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Quantifying mercury use in artisanal and small-scale gold mining for the Minamata Convention on Mercury's national action plans: Approaches and policy implications

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ABSTRACT

Establishing quantitative baseline estimates of mercury use in artisanal and small-scale gold mining is necessary to meet the requirements of the Minamata Convention on Mercury which aims to reduce and, where possible, eliminate mercury emissions. As part of this obligation, countries use baseline estimates to measure progress in reducing mercury emissions and releases. However, mercury baseline estimation methods vary widely resulting in high levels of uncertainty in estimates. Using artisanal and small-scale gold mining National Action Plans and baseline reports from 25 countries, we synthesize methods and data sets used to estimate mercury emissions and releases, demonstrating the range of techniques and quality of data used for these methods. National Action Plans often fail to report the quantitative uncertainty when reporting quantitative baseline estimates, and when reported, uncertainty often exceeds target reduction goals. Improved data transparency can increase the usefulness of such estimates in decision making, indicating areas in which more quantitative and qualitative data is needed for developing appropriate policies. This work demonstrates the limitations of quantitative baseline estimates as reported in National Action Plans and emphasizes the importance of a holistic understanding of the ASGM sector for policy decisions.

1. Introduction

Artisanal and small-scale gold mining (ASGM), characterized by rudimentary mining methods, low-grade ore, and limited ore production (Malehase et al., 2016), is attributed with releasing 37.7 % of anthropogenic emissions of mercury to the atmosphere (UN Environment, 2019). Because it is the largest anthropogenic sources of mercury pollution in the world, ASGM is one of the main sectors explicitly discussed in the Minamata Convention, the global agreement created in 2013 to encourage countries to reduce or, if possible, eliminate mercury emissions. As such, Article 7 of the Minamata Convention requires that countries that have a "more than insignificant" presence of ASGM determine baseline mercury use, or loss to the environment (O'Neill and Telmer, 2017), from ASGM sector. Baseline estimates are included in a country's National Action Plan (NAP) for mercury use in ASGM, serving as one of the metrics against which regulations that address mercury use from the ASGM sector is evaluated (Stylo et al., 2020). Baseline estimates can be used by governments and other stakeholders to formulate action plans, prioritize, and develop intervention strategies, and monitor improvements in mercury emissions and releases (O'Neill and Telmer, 2017). Furthermore, NAPs describe strategies to "to reduce, and where feasible eliminate, the use of mercury and mercury compounds in, and the emissions and releases to the environment of mercury from, such mining and processing" (UNEP, 2019). However, quantifying baseline mercury emissions and releases is challenging, resulting in significant uncertainty in current emission estimates (AMAP and UNEP, 2019) thereby limiting a country's ability to evaluate reduction strategies (Stylo et al., 2020).

The challenges in reducing mercury use within ASGM serve as the impetus for the implementation of Minamata Convention on Mercury's NAPs. Past efforts for reducing mercury use include technocentric interventions, such as proposing use of different technologies to reduce or eliminate mercury in gold production (e.g., retorts or alternative chemicals for processing) (e.g., Jønsson et al., 2009). However, such

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efforts ultimately fell short as they failed to account for the social, economic, and political constraints that reinforced the use of mercury amalgamation in ore processing (Smith, 2019; Bugmann et al., 2022). Other efforts to curb the use of mercury have included formalization efforts, which consist of efforts to "document, legalize, and normalize informal economies and bring them into the formal and regulated sector" (Weng and Margules, 2022). Yet even formalization processes have been wrought with challenges as countries have struggled with sustaining formalization efforts due to lack of resources or funding (Hilson et al., 2022). Further, excessive use of deterrent approaches to formalization, in which miners are deterred, punished, or discouraged from joining the informal sector, can damage relationships between miners and government officials and even perpetuate participation within the informal sector (Ofori et al., 2021). The NAP documents thus provide countries with the opportunity to scrutinize past interventions and propose more sustainable methods for transforming the sector and reducing overall mercury use.

NAP baseline studies document all known information on mercury use in ASGM within a specific country, containing information encompassing the legal, social, economic, and environmental considerations of the sector provide a holistic overview (Stylo et al., 2020). Although not the sole method of evaluating the ASGM sector, the quantitative baseline estimates for mercury use or, in many cases, mercury emissions and releases, plays a significant role in evaluating the efficiency of mercury policies and interventions applied to the ASGM sector. The importance of the quantitative baseline estimates can be tied to the high value placed on technical evaluations of environmental and political considerations by modern industrialized societies (Kimura and Kinchy, 2019). As such, quantitative evaluations of environmental concerns can be perceived by such societies as the only "legitimate" form of knowledge of a topic, thus limiting the influence of qualitative evaluations on environmental decisions (e.g., Li, 2015). However, rather than serving as an "unbiased" or "neutral" source of information with which environmental and political decisions can be made, the development of a quantitative baseline estimate is inherently a political one (De Pree, 2020; Kimura and Kinchy, 2019) with far-reaching consequences to those who experience the policy changes and mercury interventions (i.e., ASGM communities).

Developing a quantitative understanding of mercury use in ASGM sector proves to be challenging. Many ASGM operations are either informal and/or illegal, and as such, little data on gold production and mercury use are available to develop robust emission estimates (Yoshimura et al., 2021). Limitations to collecting data include site access restrictions due to security or accessibility (e.g., Federal Ministry of Environment of Nigeria, 2021). Likewise, time and budgetary constraints reduce the number of sites visited by researchers and mercury baseline teams (de Haan, 2019; O'Neill and Telmer, 2017), resulting in small sample sizes and thus large statistical uncertainty in baseline estimates. Miners are often reluctant to provide information to regulatory authorities due to distrust of the government or financial implications (e.g., taxes) (O'Neill and Telmer, 2017) despite being directly influenced by the policy decisions made and interventions developed from these baseline estimates.

Given the uncertainty of data from the ASGM sector, the Global Mercury Assessment (GMA) 2018 Report calculates a $\pm$ 74 % margin of uncertainty for its total mercury emissions and releases from the ASGM sector using confidence intervals based on the timeliness and reliability of each country's data (AMAP and UNEP, 2019). Quantitative baseline estimates seek to improve upon this uncertainty by reducing the confidence intervals of mercury use to between $\pm$ 30–50 % (UNEP Global Mercury Partnership, 2017), but rarely report such values in their final NAP documents as will be shown in this paper or incorporate this uncertainty into the development of their target reduction metrics. This work adds to current critiques and analyses of NAPs and their implementations (e.g., Moody et al., 2020; Hilson et al., 2018; Hilson et al., 2020) by focusing on the quantitative baseline assessment of the ASGM sector and demonstrates how purely quantitative analysis creates limitations which may inhibit NAP policy and mercury intervention evaluations. Through examination of NAPs and baseline reports from 25 countries, we identify the various methods used to calculate mercury emissions and releases. Using data from a baseline report for Paraguay's NAP, we illustrate challenges with quantitative baseline estimate methods. Such analysis leads to recommendations for future actions needed to overcome these limitations, which may lead to the improvement of baseline estimates and provide more realistic reduction targets.

The paper is organized as follows: section two describes the guidelines for developing baseline mercury estimates. Section three synthesizes the calculation methods and data sets used in the 21 published and publicly available NAPs and baseline reports to generate ASGM mercury emission estimates. Section four demonstrates the inherent uncertainty in current quantitative mercury baseline estimates using the case study of Paraguay. Section five combines the findings from the NAP baseline estimate synthesis and the Paraguay case study to summarize main limitations in using different interpretations of baseline estimate guidelines. Finally, section six offers conclusions and proposes actions for improving baseline estimates and properly evaluating the impact of NAP policies.

2. NAP baseline estimation methods

Typically, there are four stages used to develop ASGM quantitative baseline mercury estimates: review literature, conduct workshops or interviews with key stakeholders to identify ASGM sites to visit, visit mine sites to collect data, and extrapolate data to regional and national levels (e.g., Federal Ministry of Environment of Nigeria, 2021; Government of Zimbabwe, 2019; Ministère de l'Environnement de l'Ecologie et des Forêts, 2018). These stages provide countries with the flexibility to execute their quantitative baseline estimates despite their unique social and political constraints (O'Neill and Telmer, 2017). Government officials from mining and environmental administrations, UNEP and United Nations Industrial Development Organization (UNIDO) project managers, and consultant groups (e.g., the Artisanal Gold Council (AGC)) often share the responsibility of developing baseline estimates and completing each of the four stages of the baseline mercury estimate. During the first stage, ASGM records (e.g., census data, formalization records) and previous academic studies are collected and analyzed to gain a better understanding of the national scope of the ASGM sector. Such documents are usually limited in their discussion of the ASGM sector but provide some understanding of the regions in which ASGM activity is occurring as well as the size of the activity (O'Neill and Telmer, 2017). Once these records are reviewed, key stakeholders, including government and regulatory officials, heads of mining organizations, and community leaders identify mining sites to investigate further (Environment Protection Agency Sierra Leone, 2020; Federal Ministry of Environment of Nigeria, 2021; Ministère de l'Environnement de l'Assainissement et du Développement Durable, 2020). Government officials and stakeholders select sites based on the amount of ASGM activity and the variety of mining and ore-processing techniques used. Other considerations often include security and site accessibility.

Once at the site, trained baseline teams including government officials, consultants, or other researchers gather data through physical measurements or interviews to develop baseline mercury estimates. According to the AGC, ASGM mercury use (or mercury emissions and releases) are typically estimated by (O'Neill and Telmer, 2017):

$$Hg\ emissions\ and\ releases = P \times Hg{:}Au$$

where P is the gold production rate using mercury amalgamation by ASGM [metric tons/year] and $Hg{:}Au$ is the ratio of mercury consumption (loss to the environment) to gold production rates developed from ore-processing techniques and physical measurements taken during field measurements of the mass of added mercury, the amalgam, and gold

(O'Neill and Telmer, 2017). As such, site visits often focus on collecting data that will allow the baseline estimate team to estimate the site-specific gold production and/or the *Hg:Au* ratio for the type of mining (i.e., whole-ore amalgamation versus concentrate amalgamation).

The AGC and UNEP have proposed several data sources that can be used to determine gold production that account for the lack of documentation at most ASGM sites. The three most referenced data sources include official gold trade data, extraction or processing data, and earnings data from informal miners. Official gold trade data can be used as an indicator for estimating ASGM gold production. However, such data may not be reliable since ASGM often does not sell gold through conventional gold trade, meaning that most of the gold output is undocumented (Yoshimura et al., 2021). One method of calculating gold production from an ASGM operation is to determine average ore throughput from extraction or processing sites. Data on the average amount of ore produced from each extraction site (e.g., mine shaft) or processed at each processing site can be obtained through observation or through interviews and then multiplied by the number of sites and the average gold purity (O'Neill and Telmer, 2017; UNEP Global Mercury Partnership, 2017). Gold production can also be calculated by using economics and earnings data for a site. By interviewing stakeholders along the ASGM value chain, the baseline team can determine the average wages and the population of a mine site to determine the amount of gold produced (O'Neill and Telmer, 2017; UNEP Global Mercury Partnership, 2017). Given the inherent uncertainty in the estimates, countries often use multiple calculations to determine gold production to triangulate, or provide a range of estimates for, the "true" gold production for the sector (O'Neill and Telmer, 2017).

The *Hg:Au* ratio is generally determined in the field using a mass balance approach at four stages of the amalgamation process. This includes measuring the mass of (1) mercury being added to the ore, (2) the mercury recovered after the amalgamation process, (3) the amalgam, and (4) the sponge gold leftover after burning. Using these values, the baseline team can determine the mass of mercury lost per unit of gold produced (O'Neill and Telmer, 2017). As the *Hg:Au* ratio is highly dependent upon processing techniques, ore quality (grade), and ore-processor skill level (O'Neill and Telmer, 2017), there is inherent uncertainty with the *Hg:Au* ratios for use in developing mercury estimates (AMAP and UNEP, 2019). To address this uncertainty, published guidelines suggest taking three separate measurements at a site at different times to minimize the effects of ore quality as well as visiting diverse mine sites to gain a better understanding of the possible variations (O'Neill and Telmer, 2017).

Finally, the baseline team compiles the results from the limited site visits and extrapolates mercury loss to the national level. Given the extent of ASGM activity, most countries are unable to visit every active ASGM site within their borders, making it necessary to extrapolate based on a limited subset of data. Using known data about the sites that were not visited (e.g., number of miners, size of operation), representative values from the previously visited sites can be used to project the amount of gold produced at an unvisited site (O'Neill and Telmer, 2017).

3. Baseline mercury use synthesis

We analyzed the NAP documents and/or baseline reports of 25 countries (Fig. 1). Despite at least 46 countries reporting a significant presence of ASGM (Global Mercury Partnership, n.d. (a)), to date, only 22 NAPs appear on the official Minamata Convention website. We were able to find three additional NAP documents or baseline reports on government websites (Ministerio del Ambiente y Desarrollo Sostenible, 2020a, 2020b) or NGO websites (Artisanal Gold Council, 2017; Rosenbluth et al., 2021). These countries are in the process of completing their NAPs and will likely release them soon with assistance from the United Nations Environment Program (UNEP) and United Nations Industrial Development Organization (UNIDO) (Global Mercury Partnership, n.d. (b)).

Although using the same guidance documents as described in section two above, each NAP utilized different data sets and methods to develop baseline mercury estimates. The main differences between NAPs and baseline reports fall into four categories: gold production estimate data sets, *Hg:Au* ratio use and development, extrapolation strategies for estimating at regional and national levels, and target metrics for

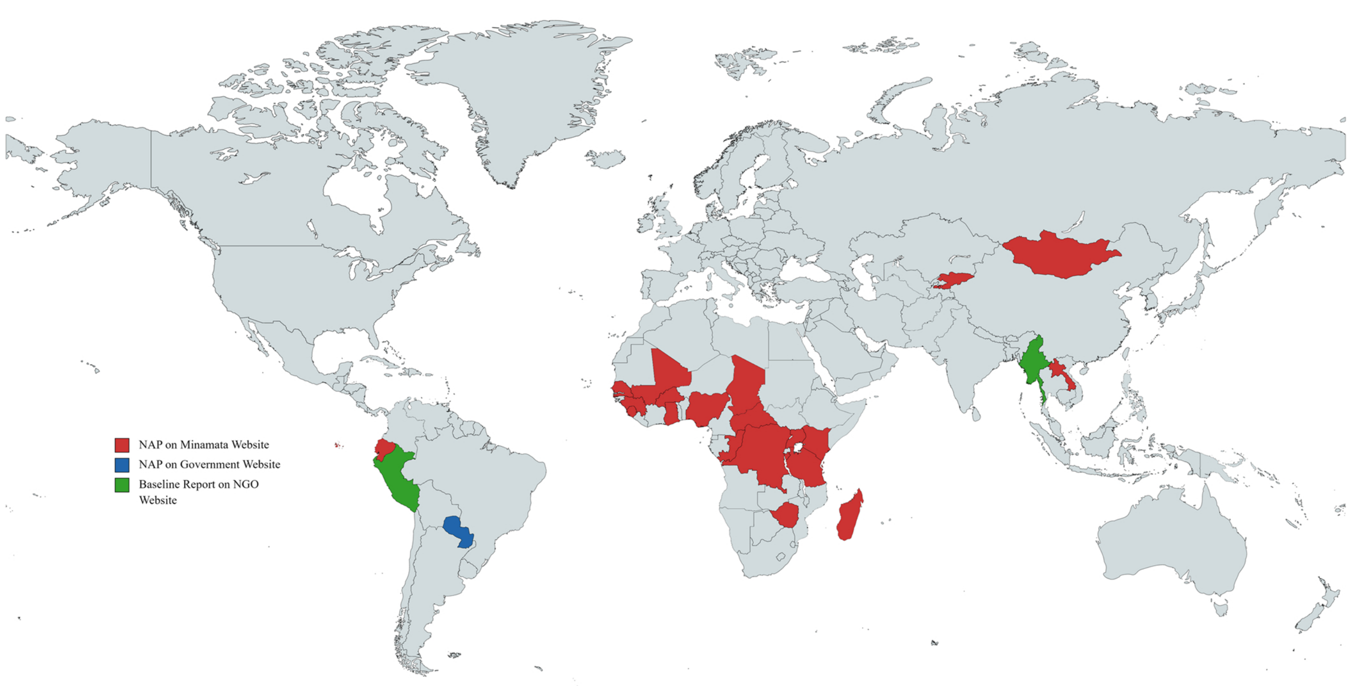

Fig. 1. Map of countries with published NAPs on Minamata Convention's official website (red), national government websites (blue), and NGO (Non-Governmental Organization) websites (green).

mercury reduction.

3.1. Gold production estimates

The UNEP Global Mercury Partnership (2017) and O'Neill and Telmer (2017) guidelines for developing a baseline mercury estimate advise countries to use multiple data sets to account for the lack of data from ASGM operations. Table 1 presents a summary of the most prevalent data sources used to estimate gold production. Of the 25 NAP report/baseline studies evaluated, only six use three or more data sources for estimating gold production. Fifteen countries use only one data source for estimating gold production, failing to validate their estimates with additional data sources (e.g., Department of Pollution Control and Monitoring, 2021; Ministerio del Ambiente y Agua, 2020; République du Congo, 2019). Finally, four reports did not specify the data source used for gold production estimates (Minamata Convention Implementation Committee, 2020; Ministère de l'Environnement et du Developpement Durable, 2019; Ministere de L'Environnement République de Guinée, 2021; State Regulation Centre of Environmental Protection and Ecological Safety, 2021).

The most common data source used for determining gold production was the use of extraction-based and/or process-based data, as shown in Table 1. This likely is because the data used for this type of estimate are based on observation and require very few interviews or physical measurements. Data could easily be collected even if miners and ore processors abandoned the site during field visits (e.g., Ministre de l'Environnement de l'Agriculture et de l'Elevage, 2019). Miner income and economics data were used in seven out of the 25 NAPs or baseline studies. This strategy was used to provide authorities with knowledge of the ASGM gold value chain and its various actors. Interviews with gold buyers and jewelers were used five times to estimate gold production, and this dataset presented an overview of gold supply at a higher level of the ASGM gold value chain. As expected, official data were used infrequently, as only two countries used official documentation as the basis for gold production estimates (Department of Pollution Control and Monitoring, 2021; Ministry of Environment and Tourism of Mongolia, 2020). Finally, ore transportation was the least used method for determining gold production, though this can be attributed to sites that both mined and processed materials in the same location, thus negating the need for transport (Government of Zimbabwe, 2019).

Only two countries included uncertainty estimates by showing the variability of gold production and/or mercury emissions and releases using different calculation data sources. Zimbabwe showed how three different data sources used for estimated gold production resulted in different mercury emissions and release estimates with standard deviations between 11 % and 55 % using 2012 mining data and 9 % and 35 % using 2018 mining data (Government of Zimbabwe, 2019). Similarly, Paraguay provided gold production estimates using three data sources and reported a standard deviation of 6 % (Ministerio del Ambiente y Desarrollo Sostenible, 2020a). One other country, Guyana, demonstrated the uncertainty of various parameters used for estimating gold production, such as showing the range of values for ore grade or for throughput in dredge systems, but this uncertainty was not incorporated into the final estimated gold value (Parsram, 2021).

3.2. *Hg:Au* Ratio Estimates

The data sources used for calculating *Hg:Au* ratios varied significantly from country to country, as shown in Table 2, resulting in a range of *Hg:Au* ratio values (Fig. 2). Five out of the 25 countries used the global average *Hg:Au* ratio values proposed by Global Mercury Assessments (GMAs) (Ministère de l'Environnement de l'Agriculture et de l'Élevage, 2019; Ministere de L'Environnement République de Guinée, 2021; Ministry of Environment and Tourism of Mongolia, 2020; République du Congo, 2019). The countries that chose to use global average values tended to use a *Hg:Au* ratio of 3 for whole-ore amalgamation. This differs from the 2018 GMA, as the *Hg:Au* ratios were 5 for whole-ore amalgamation (AMAP and UNEP, 2019). Most countries that used global averages typically did so because the process of mercury amalgamation was not able to be observed due to security concerns or an absence of miners during the time of the site visit.

Twenty of the 25 NAPs or baseline studies had unique *Hg:Au* ratios in

Table 1
Data sources used in NAP documents and baseline reports to estimate gold production. Some estimates utilize both extraction-based and processing-based methods as two separate calculations for the purposes of triangulating data, but they are grouped in this table to account for cases where extraction and processing techniques occur at a single location.

Country	Extraction/ Processing	Miner Income	Jewelry/Gold Buyer Estimates	Official Trade Documentation	Gold Transport Estimates	Not Specified
Burkina Faso	X		X		X	
Burundi	X					
Central African Republic						X
Chad	X	X				
Democratic Republic of the Congo	X					
Ecuador	X					
Ghana						X
Guinea						X
Guyana	X					
Kenya	X					
Kyrgyzstan						X
Lao People's Democratic Republic	X	X				
Madagascar	X					
Mali	X	X	X			
Mongolia				X		
Myanmar		X				
Nigeria	X					
Paraguay	X	X				
Peru	X					
Republic of the Congo			X			
Senegal	X	X	X			
Sierra Leone	X		X			
Tanzania	X	X				
Uganda	X				X	
Zimbabwe	X			X		

Table 2
Comparison of data sources used to calculate Hg:Au ratios in NAPs.

Country	Global Average *Hg:Au*	Interview-Based *Hg:Au*	Measured *Hg:Au* (Amalgam)	Measured *Hg:Au* (Daily)	Value from Previous Studies
Burkina Faso			X		
Burundi	X				
Central African Republic		X			
Chad		X	X		
Democratic Republic of the Congo			X		
Ecuador				X	
Ghana			X		
Guinea		X			
Guyana			X	X	
Kenya			X		
Kyrgyzstan		X			
Lao People's Democratic Republic	X	X			
Madagascar		X			
Mali			X		
Mongolia	X				
Myanmar					X
Nigeria		X	X		
Paraguay			X		
Peru				X	
Republic of the Congo	X				
Senegal			X		
Sierra Leone	X				
Tanzania			X		
Uganda		X	X		
Zimbabwe			X		

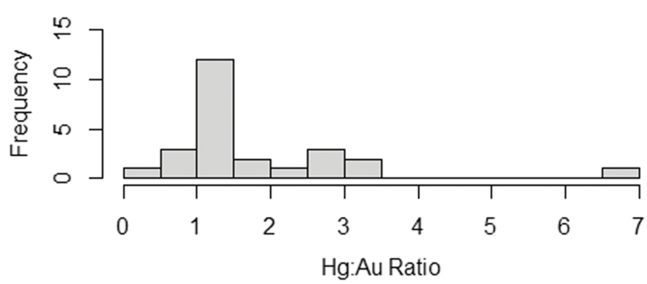

Fig. 2. Histogram of national average (or global average default) Hg:Au ratios used in NAPs or baseline reports.

accordance with NAP baseline guidelines. Some countries used more than one method for estimating the *Hg:Au* ratios. For example, eight of these NAPs relied on interview or survey data with miners to determine the *Hg:Au* value, and thirteen claimed to use the measurement protocol as proposed by O'Neill and Telmer (2017) as described in section two. In one case, *Hg:Au* ratios were estimated based on previous ASGM studies as site access and field work was prevented due to the COVID-19 pandemic and political instability (Rosenbluth et al., 2021). However, information such as the number of sites in which the *Hg:Au* ratio was measured and the uncertainty was not often released for the measured sites. The mass measurements for the different stages of the mercury amalgamation process used for calculating the *Hg:Au* ratio were only provided for two countries (Ministerio del Ambiente y Desarrollo Sostenible, 2020a; Ministry of Environment and Forestry, 2022). The number of measurements and their location was only reported by Paraguay, Guyana, Kenya, Zimbabwe, and Tanzania (Government of Zimbabwe, 2019; Ministerio del Ambiente y Desarrollo Sostenible, 2020a; United Republic of Tanzania, 2020; Parsram, 2021; Ministry of Environment and Forestry, 2022). Other countries, such as Chad, Mali, Senegal, and Lao PDR only provided the average *Hg:Au* ratio calculated for each region or processing technique (Artisanal Gold Council, 2019a, 2019b; Department of Pollution Control and Monitoring, 2021; CRCBS-AF and AGRID, 2022).

Three countries, Guyana, Peru, and Ecuador, developed their *Hg:Au* ratios based off daily mercury consumption and gold production data rather than from measuring amalgam at various stages of gold processing. Guyana, Peru, and Ecuador describe mining practices in which the process of adding mercury to equipment such as Chilean Mills or *quimbalates* does not make the guidelines' proposed methodology feasible. Instead, the countries' baseline reports describe a process where the mass of mercury added to ore throughout the day and the resulting amalgam and gold mass are measured to develop the *Hg:Au* ratio (Artisanal Gold Council, 2017; Ministerio del Ambiente, 2020; Parsram, 2021). The countries' baseline reports deviated from the guidelines by determining daily *Hg:Au* ratios rather than recording the mass of the amalgam from its initial formation to its eventual burning and release of mercury. This strategy may provide a useful tool for countries in which measuring amalgam during various stages of gold processing is not feasible given difficulty with accessing sites or limited time at each site.

3.3. *Extrapolation to national levels*

Several different extrapolation methods to scale local and regional estimates to national level estimates were implemented in the NAPs as shown in Table 3. The most common method was to determine average ore and gold production or mercury consumption of similar mine sites and multiplying these values by the total number of mine sites within the country (O'Neill and Telmer, 2017). Out of the 25 NAPs and baseline reports studied, twelve used this method. Often countries used the number of mines site inventories of previous ASGM studies to upscale their mercury baseline estimates from site-level estimates to regional or national estimates (Artisanal Gold Council, 2017; Government of Zimbabwe, 2019; Kaboré et al., 2019; Ministère de l'Environnement de l'Agriculture et de l'Élevage, 2019). In contrast, Myanmar's baseline report extrapolated the number of informal miners by multiplying the number of registered miners by a modifier value to represent the ratio of informal to formalized miners as determined through interviews with key stakeholders (Rosenbluth et al., 2021).

Two countries used satellite imagery to determine the total number of mine sites within their borders: Sierra Leone, and Zimbabwe (Environment Protection Agency Sierra Leone, 2019; Government of Zimbabwe, 2019). While Zimbabwe's NAP only briefly mentioned the use of satellite imagery, Sierra Leone's baseline report provided a detailed protocol that included both (1) manually demarking sites in which ASGM activity could be visually observed using satellite imagery

Table 3
Comparison of extrapolation methods to scale local and regional estimates to national mercury baseline emission estimates.

Country	Extrapolation with National Statistics	Extrapolation with Satellite Imagery	No Extrapolation	Not Explained
Burkina Faso	X			
Burundi	X			
Central African Republic				X
Chad	X			
Democratic Republic of the Congo				X
Ecuador	X			
Ghana	X			
Guinea				X
Guyana	X			
Kenya				X
Kyrgyzstan				X
Lao People's Democratic Republic			X	
Madagascar			X	
Mali	X			
Mongolia			X	
Myanmar	X			
Nigeria			X	
Paraguay			X	
Peru	X			
Republic of the Congo	X			
Senegal	X			
Sierra Leone		X		
Tanzania				X
Uganda			X	
Zimbabwe	X	X		

and (2) developing an algorithmic demarcation system to identify ASGM sites not listed in official records. The average number of miners and gold production per area was then used to determine gold production from the identified locations. However, Sierra Leone's baseline report noted that abandoned mine lands appear like active mining locations, thus resulting in an estimate higher than reality. This method provides an upper limit estimate for activity in the ASGM sector, which is valuable for developing national policy (Environment Protection Agency Sierra Leone, 2019).

Some NAPs or baseline reports did not fully describe methods of extrapolation. For example, the Democratic Republic of the Congo did not provide extrapolation methods, stating that mercury use was only done by foreign-owned mining groups that refused them site access. No information about the data sources or extrapolation methods were provided in the NAP document (L'Agence Congolaise l'Environnement, 2020), making further analysis impossible. In other cases, all ASGM sites were assumed to have been characterized in the NAP or baseline report, thus making extrapolation unnecessary. For Mongolia's NAP, data used to determine the national gold production were obtained through official documentation at regional-level offices. All regional offices that declared a presence of ASGM activity reported the necessary data to produce national estimates (Ministry of Environment and Tourism of Mongolia, 2020). Lao PDR's NAP summed mercury use data from 19 sites out of an estimated 69 ASGM sites within their country to establish the national baseline estimate. The baseline mercury estimate value produced from the 19 sites was said to represent the minimum value of mercury use within the country with no estimate for average or maximum mercury baseline value provided (Department of Pollution Control and Monitoring, 2021).

3.4. Mercury reduction targets

NAP reduction targets (Table 4) use the baseline mercury estimates from the aforementioned data sources and methods to evaluate the performance of a country's ASGM policies and projects (O'Neill and Telmer, 2017). Of the 22 completed NAPs, 19 developed target reduction metrics based on their mercury baseline estimates. Twelve of the NAPs developed a series of goals over the course of several years to track the performance of the established NAP policies. The remaining seven NAPs only listed their final reduction target.

Table 4
Mercury emission reduction targets for NAPs.

Country	Reduction Target
Burkina Faso	50 % by 2024, and a further 50 % by 2029
Burundi	Not provided
Central African Republic	Not provided
Chad	30 % in emissions and releases by 2025; 50 % in use by 2030
Democratic Republic of the Congo	20–30 % by 2024; 40–60 % by end of 2026; 70–90 % by December 2031; 90–100 % by 2036
Ecuador	10 % by 2022; 40 % by 2026; 80 % by 2030 (alluvial mining) OR produce 15 % of gold without mercury by 2022; 50 % gold production by 2026; 85 % gold production by 2030 (primary mining)
Ghana	30 % by 2030
Guinea	50 % by 2022; 75 % by 2025; 100 % by 2030
Guyana	75 % by 2027
Kenya	50 % by 2024
Kyrgyzstan	100 % by 2025
Lao People's Democratic Republic	20 % by 2024; 50 % by 2027; 70 % by 2030
Madagascar	50 % by 2022; 75 % by 2023; 100 % by 2024
Mali	10 % by 2023 and further 50 % by 2029
Mongolia	50 %
Nigeria	Produce 50 % gold without mercury or other toxic substances by 2030
Paraguay	25 % by 2021; 50 % by 2022; 75 % by 2023
Republic of the Congo	Not provided
Senegal	30 % by 2022; 80 % by 2030
Sierra Leone	30 % in artisanal mining and 50 % in small-scale mining by December 2022; 50 % in artisanal mining and 100 % in small-scale mining by 2024; 100 % in artisanal mining by 2029
Tanzania	30 % by 2025
Uganda	70 % by 2024; 100 % elimination in 2030
Zimbabwe	20 % by 2022

Some NAPs did not develop target metrics to evaluate the performance of NAP policies despite developing baseline mercury estimates. Central African Republic did not develop target metrics, but also reported that mercury was not actively being used in modern ASGM practice (Ministère de l'Environnement et du Developpement Durable, 2019). As such, a target percent reduction would be inappropriate when representing the ASGM sector here. Similarly, the Republic of the Congo did not develop mercury reduction targets, which likely is due to the limited use of mercury within the ASGM sector (République du Congo, 2019). Burundi was the only other country that did not provide mercury reduction targets, instead focusing solely on education, formalization, routine monitoring, and improving legislation (Ministère de l'Environnement de l'Agriculture et de l'Élevage, 2019).

4. Case study

To demonstrate the diverse NAP baseline estimation strategies and the impact of data uncertainty on quantitative analysis of the ASGM sector, we analyzed the site data used to generate mercury baseline estimates in Paraguay. Although Paraguay's NAP is not published on the Minamata Convention's website, all documentation that contributed to its development and their current draft of their NAP is publicly available on their government website. Paraguay was selected for analysis in this study due the country's transparency with calculating quantitative baselines. Paraguay's NAP and corresponding baseline report provide enough information that allows for calculations to be replicated.[1] Although Paraguay has a relatively small ASGM sector, this country still presents many characteristics present in other countries, such as heterogeneity in mining practices and ore processing techniques. Further, Paraguay's small ASGM sector demonstrates limitations with current quantitative baseline estimates methods even when the majority of mine sites are visited. The purpose of this case study is not to demonstrate the weaknesses of a single country's report, but rather to demonstrate how the inherent variability in the estimates generated by current quantitative baseline strategies may potentially interfere with future NAP evaluations if quantitative assessments are prioritized over qualitative studies.

4.1. Methods

Paraguay's ASGM sector is relatively small (Ministerio del Ambiente y Desarrollo Sostenible, 2020a), consisting of mine sites in Paso Yobái in the Guairá District (Ministerio del Ambiente y Desarrollo Sostenible, 2020b). The report lists three types of ore-processing techniques found in these different sites and categorizes them as Type 1, Type 2, and Type 3 processing.[2] Additionally, the baseline report listed values for ore production, ore grade, gold purity, ore throughput, miner population, and *Hg:Au* ratios for each site. The values are summarized in Table 5.

To determine the total gold production and mercury emissions and releases from the ASGM sector, we relied on the assumptions made in Paraguay's baseline report. This report assumed that a total of 25 extraction units were present in the Paso Yobái. Additionally, the report assumed a total of 52 Type 1 processing units, 55 Type 2 processing units, and 1 Type 33 unit within the region. For extraction and income-based estimates, the report assumed that 87% of the gold was produced using Type 1 processes, 9.33 % were produced for Type 2 processes, and 3.67 % was produced using Type 3 processes. Finally, we adopted the same weighting factors as used in the baseline report (Ministerio del Ambiente y Desarrollo Sostenible, 2020a).

Using the values in Table 5, we developed estimates for gold produced and mercury emitted and released from the ASGM sector using the equations shown in supplementary materials S.1 (UNEP, 2017). We conducted two sets of calculations: one using weighted average values for the parameters in which the weighting was determined by miner and ore-processor population size and the other using the standard average of the parameters (S.2). Using the provided data, we calculated the gold production and corresponding mercury emissions and releases using extraction, processing, and income data sources and analyzed how the mercury estimates compared.

Next, we studied the influence of using global average and measured *Hg:Au* to evaluate the impact that the global average *Hg:Au* had on predicting mercury losses. In Paraguay, Type 1 processing corresponds to concentrate amalgamation, while Type 2 and 3 processing corresponds to whole-ore amalgamation (Ministerio del Ambiente y Desarrollo Sostenible, 2020a). We used the global average *Hg:Au* ratios reported by the 2018 GMA of 1.3 and 5 for concentrate and whole-ore amalgamation, respectively (AMAP and UNEP, 2019).

We analyzed whether the number of sites studied in the NAP documentations produced statistically representative results for characterizing the national activity level. Given the small size of the sector, the government was able to visit three out of the four mine sites and 36 out of the estimated 108 mills and obtain a significant amount of data for the remaining sites through interviews with key stakeholders (Ministerio del Ambiente y Desarrollo Sostenible, 2020a). Cochran's Formula with the finite population correction allows us to determine whether this sample meets an established confidence and precision level, as shown in supplementary materials S.3 (Israel, 1992).

Finally, to better represent the uncertainty of each parameter used to calculate the mercury baseline, we propagated the weighted and unweighted standard deviations throughout the calculations using basic error propagation equations for multiplication and addition as shown in supplementary materials S.4.

4.2. Case study mercury emission estimate comparison

Fig. 3 shows the range of values obtained using weighted and unweighted averages and extraction, processing, and income data sources. For extraction-based calculations, the uncertainty value was larger than the estimated mercury emissions and releases for both the weighted and unweighted calculations. This is likely due to the variability in daily ore extraction per unit, as shown in Table 5 (27.5–225 t/d/unit). This indicates that, as with processing-based calculations, extraction-based calculations should be categorized based on type of operation (e.g., use of heavy machinery vs. handheld tools) to better characterize the variability in extraction methods present within a community. In contrast, both processing-based and income-based mercury emission and release estimates had uncertainty values less than the baseline estimate.

The standard deviation between the extraction-, processing-, and income-based baseline estimates corresponds to 35.3 % of the total average mercury loss (weighted) and 21.5 % of the total average mercury loss (unweighted). These findings demonstrate the variability between the estimates produced from different gold production data sets, demonstrating that use of a single data set may fail to accurately characterize the total amount of mercury lost from the ASGM sector.

Use of different *Hg:Au* ratios also impacted the estimated mercury baseline for Paraguay. Using the weighted average parameters for determining gold production and the global average *Hg:Au* ratios reported by the 2018 GMA of 1.3 and 5 for concentrate and whole-ore amalgamation, respectively (AMAP and UNEP, 2019), the average mercury baseline estimate produced by the three calculation techniques is 528 kg Hg/yr. In comparison, the global average *Hg:Au* ratio estimate is 11.7 % lower than the weighted average estimate using measured *Hg:Au* ratios. These findings demonstrate how the *Hg:Au* global averages may be appropriate for generating preliminary mercury loss estimates so long as the measured *Hg:Au* ratio falls between the 1.3 and 5 range.

The total number of mine sites and mills sampled in the Paraguay NAP and baseline report is statistically representative of the ASGM population in Paraguay at the 85 % confidence level and 10 % precision level, assuming maximum variability. Additional sampling is needed to

[1] The values presented in this manuscript differ from those presented in Paraguay's NAP baseline documentation due to different calculation strategies. This further demonstrates how different calculation techniques can produce extremely variable baseline estimates.

[2] The reader is referred to the baseline report produced by Ministerio del Ambiente y Desarrollo Sostenible (2020a) for a more detailed description of the ore-processing techniques used.

Table 5
Baseline values reported for Paso Yobái, Paraguay. Weighted averages used the miner and ore-processor populations to scale values.

Variable		Weighted Average	Weighted Standard Deviation	Unweighted Average	Unweighted Standard Deviation
Extraction	Ore grade (g/t)	1.69	1.02	1.03	0.93
	Daily ore extraction per unit (t/d/unit)	46.9	49.8	89.9	91.2
	Average number of miners/unit (workers/unit)	3.90	0.50	4.00	0.82
	Average number of working days per year (d/yr)	142	33.2	169	53.1
	Average gold purity (%)	85.2	5.04	85.9	5.48
Processing	Average ore grade entering mills (g/t)	0.75	0.08	0.70	0.10
	Gold purity produced from mill (%)	82.3	1.10	82.0	1.00
	Daily ore processing for Type 1 processing (t/d/unit)	42.2	14.2	38.5	19.2
	Daily ore processing for Type 2 processing (t/d/unit)	7.39	2.14	7.80	2.00
	Daily ore processing for Type 3 processing (t/d/unit)	20.0	0	20.0	0
	Number of workers per Type 1 unit (workers/unit)	3.60	1.12	3.67	1.15
	Number of workers per Type 2 unit (workers/unit)	2.00	0	2.00	0
	Number of workers per Type 3 unit (workers/unit)	3.00	0	3.00	0
Income	Annual income per extraction worker (g Au/worker/yr)	68.7	17.4	75.1	32.0
	Annual income per processing worker (g Au/worker/yr)	124	13.8	129	20.2
Hg:Au Ratio	Type 1 *Hg:Au* ratio	2.05	0.98	1.60	0.95
	Type 2 *Hg:Au* ratio	2.28	0.33	2.49	0.44
	Type 3 *Hg:Au* ratio	2.20	0	2.20	0

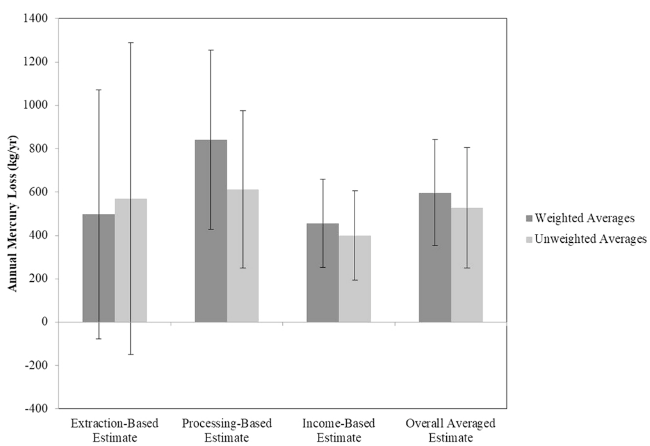

Fig. 3. Comparison of different gold production methodologies and use of weighted or unweighted average values for estimating mercury emissions and releases from the ASGM sector. Uncertainty was calculated by using basic error propagation equations (see supplemental materials S.2).

achieve higher confidence levels for the extraction and processing parameters used to extrapolate gold production and mercury losses to the national level.

Paraguay plans to reduce mercury emissions and releases by 25 % in 2021 (Ministerio del Ambiente y Desarrollo Sostenible, 2020b). Overall, the uncertainty for the average of all three data sources corresponds to 41.0 % of the estimate for weighted values and 52.5 % for unweighted values. This finding demonstrates that weighting the parameters used to calculate mercury baselines by operation size or miner population can reduce the uncertainty in baseline estimates, something that can easily be applied to most other NAPs. However, challenges may arise with future NAP evaluations, as the percent reduction in the mercury baseline estimates fall within the uncertainty of the original value.

5. Discussion

Current NAPs and baseline estimates represent an improved understanding of the ASGM sector in 25 different countries, as they provide more information regarding the scale of the sector and its broader implications on social, political, and economic conditions in the country. Examining these reports through a quantitative lens, however, indicates that reduction targets alone are insufficient for gauging the success of reducing mercury emissions and releases. One of the most significant limitations with quantitative analysis of baseline estimates is the failure to report quantitative uncertainty reported with in baseline mercury estimates. Only two countries, Paraguay and Zimbabwe, reported quantitative uncertainty for their baseline estimates. Specifically, the Paraguay case study shows 21.5–35.3% standard deviation between the mean mercury losses using extraction, processing, and income datasets, demonstrating an acceptable range of variability between datasets per the UNEP Global Mercury Partnership guidelines (i.e., estimating mercury use with an accuracy of ± 30–50%) (UNEP Global Mercury Partnership, 2017). The remaining 23 NAP and baseline reports failed to report the uncertainty associated with their baseline mercury estimates. Including the variability in gold production estimates and mercury estimates is necessary, as this information reveals the reliability of the gold production and mercury estimates. High variability in gold production or mercury estimates may reveal the need for additional field work to determine the source of the discrepancy, as this may inhibit a country's ability to effectively evaluate mitigation activities in the future. Further, high variability and uncertainty in values may also demonstrate that a more detailed qualitative assessment of the ASGM sector is necessary to provide a better understanding of the heterogeneity of the ASGM sector and to better inform policy decisions and actions. More emphasis should then be placed on the qualitative assessments found in the NAP documents, which often contain information regarding the knowledge gaps and may guide further investigation of the sector.

Another limitation with quantitative analysis can be observed with differing *Hg:Au* ratios and their influence on the baseline mercury estimates. As demonstrated by the Paraguay case study, the use of the global average *Hg:Au* ratio produced a baseline mercury estimate 11.7% lower than the estimate produced by measured *Hg:Au* ratios. The reason for the similarities between the global average *Hg:Au* estimate and the measured *Hg:Au* estimate likely can be attributed to the similarity in *Hg:Au* ranges as the measured *Hg:Au* values fell within the 1.3–5 range established by the global averages. However, as shown in Section 3.0, countries reported average *Hg:Au* values that fell outside the global average range, indicating the limitations of using the global average *Hg:Au* ratio. While the findings of this synthesis demonstrate that global average *Hg:Au* ratios predominantly fall between 1.3 and 3, as shown in Fig. 2, the presence of significantly higher or lower *Hg:Au* ratios justify the use of measured values over the global average.

Yet another limitation of current quantitative baseline estimation practices is the method being used to extrapolate national estimates.

National statistics used for extrapolating values are often based on formalization records for the region (e.g., Artisanal Gold Council, 2017; Rosenbluth et al., 2021). However, such formalization records may not fully represent the presence of informal or illegal ASGM groups operating within the country (Artisanal Gold Council, 2017). Some countries estimate the total number of formal, informal, and illegal miners by multiplying the number of registered miners by a coefficient to generate a conservative estimate for the miner population, which is later converted to estimates of gold production and mercury emissions and releases (Rosenbluth et al., 2021). Simple statistical tools such as Cochran's Formula can be used in quantitative analysis to improve transparency about whether the number of sites sampled is representative of the entire ASGM sector as shown in the Paraguay case study. Once an estimate for the total scale of the ASGM sector within a country or a region is developed, use of simple statistics can easily demonstrate the stage at which a country is for developing the baseline estimate of the country. When visiting enough sites to be statistically significant may prove to be a challenge due to security risks, time, or expenses, equations such as Cochran's Formula can easily provide the confidence value based on the number of sites visited and surveyed and demonstrate whether additional resources are needed to characterize the ASGM sector.

Further challenges arise when comparing uncertainties for the NAP baselines and the mercury reduction targets listed later in the NAP document. Many short-term mercury reduction targets are between 20% and 30%, meaning that the reduction targets fall within the range of uncertainty described by the UNEP Global Mercury Partnership guidelines (2017). As shown in the Paraguay case study, the short-term objectives for the NAP are less than the 41.0–52.5% uncertainty of the mercury baseline estimates, making it difficult to discern whether changes in mercury losses are the product of policy change or data uncertainty. Increased data transparency through representing uncertainty in current baselines is necessary for improving our understanding of the ASGM sector and critically evaluating the strategies being used to mitigate its environmental impact. As many countries work towards producing their NAP evaluations over the next few years as required by Article 7 Section 3.c, care needs to be taken to accurately represent the changes in the ASGM sector over the past few years.

Ultimately, the limitations of current quantitative baseline practices have the potential to detrimentally impact ASGM miners and operators. Policy decisions and financial distribution for policies may be based off quantitative scientific estimates as they are perceived to be "unbiased" (Kimura and Kinchy, 2019) or more "legitimate" (Li, 2015), despite failing to account for the complexity of the ASGM sector. Interventions and assistance may be developed and distributed using assumptions about standard mining practices that may not be representative of the conditions of an individual site, thereby limiting the projects' efficacy. Improved transparency about baseline methodologies could better represent the limitation in quantitative baselines and caution individuals who may prioritize quantitative estimates over more qualitative studies of the sector. Ensuring that qualitative and quantitative analysis are being used for policy making will facilitate the development of more representative baselines, ensuring that miners and operators are receiving the resources and interventions needed to successfully reduce their mercury consumption.

6. Conclusions

Baseline mercury estimates reported by NAP documents represent national and international understanding of ASGM activity and provide the metric by which mercury mitigation policies and activities are evaluated. However, the ASGM sector's informal nature limits the amount of data available for developing baseline estimates, causing significant uncertainty in reported quantitative baseline estimates which, if disregarded, may lead to challenges in developing effective and impactful mercury interventions and policies. The 25 NAP and baseline documents demonstrate the variety of methods and data sources used to develop baseline mercury estimates. The use of different data sources to estimate gold production, such as extraction, processing, and income data provide different values. Global *Hg:Au* ratios provide reasonable estimates for countries in which measured *Hg:Au* ratios fall within the range of 1.3 and 5 but fail when *Hg:Au* ratios fall outside of the range. Extrapolation methods vary from country to country, demonstrating an area in which quantitative baselines are limited in characterizing a country's ASGM sector. Finally, uncertainty in baseline mercury estimates needs to be reported to evaluate whether target metrics are being met or whether the baseline is failing to account for diverse mining operations.

Propagating the uncertainty of the values used for the calculations reveals a degree of quantitative uncertainty that needs to be accounted for in future NAP evaluations. These findings ultimately demonstrate that the use of different calculation techniques for NAPs produces significantly different estimates of mercury releases and emissions. Failing to report the quantitative uncertainty gives the illusion that the values are "unbiased" or "true," making quantitative analysis of the ASGM sector seem like the most accurate metric to evaluate NAP progress. However, the implications of such decisions have the potential to detrimentally affect the lives of miners and ore processors. Thus, the use of quantitative data alone in policy making and policy evaluation, particularly if said quantitative data fails to encompass the heterogeneity of the ASGM sector, will ultimately lead to failure in evaluating changes in mercury use in the sector.

CRediT authorship contribution statement

Michelle Schwartz: Conceptualization, Methodology, Investigation, Writing – original draft, Visualization. **Kathleen Smits:** Writing – review & editing, Supervision, Funding acquisition. **Thomas Phelan:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data used for this article are publicly available on the Minamata Convention on Mercury's website, the Artisanal Gold Council's website, and various government websites.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2022.12.002.

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