MERCURY MONITORING IN AND AROUND ARTISANAL AND SMALL-SCALE GOLD MINING SITES

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Mercury monitoring in and around artisanal and small-scale gold mining sites

A Technical Background Document

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Executive Summary

Mercury is a highly hazardous chemical that accumulates in food webs. Also known as "quicksilver", mercury was once hailed for its qualities as an essential component of research and medical instruments, as catalyst of industrial processes, gold amalgamator, and for many other uses. As a result, human activities have increased the atmospheric mercury by 450% above natural levels.

Artisanal and small-scale gold mining and processing (ASGM) is the largest human-made source of mercury pollution. 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. ASGM sites and the areas around the sites accumulate the highest levels of mercury causing irreversible impacts on the people who work in ASGM and those live around the sites, even if they do not engage directly in the mining or processing of gold. In addition, because of the long-range transport of mercury and migration of species that accumulate high levels of mercury, areas far from the original ASGM sites and their peoples are also heavily impacted.

The environmental behaviour of mercury in tropical ecosystems, where most of the ASGM occurs, 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. Improving the understanding of the dynamics and environmental fate of Hg from ASGM is of significant concern to human and environmental health.

The Minamata Convention on Mercury, which objective is to "*protect human health and the environment from anthropogenic emissions and releases of mercury and mercury compounds*", is the only international agreement that addresses the ASGM where mercury is used. Monitoring mercury in and around ASGM sites must be at the core of the implementation by Parties in which territory ASGM is deemed more than insignificant and a target of global efforts to implement the Convention.

Many of the people who are most affected by mercury pollution belong to Indigenous Peoples, as well as local communities, including women and girls among them, as recently noted by the Conference of the Parties to the Minamata Convention in its decision MC-5/1. While they are particularly vulnerable to mercury exposure and are among the first to face the serious health and environmental effects resulting from mercury pollution owing to their close relationship with the environment and its resources, Indigenous Peoples and local communities play an essential role towards achieving the objective of the Minamata Convention and the targets and goals of the 2030 Agenda for Sustainable Development.

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 mercury 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. It provides insights on how to engage with Indigenous Peoples, as well as with local communities, to integrate Indigenous Peoples' knowledge and local knowledge into monitoring programs, and the importance of effectively engaging Indigenous Peoples and local communities in the programs. Furthermore, the efforts described in this document may also inform policy makers that seek to protect human health and reduce the potential negative impacts of increased mercury pollution in sensitive ecosystems, reduce the environmental damage and human impacts of the ASGM sector, and strengthen environmental protection and biodiversity conservation in areas where ASGM is prevalent.

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1. Introduction

1.1. Mercury as a global pollutant

Mercury (Hg) is a persistent global pollutant that can be emitted to air and released into water and soil 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 kilometres from emission point sources before depositing on 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 ecosystem health (Basu et al., 2018; Canham et al., 2020; Driscoll et al., 2013; Scheuhammer et al., 2007).

Up to 2010, total anthropogenic Hg releases to the environment were estimated in 1,540 Gg (gigagram, thousand tonnes), from which 73% was released after 1850 (shortly after the start of the industrial revolution) (Streets et al., 2017). The authors estimated that 470 Gg Hg had been emitted to the atmosphere and 1,070 Gg Hg released to land and water systems, and that 40% of all released Hg to land and water systems is immobilized in contaminated sites. A more recent study reports rivers as the largest source of Hg to the global coastal ocean, delivering each year an average of 1,000 tonne Hg, threefold greater than atmospheric deposition (Liu et al. 2022). Thus, freshwater systems are important source of mercury and, although not fully understood, their contribution to global mercury cycling may be significant.

Given the global nature of mercury's emission, release and distribution, its high-level toxicity to humans and wildlife and environmental persistence, it is critical to understand and monitor the behaviour 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 impacts of this pollutant to humans and nature.

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

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

Mercury in most chemical forms is 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 inorganic mercury by microorganisms, MeHg is a potent neurotoxin that readily accumulates in living organisms and biomagnifies within food webs, becoming enriched at high trophic level[1] and long-lived piscivorous[2] predators in marine and freshwater ecosystems (Azevedo-Silva et al., 2016; Bastos et al., 2015; Callister & Winfrey, 1986; Eckley & Hintelmann, 2006). As a result, humans and wildlife that consume high trophic level predators are at elevated risk of dietary-based Hg exposure (AMAP, 2011; Hacon et al., 2020). The negative health effects of MeHg exposure have prompted an increased global awareness of the consumption of marine and freshwater species that may contain high MeHg levels and in several at-risk populations.

Governments and environmental agencies have implemented policy measures, such 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 Minamata Convention” or “Convention”) was spearheaded by the United Nations Environment Programme (UNEP) to protect human health and the environment from anthropogenic emissions and releases of mercury and mercury compounds. The Minamata Convention entered into force on 16 August 2017 and had 143 Parties at the time of this writing. 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 to the environment is artisanal and small-scale gold mining and monitoring (ASGM) (UNEP, 2013, 2018). The UNEP (2018) report estimated that ASGM accounted for almost 38% (average of 838 tonnes) of the global total mercury emissions in 2015 and to be the major contributor to the emissions from South America, Sub-Saharan Africa and East and Southeast Asia. The same report estimated that combined mercury releases from ASGM to water and soil in 2015 were about 1,220 tonnes, more than twice the estimated releases to water from other evaluated economic sectors. Also here, most of the releases occurred in South America, East and Southeast Asia 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 Minamata Convention framework

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. Along with Article 7 and annex C, Articles 19 and 22 also contain provisions that highlight the importance of well-designed and implemented strategies to monitor mercury, including those in and around ASGM sites. Together, these provisions are outlined below.

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[1] Trophic levels are a hierarchical way of classifying organisms according to their feeding relationships within an ecosystem; they are the position of an organism in the food chain. The lowest level are the primary producers (e.g., plants) and the highest the top predators (e.g., marine mammals and humans).

[2] Piscivorous are carnivorous animals that eat primarily fish.

- **Article 7** addresses Hg released from ASGM that uses mercury amalgamation to extract gold from ore. Countries ("Parties") with ASGM are required to take actions to reduce and/or eliminate the use of mercury, as well as mercury emissions and releases to the environment from such mining and processing. 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 of use, consumption and anthropogenic emissions to air and releases to water and land of mercury and its compounds. Mercury impact assessments (including information on the environmental cycle, transport, transformation and fate) and modelling 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 undertaking the work mentioned above.

- **Article 22** addresses the effectiveness evaluation 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 of the Convention (for more information, see the document "Guidance on monitoring of mercury and mercury compounds to support evaluation of the effectiveness of the Minamata Convention" (hereafter "the Monitoring Guidance"[3]) (Secretariat of the Minamata Convention on Mercury, 2021a).

1.4. Scope and objectives of the technical guide

The scope of this document is intended to provide useful technical information to support the efforts of practitioners for the monitoring of mercury and its compounds in and around ASGM sites and offers a set of practical guiding principles for compiling and/or generating mercury monitoring data to better understand the presence, movements, and trends of mercury over time in and around ASGM sites.

The main objectives of this document are to:

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[3] The Monitoring Guidance is available as document UNEP/MC/COP.4/INF/12, along with its supplementary material available as document UNEP/MC/COP.4/INF/25.

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 at program/project managers and technical practitioners in governmental and civil society 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, design and implementation of policies with regulatory requirements on environmental conservation and biodiversity protection or protection of ecosystems and human health.

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 implementation of national policies and action plans (e.g., implementation of National Action Plans (NAP) under Article 7 and Annex C) 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. While the requirement in Article 22 concerns the COP, individual Parties may wish to contribute to the effectiveness evaluation of the Convention by sharing available monitoring data and other types of information.

The Convention's effectiveness evaluation (Secretariat of the Minamata Convention on Mercury, 2021a) aims to measure change in key environmental compartments that results from activities under the Convention to address 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?

This document is intended 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 information generated by the monitoring efforts that are discussed in this document can 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, and as a contribution to the effectiveness evaluation of the Convention.

To aid readers in placing this document within the suite of reference documents developed by UNEP and the Secretariat of the Minamata Convention, linkages have been made in the text to relevant documents such as *Guidance on monitoring of mercury and mercury compounds to support evaluation of the effectiveness of the Minamata Convention* (Secretariat of the Minamata Convention on Mercury, 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 technical document is structured in eight sections, as 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 the 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: Mercury monitoring case study I

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: Mercury monitoring case study II

Presents an illustrative fictional case study of a government Environment monitoring office tasked with a mercury monitoring program for the first time.

Section 6: 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 7: References

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

Section 8: Supplemental materials

Two supplemental materials are provided along with this document: 1. An annotated literature review of peer-reviewed scientific reports of mercury from terrestrial and aquatic ecosystems affected by ASGM and 2. A table with selected analysis methods for total mercury and methylmercury.

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

2.1. ASGM as a major source of elemental mercury

Artisanal and small-scale gold mining and processing (ASGM) is the largest economic sector that uses mercury globally, and the largest source of anthropogenic mercury emissions and releases and 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, widespread poverty and lack of other economically viable alternatives. 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 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. The average ratio of Hg releases to gold produced by ASGM has been estimated at 4.63:1 in Latin America, 1.96:1 in Africa and 1.23:1 in Asia, with these differences attributed to the amalgamation process practiced in each region[4] (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. As an example, see the Mining Impacts Calculator developed by Conservation Strategy Fund[5]

2.2. 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[6] 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 an amalgam, which is typically 50:50 gold and mercury. The amalgam is then placed into a cloth and squeezed to sieve out excess liquid mercury. Although there is usually an effort to recapture the extruded mercury during this step, small amounts can be lost to the environment.

To further recover the gold fraction from the produced amalgams, miners heat or “roast” the amalgam using an open flame to boil off the mercury. This process emits large amounts of mercury vapor into the air and can be the main route of elemental 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 occur in gold buying shops (commonly referred to as “gold shops"), where gold buyers roast amalgams offered for sale to drive off residual Hg before sale. Although this secondary roasting typically releases lower quantities of mercury, they frequently occur in gold shops that are located in urban or semi-urban settings, increasing the inhalation exposure risk for nearby people. Although the use

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[4] Whole-ore amalgamation is predominant in Latin America and Asia, while concentrate amalgamation is predominant in Africa (AMAP-UNEP, 2018; Yoshimura et al., 2021).

[5] The Mining Impact Calculator is available at: https://miningcalculator.conservation-strategy.org/.

[6] The amalgamation process consists in mixing the concentrates or whole-ore with liquid Hg to form an amalgam that will allow extracting the gold from the rest of the material. The mix is frequently done manually and with simple tools. The amount of Hg needed to form the amalgam is calculated based on a rough estimate based on the miner’s experience of how much gold is present in the concentrate or ore mix. For example, in concentrate amalgamation of alluvial deposits extracted by semi- or mechanized techniques (see footnote 10-13), a miner starts by having a bucket with the concentrate mixture. To estimate the amount of Hg needed, first, he covers the concentrate with water and shakes it by hand to suspend the material. Once all the material is in suspension, the miner places his hand in the bottom of the bucket and waits for the material to begin to settle. At this point, he closes his hand and removes it from the container. The miner visually estimates how much gold is present in the mixture and adds about twice the amount of liquid Hg to the bucket. He either adds it directly to the bucket or tries to measure it first on his hand. He then proceeds to mix everything with a hand or foot to ensure that the Hg traps all the gold present and forms the amalgam. According to how the amalgam starts to look, more Hg may be added. Once the amalgam is formed, it is separated from the remaining material by panning, shaking tables or centrifugal concentrators. The remaining material may be discarded or reprocessed once more later.

of mercury retorts (devices that condense and recover Hg during amalgam roasting) has been actively promoted by governments and NGOs to reduce types of emissions (Bosse Jønsson et al., 2013; UNEP, 2012), several studies have shown that its effective uptake and use by miners has been limited (Bosse Jønsson et al., 2013). The effects of intervention strategies and potential unintended consequences of mercury mitigation measures in ASGM were the focus of a recent study (Kosai et al., 2023).

The use of cyanide (CN) to leach gold from gold-bearing sediments (cyanidation), is also becoming common, in part as a response to initiatives to reduce the use of mercury in ASGM, and to its higher gold extraction efficiency, especially from low-grade ores. ASGM miners use cyanide either as an alternative extractive method, following the practices of conventional/large scale mining operations which use cyanide leaching as the principal extraction method (Verbrugge et al., 2021) or as a secondary step to Hg amalgamation as means to extract residual gold from mining tailings that have been previously treated with mercury (Carling et al., 2013; Razanamahandry et al., 2016; Sousa et al., 2010; Secretariat of the Minamata Convention on Mercury, 2021b). The combination of Hg amalgamation and CN extraction has been shown to produce hazardous Hg-CN complexes, (such as Hg $(CN)_{2,}$), increased bioavailability of mercury in the environment (i.e., Hg can be more easily absorbed by living organisms), negative public health impacts, and long-range transport of mercury in watersheds (da Silva et al., 2023; Seney et al., 2020). Although the environmental behavior of Hg-CN complexes and their role on long-range waterborne Hg transport is still not entirely understood, studies in the ASGM mining area of Portovelo-Zaruma in southern Ecuador have shown that Hg-CN complexes enhance the downstream transport of Hg (Schudel et al., 2018; 2019). In Ghana, studies have shown methylmercury concentrations were found to be higher in sediments from rivers draining ASGM areas using Hg/CN processing compared to those from rivers draining Hg-only ASGM processing sites (Tulasi et al., 2021). Accordingly, 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 the environment and human health.

Broader social, environmental and economic impacts related to the use of mercury in ASGM were also highlighted by the UN Special Rapporteur to address human rights violations and protect the environment by prohibiting mercury trade and use in ASGM. The reports noted that Indigenous Peoples are particularly affected by the destruction and pollution of their territories, deforestation, loss of biodiversity and contamination of their food sources. Children are also disproportionately impacted by the dangerous work in the mines, sexual exploitation, and slavery-like conditions[7].A complete understanding of the dynamics of ASGM-related Hg remains unclear (Moreno-Brush et al., 2020). Several studies have found high levels of mercury pollution 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; Murao et al., 2019; Pataranawat et al., 2007; Rajaee et al., 2015; van Straaten, 2000). There have been fewer studies that show evidence on the extent of downstream impacts of mercury released by ASGM in aquatic ecosystems (Liu et al., 2021). In watersheds that have ASGM present, higher Hg concentrations have been reported in river sections that have active mining as compared to sections that are upstream from mining activities (Corpus et al., 2011: Diringer et al., 2015; Marshall et al., 2018). Despite this evidence, a clear downstream pattern that can be directly

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[7] The reports are available as the UN documents A/77/183 and A/HRC/51/35

associated with ASGM has not always been found. Reasons for this may include that mercury concentrations in sediments can rapidly decline within relatively short distances from mining sites down to concentration values similar to those found in unpolluted areas (e.g., Lechler et al. (2000); Roulet et al. (1998a); Taylor et al. (2005); Tomiyasu et al. (2019); van Straaten, (2000)).

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. For example, some 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). High mercury levels in these watersheds may be due to certain types of mercury releases that are not directly related to ASGM. In some regions, such as the Rio Negro basin in Brazil, for example, forest soils can have naturally elevated Hg background concentrations, and can be a significant natural source of Hg to aquatic systems (de Oliveira et al., 2001; Fundação Oswaldo Cruz 2023; Roulet et al., 1998b; Roulet & Lucotte, 1995). Forest fires, flooding, deforestation, agriculture– and ASGM itself– also increase soil erosion and mobilization of Hg-rich surface soils into rivers and lakes (Lacerda et al., 2004; Miserendino et al., 2018; Schudel et al., 2019; Takenaka et al., 2021).

Tracking the environmental fate of mercury in and around ASGM sites remains a challenge, particularly in tropical areas where the biogeochemistry and dispersal trends of mercury 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 geochemical composition and grain-size sediments distribution 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.

The use of mercury stable isotopes to differentiate Hg in and around ASGM sites is a new and promising approach to determine Hg sources more clearly. As an example, a study looking at Hg in the Amapá region of the Brazilian Amazon used Hg isotope analysis to determine that elevated mercury concentrations downstream from ASGM activities were a result of increased soil erosion, and not from mercury released by ASGM (Miserendino et al., 2018). Another study used Hg isotopes analysis to determine that ASGM that used a combination of mercury amalgamation and cyanidation was the source of downstream mercury pollution in the Puyango-Tumbes River on Ecuador and Peru border (Marshall et al., 2018; Schudel et al., 2019). This development of this technology is rapid evolving, and its availability is currently limited and relatively costly. However, the use of stable isotopes analysis for mercury monitoring has the potential to greatly improve understanding of the contributions 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.

2.3. 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 (Corpus et al., 2011). 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). Oxidized mercury is also continuously supplied from the atmosphere by dry and wet deposition. 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, oxidized 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 Indigenous Peoples and riverine local communities.[8]

ASGM often takes place in areas of high biodiversity importance and mercury impacts biodiversity and ecosystems in several ways. Many wildlife species, including those that are already threatened by other stressors, are under additional pressure from mercury used in ASGM. Dietary exposure of wildlife to MeHg is also a significant concern, particularly for those species that are threatened by other drivers of biodiversity loss and environmental degradation (UNEP 2021; Secretariat of the Minamata Convention on Mercury 2023a; 2023b). Furthermore, mercury pollution from ASGM activities decreases the quality and quantity of the ecosystem services supporting and providing a variety of benefits to people living around mining areas, and leads to increased risks for Indigenous Peoples and for local communities dependent on natural resources for subsistence and livelihood Secretariat of the Minamata Convention on Mercury (2023c).

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 tropical aquatic environments may have more favourable 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 sulphate-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 favour the formation of anoxic conditions and generate an increase in bacterial activity (Achá et al., 2011; Guimarães et al., 2000; Lázaro et al., 2016; Roulet et al., 2001).

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[8] For the purpose of this document, the term "local communities" is being used to refer to non-Indigenous communities that embody traditional lifestyles but do not self-identify as Indigenous Peoples or lack formal recognition as such. Similarly, according to the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), "*'local communities' refers to non-indigenous communities with historical linkages to places and livelihoods characterized by long-term relationships with the natural environment, often over generations*" (source: IPBES glossary https://www.ipbes.net/node/41450).

2.4. 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 are governed by soil texture and geochemical composition, specifically by the content of iron oxides (do Valle et al., 2005; Roulet et al., 1998b). 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 animal/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 et al., 1998b). Ferralitic soils are enriched in minerals containing aluminium 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. Such mercury predominantly comes from mercury sulphide (HgS), which is less soluble and more inert than elemental mercury.

2.5. 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 this document (supplemental material 1) provides three 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.

1. **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 studies that report Hg data because of the wide range of protocols that are used for field sampling and measuring Hg concentrations in the laboratory. The review highlighted that the inconsistent use of protocols for sample collection, handling, treatment, storage, and sample and data analysis were identified as factors that limit inter-comparability across sites, laboratories and from one time to another.

2. **The use of methods not suitable for the stated monitoring objective limited the production of accurate or valid data**. The literature review conducted revealed that in many cases, monitoring programs used approaches and methods unsuitable for assessing the Hg processes of interest. The chemical behaviour of mercury (e.g.: volatility, instability, affinity to other elements, bioavailability) seems often not to be

considered when selection the protocols for sample collection or processing (e.g.: drying technique, sample preservation, purity grades for chemicals) prior to Hg analysis. In the case of water studies, there are different analytical methods for determining Hg concentrations but not all of them provide information about the bioavailable fraction, which is the one of most interest from an ecotoxicological perspective. Determining total Hg is often insufficient to accurately elucidate the bioavailability and toxicity of Hg in aquatic systems.

3. **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 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., the European Union and the Canadian government[9]) to compare 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).

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[9] See the guidelines from the European Union for maximum levels of mercury in fish in the Commission Regulation (EC) No. 1881/2006 and the guidelines from the Canadian Council of Ministers of the Environment for mercury levels in water, sediment and soil in the Canadian Environmental Quality Guidelines.

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

3.1. Introduction

This section outlines a simple and straightforward approach for designing and implementing an *in situ* monitoring program for mercury in and around ASGM sites. 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 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 an engagement plan with relevant Indigenous Peoples, local communities and other stakeholders 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:** Implementing record keeping plans for evaluation and improvement of monitoring operations
- **Phase 9:** 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 approach presented in 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 fulfilment 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.

3.2. 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 endeavour. 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 (e.g., quarantine of soil and/or water in importing country, etc.) 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, grey literature), and 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 centres, 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?
    - Size of the mining operation[10]
        - Are ASGM operations done by a few individual miners or as a larger operation?
        - What is the level of investment and mechanization?
    - Mining type

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[10] ASGM can include a wide range of practices and levels of investment, from individual miners using basic tools and manual processes to more organized and mechanized operations involving several miners.

        - What type of ASGM mining is being conducted (e.g., hydraulic alluvial mining[11], fluvial dredge mining[12], placer mining using heavy machinery[13])?
    - 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

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[11] Hydraulic alluvial mining is semi-mechanized and uses high-pressure water jets to dislodge or erode gravel and sediment (and gold) from alluvial deposits. Typically, it uses a motor, a suction pump and a network of PVC pipes and hoses for the water supply (water is diverted from nearby rivers or streams), nozzles and sluice boxes to separate the gold.

[12] Fluvial dredge mining, also known as river dredging, is conducted in riverbeds and floodplains using dredges. In ASGM, commonly suction dredges. The equipment includes a floating platform that is positioned in the river channel and equipped with a motor, a dredge, and a pump to suck up the bottom sediment. The extracted material is transported onboard, where it is processed using sluice boxes to separate the gold. The sediment left after processing (tailings) is typically discharged back into the river.

[13] Placer mining using heavy machinery is conducted inland and typically performs deep excavations using trucks, front loaders, and excavators. The excavated material is transported to processing areas, where the gold is separated using trommels, sluice boxes or shaking tables, and then recovered using mercury amalgamation. An exploration phase is typically conducted before mining to identify promising placer gold deposits. Once identified, the area is prepared by clearing vegetation and creating access roads for the machinery.

- 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 kilometre 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

An updated list of National Action Plans is available on the Minamata Convention's webpage[14].

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, civil society organizations (e.g., NGOs, women's associations) and local residents (e.g., Indigenous Peoples, local communities and the miners themselves) can provide important and timely information not available in published reports. Geospatial data 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 platforms that are specific to mapping general deforestation events (Global Forest Watch, Terra-I) and to identifying ASGM (RAMI, ASMspotter, Project Inambari). For more on these useful tools, refer to the remote sensing tools for ASGM assessments[15] , which can help practitioners understand how to use remote sensing approaches, methods, and tools to detect and monitor ASGM activities (Moomen et al., 2022).

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. Evaluating 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 Time-bound. 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 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, biota, and wildlife). However, it is useful to define the end goals and objectives more narrowly and tie them to the purpose of the monitoring effort. For example, Hg monitoring of

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[14] The National Action Plans are available at https://mercuryconvention.org/en/parties/national-action-plans

[15] https://www.mapx.org/projects/remote-sensing-for-asgm/

biota conducted in watersheds with nearby population centres 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. Hg monitoring in wildlife could be conducted to assess the impacts on biodiversity. 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, including to Indigenous Peoples and to local 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 AN ENGAGEMENT PLAN WITH RELEVANT INDIGENOUS PEOPLES, LOCAL COMMUNITIES AND OTHER STAKEHOLDERS TO CREATE EFFECTIVE COMMUNICATIONS CHANNELS

Phase three involves the creation and implementation of an engagement plan with local stakeholders, including Indigenous Peoples, local communities and other stakeholders that may be exposed to mercury in or around the ASGM sites. A stakeholder engagement plan goes beyond simple notification of relevant local stakeholders (e.g., Indigenous Peoples, women, local communities and miners) of sampling or *post hoc* presentation of findings. Instead, this phase involves actions to create relationships with the local stakeholders to integrate and build upon their knowledge and capacity, from the planning of the monitoring effort, through initial scoping and environmental samples, to the reporting of findings and a meaningful interpretation tailored to the needs of the stakeholders. Furthermore, engaging universities, research institutes, laboratories, and environmental organizations, particularly those located in the region, 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 integrate and engage local stakeholders (e.g., Indigenous Peoples, women, local communities and miners), by promoting feelings of co-creation and co-ownership in monitoring programs, is frequently a key factor in the overall successful outcome of monitoring programs (Brooks et al., 2013; Steckling 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.[16]

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[16] An illustrative Stakeholder Engagement Plan prepared for a project funded by the Global Environment Facility in Kenya is available here.

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. A matrix method can be used to classify each stakeholder in accordance with their influence and interest and determine their optimal level of engagement throughout the project.

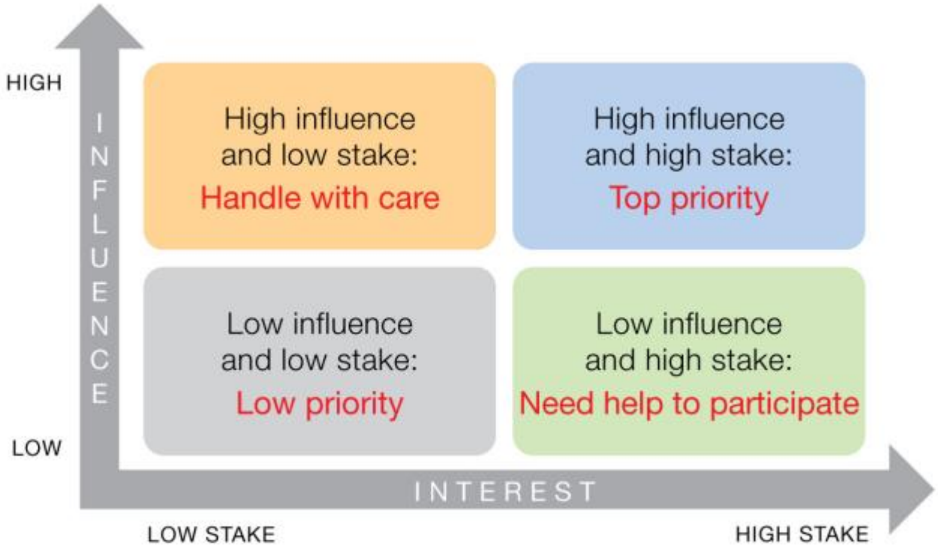

Figure 1: Example of a priorizitation matrix used for mapping stakeholders in accordance with influence and interest in project (IAEA, n.d.).

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 behavioural 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 establish regular communication during the monitoring activities and return the findings of any assessments to relevant stakeholders by presenting them in a manner that can be best understood and made use of. Far too many monitoring programs fail to provide monitoring results back to the relevant local stakeholders in a timely, effectively and comprehensive manner, if at all. This lack of feedback and reporting can be interpreted as a lack of respect and concern for the local stakeholders 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 pre-emptively 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, Indigenous Peoples' organizations, local non-governmental 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 analysed 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
- develop training plans for local staff, especially for those that will be involved in sample collection and treatment

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 analysed 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 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 a series of actions for the design and development of a robust sampling and analysis plan for mercury monitoring in areas in and around ASGM are presented.

- *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 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 (supplemental material 1). Sampling from only one environmental compartment is considered insufficient for developing a comprehensive understanding of the behaviour, 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, and there are also two aquatic environments relevant for ASGM monitoring: freshwater and coastal 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 show an accumulation of the bioavailable mercury present in an aquatic ecosystem over time. 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. On the other hand, it should also be mindful that some high-trophic species have mercury detoxication metabolism, and substantial amount of mercury may exist in inorganic form.

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[17]. 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 a 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

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

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 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.

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. The reasons why water is not recommended as a priority media are described in section 5.D.4. *Sensitive ecosystems* are defined as those ecosystems with characteristics that favour the production and bioaccumulation of methylmercury that could represent an exposure route for vulnerable populations and wildlife.

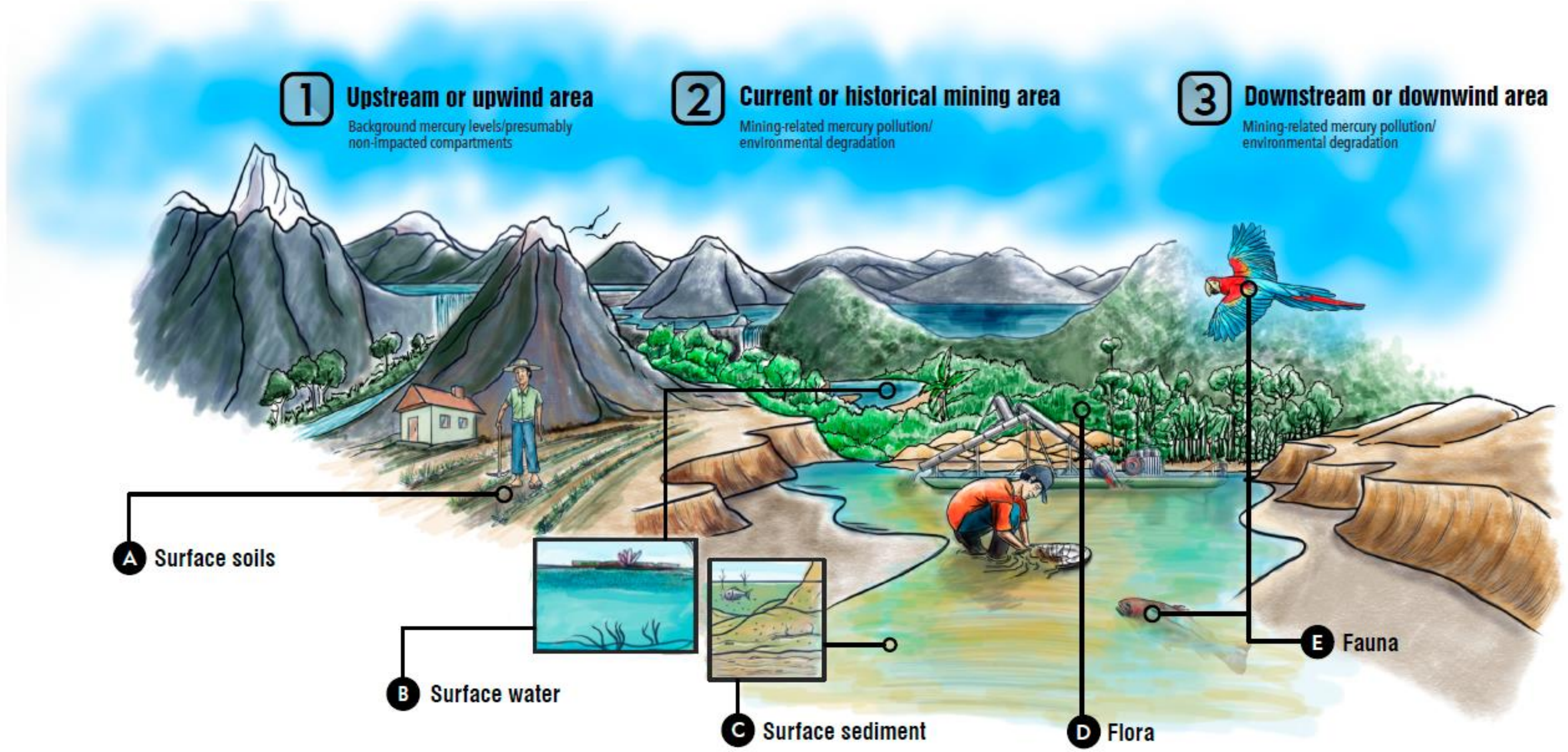

Figure 2: Diagram of the Hg cycling, showing order of magnitude of mercury concentrations in different compartments. Area 1 (Upstream or upwind area), Area 2 (Current or historical mining area), and Area 3 (Downstream or downwind area) are where mercury should be sampled in programmes intended to monitor mercury in and around ASGM sites. Area 1 can be considered as control sites, whereas Areas 2 and 3 would be study areas. Samples can be collected from environmental compartments A-E for assessments of mercury pollution in the environment (i.e., not including human biomonitoring). Generally, abiotic samples (A, B, C) are useful for monitoring the distribution and transport of mercury in the environment, whereas biotic samples (D, E) can be used for monitoring mercury exposure to wildlife and bioaccumulation in food webs. Important factors for sampling and chemical analysis are noted for each compartment. Integrating the knowledge of Indigenous Peoples and of traditional local communities living in the area of study can add value and support the planning, implementation and communication phases of monitoring programmes. *(Continued on the next page)*

A Surface soils

1. Typical THg concentration range: medium (µg/kg) to high (mg/kg)
2. Major Hg species present: inorganic (Hg^0, Hg^{2+})
3. Sampling difficulty level: low
4. Sample preservation difficulty level: medium (cold chain/dark)
5. Maximum sample storage time prior to analysis: years if dried or deep frozen
6. Sample preparation difficulty level: low (air or freeze drying, homogenisation) to high (additional acid digestion)
7. Common analytical methods: DTD-AAS, CV-AAS*
8. Cost of Hg analysis per sample: $ - $$
9. Overall difficulty of monitoring Hg pollution using soils: low

Legend

THg: total mercury (all forms of mercury combined)

Hg^0: elemental mercury (inorganic)

Hg^{2+}: oxidised mercury (inorganic)

MeHg: methylmercury (organic)

DTD-AAS: direct thermal decomposition atomic absorption spectrometry (acid digestion is not required)

CV-AAS: cold vapor atomic absorption spectrometry (acid digestion is required)

CV-AFS: cold vapor atomic fluorescence spectrometry (acid digestion is required)

ICP-MS: inductively coupled plasma mass spectrometry (acid digestion is required)

B Surface water

1. Typical THg concentration range: low (ng/L) to medium (µg/kg)
2. Major Hg species present: inorganic Hg (Hg^0, Hg^{2+})
3. Sampling difficulty level: low
4. Sample preservation difficulty level:
   a. Suspended solids: medium (cold chain/ dark)
   b. Unfiltered or filtered water: medium (cold chain/dark/acidification)
5. Maximum sample storage time prior to analysis:
   a. Suspended solids: years if dried or deep frozen
   b. Acidified water in cold chain: one year
   c. Non-acidified water in cold chain: hours
6. Sample preparation difficulty level: medium (stabilization with oxidising agent)
7. Common analytical methods: ICP-MS, CV-AFS*
8. Cost of Hg analysis per sample: $$ - $$$
9. Overall difficulty level of monitoring Hg pollution using water: high**

C Surface sediment

1. Typical THg concentration range: medium (µg/kg) to high (mg/kg)
2. Major Hg species present: inorganic (Hg^0, Hg^{2+})
3. Sampling difficulty level: low
4. Sample preservation difficulty level: medium (cold chain/dark)
5. Maximum sample storage time prior to analysis: years if dried or deep frozen
6. Sample preparation difficulty level: low (air or freeze drying, homogenisation) to high (additional acid digestion)
7. Common analytical methods: DTD-AAS, CV-AAS*
8. Cost of Hg analysis per sample: $ -$$
9. Overall difficulty of monitoring Hg pollution using surface sediments: low

D Flora

1. Typical THg concentration range: low (ng/kg) to medium (µg/kg)
2. Major Hg Species present: unsure, likely a mixture of inorganic (Hg^0, Hg^{2+}) and MeHg
3. Sampling difficulty level: generally low, depends on the target species and sample type
4. Sample preservation difficulty level: low
5. Maximum sample storage time prior to analysis: years, if dried.
6. Sample preparation difficulty level: low (air or freeze drying, homogenisation) to high (additional acid digestion)
7. Common analytical methods: DTD-AAS, CV-AAS*
8. Cost of Hg analysis per sample: $ -$$
9. Overall difficulty of monitoring Hg pollution using flora: low

E Fauna

1. Typical THg concentration range: medium (µg/kg) to high (mg/Kg)
2. Major Hg species present: Mixture of MeHg and inorganic Hg
3. Sampling difficulty level: high relative to abiotic samples. Dependant on target organism, sample type, sampling strategy used.
4. Sample preservation difficulty level:
   a. non-perishable samples (e.g. fur, hair): low
   b. perishable samples (e.g. fish tissue, insects): medium (isopropanol/cold chain/dark)
5. Maximum sample storage time prior to analysis: months to years, if frozen or freeze dried.
6. Sample preparation difficulty level: low (optional air or freeze drying, homogenisation) to high (additional acid digestion).
7. Common analytical methods: DTD-AAS, CV-AAS*
8. Cost of Hg analysis per sample: $- $$
9. Overall difficulty of monitoring mercury pollution using fauna: high

* Analytical method recommendations are based on likely Hg levels in each sample type, instrument detection ranges, and relative cost/benefits of method use. Instruments with lower detection ranges could also be used, at an increased cost of analysis per sample.

** As Hg in water is present in dissolved and particulate phases, Hg should ideally be analysed in both filtered water and suspended solids. Unfiltered water samples require stabilisation, and samples with a high content of suspended solids require microfiltration. Hg levels in water samples can be low (ng/L range) requiring higher resolution (and more expensive) analysis instruments for measurement.

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It should be noted that the present 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, there can be a value for including air monitoring in a mercury monitoring effort 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. Several ambient air survey methods have been employed for mercury hotspot monitoring that could be useful references for ASGM survey. As for the background monitoring of ambient mercury, 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 Monitoring Guidance (Secretariat of the Minamata Convention on Mercury, 2021a). Likewise, although human mercury biomonitoring is also not addressed in this document; it should also be considered as a component in a comprehensive mercury monitoring program. Exposure assessment of ASGM workers and residents can be done clinically and analytically. As for more epidemiological level, information on developing a human mercury monitoring program is presented in Chapter 5 of the Monitoring Guidance 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, behavioural, 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 Monitoring 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 humans, particularly Indigenous Peoples and local 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 for impacts on human health and biodiversity because they provide information that can be directly associated with Hg exposure through the food web. 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 behavioural 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 molluscs), 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). Dragonfly 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. It should be noted that the mercury in paddy rice also include atmospheric deposition of elementary mercury, so the speciation of mercury species is important. 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 analysed 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. It should be noted that such approaches may not the most appropriate for high mercury emission environments such as ASGM sites. Instead, approaches using methylmercury analysis can provided a more accurate assessment of the mercury risks to human health and the environment.

5.D.1.3 Monitoring sites

The selection of monitoring sites for mercury biomonitoring should be done based on the ecosystem's 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 are found in the Monitoring Guidance, sections 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 Monitoring 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 characteristics 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 buy-in and a sense of ownership of the monitoring effort by Indigenous Peoples and by local communities. For example, in the case of sampling fish, consulting with local fishers who are familiar with target species and its behaviour, 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 practitioners are encouraged 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 analysed in a wet or dry form. If the sample is to be analysed 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 behaviour, 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.

Soil is a media with high levels of spatial variability in concentration, both horizontally and vertically. Hence, the importance of developing 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. Several soil Hg studies often report collecting samples from the “topsoil” (upper soil layer) without specifying depth or soil horizons sampled which hampers repeatability and comparability with other studies.

Figure 3: Commonly used soil samplers. Soil augers (left and right), shovels (middle). Source (clockwise starting top left): iStock, iStock, Flickr, iStock, Kim et al. (2012), iStock.

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 analysed 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 analysed for pH, cation exchange capacity (CEC), organic matter, clay, silt, sand and iron and aluminium oxide contents. Because soils can help to predict the behaviour 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 colour (yellow or red colour 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 distribution of mercury in geological strata is influenced by the timing and mechanism of strata deposition, especially at the boundary (unconformity) between anthropogenic strata such as tailings dams and natural strata (Nirei et al., 2012). 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 4: Commonly used sediment samplers. Sediment corer (left), manual grabs (centre and top right), shovels (bottom right). Source: (from left to right): Flickr, Flickr, ©CINCIA (top), geografiafisicaou.blogspot.com.

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, considerations for sampling in this medium are highlighted 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 behaviour 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 analysing 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 analysing total mercury in water, samples should be filtered as described above, and the filters should be kept to also be analysed 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 5: Commonly use surface water samplers. Flasks or bottles (top left and right), flask or bottle attached to a telescopic rod (bottom right). Source: iStock.

Figure 6: Commonly used process to sample water for dissolved and total mercury. Manual water sampling in flasks or bottles (right), water samples are afterward microfiltered in the lab or field to separate the particulate and dissolved phases (centre). View of a water sample prior and after microfiltration (right). Source (from left to right): iStock, Flickr, iStock, iStock.

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, random or cluster[18]), sample collection protocol

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[18] Random sampling means that each data point has equal probability of being chosen. Systematic sampling means that data points are selected using a pattern (e.g., distance, even number). Stratified sampling means that a population is first divided into subgroups known as strata based on shared characteristics (e.g., age, gender, geographical location) of the data points. Then, data points are randomly selected from each subgroup. Cluster sampling is advantageous with large populations to

(e.g., sample collected in centre of 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 analyse the samples.

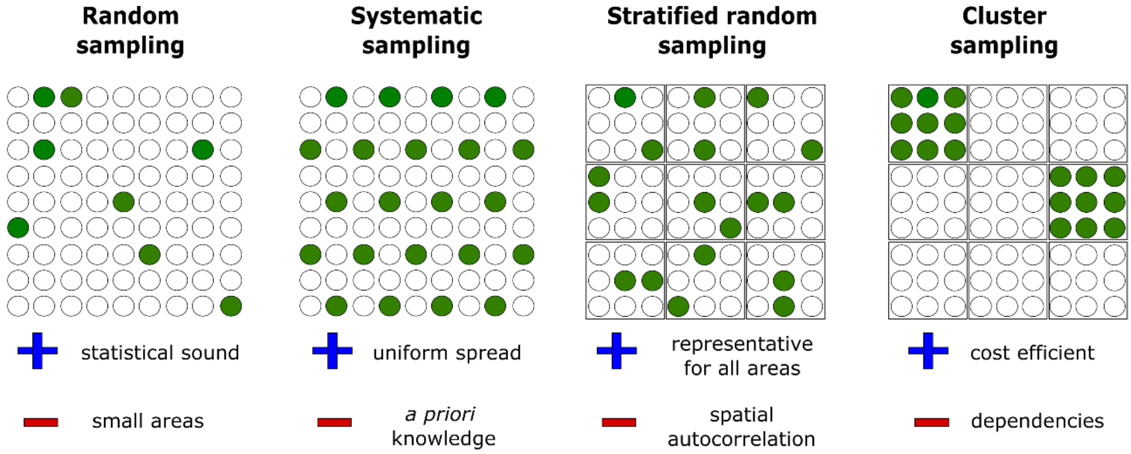

Figure 7: Field sampling approaches with advantages and disadvantages (modified from Banko 1998).

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. Indigenous Peoples, local communities and other stakeholders in sensitive or affected areas can also provide useful information based on Indigenous Peoples' knowledge and traditional local knowledge.

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reduce the sampling effort and cost. It involves dividing the population into subgroups or clusters, from which sampling takes place in two stages: 1. A sample of clusters is randomly selected from the population, and 2. A sample of data points are selected from one or multiple clusters. The difference between stratified and cluster sampling is that stratified sampling ensures representation from each subgroup (data points from all groups), while cluster sampling simplifies the sampling process by selecting entire clusters. The selection of each method will depend on the study objectives, available resources and the characteristics of the study population.

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) and 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 analysing 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 analysing Hg include the multi-element analysers 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). Several methods of methylmercury analysis are proposed by using gas chromatography electron-capture detector (GC-ECD) or atomic absorption spectrometry (AAS) preceded by extraction or chromatographic separation.

Analytical advantages and limitations

The selection of a suitable analytical technique will depend on the detection limits needed to produce meaningful data with 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 (supplemental material 2). 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, labour, instrument time and administrative costs and the number of samples to be analysed. For example, the cost of analysing a sediment sample by DTD-AAS which does not require prior sample preparation should be significantly lower than analysing 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.

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 analysed, interpreted and reported according to the research hypothesis and objectives of the monitoring plan. When analysing 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 document. 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 understand the findings easily and quickly.

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 populations 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, including assumptions and data uncertainty, 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. They would also serve as useful information to feed into the effectiveness evaluation of the Minamata Convention. 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 diverse 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-technically literate population groups, Indigenous Peoples, local 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: IMPLEMENTING RECORD KEEPING PLANS FOR EVALUATION AND IMPROVEMENT OF MONITORING OPERATIONS

An environmental monitoring program may last for several years or decades, and be subject to modifications due to new findings, variations in national and international guidelines, or changes in available financial, logistical, and human resources. Implementing good data and record management practices (GDRP) is a useful tool to keep track of the monitoring effort and decision-making, as well as facilitate the evaluation and improvement throughout time.

Record keeping is defined as the practice of recording, organizing and storing important information for future reference. A record is an information created or received by an institution that documents the organization, functions, policies, decisions, procedures, operations or other activities of the institution. Records can be physical or digital, and range from paper documents, publications, procedures, methodologies, meeting minutes and databases to photographs, slides, audiovisual recordings, maps, drawings and emails. Records are evidence of decision-making. Thus, the data or information in them should be reliable and complete, as well as attributable, legible, contemporaneous, original and accurate (the ALCOA principles for data integrity).

GDRP is important as it allows practitioners to evaluate how the mercury monitoring program is performing, whether it is effective, and whether the set objectives are being met. It also helps to identify areas that require further attention or new methodologies that can be implemented. GDRP also allows to assess the conformity with best practices, the guidelines of the Minamata Convention and the country's Minamata Convention National Action Plan.

Program managers and technical practitioners are encouraged to inform themselves of their institution's policies for record management, retention and destruction to comply with legal, administrative and operational requirements. They should also make sure that all personnel involved in the execution of the mercury monitoring program is trained on the subject according to their functions and responsibilities. Good documentation practices help achieve robust decisions.

PHASE 9: 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 are not essential for addressing and monitoring mercury pollution in and around ASGM sites but may be interesting for research purposes. They 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 a short list of examples of activities that fall under this category is provided. 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 in areas in and around ASGM to separate out emissions from anthropogenic emission events from natural release events – though regardless of source, all bioavailable mercury can represent a risk to humans and wildlife). 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 (see supplemental materials 1). The available literature reports that Hg in ASGM-contaminated sites is present primarily as metallic mercury (Hg^0), whereas in nonmining sites and downstream ecosystems mercury is present primarily as Hg^{2+} bound to organic matter (Cesar et al., 2011; Pinedo-Hernández et al., 2015) Hg bound to organic matter is also found in ASGM sites but in lower proportions to mining related Hg^0.

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 amalgam processing sites (e.g., gold shops) to investigate atmospheric Hg deposition and accumulation patterns.

Figure 8: Lake sediment core sampling. Madre de Dios, Peru. Source: CINCIA.

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 behaviour 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.

3.3. 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 Monitoring Guidance ("*Guidance on monitoring of mercury and mercury compounds to support the effectiveness evaluation of the Minamata Convention*" (Secretariat of the Minamata Convention on Mercury, 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."

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

Figure 9: Remnant mining ponds in the post-ASGM landscape of the “La Pampa” mining zone, Madre de Dios, Peru. Source: CINCIA.

Background and challenges

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 in the southern Peruvian Amazon (Caballero 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 centre 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 2,000 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) analyser platform, in partnership with the Peruvian Ministry of Environment's Instituto de Investigation 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 synthesized 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 with 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 an engagement plan that includes relevant Indigenous Peoples, local communities and other stakeholders to create effective communication channels for information exchange

CINCIA conducted a comprehensive stakeholder mapping effort to identify key local stakeholders and potential partners and understand how the monitoring project would engage with each. Identified stakeholders, collaborators and research partners included Indigenous Peoples' organizations, women associations, mining cooperatives, and 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 were 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 the Indigenous Peoples and the local communities an opportunity to exchange information on their experiences and receive training and technical capacity building on mercury monitoring techniques. CINCIA's effort to work closely with the local stakeholders served to ensure 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 analyser 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 local 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 by the available literature reviewed in Phase 1, Indigenous Peoples' knowledge, local knowledge 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 are the main protein source for a high number of riverine communities and Indigenous Peoples 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 impact of mercury exposure on terrestrial biodiversity.

Focus 3: Mercury levels in air: 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 on 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 newly developed passive air sampler for the collection of gaseous elemental mercury. Because the 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 the 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 analysed for total mercury.

Figure 10: 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). Source: CINCIA.

Focus 2. Mercury in wildlife

To assess the risk of Hg exposure posed by contaminated abandoned mining ponds, feathers from birds and fur from bats 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 desiccant. As a control site, a natural oxbow lake located in a pristine forest from a protected area was used.

Figure 11: CINCIA researchers sampling feathers from a bird (top) and fur from a bat (bottom) for a wildlife mercury exposure assessment. Source: CINCIA.

Focus 3. Mercury levels in air: Amalgam burning gold shops

The monitoring effort was designed and implemented with the 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 to map the temporal-spatial variability of GEM at larger spatial scales.

Figure 12: UofTPAS passive air samplers for gaseous mercury installed in a tree in Manu National Park in Madre de Dios, Peru. Source: CINCIA.

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. 13a). 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. 13b). 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.

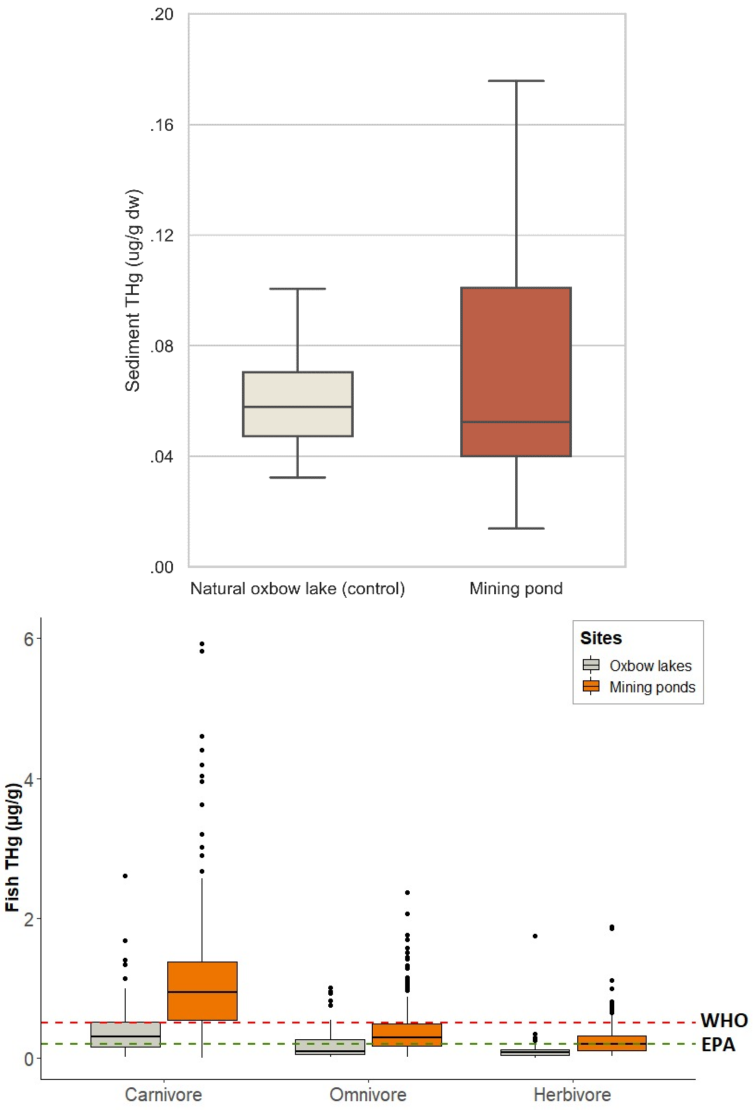

Figure 13: Mercury concentrations in abandoned mining ponds and natural oxbow lakes from Madre de Dios, Peru **A.** Mercury in bottom sediments (n=131) **B.** Mercury in fish (n=1148) from different trophic levels.

Focus 2: Mercury in wildlife

Mercury concentrations in birds and bats responded primarily to differences in feeding habits within each taxonomic group (animal group), 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 were complex, and the resource demands 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 on a scoping study for monitoring mercury in wildlife. The program will help identify potentially 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.

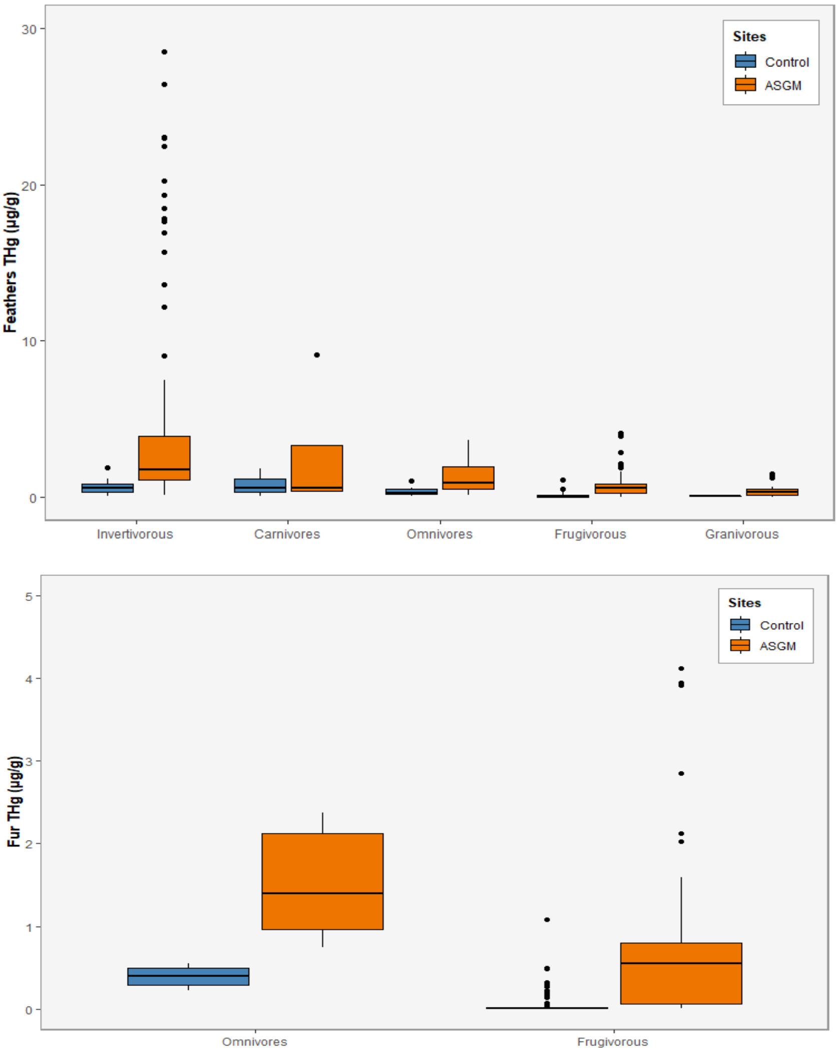

Figure 14: Mercury concentrations in wildlife of different feeding habits[19] from Madre de Dios. **A.** Mercury in feathers from birds **B.** Mercury in fur from bats. Specimens were captured and sampled at different distances from abandoned mining ponds and compared against specimens captured near 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: Amalgam burning gold shops

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[19] In this context, insectivores, also known as entomophages, are carnivorous animals that eat mainly insects; frugivores are animals that feed primarily or exclusively on fruit; and granivores are animals that feed primarily or exclusively on seeds.

Monitoring data were 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.

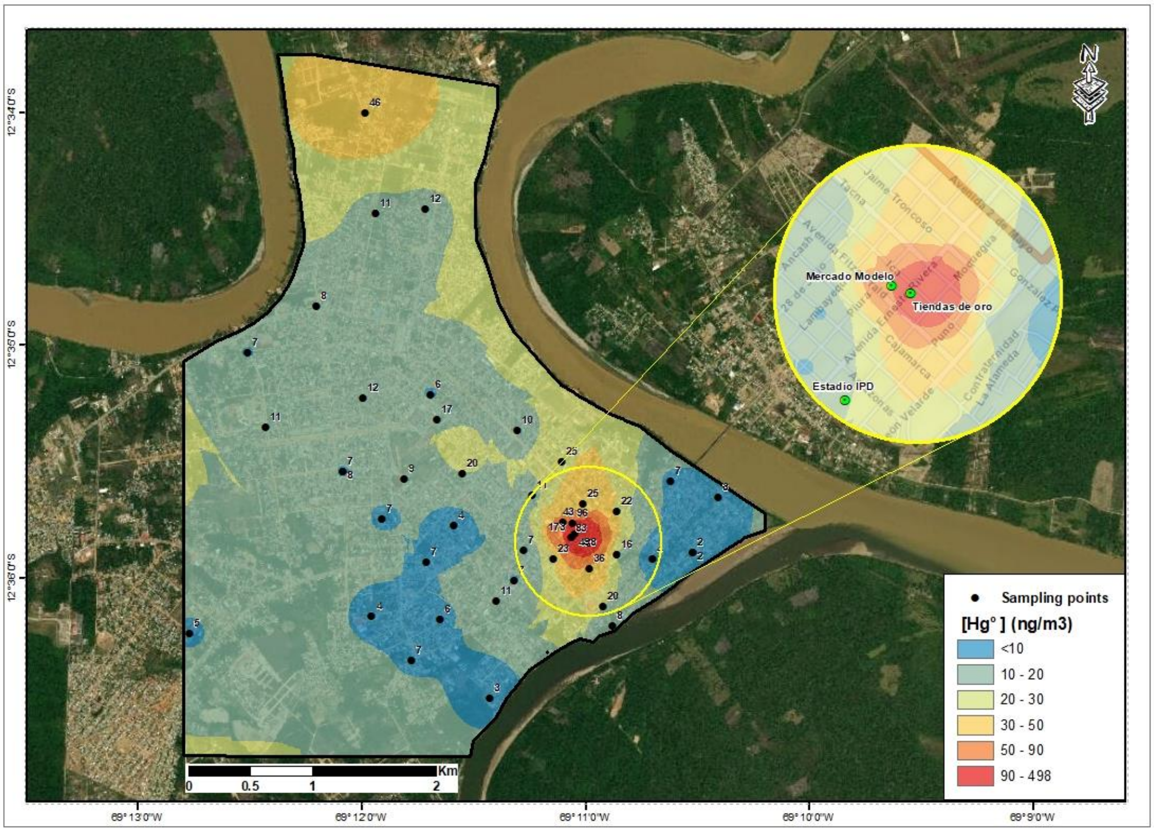


Figure 15: Mercury concentration gradient of GEM in Puerto Maldonado, capital of the Madre de Dios region in Peru.

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: Implementing record keeping plans for evaluation and improvement of monitoring operations

CINCIA uses a cloud-based storage service for keeping record of its mercury monitoring program. The Mercury program has a specific work folder, which is divided according to the subject of the documents. There, the Hg data are stored in a semi-automated database according to the sample type (matrix). The database includes sampling information (sampling site, date, coordinates, presence of mining, responsible person, etc.), ancillary data (for example, in case of fish, body length and weight and water quality parameters) and mercury analysis. Information on the status of the sample preparation process can also be found in the database, as well as a dictionary specifying all the codes to assure their correct use by users. Access to the mercury data is controlled by CINCIA's managers and the Mercury program coordinator. To avoid possible loss of information, and as good data and record management practice (GDRP), CINCIA keeps copies of all files stored in a separate file in the cloud-based storage service with limited access.

Phase 9: Conducting high-complexity mercury data analysis to identify and understand sources, processes, and projections

CINCIA has also worked on a joint project with the University of Toronto to investigate the mercury isotope signature in air, sediment, and soil samples to provide insight into Hg sources in the Madre de Dios region and enhance the understanding of the extent 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 in local environments.

Take aways 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 behaviour and dynamics of mercury in the environment and the potential threats to human and wildlife health.
- Working with Indigenous Peoples, local communities and local non-governmental 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 rightsholders and stakeholders.

5. Case study II: Fictional case study on environmental mercury pollution monitoring

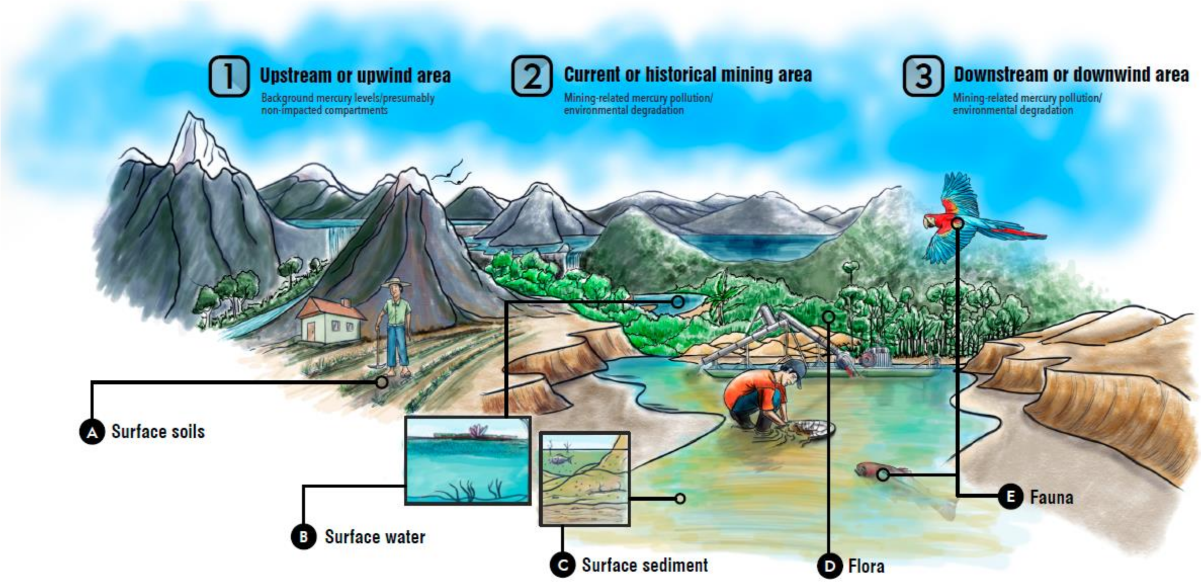


Figure 16: Schematic representation of the study area in a mining region in the fictional country of Brantalia (see figure 2 for more details).

Introduction

In this section presents an illustrative case study describing the work of a fictional regional-level environmental agency in a fictional country that has been joined the Minamata Convention and has been tasked with developing a monitoring program for mercury in and around artisanal gold mining operations. The intention of presenting this fictional case study is to help readers understand how the monitoring framework presented in this document can be used by practitioner to develop a mercury monitoring program in a practical, efficient and cost-effective manner.

Background and challenges

This case study is based on a fictional country called “Brantalia” that has recently joined the Minamata Convention on Mercury. Brantalia is classified as a middle-income country by the World Bank and is located in the tropics. It has a small, but growing ASGM sector that has traditionally used minimally mechanized methods, and mercury amalgamation to mine alluvial sediments in several watersheds in its more remote provinces. The ASGM sector is mainly informal, with a small percentage of miners operating illegally in protected areas, private lands and on Indigenous Peoples lands and territories. The country has attempted to formalize its ASGM sector during the last 5 years, but progress has gone slower than planned.

As a new member of the Minamata convention, Brantalia has started the process of designing and implementing its Minamata National Action Plan (NAP). This task has been delegated to the Ministry of Environment's Environmental Monitoring Office, which has been given the responsibility of managing the environmental impacts of ASGM in the country, including reducing the amount of mercury that is released to the environment by the sector. The work of Brantalia's Environmental Monitoring Office has so far largely focused on the deforestation caused by ASGM in the southern part of the country, a region that has seen a rapid expansion of unregulated mining due to the increase of global gold prices. The inclusion of mercury monitoring in relation to ASGM activities presents the Environmental Monitoring Office a set of new responsibilities and tasks.

One of these tasks is to develop a mercury monitoring program for areas in and around ASGM sites. The personnel in the Environmental Monitoring Office have limited experience with such monitoring programs but has been deemed necessary to generate the needed information for decision-making and compliance with reporting requirements under the Minamata Convention.

To begin designing a mercury assessment and monitoring program for their NAP, the staff of the Environmental Monitoring Office decided to follow the phase-based framework for *in situ* mercury monitoring in and around ASGM sites presented in this technical guide. Below is a description of the sequential work steps conducted by the Brantalia's Environmental Monitoring Office staff to meet their program's monitoring goals.

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

As a first step in designing and implementing a monitoring program, the practitioners from the Environmental Monitoring Office collected, reviewed, and synthesized information on ASGM and mercury pollution in the country. They first conducted a literature review, including scientific publications and grey literature. After, the staff conducted a rapid review of government reports and studies published in the scientific and grey literatures that reported Hg in the area of interest and found only four academic studies. These studies reported elevated hair mercury concentrations in local residents living close to mining sites, as well as in root vegetables cultivated and consumed by these residents. Some of the studies also reported that the local residents frequently fished and consumed local fish from rivers downstream mining operations. However, all these studies date back more than 10 years, and reported findings based on a very low (<10) number of samples. No mercury analysis of sediments, soils or fish was done in any of the studies. Based on insights provided by the literature review, and combined with the confirmation that all ASGM operations in the region were using mercury amalgamation, the Environmental Monitoring Office staff concluded that there was a high likelihood that mercury releases from ASGM operations were causing or contributing to elevated mercury exposure to local residents. However, it remained unclear how ASGM related mercury emissions and releases were affecting mercury levels in nearby aquatic or terrestrial ecosystems. Finally, definitive evidence regarding the source(s) of the mercury was lacking.

The literature review identified two main regions with ASGM. The larger area was located in the in the Southern Lowlands of the country, and a smaller one located in the mountainous region in the north. In the Southern Lowland region, hydraulic ASGM was conducted on alluvial plains, and fluvial dredging mines placer deposits in the bottom sediments in several of the region's rivers. In the Northern Mountain region, hard rock gallery mining predominated. A recent government assessment estimated ASGM in Southern region was ~10,000 ha in extent with 1,000 miners working in the area. The Northern site had an estimated 2,000 ha of mining extent with about 300 miners active in the region. The Environmental Monitoring Office staff conducted telephone and Zoom interviews with local government authorities, local residents and a staff member of a small environmental NGO to gather baseline knowledge and information.

Once the two candidate ASGM regions in the country were identified, the staff analysed recent satellite images of the two regions on the Global Forest Watch Forest mapping platform to confirm and better estimate the location and extent of ASGM in the study area. This review provided more information on the current extent and on the growth rate of ASGM, as well as the proximity of human settlements and protected areas, as well as some information on where potential mercury hotspots could be located. The mapping also helped understand the transportation requirements that would be needed is *in situ* site visits would be needed.

The satellite data analysis showed that, in the Southern Lowland site the extent of ASGM was indeed approximately 10,000 ha and had grown by a factor of two in only two years, whereas the northern site had about 2,000 ha and expanded little in the last five years. Further, ASGM in the Southern Lowland region was being done in slow moving tropical rivers that had mountain headwaters with no known history of mining. Mining was upstream from a protected area and a number of small villages that, according to the most recent population census, together had about 10,000 inhabitants. These villages had residents that focused on mining and subsistence agriculture, with resident diets based largely on locally grown crops, local fisheries, livestock production, and few imported food stuffs from the country's capital. The Southern Lowland region is also home to an endemic sub-species of river otter (*Lutra* sp.) that is classified as "endangered" in the IUCN Red List™.

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

The Environmental Office set as the overall goal of their mercury monitoring program to characterize the presence, magnitude, and spatial distribution of mercury pollution in and around ASGM sites, with a budget of USD 300,000, and a period of 3 years was assigned to the program.

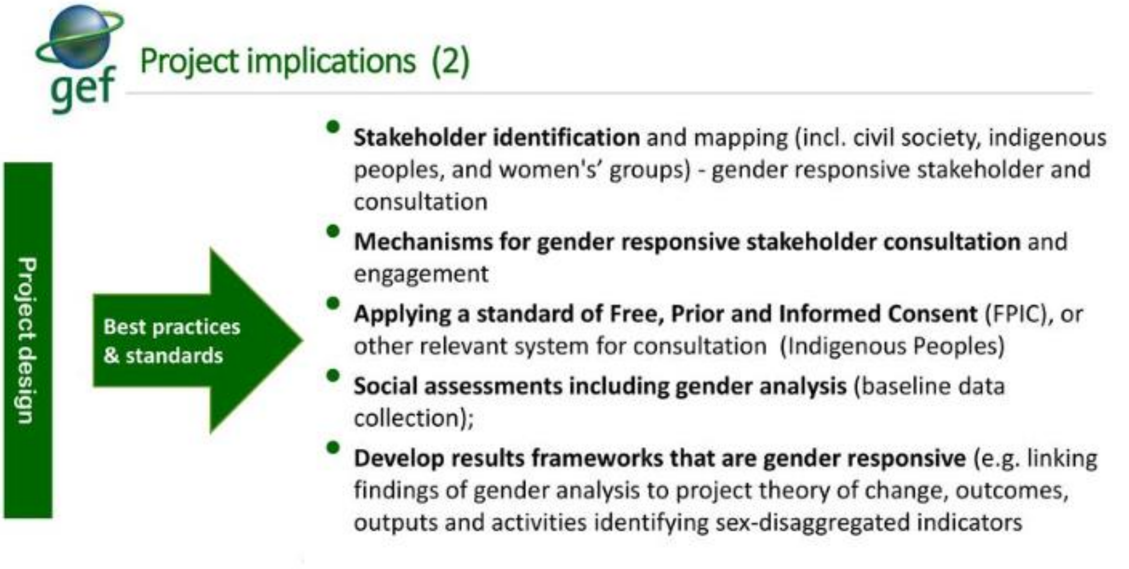
Given the stated objectives and assigned resources, and the findings provided by the data collected in Phase 1, the Environmental Monitoring Office program manager decided to prioritize the site in the Southern Lowlands as ASGM was expanding at a higher rate, and nearby human communities were needed to be at greater potential health risk to the community's consumption of fish from local rivers. Further, some community members had raised safety concerns about crops irrigated with river water that was potentially contaminated with mercury from upstream mining operations. Also, from a logistics point of view, the monitoring team considered this site more accessible if on-site monitoring was needed.

The work team initially proposed monitoring mercury concentrations in the rivers where dredging was taking place, i.e., sediment, water and fish; in the agriculture areas, i.e., soil and crops; and in the air close to gold processing sites. However, given the limitations of time, budget and resources, monitoring so many different types of samples consistently in a 3-year period would have been unfeasible. Faced with this situation, the team carefully reevaluated the monitoring purpose, needs and logistic requirements and decided to begin the monitoring program only looking at terrestrial and aquatic environments. Specifically, they would examine mercury levels in soil, crops, river sediment, fish and the river otter.

Phase 3: Develop an engagement plan that includes relevant Indigenous Peoples, local communities and other stakeholders to create effective communication channels for information exchange

Once the monitoring goal and objective had been set, the practitioners made a stakeholder map to identify key local stakeholders and potential partners, as well as their potential interests and influence in the monitoring program. As local stakeholders, a women's association, an NGO working on wildlife conservation and the local community, including community leaders, residents, and miners, were identified. Other relevant stakeholders included the Regional Lowland Forestry Agency, the National Agency for Water Management, and the Health Ministry. As potential partners, national academic researchers working on environmental pollution and certified laboratories were identified.

To build a good working relationship with local stakeholders, the Environmental Monitoring Office team worked with a communications specialist to design a stakeholder engagement plan and outreach strategy based on UNEP's Stakeholder Engagement Handbook (UNEP, 2015). To do this, the communication team organized in-person meetings at the study site and invited representatives from all stakeholder organizations. At the meeting, the team from the Environmental Monitoring Office in charge of the mercury monitoring program presented the project, its objectives, and the execution period, and expressed its interest in having the contribution of all the groups and organizations attending. Views were exchanged and the plans were adjusted. After a few weeks of exchange, cooperative working agreements were signed between the stakeholders and the Brantalia Environmental Monitoring Office. The Regional Lowland Forestry Agency offered a working space in its facilities for the Environmental Monitoring Office team in charge of the mercury monitoring program. The community leaders of the village invited the Environmental Monitoring Office team to regularly visit them to learn more about the situation of the population in the area of interest.



Project implications (2)

- **Stakeholder identification** and mapping (incl. civil society, indigenous peoples, and women's' groups) - gender responsive stakeholder and consultation
- **Mechanisms for gender responsive stakeholder consultation** and engagement
- **Applying a standard of Free, Prior and Informed Consent** (FPIC), or other relevant system for consultation (Indigenous Peoples)
- **Social assessments including gender analysis** (baseline data collection);
- **Develop results frameworks that are gender responsive** (e.g. linking findings of gender analysis to project theory of change, outcomes, outputs and activities identifying sex-disaggregated indicators

Figure 17: Illustrative example of best practices for stakeholder engagement and gender mainstreaming during project design (GEF, 2017).

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

The necessary resources to start the field work of the monitoring program were secured by hiring personnel with experience in the collection of environmental samples for pollution assessments. These personnel will lead the sampling process and train the rest of the work team and the local people who would collaborate with the field work of the project. Once decided the matrix that will be sampling and revising protocols of sample collection and preservation, the purchase of materials for the sample collection (shovels, bags and a manual dredge) and preservation (refrigerators, coolers, containers, etc.) was a made. The team would receive logistical support (transportation, permits, security advice, etc.) from the local stakeholders to reach the study sites. Finally, for the mercury analysis of the samples, a cooperation agreement was signed with one of Brantalia's certified chemical laboratories to receive and analyse the samples at a preferential rate.

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

The Brantalia Environmental Monitoring Office established the work plan of the field work according to the established objectives and priorities (Phase 2), the available resources and the support of the stakeholders (Phases 3 and 4), as well as the information of the area of interest (impacted and control) collected at the beginning of the project (Phase 1).

As a first step, the work team coordinated with the Regional Lowland Forestry Agency and the community leaders to visit the study area and carry out a pilot project. The pilot project would allow surveying the study area and defining the sampling environments and sites (impacted and control sites) according to the level of ASGM-related impact, distance from mining operations, access and required logistics. It would also allow testing alternatives for the sampling design and the protocols for the collection, preservation and transport of the samples. Visits to the study area included drone overflights by staff from the Regional

Lowland Forestry Agency. All this information made it possible to define the work protocol and refine the list of logistical, human, and economic resources necessary to comply with the monitoring plan requested by the Brantalia government.

At the end, the Brantalia government decided the focus of its monitoring program according to the information collected from the study area (Phase 1), research priorities (Phase 2), input from stakeholders (Phase 3), available resources (Phase 4) and the results of the pilot project (Phase 5). The program would focus on a river system (aquatic environment) with ongoing ASGM for sediment and fish, as well as on an agricultural field (terrestrial environment) close to the villages for soil and crop, and on the protected area for river otter biomonitoring. The results would be compared with control sites identified during the pilot study. All this would ensure that the recommendations in this guide are followed for a detailed assessment of the study area. Data would be acquired from more than one environmental compartment and from at least two sample types. Furthermore, both abiotic and biotic samples would be considered. The work protocols are detailed below:

Focus 1. Mercury in rivers: sediment and fish

Sampling in the study river was carried out systematically every certain number of kilometres twice a year, once during the rainy season and again during the dry season. The sampling of bottom sediments and fish began in the upper part of the river, with no mining activities, continued downstream where mining activities were taking place, and ended in the lower part of the river, downstream from mining activities. In this way, mercury concentrations could be compared before, during and after mining. A standardized sampling of fish was difficult to achieve, but the protocol aimed for at 10 specimens, of the same size, of carnivore fish species at each sampling point. Carnivore species found in the study river had commercial value for the local population and served as good bioindicators of mercury pollution for being in the highest levels of the local trophic web.

Focus 2. Mercury in agricultural areas: soil and crop

Sampling in the agricultural area was performed using a random stratigraphic design. The design was decided based on the distribution of the agricultural zone, which was made up of three small farms (all with similar area) belonging to different local inhabitants. As all the residents wished to receive information on the state of contamination of their farms, it was agreed to take random samples of the soil and the harvest in all of them. Sampling was done twice (dry and wet season) a year and with the help of the farm owners, who were trained to take the samples. As a control site, a distant agricultural area, with the same type of crop and without mining impact, was sampled. In Phase 1, no information was found available on baseline mercury values at Brantalia.

Focus 3. Biodiversity conservation: river otter

Non-invasive and low-cost sampling of river otters in the protected area was performed by setting up “hair traps” to obtain hairs from the otters. The hair was caught by a Velcro® patch fitted to the upper surface of the tunnel as described the literature (Anderson et al., 2006). The hair traps were placed along the shores of the river where the otters were known to roam. Sampling was done twice (dry and wet season) a year. The location of the traps was informed by the Indigenous Peoples living in the area who also confirmed that the material collected was indeed otter hair. Control samples were collected in a similar manner in the upper part of the river, with no mining activities.

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 rivers: sediments and fish

Sediment sampling was carried out, to the extent possible, in transects, considering the middle point and the banks of the river channel, using a manual grab and shovels. Based on the results of the pilot project, where higher concentrations of mercury were found in the fine, clayish fraction of sediment, the samples were passed through a 0.063 mm nylon sieve to separate the fine and coarse soil fractions for independent analysis. The sieving also allowed to standardize the samples according to their texture, which was quite variable (from coarse sand to clay) between the different sampling points. Both fractions were kept for their independent analysis. According to the instructions of the laboratory that would receive the samples for analysis, approximately 250 g of sediment was collected at each sampling point. Samples were kept in cold and dark labelled air-tight plastic bags, using cooling boxes with ice. In some cases (bad weather, limited field staff), fractionation of the samples in the field was not possible. In these cases, the samples were stored unfractionated and sieved later at the Regional Lowland Forestry Agency facilities.

The target fish species were caught using gillnets in areas of low river flow. Following the advice of local fishermen, who joined the monitoring team as field assistants, the fishing was done at night, when the species were most active. All captured specimens were weighed and measured in length and identified to species level by local fishermen. From each collected specimen, a sample of the dorsal muscle was taken with a stainless-steel scalpel and placed in a clean air-tight plastic bag labelled with the data of the collection point (date and coordinates) and the name of the fish species. The fish and sediment samples were kept cold and dark using ice-filled storage boxes until they arrived at the designated village, where a freezer had been placed by the monitoring team at the medical centre. At the end of the field campaign, all samples were transported in a cold chain to the facilities at the Regional Lowland Forestry Agency, where larger refrigerators and freezers were available to preserve the samples for a longer period.

Focus 2. Mercury in agricultural areas: soil and crop

Soil samples were taken randomly from the three farms of the town. Given some publications that were reviewed in Phase 1 on mercury in soils, where concentrations varied spatially and temporally, two samples were taken from each farm at two different depths (0-5 cm and 5-10 cm) using a soil auger. Soil samples were no fractionated as in the case of sediments but were still passed through a mesh to clean them from small stones and debris. About 250 g of soil was transferred to an air-tight and labelled plastic bags using a shovel. If sieving the samples in the field was not possible, this was carried out later at the Regional Lowland Forestry Agency.

The crop sampling consisted of extracting from the soil three to five adult root vegetables per soil sampling point. Crops were selected according to their distance from the soil sampling point. The sampling procedure consisted of cutting a piece of the edible part of the vegetable with a stainless-steel scalpel and placing it in a labelled plastic bag. The first soil and crop collections were carried out by the Environmental Monitoring Office team. After a training process, the owners of the farms were the main responsible for the collection of the samples. Crop sampling was conducted twice a year, in the same period that the soil samples were collected.

Focus 3. Biodiversity conservation: river otter

Following the advice of local Indigenous Peoples, who joined the monitoring team as field assistants, the river otter hair samples were collected in the mornings, as the species is most active at night and more likely to go through the tunnels that served as hair traps. All samples were kept separate, and were weighed and measured in length and confirmed to be from a river otter by local Indigenous Peoples. Each collected sample was placed in a clean air-tight plastic bag using tweezers labelled with the data of the collection point (date and coordinates) and the otter species. At the end of the field campaign, all samples were transported in a cold chain to the facilities at the Regional Lowland Forestry Agency, where larger refrigerators and freezers were available to preserve the samples for a longer period.

Sample preservation and transport to the laboratory

All collected samples were kept cold and dark using cooling boxes with ice during field work. Subsequently, the samples were transported from the study area to the Regional Lowland Forestry Agency facilities, where they were stored in freezers. From the Regional Lowland Forestry Agency, the samples were transported in a cold chain to the capital of Brantalia, where they were received by the cooperating university. The cooperating university freeze-dried the samples and delivered them to the chemical laboratory that would perform the mercury analysis. In cases of failures in the electrical system or with the freeze dryer, the samples were dried at room temperature. For the river otter samples, an additional low-cost and standard PCR test using a method developed by the university was made to confirm their origin. Negative control PCR test was done using hair from laboratory mice.

Mercury analysis

The laboratory responsible for the mercury analyses analysed all the samples using the technique of thermal desorption followed by mercury amalgamation (DTD-AAS) and the EPA 7473 method. As a quality control for precision and reproducibility, the samples were analysed using certified reference materials, blanks and analytical replicates.

Data analysis and interpretation

Focus 1. Mercury in rivers: sediments and fish

The concentrations of mercury in all samples were higher in the fine fractions (<0.063 mm) than in the coarse fractions (>0.063 mm), confirming that mercury in the study area adheres preferentially to fine sediments, that is, to those with a clayish texture. Both in the rain and dry seasons, the samples collected at or close to ongoing mining activities presented higher concentrations of mercury than those collected in upstream areas. Mercury in sediment immediately downstream from ASGM operations were also above international guidelines for sediment quality but decreased rapidly to concentrations like those in upstream areas. These results indicate that ASGM is a source of mercury to the study river system. The rapid decrease of the concentrations in the downstream area might respond to a dilution effect.

Mercury concentrations in fish varied primarily according to the species' feeding habit, which is consistent with other studies on mercury in fish and wildlife. Mercury concentrations in all caught carnivore fish were above international guidelines for human consumption, but no clear relationship with the distance from the mining sites was found, possibly because the fish travel up and downstream from the mining areas and may also accumulate mercury from other activities in the areas that are also known to release mercury, such as logging and biomass burning. The elevated mercury concentrations in fish pose a risk for dietary exposure of the Indigenous Peoples and of local communities living in the area.

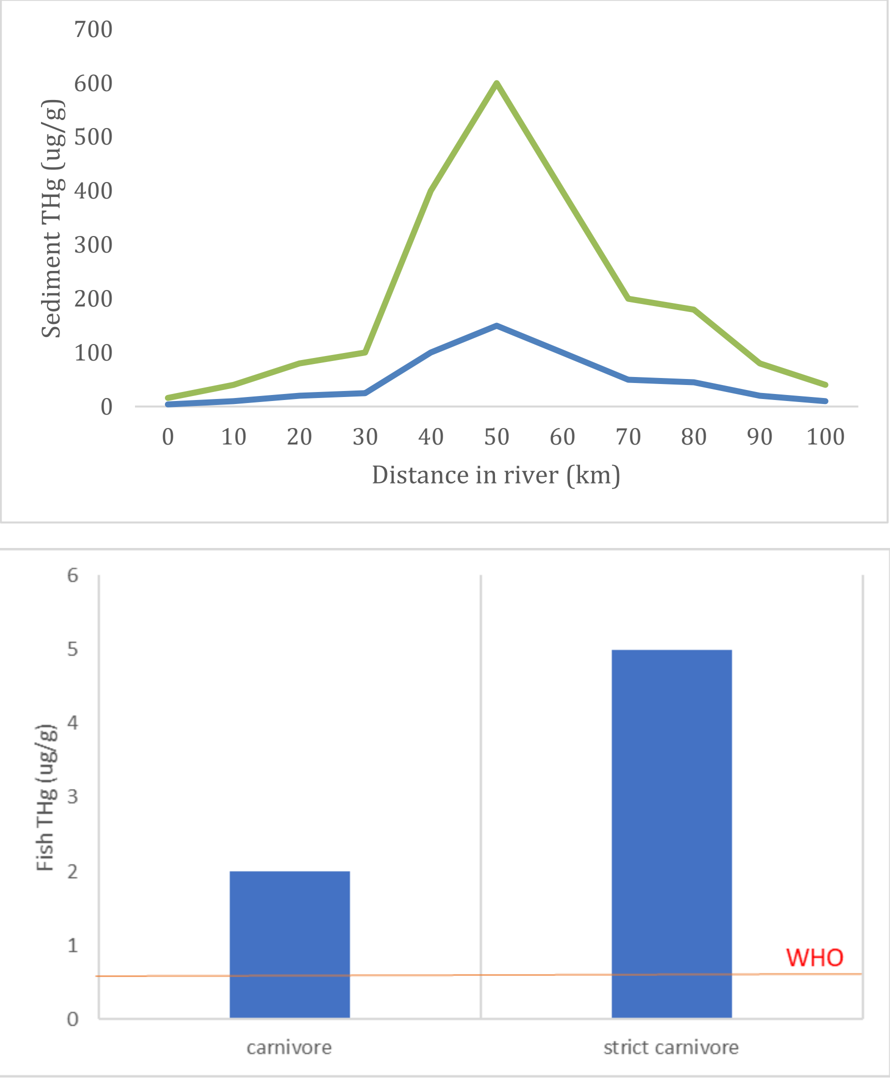


Figure 18: Mean mercury concentrations in sediment and fish from the study river. Top: total mercury concentrations in fine fraction (grey colour) and coarse fraction (blue colour) along a 100 km stretch of the study river. Mining operations in the river are conducted between km 30 and 70. Bottom: mean mercury concentration in carnivore and strict carnivore fish capture in the study river stretch.

Focus 2: Mercury in agricultural areas: soil and crop

The highest mercury concentrations were found in the soils of the farm located closer to the town rather than to the river where dredging operations were carried out and where the irrigation water for the crops comes from. When examining the neighbourhood adjacent to the farm, an amalgam burning site was identified, confirming that the main input of mercury to the farm soils was not the irrigation water but the deposition of atmospheric mercury emitted during the amalgam burning process. No significant variation in mercury concentrations was found among soil samples collected at different depths. Mercury concentrations in the root vegetables were in all cases below the recommended values for human consumption, meaning that local root vegetables do not represent a route of dietary exposure for the local population.

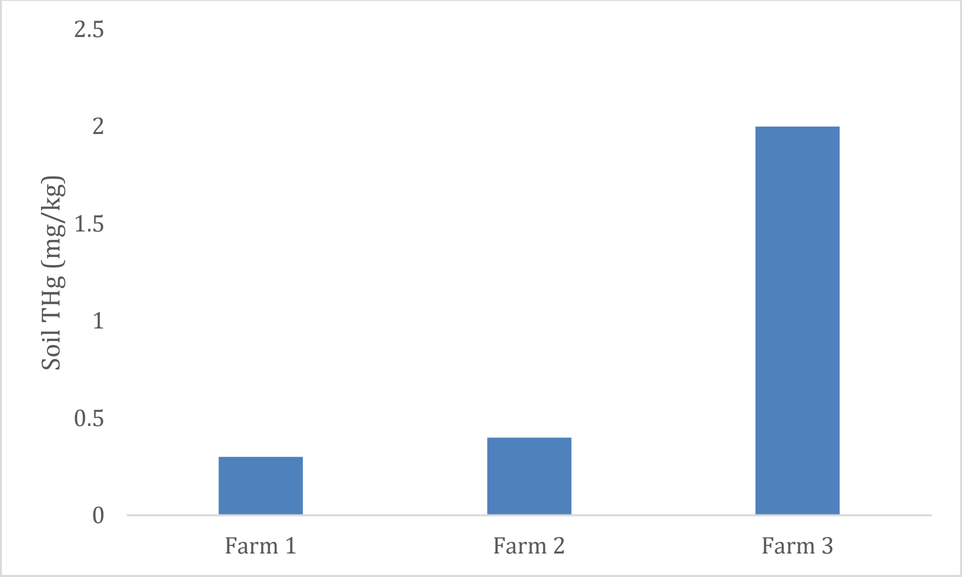


Figure 19: Mean mercury concentrations in soil from the three study farms. Farm 1 was the closest to the river, whereas Farm 3 was closest to the urban area.

Focus 3: Biodiversity conservation: river otter

High levels of mercury were found in the hair of river otters. There was high variability among the samples, probably due to individual characteristics such as age and sex, which could not be determined through the monitoring program. Mercury concentrations in river otter were above the levels found in the literature for other species, such as the Canadian river otter. No clear relationship with the distance from the mining sites was found. This is possibly because, while river otters are highly territorial and have limited home ranges, the fish they feed upon may travel up and downstream from the mining areas. Other sources of mercury cannot be excluded. The results of the monitoring program in the endangered river otter species can be used as baseline for future mercury monitoring activities and for assessing the impact on the species as part of ongoing conservation efforts.

Phase 7: Communicate results to stakeholders and interested parties

Brantalia's Environmental Monitoring Office communicated the results of its monitoring program to stakeholders in meetings at the end of each milestone through progress reports, and a report at the end of the first three years of the monitoring program. Each report was written in two versions, one technical and detailed for readers interested in the scientific and technical details of the work, and another summarized, with only the main findings, and written in simple language for a non-technical audience. Recorded video messages were shared using online platforms, social network and free cross-platform messaging services at regular intervals to update the local stakeholders. At the end of the monitoring program, a seminar open to the public and to other regional and national organizations was also organized to show the results of the monitoring program and the next steps. The event was live streamed to connect with audiences in other parts of Brantalia and in other countries.

Phase 8: Implementing record keeping plans for evaluation and improvement of monitoring operations

Record management of the monitoring program was performed using cloud-based software and the record management policy of the Environmental Monitoring Office. However, due to limited internet access in the study area, especially in the rainy season, active documents, still subject to change, were stored on the Regional Lowland Forestry Agency's server. In this way, documents and data were accessible without the need for internet access. The policy for transferring or copying files to the cloud-based software Environmental Monitoring Office varied depending on the type of file. All raw chemical or numerical data files were immediately copied to the cloud-based software. All other files were transferred or copied at the end of each month by the assigned staff. In the case of physical files, these were digitized for easier and more automated storage and access.

Phase 9: Conducting high-complexity mercury data analysis to identify and understand sources, processes, and projections

Because this was the first experience of Brantalia's Environmental Monitoring Office in the field of mercury environmental monitoring and the availability of resources was limited, its monitoring program for the first three years did not include high-complexity mercury data analysis. However, at the cooperating university, duplicates of all the samples collected were kept for possible future analysis. The sample database would be reviewed after the first three years of the program to evaluate future analyses. In the event that the Environmental Monitoring Office decides not to implement high-complexity analyses in the second stage of its program, the samples would be available to the cooperating university and other organizations interested in exploring other aspects of the environmental behaviour and impacts of mercury in the study area. Such data would be shared with Brantalia's Environmental Office.

Takeaways and lessons learned

Achieving mercury monitoring goals

- This fictional case study shows how an organization with no prior experience in environmental mercury monitoring has the capacity to design and execute a monitoring program to assess mercury contamination in areas affected by mining following the recommendations in this technical guide.

- The work of Brantalia's Environmental Monitoring Office demonstrated that ASGM is a source of mercury pollution in Aquatic ecosystem in the southern lowlands of the country and highlights the importance of following the phase-based framework for *in situ* mercury monitoring in and around ASGM sites presented by this technical guide.

- A pilot study prior to the monitoring program, the simultaneous assessment of more than one ecosystem and more than one sample type, and stakeholder engagement, including the use of Indigenous Poeples' knowledge, are critical steps for the success of a monitoring program.

- Edible plants, except for rice, are not as effective as fish for estimating risk from mercury exposure because it is not known with certainty which mercury species are present in the soil and whether they are present in a bioavailable form to plants. Finally, not all plants have the same capacity to absorb the mercury present in the environment.

- Variations in mercury concentrations in soils depend to a large extent on the properties of the soil and its geochemistry. Therefore, projects that include the analysis of mercury in soils should include an analysis to determine the type of soil with which they work. This will allow designing a better sampling and will facilitate the interpretation of the results.

- If the objective is to assess the dispersion of the contaminant in terrestrial ecosystems, analysing soil sample for Hg including ancillary data, may be a good choice, however these results cannot be extrapolated to Hg exposure in the agriculture products.

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 behaviour 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 protect human health and reduce the potential negative impacts of increased mercury pollution in sensitive ecosystems, better address the ASGM sector, and strengthen environmental protection and biodiversity conservation 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 health and biodiversity 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 or if they are relevant to biodiversity conservation efforts.

Although water is often used for assessing mercury pollution in ASGM sites due to concern of drinking contamination, water as a monitoring medium is challenging, due in part to specifics of the inherent chemical instability of mercury in water. Though the actual sample collection is simple, protocols for the preservation of the samples to avoid sample degradation and contamination are complex and highly sensitive to error. Finally, measuring mercury in water requires the use if expensive, high-sensitivity analytical techniques required for an accurate measurement. The standardization and adoption of field and laboratory working protocols for mercury monitoring, and the establishment of locally derived mercury background levels to serve as study controls will improve the quality of Hg monitoring and field assessments. In the context of the Minamata Convention on Mercury, these improvements will, in addition to supporting Parties in mainstreaming mercury control into policies and regulations, 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 the effectiveness evaluation of the Convention.

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8. Supplemental materials

Supplemental Material 1: Literature review

An annotated literature review of peer-reviewed scientific reports of mercury from terrestrial and aquatic ecosystems affected by ASGM. A list with over 130 publications is organized by regions and countries. For each publication, the title, link, authors, study objectives, study environment, study design, type of mercury reported, type of sample and conclusions.

Available at: https://minamataconvention.org/sites/default/files/documents/2024-12/Mercury_Monitoring_ASGM_Sites-Literature_Review-Supp1.xlsx

Supplemental Material 2: Analytical methods

This supplemental material contains a table with selected analytical methods for total mercury (THg) and methylmercury (MeHg). For each method, the document provides details on the matrix, analytical method type, method name, source and list of references, among others.

Available at: https://minamataconvention.org/sites/default/files/documents/2024-12/Mercury_Monitoring_ASGM_Sites-Analytical_Methods-Supp2.docx