are still some limitations for its use in areas in and around ASGM, the potential for estimating Hg loading in rivers through remote estimation of particulate matter loads is promising. Further exploration of these new methods will be needed to have a better understanding of the changes in the loads of suspended particulate matter and the mercury that is bound to suspended matter over space and time.

4.4 Framing mercury monitoring in ASGM sites using a three-tier approach

The effective monitoring of mercury in ASGM sites can provide valuable information on mercury levels and how they are changing over time, and in response to mining activities and intervention strategies. Practitioners who may wish to develop new monitoring programs or improve existing ones either for local needs, or to contribute to the Minamata Convention's Effectiveness Evaluation should consider framing the monitoring effort using the three-tiered approach to monitoring mercury below. The use of these tiers by practitioners can be useful for developing a more nuanced understanding of effective mercury monitoring plans in ASGM sites. This approach is used in the document, “*Guidance on monitoring of mercury and mercury compounds to support the effectiveness evaluation of the Minamata Convention*” (UNEP 2021a).

- **Tier 1** is intended to provide guidance on mercury monitoring under a limited set of parameters for circumstances where available resources are not sufficient to implement the actions in Tier 2. The methods in Tier 1 are cost effective, practical, feasible, and sustainable and will contribute essential information and create a foundation for Tier 2 monitoring. The Tier 1 methods are intended to provide information that are useful in identifying and characterizing gaps and needs of national, regional, or local interest and to provide information that is useful to the collective effort for the Effectiveness Evaluation.
- **Tier 2** is intended to build upon Tier 1 methods to provide information that will address the policy questions mentioned in chapter 2, and to create a basis for assessing source attribution at the local, national, and global scales. The methods and approaches in this tier may be more expensive or complex than those under Tier 1. The more comparable data from Tier 2 becomes available, the more robust the Effectiveness Evaluation will be.
- **Tier 3** identifies research methods and approaches that may play a vital role in supporting the Tier 1 and Tier 2 programs and the Effectiveness Evaluation, primarily by improving our understanding of key processes that link sources to environmental concentrations and exposures. Because Tier 3 focuses on processes, the results would likely yield insights that are broadly applicable and that should be taken into consideration in the Effectiveness Evaluation when available.”

5. Case study: Monitoring environmental mercury pollution in a ASGM hotspot in the Peruvian Amazon

Figure 8. Remnant mining ponds in the post-ASGM landscape of the “La Pampa” mining zone, Madre de Dios, Peru.

Background and Challenge

Over the last 20 years, ASGM has deforested and degraded nearly 100,000 ha of high-biodiversity rainforests landscapes in the department of Madre de Dios, located southern Peruvian Amazon (Espejo et al. 2018), and created highly degraded landscapes that are pock-marked by thousands of hectares of mining ponds (Gerson et al., 2020). A 2018 study estimated that 181 tons of mercury are released to the region’s waterways, soils, and air every year. As of this writing, Madre de Dios is considered the largest hotspot of ASGM activity, and ASGM-related mercury pollution in Latin America (Cardo & Vargas, 2017).

The *Centro de Innovacion Cientifica Amazonica* (CINCIA) is a Peruvian non-for-profit scientific research center that conducts applied research on the dynamics and impacts of ASGM on terrestrial and aquatic landscapes in the Peruvian Amazon. Since 2016, CINCIA has worked with governmental and academic partners to conduct research on the extent of mercury contamination in Madre de Dios with the goal of developing a framework to characterize the presence, magnitude, and spatial distribution of mercury pollution in and around ASGM sites. CINCIA focused on measuring mercury concentrations in biota, sediment, and air across an area that spanned more than 2000 km^2.

To meet these research and monitoring goals, in 2017 CINCIA established a field-forward analytic mercury laboratory, based on a direct thermal decomposition atomic absorption spectrometry (DTD-AAS) analyzer platform, in partnership with the Peruvian Ministry of Environment's Instituto de Investigación de la Amazonía Peruana (IIAP), outside the city of Puerto Maldonado in Madre de Dios. CINCIA set up a mercury research program run by a highly trained team that was tasked with the design, coordination, and execution of multiple mercury field studies in both ASGM and remote pristine sites in multiple Amazonian ecosystems.

The case study presented here is derived from the experience of the CINCIA Mercury Research Program from 2017 to 2021. Based on the working experience and research findings from its first four years, CINCIA is now implementing a larger research program, expanding its mission to detect and monitor ASGM-derived Hg across the department of Madre de Dios, and setting up a similar research program in the Department of Loreto in the northern Peruvian Amazon.

Phase 1: Gather initial information on the potential mercury use in ASGM.

Prior to planning and executing the mercury assessment, CINCIA researchers collected, reviewed and synthetized pre-existing information on mercury pollution in the Madre de Dios region and other areas in the Amazon. This provided an overview of the state of knowledge, and helped to identify knowledge gaps on ASGM and mercury pollution in the study region. Remote sensing and GIS data were also used to identify and categorize abandoned mining ponds according to their age, and estimate the extension of ASGM-related deforestation and the increase rate during the last three decades.

Phase 2: Define the scope, goals, and priorities of the monitoring action.

The goal of CINCIA's mercury monitoring effort was to characterize the presence, magnitude, and spatial distribution of mercury pollution in and around ASGM sites. Given the limited information that was available on Hg in Madre de Dios in 2017, CINCIA researchers planned to first conduct a screening procedure to evaluate mercury levels in different environments and media across the region to identify Hg hotspots, provide initial insights into potential effects on human and wildlife health, and select the most suitable field and laboratory working protocols and methodologies.

CINCIA used information gathered in Phase 1 in combination expert knowledge, these screening studies were designed to include simultaneous evaluations of aquatic and terrestrial environments using both abiotic and biotic compartments. Specific objectives were set to investigate Hg levels in sediment and fish from abandoned mining ponds, wildlife in and around ASGM areas, as well as in air around amalgam-burning gold shops in Madre de Dios.

Phase 3: Develop a stakeholder engagement plan that includes relevant local communities to create effective communications channels for information exchange.

CINCIA conducted a comprehensive stakeholder mapping effort to identify key stakeholders and potential partners, and understand how the monitoring project would engage with each. Identified stakeholders, collaborators and research partners included research institutions such as *Instituto de Investigaciones de la Amazonía Peruana* – IIAP (Research Institute of the Peruvian Amazon), national government agencies, such as *Servicio Nacional de Áreas Protegidas por el Estado - SERNANP* (Nacional Service of Protected Areas) and the Madre de Dios regional government, as well as government ministries such as the Ministry of Environment.

Because of a conscious decision to prioritize local stakeholder relationships, CINCIA became one of the few organizations that was able to work in mining zones that were otherwise resistant to outside groups. As knowledge-holders, local miners and residents were invited to be involved in CINCIA’s research. This not only allowed CINCIA’s researchers to access more areas, but also provided local people the opportunity to exchange information on their experiences and receive training and technical capacity building on mercury monitoring techniques. CINCIA maintains that the effort to work closely with local people ensured the success and continuity of its mercury monitoring programs.

Phase 4: Identify and secure initial resources needed for field monitoring programs.

The selection of the mercury analysis instruments was made on factors that included sampling reading accuracy and sensitivity, sample matrix flexibility, robustness, long term maintenance cost and installation costs. Using these criteria, a Milestone DMA-80 direct mercury analyzer was selected for use in the monitoring program. The DMA-80 is an instrument that uses thermal decomposition atomic absorption spectrometry and requires little or no sample pretreatment. The DMA-80 also has the advantage of using compressed air as a carrier gas, which was a consideration due to the limited availability of research grade oxygen. Standard mercury solutions and certified reference materials were purchased for QA/QC procedures.

Phase 5: Design a field sample collection and sample analysis plans that fit time, logistical and budget constraints.

CINCIA program managers first established monitoring work plans and timelines based on objectives (Phase 2), and informed by information on logistical support offered by stakeholders and research collaborators (Phase 3) and available resources for the effort (Phase 4). Potential study and control sites were identified using remote sensing, GIS tools and drone flights, and a final selection was made based on multiple factors, with the distance to ASGM activities, field logistics and ease of access being more important. The environments and compartments that the monitoring effort would focus on were informed on the available literature reviewed in Phase 1, the guidance of local people and scientific expertise. Control sites were selected to have very similar features as the study sites but without ASGM. Main aspects of the working protocols for each “focus” study environment and media are described below:

Focus 1. Mercury in abandoned mining ponds: sediment and fish

The methodology to assess mercury levels in mining ponds included the sampling of bottom sediments and fish from mining ponds located in different ASGM areas of the Madre de Dios region. Natural oxbow lakes were used as control sites. Many of the mining ponds were located along the mining corridor, an area that the Peruvian Government has defined as potentially legal for mining activity and were within the properties of collaborating miners.

Focus 2. Mercury in wildlife

CINCIA’s biomonitoring surveys were initially focused on fish because they were the predominant source of methylmercury dietary exposure for humans and is the main protein source for a high number of riverine and indigenous communities in Madre de Dios. However, the program afterward expanded to wildlife species, such as birds and bats, to develop a better understanding of the transfer of mercury along the food web (biomagnification) and the potential health effects of mercury exposure on terrestrial wildlife.

Focus 3: Mercury levels in air: Au-Hg amalgam burning gold shops

CINCIA monitored atmospheric mercury concentrations between 2017-2019 to determine the regional background of gaseous elemental mercury (GEM), and to assess the impact of local and regional ASGM sources to the overall mercury in the atmosphere in the Madre de Dios region. CINCIA partnered with an academic partner, the University of Toronto, to use their UT's newly developed passive air sampler for the collection of gaseous elemental mercury. Because the UoTPAS air samplers were low cost, power-free, and easily deployed, CINCIA researchers could deploy them throughout the city of Puerto Maldonado using a grid sampling design.

Phase 6: Conduct field sample collection, sample analysis and interpretation of the results to develop basic knowledge of mercury levels in target sites

Focus 1. Mercury in abandoned mining ponds: sediment and fish

The sampling consisted in collecting bottom sediments, when possible, from the inlet, middle and outlet of the water bodies using Eckman dredges. Fish were caught using drag and gill nets. The species, weight and length of each specimen were recorded, and bone free dorsal muscle tissue was sampled using a stainless-steel scalp. All samples were stored in Ziplock bags and were kept in dark and cold in the field until their arrival to CINCIA's Mercury Lab in Puerto Maldonado (the region's capital city) where they were processed and analyzed for total mercury.

Figure 9. CINCIA researchers sampling bottom sediments in mining ponds using manual dredges (top) and sample material for mercury analysis taken from the middle section of the dredge using wood or plastic spoons (bottom).

Focus 2. Mercury in wildlife

For assessing the risk that pose abandoned mining ponds to Hg exposure, feathers and fur from birds and bats, respectively, were collected using a non-invasive, line transect method. Animal capturing and sampling were conducted in the surrounding of selected mining ponds from four different ASGM areas using mist nets set up along a 1-km transect from the water body. Feathers and fur were collected from the chest and back, respectively, and were stored in paper bags and then in Ziplock bags with silica. As a control site, a natural oxbow lake located in a pristine forest from a protected area was used.

Figure 10. CINCIA researchers sampling feathers from a bird (top) and fur from a bat (bottom) for a wildlife mercury exposure assessment.

Focus 3. Mercury levels in air: Au-Hg amalgam burning gold shops

The monitoring effort was designed and implemented with University of Toronto collaborators, who also provided field and lab training for CINCIA researchers. CINCIA also deployed these air samplers along a 200 km stretch of the Interoceanic highway Monitoring to map the temporal-spatial variability of GEM at larger spatial scales.

Figure 11. UofTPAS passive air samplers for gaseous mercury installed in a tree in Manu National Park in Madre de Dios, Peru.

Mercury analysis

CINCIA conducted all sample treatment and mercury analysis at the CINCIA/IIAP's mercury lab in Puerto Maldonado: the *Laboratorio de Mercurio y Química Ambiental* (LAMQA). Sample preparation and analysis were done according to CINCIA's established protocols. The sample analysis for total mercury (THg) was done using a Milestone DMA-80 Direct Mercury Analyzer and the EPA method 7473 following standard QA/QC, such as blank control, replicates, and certified reference material during everyday analysis.

Data analysis and interpretation

Focus 1: Mercury in abandoned mining ponds: Sediment and fish

CINCIA found that there was no significant difference between mercury concentrations in surface bottom sediments from mining ponds compared to natural lakes (Fig. 2a). However, bottom sediments from the ponds showed a higher maximum mercury concentration compared to natural lakes. In fish, the total mercury concentrations increased by trophic level indicating mercury biomagnification in the food web, with a higher effect in mining ponds compared to natural lakes (Fig. 2b). Overall, this study showed that sediments do not always reflect the concentrations of mercury in local wildlife, which also demonstrates the importance of examining more than one type of sample when investigating mercury pollution and its potential bioaccumulation.

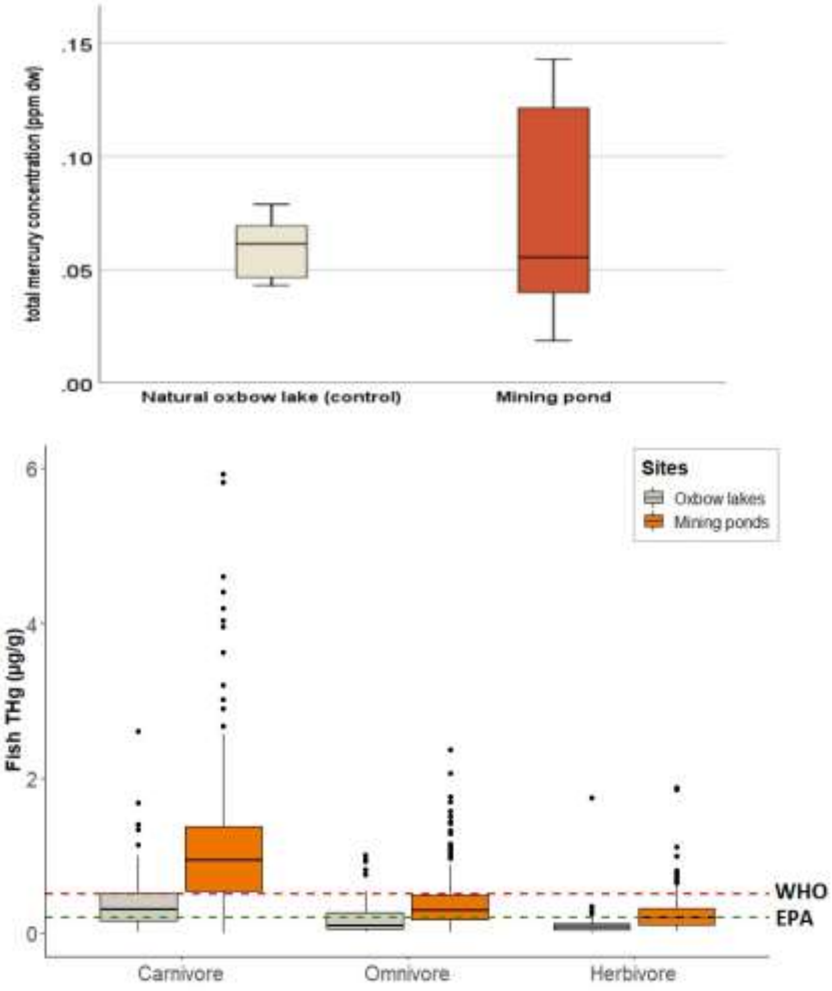
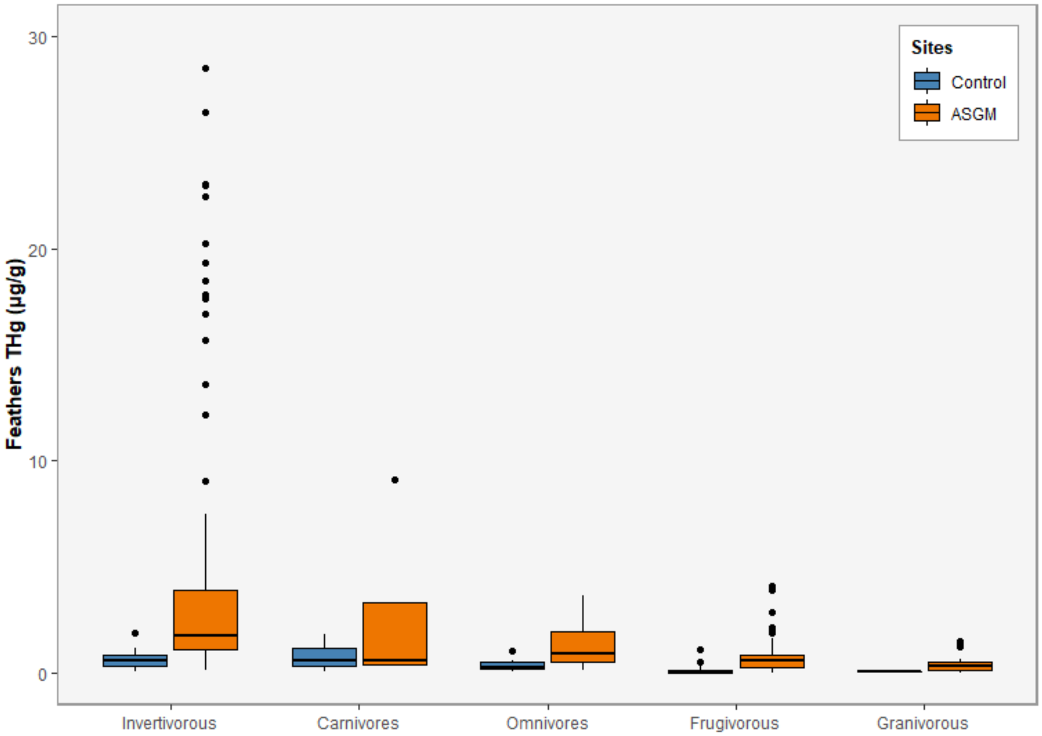


Figure 12. Mercury concentrations in abandoned mining ponds and natural oxbow lakes from Madre de Dios, Peru **A.** Mercury in bottom sediments (n=131) **B.** Mercury in fish (n=1148) from different trophic levels.

Focus 2: Mercury in wildlife

Mercury concentrations in birds and bats were found to primarily respond to differences in feeding habits, which agrees with previous wildlife mercury assessments. Furthermore, higher concentrations were found in specimens collected close to gold processing sites compared to those collected in control sites. Though valuable information was obtained from the wildlife study, the required field logistics and resources were notably high.

As a result of these initial findings, CINCIA started to explore alternative approaches that would generate similarly useful information on mercury levels, while also increasing public engagement on mercury issues. The new approach that CINCIA decided on was to develop a Citizen Science program based on the use of dragonflies to monitor mercury in aquatic ecosystems. This program is an adaptation of the *Dragonfly Mercury Program* developed by the US Geological Survey and The US National Park Service (Eagles-Smith et al., 2020). CINCIA's Amazon Dragonfly Mercury Program involves local students and volunteers to work in a scoping study for monitoring mercury in wildlife. The program will help identify potential contaminated water bodies that should be prioritized for mercury monitoring over time, and help determine where sampling of higher-level taxa (e.g., fish, birds) or abiotic matrices (e.g., sediments) should be considered.



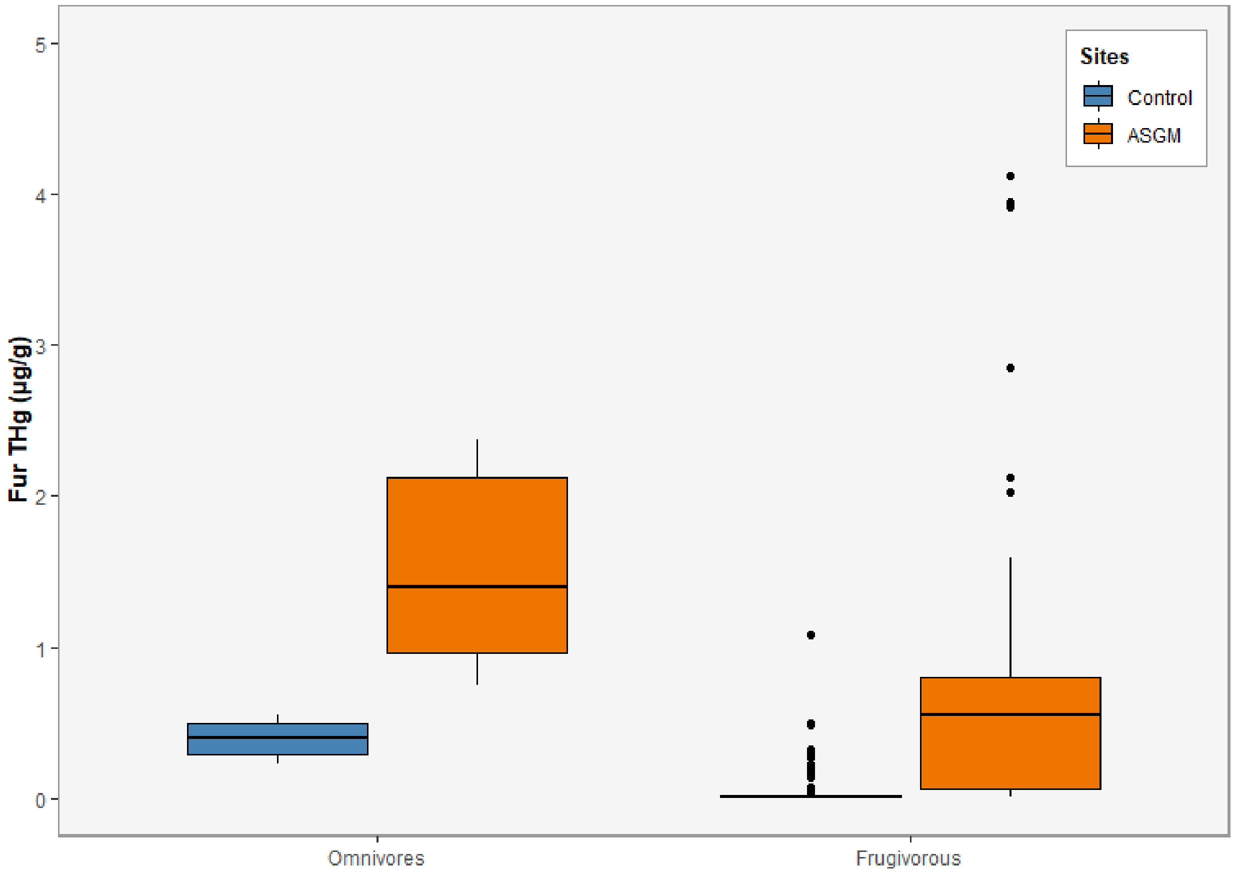


Figure 13: Mercury concentrations in wildlife from Madre de Dios. **A.** Mercury in feathers from birds **B.** Mercury in fur from bats. Specimens were captured and sampled at different distances from abandoned mining ponds and compared against specimens captured near natural oxbow lakes with no history of ASGM. For bats, only omnivores and frugivores were captured both in the control and study sites.

Focus 3: Mercury levels in air: Au-Hg amalgam burning gold shops

Monitoring data was processed to map the temporal-spatial variability in the concentration of gaseous elemental mercury (GEM). Key observations from the data collected in 2017 include GEM concentrations up to 280 ng/m^3 in Puerto Maldonado and up to 21,100 ng/m^3 in ASGM districts near gold shops, whereas concentrations in sites distant from gold processing point sources ranged from 0.6 to 2 ng/m^3. Findings from this study demonstrate that gold shops are a source of Hg contamination in the city of Puerto Maldonado and that the UofTPAS passive samplers are a good method for monitoring Hg in ASGM impacted areas.

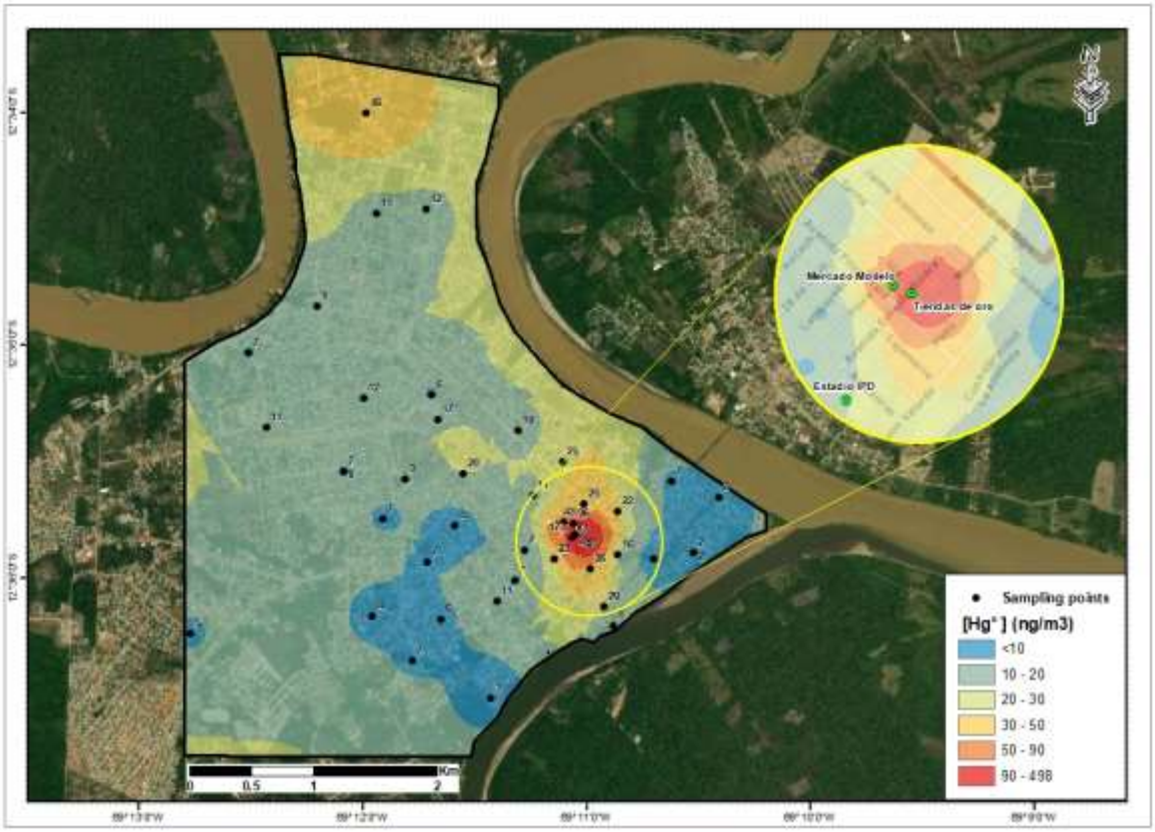


Figure 14: Mercury concentration gradient of GEM in Puerto Maldonado, capital of the Madre de Dios region in Peru.

Phase 7: Communicate results to stakeholders and interested parties

CINCIA conducted rapid and iterative communication of key findings to the local government actors and the public using research briefs, which were specifically written in a visually attractive and engaging manner for non-technical audiences. CINCIA researchers and program managers actively participated in civic dialogs contributing scientific information and strategic recommendations to inform public debates, and regional and national level decision-makers with the expectation that these contributions would result in better informed discussion and improved public policies that minimize impacts caused by mercury pollution.

CINCIA also engaged with local education agencies, and other civil society organizations to translate its findings to easily understandable information for the greater public. CINCIA's mercury monitoring work has been used by the Madre de Dios regional government to inform thousands of residents in Madre de Dios of the risks of mercury exposure. Notably, its findings have also been used by the Madre de Dios Regional Education Agency to develop a school curriculum that has educated over 35,000 public school children on the presence and risk of mercury in their local environment.

Phase 8: Conducting high-complexity mercury data analysis to identify and understand sources, processes, and projections

CINCIA has also worked in a joint project with the University of Toronto to investigate the mercury isotope signature in air, sediment, and soil samples to provide insight to Hg sources in the Madre de Dios region and enhance the understanding of the extend of Hg emissions and releases from ASGM activities. Moreover, CINCIA has also collected sediment cores from oxbow lakes located upstream (control) and downstream or near ASGM working areas to investigate the contamination of ASGM-related Hg on local environments.

TAKEAWAYS AND LESSONS LEARNED

Achieving Mercury Monitoring Goals

- CINCIA's work demonstrated that ASGM is a source of mercury pollution in the Peruvian Amazon and highlights the importance of conducting a first screening or pilot study prior to the design and implementation of a long-term mercury monitoring program.
- Examining and monitoring multiple environments and media (sample types) simultaneously is critical to have a comprehensive understanding of the behavior and dynamics of mercury in the environment and the potential threats to human and wildlife health.
- Working with local people, communities and organizations is a critical success factor for executing a long-term monitoring program.
- By building Peru's first analytical laboratory dedicated to studying environmental mercury in an ASGM region, CINCIA demonstrated that high-precision and high-volume mercury analysis program can be done in field-forward locations; reducing costs, building scientific capacity in local scientific and technical communities (academia, NGO, government, and

students), and contributing to a culture of transparency, respect and accountability between the monitoring program and local stakeholders.

6. Summary and recommendations

ASGM is the largest source of mercury pollution in the world. ASGM occurs in more than 80 countries, but it is most prevalent in tropical and subtropical regions, particularly in South America, South-East Asia, and Sub-Saharan Africa. To date, medium and long-term mercury pollution research and monitoring programs have focused on temperate and boreal sites leaving large knowledge gaps in tropical areas. Currently, the environmental behavior of mercury in tropical ecosystems remains insufficiently understood. The monitoring of mercury in and around ASGM sites is challenging because of the informal, and sometimes illegal, nature of the activity, and because it is mostly conducted in remote areas with difficult access.

This technical background document highlights the importance of developing well designed, scientifically valid and clearly communicated mercury monitoring plans that can form the foundation of effective Hg monitoring programs that generate robust and reliable data. In turn, these data can be used to improve our understanding of the dynamic of mercury around ASGM sites and be used to generate prediction scenarios. These efforts will also inform policy makers that seek to reduce the potential negative impacts of increased mercury pollution in sensitive ecosystems, better regulate the ASGM sector, and strengthen environmental protections in areas where ASGM is prevalent.

Due to the complexity of mercury cycling in the environment, the selection of the sampling media for assessing Hg pollution and risk exposure to human and wildlife populations should be carefully evaluated. To ensure a more complete understanding of mercury in ASGM areas, assessing at least two different environmental compartments, including abiotic and biotic media, is recommended.

Given that soils and sediments are major sinks of mercury, and strongly influence its mobility and bioavailability in the environment, these media are more suitable for monitoring mercury in aquatic and terrestrial ecosystems. Furthermore, they require less economical and logistic resources during the field and laboratory work. However, because soil Hg concentrations often are not predictive of biota Hg concentrations the use of biota for mercury monitoring is also recommended. Aquatic biota such as fish, are well-known bioindicators for estimating human exposure, while terrestrial bioindicators such as birds and bats are relevant and are supported by extensive literature for interpretation. Nevertheless, if resources are limited, other taxa can be considered if they are proven to be good bioindicators.

Although water is often used for assessing mercury pollution in ASGM sites due to concern of drinking contamination, the use of water as a monitoring medium is not ideal, due in part to specifics of how mercury behaves in water, significantly higher sampling costs, and the need for expensive high-sensitivity analytical techniques that are required for an accurate sampling and sample analysis.

The standardization and adoption of working protocols for mercury monitoring, and the establishment of locally derived mercury background levels to serve as study control will improve the quality of Hg monitoring and field assessments. In the context of the Minamata Convention on Mercury, these improvements will allow for the development of more accurate and robust mercury time series data, support efforts to compare these data with other ongoing mercury monitoring programs in other sectors and provide improved data for Effectiveness Evaluation under the Minamata Convention.

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