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# Reducing Mercury Emission Uncertainty from Artisanal and Small-Scale Gold Mining Using Bootstrap Confidence Intervals: An Assessment of Emission Reduction Scenarios

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**Abstract:** Atmospheric mercury emission scenarios from artisanal and small-scale gold mining for 56 tropical and subtropical countries have been elaborated and assessed for their comparative significance. A multi-step quantitative method that yields narrow and robust confidence intervals for mercury emission estimates was employed. Firstly, data on gold production for different years, the ratio of mercury used in the different amalgamation processes, and ancillary input parameters were retrieved from official and unofficial sources, and their potential for emission reduction examined. Then, a Monte Carlo method to combine the data and generate mercury emission samples was used. These samples were processed by a non-parametric re-sampling method (bootstrap) to obtain robust estimates of mercury emissions, and their 95% confidence intervals, both for the current state and for the emission scenarios designed in this study. The artisanal and small-scale gold mining mercury emission (to the atmosphere) estimates agree with those reported in the Global Mercury Assessment 2018; however, the overall uncertainty is reduced from roughly 100% in the Global Mercury Assessment (779.59 tons/y; uncertainty range: 361.07–1197.97) to 27% (1091.93 tons/y; confidence interval at 95% level of confidence: 964.54–1219.77) in this study. This is a substantial outcome since the narrowing of the confidence intervals permits a more meaningful evaluation of the different emission scenarios investigated, which otherwise, given the broad uncertainty of other estimates, would have led only to vague conclusions in a study of this nature.

**Keywords:** Hg; ASGM; mining; emission; pollution; atmosphere



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## 1. Introduction

Mining, and in particular gold (Au) mining, is one of the oldest activities of mankind [1]. Illegal and unregulated Au mining activities, namely artisanal and small-scale gold mining (ASGM), currently represent one of the most serious environmental issues globally, not only because the extracted raw material may contain harmful metals, such as As and Pb, but also because ASGM commonly uses mercury (Hg) to refine Au due to its cheap price, easy handling and its ability to form an amalgam with Au [2,3].

Au is extracted from a great variety of deposits in different geological contexts: in very ancient Precambrian metamorphic rocks; in various meso and epizonal deposits; and also in much younger alluvial placer deposits. For example, in Southeast Asia, Au is found in Cenozoic and Mesozoic deposits [4], while in Africa and Brazil, it is extracted from Precambrian quartz veins and also alluvial placer deposits [5].

The Au grade differs among lithologies on the basis of petrogenesis, and in some lithologies, depends on the type of weathering. The productivity of a site depends not only on the grade of the ore, but also on the technology used, which differs from country to country: greater recovery rates and quantities of Au produced are found in South America where newer technologies are in use, compared to Africa, where less modern and less efficient techniques are more common [6]. Therefore, each combination of ore type and technique can result in different ratios of Hg used to Au produced [7].

In order to extract Au, one of two (Hg) amalgamation processes are generally used: concentration amalgamation (CA) or whole ore amalgamation (WOA). While both techniques involve the use of Hg, they are very different in terms of the Hg quantities used. CA typically concentrates the ore using gravitational separation techniques (such as the traditional panning method) in order to discard lighter minerals and retain the heavier fraction containing Au. This concentrate is then mixed with Hg to produce the amalgam. Due to the pre-concentration step, less Hg is required in CA than in WOA. WOA crushes the ore and without pre-concentration, Hg is added to produce the amalgam. This technique has a higher Hg:Au ratio and Au recovery is less efficient [8]. Once produced, the Au-Hg amalgam is then heated to remove Hg, leaving relatively pure Au.

The employment of CA or WOA techniques also has profound implications in terms of the environmental matrices affected by Hg contamination [9].

During amalgam heating, if a retort is not used to condense the Hg, its vapors are emitted to the atmosphere and can be inhaled by the operators [10]. Furthermore, the washing of amalgams can release Hg to soils and waters, exposing indigenous peoples that live in the neighborhood to high levels of Hg [11].

Hg is a potent neurotoxin and nephrotoxin that can cause chronic and acute ill-health [12]. Humans and other mammals are mainly exposed to Hg via consumption of its methylated form (MeHg) that bio-magnifies through the food web [13–15], although gaseous Hg at elevated concentrations can expose people to Hg poisoning via inhalation [10]. It has been reported that roughly 15 million people, including 4 to 5 million women and children, are employed in ASGM activities worldwide (https://www.planetgold.org/asgm-101) (accessed on 15 January 2021) without any training regarding the health risks they face [16].

However, the extent of the threat from Hg for human health is not only local, but it is global [17,18]. Elemental Hg is volatile and can join the global atmospheric Hg pool if not deposited locally, and therefore affects areas and ecosystems far away from release points [19,20].

Since the impact of Hg is world wide, Hg production, trade, use and disposal are now regulated under the Minamata Convention on Mercury(MC) (www.mercuryconvention.org/) (accessed on 15 January 2021), which was adopted in October 2013 and came into force in August 2017. Within the convention, a number of approaches are suggested to the parties to estimate the emissions of Hg from ASGM, and to prepare a national action plan (NAP) to reduce Hg utilization in order to fulfill the requirements under Article 7 of the MC [7]. Many of these are applicable only at a national level and require direct interaction between government departments, civil society organizations and other parties, and workers. Moreover, in many cases, ASGM is poverty-driven and therefore a long-standing, and often unofficial activity in many developing countries [21]; therefore, ASGM sometimes escapes official statistics and policy measures under the MC. A number of local scale studies have focused on quantifying the Hg emissions from ASGM in small areas using soil, water or air samples [22–24]; however, a global picture of the phenomena is missing. A better knowledge of the social, environmental, and financial development efforts in the sector and measurements of Hg used over a cross section of ore-processing techniques and operators permitted the most recent Global Mercury Assessment (GMA) [25] to reduce the overall uncertainty of the amount of Hg used for Au production, and therefore to improve the assessment of Hg emissions from ASGM. Among the anthropogenic sources of Hg, ASGM is now believed to be the most important, accounting for 838 tons $yr^{-1}$ (38%) of the emissions to the atmosphere and 1200 tons $yr^{-1}$ (67%) released to waters and soils [25]. Four main approaches were used to estimate Hg emissions from ASGM in the GMA: *(1) direct measurements—using a balance to directly weigh amounts of Hg used; (2) applying a Hg:Au ratio to the quantity of Au produced based on the type of process used (whole ore amalgamation, concentration amalgamation, and also taking into account of the use of emission* *controls, such as retorts, etc.); (3) interviewing miners and Au merchants who buy or sell Hg; and (4) using official production data* [26].

This multi-faceted approach has, however, many issues. One limitation of the GMA is that it cannot be updated frequently due to the need to arrange interviews and collect socio-economic information. In addition, given the not-always-legal nature of ASGM, it is not surprising that some information is not forthcoming. Moreover, the uncertainty of the estimates is given by expert consideration and varies across the approaches used [26]. Indeed, the GMA applied four different error ranges to its estimates, based on the approach used, and on the assumed quality of data. The lowest error range was applied for the approach using recent quantitative data, namely ±30%, whereas when no quantitative information was present, the GMA used its widest error range, ±100%. The two remaining approaches consider error ranges of ±50% when quantitative data were present but significantly updated within the past 5 years, and of ±75% when some indication of the quantity of Hg used was given [27]. Another limitation is the fact that emissions were estimated using different individual years for the various countries where ASGM is practiced [26].

All these features point to a drawback of the GMA estimates: they lack temporal and internal consistency, which is a key issue for generating emissions scenarios; see Mahmoud et al. [28] and references therein. Indeed, for policy considerations, a crucial aspect is the assessment of a set of plausible alternative states of Hg emissions from ASGM under different scenarios [17,29], and the issues underscored above clearly hamper the development of a coherent methodology to calculate alternative emissions scenarios. For all these reasons, there are few studies dealing with ASGM Hg emission scenarios. Streets et al. [30] developed a projection of Hg emissions to 2050 under two increasing emission scenarios, namely A1B and A2, however these are driven by coal combustion in developing countries and no information is given explicitly for ASGM. Pacyna et al. [31] projected Hg emissions to 2035 under different scenarios, where ASGM is reduced by 46% (new policies scenario) and by 76% in the maximum feasible reduction scenario). However, also in this case, these reductions appear to come from an expert evaluation rather than from a quantitative and reproducible methodology. In contrast, Telmer and Veiga [16] qualitatively developed two Hg emissions scenarios, providing two levels of reduction based on two different Hg recycling schemes.

Tong et al. [32] developed a multi-step procedure, based on bootstrap, to estimate the uncertainty associated with the national greenhouse gas inventory of Taiwan. The procedure was applied in a case study involving the carbon stock of Japanese cedar in Taiwan, whose evaluation depends on a multiplicative equation of parameters characterized by their own distribution and/or bounds. To overcome the limitations listed above in the evaluation of Hg from ASGM, in this work, we have applied the multi-step procedure proposed by Tong et al. [32]. It is based on the non-parametric re-sampling of homogeneous and comparable data regarding Au production, the scale of ASGM, and the ratio of Hg used in the different amalgamation processes, collected by scrutinizing official and unofficial documents for 56 tropical and subtropical countries for different years in the time window 2006–2019. This allowed us to obtain estimates of the Hg emissions from ASGM, along with robust confidence intervals, greatly reducing the associated uncertainty.

## 2. Materials and Methods

Through this work, the concept of "releases" is well-described by Kocman et al. [33], in particular on definition of "remobilization from terrestrial systems". In this case, the source of Hg pollution derives from the remobilization of contaminated land and water management practices, associated with active or abandoned ASGM. Instead, the "emissions" represent the Hg discharge into the atmosphere, during amalgam burning operations which can take place at very variable distances from the extraction site.

### 2.1. Uncertainty Associated to ASGM Hg Emission Estimates

In order to estimate the emissions and releases of Hg from ASGM, we used the production of Au as the main driver, exploiting the equation from O'Neill et al. [7]:

$$Hg_{Us} = \frac{Hg}{Au} * Au_{ASGMPr} \tag{1}$$

where $Au_{ASGMPr}$ is the national production of Au from ASGM, and Hg:Au represents the Hg:Au ratio used, which depends mostly on the extraction methods used, namely CA and WOA, but there are significant differences among ASGM sites.

In general, estimating the Hg emissions from different sources sectors is not a simple task due to the uncertainties involved. For the ASGM sector, the situation is somewhat complicated due to the irregular nature of the activities. In the literature, since the amount of amalgam, and therefore Hg, used is proportional to the quantity of Au produced, the uncertainty related to the Hg emissions from ASGM in the atmosphere has been considered roughly equivalent to the uncertainty in the quantity of Au produced [27]. However, this assumption seems to be too simplistic, for a number of reasons.

The first parameter that influences Hg emissions is the scale of ASGM, $Au_{ASGMPr}$, in a given country, which is variable and depends on a number of factors. It is considered to be on average in the range 20–30% but in some countries, it can be up to 100%; see Yoshimura et al. [8] and references therein. A major parameter associated with the fraction of Hg that goes into the atmosphere is the amalgamation technique used; hence, if this is not known, the uncertainty increases. The Hg:Au ratios reported vary from 3:1 to 5:1 for WOA and 1:1 to 3:1 for CA [34,35]. In a recent study, Hg:Au ratios were proposed that represent, on average, the characteristic ratios at a continental scale: 1.96 for Africa, 1.23 for Asia and Oceania, and 4.63 for Central and South America [8,36]. However, single direct measurements at sites employing WOA have shown far higher ratios, including 6.5 in Colombia [37], 15 in Antioquia, Colombia [38], 40–60 in Indonesia [39] and 70 in Burkina Faso [40]. As well as the amalgamation technique used, another source of uncertainty is the fate of the Hg released, where a fraction goes to the atmosphere and the remainder to local soils and rivers. Pfeiffer et al. [41] reported that 55% Hg is released to the atmosphere, while Pfeiffer et al. [42] estimated that 65–83% of the total Hg losses go to the atmosphere. More recently, CA and WOA were estimated to emit 75% and 20% of the Hg to the atmosphere, and 25% and 80% to soils and water, respectively [9].

### 2.2. Multi-Step Bootstrap Procedure to Estimate ASGM Hg Emissions

In this study, we used a multi-step procedure to address the uncertainties mentioned above in order to give robust estimates of Hg emissions and their associated confidence intervals. The method follows the work of Tong et al. [32], which was applied to the national greenhouse gas inventory of Taiwan.

In the first step, (1) the data on Au production for 56 countries belonging to tropical and sub-tropical region for the period 2006–2019 were collected. The length of the period was chosen to take in account inter-annual variability, which may arise from poor or incomplete reporting, fluctuations in the price of Au and changing work opportunities among others. Data relative to the Hg:Au ratio and the scale of ASGM, $Au_{ASGMPr}$ were also collected. In the second step, (2) a Monte Carlo method was employed to generate emissions samples of Hg (Equation (1)) with all the possible combinations of collected parameters, as reported in Table 1. These sample were then processed (3) by a non-parametric re-sampling method with replacement (bootstrap [43]) in order to obtain robust estimates of the mean of the Hg emissions, and their 95% confidence intervals.

Bootstrap is the core of the multi-step procedure presented in this study and has many advantages in contexts where the underlying distribution of the population is unknown and/or the number of available samples are limited [43,44]. Among the available methods to evaluate the confidence intervals of the mean, the percentile approach was used; see [32] for a detailed description. To assure the convergence of the mean and of the relative confidence intervals, N = 10000 re-sample extractions were used.

**Table 1.** The combination of parameters used in this study for the bootstrap-based estimates of Hg emissions from ASGM. "Atm" indicates the fraction of Hg emitted into the atmosphere.

| | | | | | CA | | WOA | | |
|---|---|---|---|---|---|---|---|---|---|
| **Country** | **Region** | **ASGM (%)** | **Ratio** | **Atm.** | **Ratio** | **Atm.** | **Ratio** | **Atm.** | **Reference** |
| Algeria | Northern Africa | 20–30 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [45–47] |
| Bolivia | South America | 90–100 | 4.63 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [48] |
| Brazil | South America | 10–25 | 4.63 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [49,50] |
| Burkina Faso | Western Africa | 10 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [49,51] |
| Burundi | Eastern Africa | 20–30 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [45,46,52–54] |
| Cameroon | Middle Africa | 20–30 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [53,55] |
| Chad | Middle Africa | 20–30 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [53,56] |
| Chile | South America | 20–30 | 4.63 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [53,57] |
| China | Eastern Asia | 50–75 | 1.23 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [58] |
| Colombia | South America | 90–100 | 4.63 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [33,37,49] |
| Congo | Middle Africa | 20–30 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [49,59] |
| Côte d'Ivoire | Western Africa | 20–30 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [16,60] |
| Ecuador | South America | 100 | 4.63 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [61–63] |
| Egypt | Northern Africa | 20–30 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [45,53,64] |
| El Salvador | Central America | 20–30 | 4.63 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [16,65] |
| Equatorial Guinea | Middle Africa | 20–30 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [16,45,53] |
| Ethiopia | Eastern Africa | 20–30 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [16,53,66,67] |
| Fiji | Melanesia | 20–30 | 1.23 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [49,68] |
| French Guiana | South America | 100 | 4.63 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [69] |
| Ghana | Western Africa | 25–50 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [16,68,70] |
| Guinea-Bissau | Western Africa | 10–25 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [71,72] |
| Guyana | South America | 90–100 | 4.63 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [53,73,74] |
| Honduras | Central America | 10 | 4.63 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [8,45,53,75] |
| Indonesia | South-eastern Asia | 25–50 | 1.23 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [45,53,76] |
| Kenya | Eastern Africa | 20–30 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [45,47,53,77,78] |
| Kyrgyzstan | Central Asia | 20–30 | 1.23 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [79] |
| Lao People | South-eastern Asia | 20–30 | 1.23 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [8,53,80] |
| Liberia | Western Africa | 20–30 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [47] |
| Madagascar | Eastern Africa | 20–30 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [45,47,81] |
| Mali | Western Africa | 10–25 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [16] |
| Mongolia | Eastern Asia | 25–50 | 1.23 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [63] |
| Morocco | Northern Africa | 20–30 | 1.23 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [47,77,82] |
| Mozambique | Eastern Africa | 100 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [53,83,84] |
| Myanmar | South-eastern Asia | 20–30 | 1.23 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [85,86] |
| Namibia | Southern Africa | 20–30 | 1.23 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [49,87] |
| Nicaragua | Central America | 25–50 | 4.63 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [69,88,89] |
| Niger | Western Africa | 20–30 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [53] |
| Nigeria | Western Africa | 100 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [90] |
| Papua New Guinea | Melanesia | 20–30 | 1.23 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [8,45,53,85] |
| Perù | South America | 25–50 | 4.63 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [45,53,63] |
| Philippines | South-eastern Asia | 50–75 | 1.23 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [8,53] |
| Rwanda | Eastern Africa | 20–30 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [49] |
| Senegal | Western Africa | 10 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [91,92] |
| Sierra Leone | Western Africa | 100 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [45,46,53] |
| Somalia | Eastern Africa | 20–30 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [49,93] |
| South Africa | Southern Africa | 20–30 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [45,53] |
| Sri Lanka | Southern Asia | 20–30 | 1.23 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [63,77] |
| Sudan | Northern Africa | 90–100 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [16,53,94] |
| Suriname | South America | 50–75 | 4.63 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [45,53] |
| Tajikistan | Central Asia | 20–30 | 1.23 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [8,53] |
| Tanzania | Eastern Africa | 10–25 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [63] |
| Togo | Western Africa | 20–30 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [16,95] |
| Uganda | Eastern Africa | 20–30 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [16,53,63,96] |
| Uzbekistan | Central Asia | 20–30 | 1.23 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [53,74] |
| Venezuela | South America | 100 | 4.63 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [8,53,74] |
| Zimbabwe | Eastern Africa | 20–30 | 1.96 | 0.65–0.83 | 1.0–3.0 | 0.75 | 3.0–5.1 | 0.2 | [86] |

The full workflow of the tasks is shown in Figure 1.

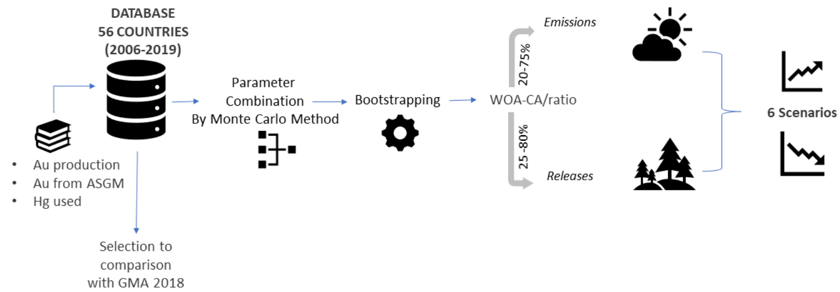


**Figure 1.** Conceptual workflow of the tasks performed in this study. From an initial database of 56 countries, with more than a decade of observations for the most part of countries, the estimates of Au produced, Hg used, emitted and released were obtained. On the basis of bootstrap method, the emissions and releases of Hg were estimated, then six Hg emissions scenarios were devised, and the corresponding emissions calculated. The comparison with the GMA served also as an out-of-sample evaluation of the procedure.

### 2.3. Scenario of Hg Emissions from ASGM

Using the same multi-step procedure, six ASGM Hg emissions scenarios were developed, using the production of Au as the main driver, and considering different combinations of Hg extraction and recycling techniques, applied in a variable fraction of ASGM sites worldwide. In some cases, indeed, the utilization of fume hoods, retorts, and other Hg recovery procedures meaningfully reduced Hg consumption, with low costs, that were recovered rapidly due to the decreased Hg purchases. These anecdotal cases reported in Telmer and Veiga [16] demonstrate that the main impediment of the adoption of these simple and cheap technologies is their slow spread across the mining communities.

The baseline Scenario 1, "Business As Usual" ($Scen_{Base}$), represents the current state, namely the Au production, the scale of ASGM activity, the ratio of WOA/CA extraction technologies and the current negligible use of Hg recycling.

Scenario 2, "Reduction of 90% of Hg in 75% of ASGM" ($Scen_{Red90-75}$), was adopted from an idea of Telmer and Veiga [16] to conceptualize the possible reduction of Hg. They estimated a plausible reduction of 90% Hg emissions to the atmosphere by the adoption of fume hoods and retorts in every ASGM site. In this study, we relax somewhat the diffusion of these technologies, assuming their adoption in 75% of ASGM sites.

Scenario 3, "Reduction of 50% of Hg in 50% of ASGM" ($Scen_{Red50-50}$), is also adopted from Telmer and Veiga [16], in which they estimated a reduction of 50% in Hg emissions to the atmosphere from the adoption Hg reactivation or cleaning methods. As for the previous scenario, in this study, we assume the adoption in 50% of ASGM sites.

Scenario 4, "An increase of 33% of Au extraction activity" ($Scen_{Incr33}$), was developed to reflect a possible increase of Au extraction if the price of Au rises and/or economic instability, leading to an increase in Au extraction via ASGM. This scenario assumes that the CA/WOA ratio remains unchanged.

Scenario 5, "Minimum feasible amount of Hg in CA/WOA" ($Scen_{MinHg}$), was developed to assess the effect of using the minimum feasible amount of Hg for each extraction technique employed at ASGM sites.

Scenario 6, "Maximum feasible reduction" ($Scen_{MFR}$), was developed as the minimum environmental impact scenario in which each ASGM site adopts retorts and fume hoods along with the absolute minimum use of Hg by CA. This scenario assumes WOA is no longer employed anywhere.

The first scenario does not involve any variation with respect to the current conditions, while scenarios 2 and 3 were proposed by Telmer and Veiga [16] and are quite realistic since they are based on the diffusion of cheap and easy-to-use techniques. Scenarios 4, 5 and 6 represent hypothetical cases.

## 3. Results

Figure 2 shows the level of ASGM for the countries analyzed in this study. The greatest proportion of ASGM in terms of national total Au production was found to be in Colombia, Ecuador, French Guiana, Guyana, Mozambique, Nigeria, Sierra Leone, Sudan and Venezuela, where over 90% of Au production comes from ASGM.

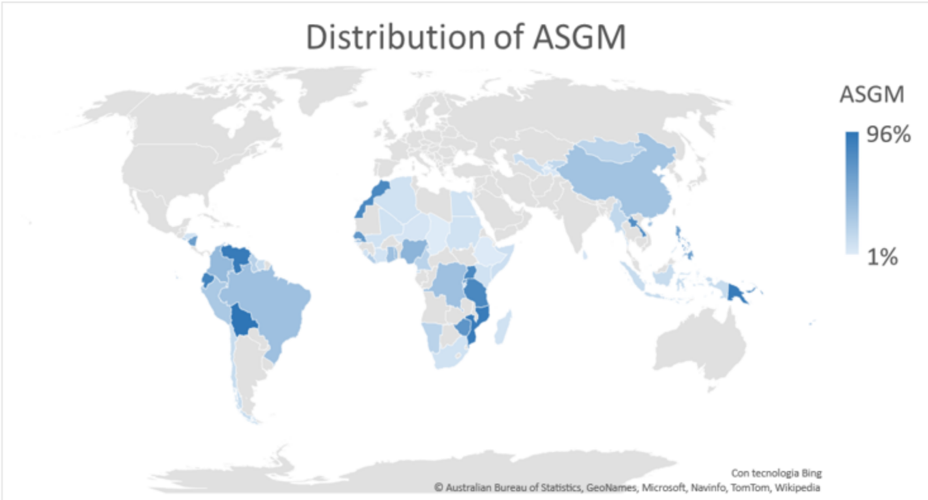


**Figure 2.** Level of ASGM for each country.

The ASGM Hg emissions estimated employing the multi-step procedure used in this study are reported in Table 2.

**Table 2.** Summary of the Hg emissions from ASGM estimated in this study, compared to GMA estimates. NoASGM indicates that for that country, no Hg emissions from ASGM is assessed by GMA.

| Country | Hg Emissions—Ton/y | | Uncertainty—Ton/y (%) | | Hg Releases—Ton/y |
|---|---|---|---|---|---|
| | This Study | GMA | This Study | GMA | This Study |
| Algeria | 0.11 [0.09–0.13] | NoASGM | 0.04 (34%) | NO ASGM | 0.13 [0.09–0.16] |
| Bolivia | 39.81 [33.31–46.32] | 40.50 [28.35–52.65] | 13.02 (33%) | 24.3 (60%) | 34.31 [27.81–40.72] |
| Brazil | 30.10 [25.65–34.56] | 49.88 [24.94–74.81] | 8.91 (30%) | 49.87 (100%) | 25.94 [21.51–30.35] |
| Burkina Faso | 5.58 [5.06–6.10] | 26.33 [13.16–39.49] | 1.04 (19%) | 26.33 (100%) | 6.31 [5.15–7.49] |
| Burundi | 0.55 [0.44–0.66] | 0.23 [0.06–0.39] | 0.23 (41%) | 0.33 (143%) | 0.62 [0.44–0.81] |
| Cameroon | 0.51 [0.47–0.55] | 1.13 [0.28–1.97] | 0.08 (16%) | 1.69 (150%) | 0.58 [0.48–0.67] |
| Chad | 0.02 [0.02–0.02] | 0.23 [0.06–0.39] | 7.18 (36%) | 0.33 (143%) | 0.02 [0.02–0.03] |
| Chile | 20.60 [18.31–22.92] | 1.90 [0.48–3.33] | 4.61 (22%) | 2.85 (150%) | 17.76 [15.34–20.18] |
| China | 280.20 [251.51–308.92] | 33.75 [8.44–59.06] | 57.41 (20%) | 50.62 (150%) | 353.25 [283.52–423.02] |
| Colombia | 85.89 [75.94–95.93] | 51.04 [25.52–76.56] | 20.00 (23%) | 51.04 (100%) | 74.02 [63.54–84.50] |
| Congo | 10.26 [9.17–11.35] | 1.13 [0.28–1.97] | 2.18 (21%) | 1.69 (150%) | 11.59 [9.36–13.86] |
| Côte d'Ivoire | 3.40 [2.90–3.89] | 0.23 [0.06–0.39] | 0.99 (29%) | 0.33 (143%) | 3.84 [2.98–4.70] |
| Ecuador | 26.46 [23.33–29.60] | 26.35 [13.18–39.53] | 6.27 (24%) | 26.35 (100%) | 22.81 [19.58–26.07] |
| Egypt | 2.65 [2.23–3.07] | NoASGM | 0.84 (32%) | NO ASGM | 2.99 [2.26–3.72] |
| El Salvador | 0.10 [0.05–0.15] | 0.23 [0.06–0.39] | 0.09 (92%) | 0.33 (143%) | 0.09 [0.04–0.13] |
| Equatorial Guinea | 0.41 [0.37–0.45] | 0.23 [0.06–0.39] | 0.08 (19%) | 0.33 (143%) | 0.46 [0.38–0.54] |
| Ethiopia | 0.17 [0.14–0.21] | 0.23 [0.06–0.39] | 0.06 (36%) | 0.33 (143%) | 0.20 [0.14–0.25] |
| Fiji | 0.35 [0.32–0.39] | NoASGM | 0.07 (20%) | NO ASGM | 0.44 [0.36–0.53] |
| French Guiana | 37.20 [32.55–41.87] | 5.63 [2.81–8.44] | 9.32 (25%) | 5.63 (100%) | 32.06 [27.17–36.95] |
| Ghana | 52.60 [46.92–58.30] | 41.25 [20.63–61.88] | 11.38 (22%) | 41.25 (100%) | 59.44 [47.83–71.06] |
| Guinea–Bissau | 23.73 [20.80–26.63] | 0.23 [0.06–0.39] | 5.83 (25%) | 0.33 (143%) | 26.81 [21.10–32.54] |
| Guyana | 24.52 [21.49–27.55] | 11.25 [5.63–16.88] | 6.06 (25%) | 11.25 (100%) | 21.13 [18.09–24.21] |
| Honduras | 0.45 [0.40–0.50] | 2.38 [1.19–3.56] | 0.10 (22%) | 2.37 (100%) | 0.39 [0.34–0.44] |

**Table 2.** *Cont.*

| Country | Hg Emissions—Ton/y | | Uncertainty—Ton/y (%) | | Hg Releases—Ton/y |
|---|---|---|---|---|---|
| | This Study | GMA | This Study | GMA | This Study |
| Indonesia | 39.41 [34.79–44.12] | 124.54 [62.27–186.81] | 9.33 (24%) | 124.54 (100%) | 49.68 [39.38–59.91] |
| Kenya | 0.41 [0.33–0.48] | 2.63 [0.66–4.59] | 0.15 (36%) | 3.93 (149%) | 0.46 [0.34–0.58] |
| Kyrgyzstan | 3.23 [2.90–3.56] | 3.56 [0.89–6.23] | 0.66 (20%) | 5.34 (150%) | 4.07 [3.26–4.89] |
| Lao | 1.52 [1.36–1.67] | 2.25 [1.13–3.38] | 0.31 (20%) | 2.25 (100%) | 1.91 [1.55–2.28] |
| Liberia | 15.99 [14.50–17.49] | 2.38 [1.19–3.56] | 2.99 (19%) | 2.37 (100%) | 18.06 [14.72–21.42] |
| Madagascar | 0.13 [0.09–0.18] | 1.13 [0.28–1.97] | 0.09 (71%) | 1.69 (150%) | 0.15 [0.08–0.22] |
| Mali | 9.33 [8.32–10.34] | 9.38 [4.69–14.06] | 2.02 (22%) | 9.37 (100%) | 10.54 [8.52–12.54] |
| Mongolia | 5.11 [4.42–5.79] | 5.46 [2.73–8.19] | 1.37 (27%) | 5.46 (100%) | 6.44 [5.04–7.86] |
| Morocco | 2.50 [2.20–2.79] | NoASGM | 0.59 (24%) | NO ASGM | 3.15 [2.46–3.82] |
| Mozambique | 0.29 [0.26–0.33] | 3.00 [1.50–4.50] | 0.07 (25%) | 3 (100%) | 0.33 [0.26–0.40] |
| Myanmar | 17.34 [15.60–19.09] | 11.25 [2.81–19.69] | 3.50 (20%) | 16.88 (150%) | 21.86 [17.60–26.17] |
| Namibia | 0.05 [0.04–0.05] | NoASGM | 0.01 (20%) | NO ASGM | 0.06 [0.05–0.07] |
| Nicaragua | 0.03 [0.02–0.03] | 0.70 [0.49–0.91] | 0.01 (27%) | 0.42 (60%) | 0.02 [0.02–0.03] |
| Niger | 0.51 [0.45–0.57] | 0.23 [0.06–0.39] | 0.12 (23%) | 0.33 (143%) | 0.57 [0.46–0.69] |
| Nigeria | 12.31 [10.91–13.70] | 15.00 [7.50–22.50] | 2.79 (23%) | 15 (100%) | 13.91 [11.04–16.72] |
| Papua New Guinea | 16.91 [15.37–18.46] | 3.33 [0.83–5.82] | 3.09 (18%) | 4.99 (150%) | 21.32 [17.45–25.21] |
| Perù | 108.39 [94.80–122.09] | 110.36 [55.18–165.54] | 27.29 (25%) | 110.36 (100%) | 93.41 [79.69–107.31] |
| Philippines | 17.98 [16.00–19.96] | 23.63 [11.81–35.44] | 3.96 (22%) | 23.63 (100%) | 22.67 [18.16–27.10] |
| Rwanda | 0.02 [0.02–0.02] | 0.23 [0.06–0.39] | <0.01 (22%) | 0.33 (143%) | 0.02 [0.02–0.03] |
| Senegal | 2.97 [2.69–3.26] | 2.25 [1.58–2.93] | 0.57 (19%) | 1.35 (60%) | 3.36 [2.73–4.00] |
| Sierra Leone | 0.23 [0.20–0.25] | 8.25 [4.13–12.38] | 0.06 (25%) | 8.25 (100%) | 0.25 [0.20–0.31] |
| Somalia | 16.32 [14.85–17.77] | NoASGM | 2.92 (18%) | NO ASGM | 18.45 [15.08–21.79] |
| South Africa | 44.98 [40.44–49.49] | 1.66 [0.42–2.91] | 9.05 (20%) | 2.49 (150%) | 50.83 [41.20–60.32] |
| Sri Lanka | 4.61 [4.05–5.17] | NoASGM | 1.11 (24%) | NO ASGM | 5.81 [4.49–7.13] |
| Sudan | 63.93 [55.12–72.85] | 62.25 [15.56–108.94] | 17.72 (28%) | 93.38 (150%) | 72.25 [56.19–88.42] |
| Suriname | 29.68 [25.76–33.60] | 14.33 [10.03–18.63] | 7.84 (26%) | 8.6 (60%) | 25.58 [21.67–29.51] |
| Tajikistan | 0.87 [0.75–0.98] | 3.00 [0.75–5.25] | 0.23 (26%) | 4.5 (150%) | 1.09 [0.86–1.33] |
| Tanzania | 8.97 [8.02–9.92] | 26.25 [6.56–45.94] | 1.89 (21%) | 39.38 (150%) | 10.14 [8.24–12.05] |
| Togo | 8.70 [7.78–9.61] | 3.00 [0.75–5.25] | 1.82 (21%) | 4.5 (150%) | 9.83 [7.90–11.76] |
| Uganda | 0.49 [0.41–0.57] | 3.00 [0.75–5.25] | 0.16 (33%) | 4.5 (150%) | 0.55 [0.41–0.69] |
| Uzbekistan | 0.21 [0.17–0.24] | 0.23 [0.06–0.39] | 0.07 (34%) | 0.24 (104%) | 0.26 [0.19–0.33] |
| Venezuela | 8.08 [6.30–9.85] | 34.43 [17.21–51.64] | 3.55 (44%) | 34.43 (100%) | 6.96 [5.26–8.66] |
| Zimbabwe | 4.78 [4.15–5.43] | 7.75 [3.88–11.63] | 1.28 (27%) | 7.75 (100%) | 5.40 [4.24–6.55] |

The five countries that emit most Hg were found to be China, Peru, Colombia, Sudan and Ghana, with 280, 108, 86, 64 and 53 *Tons* emitted each year, respectively. Together, these five countries represent roughly half of the overall estimated Hg emissions from ASGM calculated in this study. Except for China, the estimated Hg emissions for these countries agree (within the estimated uncertainty ranges) with those of the GMA.

Hg emissions from China in our study are considerably higher when compared to the Hg ASGM emissions estimated by GMA. A similar difference was also found recently in the calculation of the gap between the demand and supply of Hg to the ASGM sector, where Asia showed an amount of Hg supplied to ASGM significantly lower than the apparent Hg consumption [36].

Other notable differences between our estimates and those of the GMA are found for Indonesia (underestimated) and South Africa (overestimated). Similar deviations for these countries are also seen in the study by Cheng et al. [36].

Overall however, our estimates generally agree with those of the GMA. More importantly, the overall uncertainty is reduced from roughly 100% in the Global Mercury Assessment (779.59 tons/y; uncertainty range: 361.07–1197.97) to 27% (1091.93 tons/y; confidence interval: 964.54–1219.77) in this study.

Estimates from this study agree with those of the GMA not only when considering all the countries, but also when grouped into macro-areas, as illustrated in Figure 3.

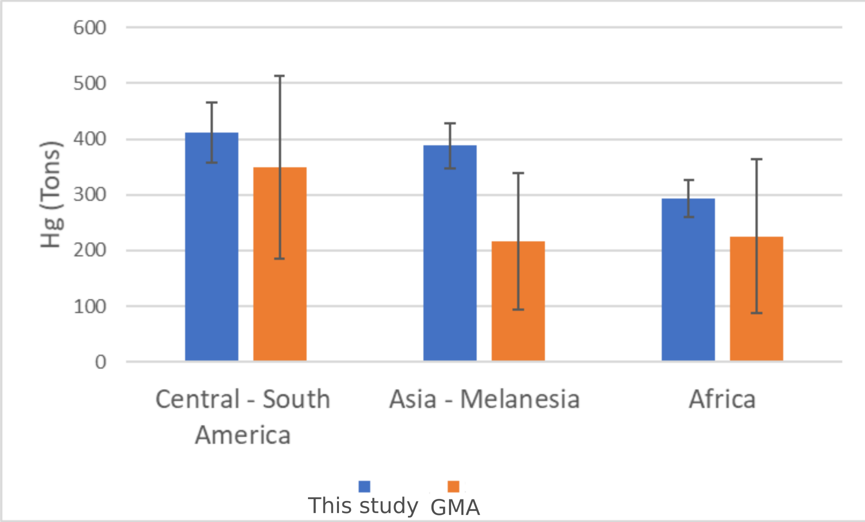


**Figure 3.** ASGM Hg emissions estimated in this study grouped by macro-area. Estimates from GMA are also reported for comparison purposes.

Our estimates are generally somewhat higher than those from the GMA, although for Central and South America and Africa, they agree within the uncertainty range. For Asia—Melanesia, on the contrary, the estimates do not agree: 387.73 tons/y (confidence interval: 347.27–428.36) for this study vs. 216.63 tons/y (94.53–338.70) according to the GMA. The discrepancy (within the uncertainty range) is only a few tons/y and is due predominantly to the large difference in the China emissions estimates, as described above. Also for the macro-areas, it is important to underscore how our approach leads to much narrower uncertainty ranges compared to those of the GMA.

The emission estimates vary greatly between countries even within the same macro-area. This obviously depends on a number of interconnected factors, including the abundance of Au veins, the geomorphology of the terrain, and the individual nations socio-economic conditions. Indeed, the poverty of a country is considered a main driver of ASGM activity. A number of macro-economic variables are available, such as GDP (data.worldbank.org/indicator/) (accessed on 15 January 2021) to understand the underlying causes of ASGM; however, this is not a simple task due to all the interconnected factors, and does not follow a simple pattern. A detailed investigation is beyond the scope this study.

*ASGM Hg Emission Scenarios*

To further this analysis, we assessed the impact of the six different ASGM Hg emissions scenarios conceptualized in this study.

Figure 4 presents the total Hg emissions from ASGM for each country in each scenario, along with the relative confidence intervals (95%), compared with the corresponding data from the GMA. The detailed Hg emissions by country in each scenario are reported in Table 3.

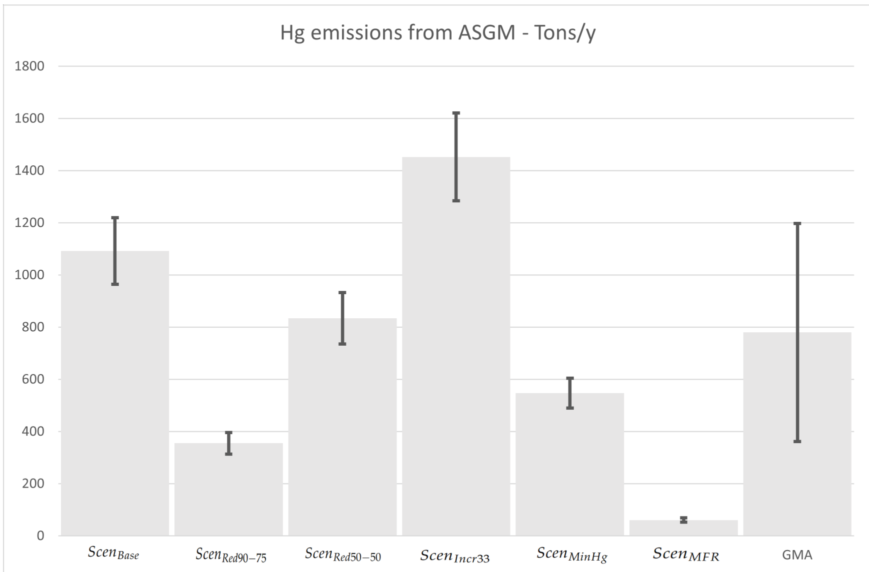


**Figure 4.** Six emission scenarios of Hg from ASGM compared to GMA. The reduced uncertainty associated to estimates of this study allows for a critical assessment of the scenarios conceptualized.

The adoption of fume hoods and retort in 75% of ASGM sites, $Scen_{Red90-75}$ causes a significant (at 95% level of confidence) reduction of roughly 68% in the Hg emissions, whereas the adoption of Hg reactivation or cleaning methods in the 50% of ASGM sites ($Scen_{Red50-50}$) causes a reduction, also significant (at 95% level of confidence) of approximately 24% in the Hg emissions with respect to current emission estimates.

The other two scenarios that consider a reduction in Hg emissions from ASGM are somewhat hypothetical. $Scen_{MinHg}$ assumes a complete diffusion of the awareness by the mining communities regarding the impact of Hg in the environment and therefore minimal use of Hg regardless of the amalgamation technique used, but without the adoption of any methods to recycle the Hg employed. This greater awareness would significantly (at 95% level of confidence) reduce the Hg emissions by half. $Scen_{MFR}$ examines the maximum feasible reduction of ASGM Hg emissions, assuming the minimal use of Hg in the CA technique along with the adoption of fume hoods and retorts in every site. In this scenario, the emissions of Hg from ASGM to the atmosphere would be almost eradicated, being reduced by over 94%.

In the remaining scenario, $Scen_{Incr33}$, the only one that assumes an increase, of 33% in the Au extraction activity, potentially due to an increase in the price of Au, or to changing the socio-economic conditions, the ASGM Hg emissions increase (at 95% level of confidence) proportionally.

The most desirable condition, from an environmental point of view is, of course, the $Scen_{MFR}$ scenario. However, both this scenario and the $Scen_{MinHg}$ scenario are hypothetical. In contrast, both the $Scen_{Red90-75}$ and $Scen_{Red50-50}$, already proposed by Telmer and Veiga [16], are, broadly speaking, plausible scenarios that could be implemented, leading to an important and significant reduction in emissions of Hg from ASGM, and therefore to a consistent reduction in primary anthropogenic Hg emissions.

**Table 3.** Summary of the Hg emissions from ASGM estimated in this study in the different Hg emission scenarios envisaged.

| | $Scen_{Base}$ | | | $Scen_{Red90-75}$ | | | $Scen_{Red50-50}$ | | | $Scen_{Incr33}$ | | | $Scen_{MinHg}$ | | | $Scen_{MFR}$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Country** | **LB** | **Mean** | **UB** | **LB** | **Mean** | **UB** | **LB** | **Mean** | **UB** | **LB** | **Mean** | **UB** | **LB** | **Mean** | **UB** | **LB** | **Mean** | **UB** |
| Algeria | 0.09 | 0.11 | 0.13 | 0.03 | 0.04 | 0.04 | 0.07 | 0.08 | 0.10 | 0.12 | 0.15 | 0.17 | 0.05 | 0.06 | 0.07 | 0.00 | 0.01 | 0.01 |
| Bolivia | 33.31 | 39.81 | 46.32 | 10.81 | 12.94 | 15.06 | 24.98 | 29.86 | 34.69 | 44.39 | 52.95 | 61.63 | 11.55 | 14.05 | 16.55 | 1.17 | 1.56 | 1.95 |
| Brazil | 25.65 | 30.10 | 34.56 | 8.33 | 9.78 | 11.22 | 19.23 | 22.57 | 25.93 | 34.14 | 40.03 | 45.84 | 9.11 | 10.63 | 12.16 | 0.95 | 1.18 | 1.41 |
| Burkina Faso | 5.06 | 5.58 | 6.10 | 1.65 | 1.81 | 1.98 | 3.79 | 4.19 | 4.58 | 6.73 | 7.43 | 8.13 | 2.75 | 3.01 | 3.26 | 0.30 | 0.33 | 0.37 |
| Burundi | 0.44 | 0.55 | 0.66 | 0.14 | 0.18 | 0.22 | 0.33 | 0.41 | 0.50 | 0.58 | 0.73 | 0.88 | 0.21 | 0.30 | 0.39 | 0.02 | 0.03 | 0.05 |
| Cameroon | 0.47 | 0.51 | 0.55 | 0.15 | 0.17 | 0.18 | 0.35 | 0.38 | 0.41 | 0.62 | 0.68 | 0.73 | 0.26 | 0.27 | 0.29 | 0.03 | 0.03 | 0.03 |
| Chad | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 | 12.39 | 15.08 | 17.73 | 0.02 | 0.03 | 0.03 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 |
| Chile | 18.31 | 20.60 | 22.92 | 5.94 | 6.70 | 7.45 | 13.71 | 15.45 | 17.20 | 24.32 | 27.40 | 30.49 | 6.76 | 7.27 | 7.79 | 0.73 | 0.81 | 0.88 |
| China | 251.51 | 280.20 | 308.92 | 81.85 | 91.06 | 100.31 | 188.79 | 210.15 | 231.47 | 335.37 | 372.66 | 410.38 | 162.85 | 176.20 | 189.72 | 17.68 | 19.58 | 21.49 |
| Colombia | 75.94 | 85.89 | 95.93 | 24.66 | 27.91 | 31.16 | 56.92 | 64.42 | 71.88 | 101.09 | 114.23 | 127.34 | 28.92 | 30.32 | 31.73 | 3.22 | 3.37 | 3.52 |
| Congo | 9.17 | 10.26 | 11.35 | 2.98 | 3.33 | 3.69 | 6.90 | 7.69 | 8.48 | 12.20 | 13.65 | 15.07 | 4.88 | 5.53 | 6.17 | 0.52 | 0.61 | 0.71 |
| Côte d’Ivoire | 2.90 | 3.40 | 3.89 | 0.94 | 1.10 | 1.26 | 2.18 | 2.55 | 2.92 | 3.86 | 4.52 | 5.17 | 1.46 | 1.83 | 2.19 | 0.15 | 0.20 | 0.26 |
| Ecuador | 23.33 | 26.46 | 29.60 | 7.61 | 8.60 | 9.60 | 17.53 | 19.85 | 22.20 | 31.08 | 35.20 | 39.32 | 8.82 | 9.34 | 9.87 | 0.97 | 1.04 | 1.10 |
| Egypt | 2.23 | 2.65 | 3.07 | 0.72 | 0.86 | 1.00 | 1.67 | 1.99 | 2.30 | 2.96 | 3.52 | 4.08 | 1.10 | 1.43 | 1.75 | 0.11 | 0.16 | 0.21 |
| El Salvador | 0.05 | 0.10 | 0.15 | 0.02 | 0.03 | 0.05 | 0.04 | 0.08 | 0.11 | 0.07 | 0.13 | 0.20 | 0.01 | 0.04 | 0.06 | 0.00 | 0.00 | 0.01 |
| Equatorial Guinea | 0.37 | 0.41 | 0.45 | 0.12 | 0.13 | 0.14 | 0.28 | 0.31 | 0.34 | 0.49 | 0.54 | 0.59 | 0.20 | 0.22 | 0.24 | 0.02 | 0.02 | 0.03 |
| Ethiopia | 0.14 | 0.17 | 0.21 | 0.05 | 0.06 | 0.07 | 0.11 | 0.13 | 0.15 | 0.19 | 0.23 | 0.27 | 0.07 | 0.09 | 0.12 | 0.01 | 0.01 | 0.01 |
| Fiji | 0.32 | 0.35 | 0.39 | 0.10 | 0.11 | 0.13 | 0.24 | 0.26 | 0.29 | 0.42 | 0.47 | 0.51 | 0.20 | 0.22 | 0.24 | 0.02 | 0.02 | 0.03 |
| French Guiana | 32.55 | 37.20 | 41.87 | 10.55 | 12.09 | 13.62 | 24.38 | 27.90 | 31.42 | 43.35 | 49.48 | 55.77 | 12.03 | 13.13 | 14.24 | 1.30 | 1.46 | 1.61 |
| Ghana | 46.92 | 52.60 | 58.30 | 15.24 | 17.09 | 18.96 | 35.19 | 39.45 | 43.68 | 62.47 | 69.96 | 77.53 | 24.70 | 28.33 | 31.96 | 2.60 | 3.15 | 3.69 |
| Guinea-Bissau | 20.80 | 23.73 | 26.63 | 6.77 | 7.71 | 8.66 | 15.64 | 17.79 | 19.97 | 27.74 | 31.56 | 35.37 | 10.83 | 12.78 | 14.71 | 1.13 | 1.42 | 1.71 |
| Guyana | 21.49 | 24.52 | 27.55 | 6.98 | 7.97 | 8.96 | 16.12 | 18.39 | 20.68 | 28.58 | 32.61 | 36.67 | 7.76 | 8.66 | 9.56 | 0.83 | 0.96 | 1.10 |
| Honduras | 0.40 | 0.45 | 0.50 | 0.13 | 0.15 | 0.16 | 0.30 | 0.34 | 0.38 | 0.54 | 0.60 | 0.67 | 0.15 | 0.16 | 0.17 | 0.02 | 0.02 | 0.02 |
| Indonesia | 34.79 | 39.41 | 44.12 | 11.27 | 12.81 | 14.32 | 26.06 | 29.56 | 33.05 | 46.20 | 52.41 | 58.69 | 21.43 | 24.78 | 28.14 | 2.24 | 2.75 | 3.27 |
| Kenya | 0.33 | 0.41 | 0.48 | 0.11 | 0.13 | 0.16 | 0.25 | 0.31 | 0.36 | 0.44 | 0.54 | 0.64 | 0.16 | 0.22 | 0.28 | 0.02 | 0.02 | 0.03 |
| Kyrgyzstan | 2.90 | 3.23 | 3.56 | 0.94 | 1.05 | 1.16 | 2.18 | 2.42 | 2.67 | 3.86 | 4.30 | 4.74 | 1.86 | 2.03 | 2.20 | 0.20 | 0.23 | 0.25 |
| Lao | 1.36 | 1.52 | 1.67 | 0.44 | 0.49 | 0.54 | 1.02 | 1.14 | 1.25 | 1.81 | 2.02 | 2.22 | 0.87 | 0.95 | 1.04 | 0.09 | 0.11 | 0.12 |
| Liberia | 14.50 | 15.99 | 17.49 | 4.71 | 5.20 | 5.68 | 10.85 | 11.99 | 13.15 | 19.24 | 21.26 | 23.23 | 7.86 | 8.61 | 9.37 | 0.85 | 0.96 | 1.07 |
| Madagascar | 0.09 | 0.13 | 0.18 | 0.03 | 0.04 | 0.06 | 0.06 | 0.10 | 0.14 | 0.12 | 0.18 | 0.24 | 0.03 | 0.07 | 0.11 | 0.00 | 0.01 | 0.01 |

**Table 3.** *Cont.*

| Country | $Scen_{Base}$ | | | $Scen_{Red90-75}$ | | | $Scen_{Red50-50}$ | | | $Scen_{Incr33}$ | | | $Scen_{MinHg}$ | | | $Scen_{MFR}$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | LB | Mean | UB | LB | Mean | UB | LB | Mean | UB | LB | Mean | UB | LB | Mean | UB | LB | Mean | UB |
| Mali | 8.32 | 9.33 | 10.34 | 2.71 | 3.03 | 3.36 | 6.24 | 7.00 | 7.75 | 11.07 | 12.41 | 13.75 | 4.36 | 5.02 | 5.70 | 0.46 | 0.56 | 0.66 |
| Mongolia | 4.42 | 5.11 | 5.79 | 1.44 | 1.66 | 1.88 | 3.33 | 3.83 | 4.34 | 5.90 | 6.80 | 7.70 | 2.68 | 3.21 | 3.74 | 0.28 | 0.36 | 0.44 |
| Morocco | 2.20 | 2.50 | 2.79 | 0.71 | 0.81 | 0.91 | 1.65 | 1.87 | 2.10 | 2.93 | 3.32 | 3.71 | 1.38 | 1.57 | 1.76 | 0.14 | 0.17 | 0.20 |
| Mozambique | 0.26 | 0.29 | 0.33 | 0.08 | 0.10 | 0.11 | 0.19 | 0.22 | 0.25 | 0.34 | 0.39 | 0.44 | 0.13 | 0.16 | 0.18 | 0.01 | 0.02 | 0.02 |
| Myanmar | 15.60 | 17.34 | 19.09 | 5.07 | 5.63 | 6.20 | 11.69 | 13.00 | 14.33 | 20.74 | 23.06 | 25.37 | 10.09 | 10.90 | 11.72 | 1.10 | 1.21 | 1.32 |
| Namibia | 0.04 | 0.05 | 0.05 | 0.01 | 0.01 | 0.02 | 0.03 | 0.03 | 0.04 | 0.06 | 0.06 | 0.07 | 0.03 | 0.03 | 0.03 | 0.00 | 0.00 | 0.00 |
| Nicaragua | 0.02 | 0.03 | 0.03 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.03 | 0.04 | 0.04 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 |
| Niger | 0.45 | 0.51 | 0.57 | 0.15 | 0.16 | 0.18 | 0.34 | 0.38 | 0.42 | 0.60 | 0.67 | 0.75 | 0.23 | 0.27 | 0.31 | 0.02 | 0.03 | 0.04 |
| Nigeria | 10.91 | 12.31 | 13.70 | 3.56 | 4.00 | 4.44 | 8.21 | 9.23 | 10.25 | 14.56 | 16.37 | 18.18 | 5.78 | 6.63 | 7.48 | 0.61 | 0.74 | 0.86 |
| Papua New Guinea | 15.37 | 16.91 | 18.46 | 4.99 | 5.50 | 6.00 | 11.51 | 12.68 | 13.85 | 20.42 | 22.49 | 24.57 | 9.91 | 10.64 | 11.38 | 1.08 | 1.18 | 1.28 |
| Perù | 94.80 | 108.39 | 122.09 | 30.80 | 35.23 | 39.63 | 71.17 | 81.29 | 91.33 | 126.50 | 144.16 | 162.07 | 34.21 | 38.26 | 42.27 | 3.65 | 4.25 | 4.86 |
| Philippines | 16.00 | 17.98 | 19.96 | 5.21 | 5.84 | 6.49 | 12.01 | 13.48 | 14.95 | 21.23 | 23.91 | 26.57 | 9.96 | 11.31 | 12.65 | 1.06 | 1.26 | 1.46 |
| Rwanda | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.03 | 0.03 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 |
| Senegal | 2.69 | 2.97 | 3.26 | 0.87 | 0.97 | 1.06 | 2.02 | 2.23 | 2.45 | 3.57 | 3.95 | 4.34 | 1.45 | 1.60 | 1.75 | 0.16 | 0.18 | 0.20 |
| Sierra Leone | 0.20 | 0.23 | 0.25 | 0.06 | 0.07 | 0.08 | 0.15 | 0.17 | 0.19 | 0.26 | 0.30 | 0.34 | 0.10 | 0.12 | 0.14 | 0.01 | 0.01 | 0.02 |
| Somalia | 14.85 | 16.32 | 17.77 | 4.82 | 5.30 | 5.79 | 11.14 | 12.24 | 13.35 | 19.75 | 21.71 | 23.67 | 8.13 | 8.79 | 9.44 | 0.88 | 0.98 | 1.07 |
| South Africa | 40.44 | 44.98 | 49.49 | 13.13 | 14.62 | 16.10 | 30.33 | 33.74 | 37.12 | 53.73 | 59.82 | 65.84 | 21.48 | 24.22 | 26.94 | 2.28 | 2.69 | 3.10 |
| Sri Lanka | 4.05 | 4.61 | 5.17 | 1.32 | 1.50 | 1.68 | 3.05 | 3.46 | 3.87 | 5.40 | 6.13 | 6.87 | 2.60 | 2.90 | 3.21 | 0.28 | 0.32 | 0.37 |
| Sudan | 55.12 | 63.93 | 72.85 | 17.90 | 20.78 | 23.70 | 41.26 | 47.95 | 54.65 | 73.11 | 85.03 | 97.01 | 27.88 | 34.43 | 40.94 | 2.80 | 3.83 | 4.85 |
| Suriname | 25.76 | 29.68 | 33.60 | 8.35 | 9.65 | 10.92 | 19.30 | 22.26 | 25.25 | 34.22 | 39.48 | 44.76 | 9.19 | 10.48 | 11.78 | 0.97 | 1.16 | 1.36 |
| Tajikistan | 0.75 | 0.87 | 0.98 | 0.25 | 0.28 | 0.32 | 0.57 | 0.65 | 0.73 | 1.00 | 1.15 | 1.30 | 0.46 | 0.54 | 0.63 | 0.05 | 0.06 | 0.07 |
| Tanzania | 8.02 | 8.97 | 9.92 | 2.61 | 2.92 | 3.23 | 6.01 | 6.73 | 7.45 | 10.65 | 11.94 | 13.22 | 4.22 | 4.83 | 5.45 | 0.44 | 0.54 | 0.63 |
| Togo | 7.78 | 8.70 | 9.61 | 2.53 | 2.83 | 3.12 | 5.84 | 6.52 | 7.20 | 10.34 | 11.57 | 12.78 | 4.16 | 4.68 | 5.22 | 0.44 | 0.52 | 0.60 |
| Uganda | 0.41 | 0.49 | 0.57 | 0.13 | 0.16 | 0.18 | 0.31 | 0.37 | 0.43 | 0.54 | 0.65 | 0.76 | 0.20 | 0.26 | 0.33 | 0.02 | 0.03 | 0.04 |
| Uzbekistan | 0.17 | 0.21 | 0.24 | 0.06 | 0.07 | 0.08 | 0.13 | 0.16 | 0.18 | 0.23 | 0.28 | 0.32 | 0.10 | 0.13 | 0.16 | 0.01 | 0.01 | 0.02 |
| Venezuela | 6.30 | 8.08 | 9.85 | 2.05 | 2.62 | 3.20 | 4.70 | 6.06 | 7.41 | 8.40 | 10.74 | 13.06 | 2.03 | 2.85 | 3.67 | 0.19 | 0.32 | 0.44 |
| Zimbabwe | 4.15 | 4.78 | 5.43 | 1.35 | 1.55 | 1.76 | 3.12 | 3.59 | 4.05 | 5.53 | 6.36 | 7.20 | 2.11 | 2.57 | 3.04 | 0.22 | 0.29 | 0.36 |

## 4. Conclusions

All the 56 countries analyzed in this study, located in the tropical–subtropical zone, are characterized by three typical environments: desert, Savannah and rain forest. While the Sahara desert in Africa and the dense rain forest of South America are mostly not heavily populated, and thus ASGM does not present an immediate threat to large numbers of people, Savannah regions in the Indian subcontinent and Southeast Asia are home to more than a billion people. Although all these areas have significant natural resources, in many cases, they lack strong legislation to guard against environmental risks [16]. Further, many of these countries have a high pollution risk with regard to their hydrological resources. Typically, ASGM sites are situated in some of the most important water resources worldwide.

A multi-step procedure has been employed to estimate ASGM Hg emissions and their relative confidence intervals for 56 tropical and sub-tropical countries. The procedure, based on the bootstrap estimate approach, yields estimates that generally agree with those available from the GMA; however, the uncertainty is greatly reduced, on average, from 100% to 23%. The most noticeable deviations were found for China, and South Africa (higher estimates in this study), and for Indonesia (a lower estimate in this study). The same differences were recently found in a study by Cheng et al. [36] and are probably due to inconsistencies in the officially reported data.

Six ASGM Hg emissions scenarios were investigated to evaluate the impact of a number of different Hg recycling strategies with varying uptakes among mining communities, and also of external drivers. Each scenario was developed using the same multi-step procedure acting on the appropriate (set of) parameters.

The most significant outcome of this study is that all of the ASGM Hg emission scenarios analyzed in this study are significantly different (at a 95% level of confidence) from the current Business as Usual $Scen_{Base}$ situation. This is intrinsically due to the quantitative method employed to estimate the ASGM Hg emissions in each scenario that greatly reduced the related uncertainties, compared to the GMA estimates. Indeed, using the approach employed by the GMA experts, no single reduction scenario, except for the near utopian $Scen_{Bestcase}$ case, could be statistically distinguished from the current situation. Such an outcome is essential from a policy point of view since it becomes possible to critically assess the impacts of any ASGM Hg emission scenarios.

The impact of the conceptualized emission scenarios on the ecosystem and human health are potentially significant, with implications from a policy perspective, not only when considering the direct costs of Hg emissions abatement from more technological/industrial sectors, but also the direct saving from the reduced pressure on the health and welfare systems of countries involved in ASGM.

ASGM represents an important income for people living in underdeveloped countries. The underlying roots of ASGM activities are due to a number of different and interacting factors affecting the scale of ASGM, even locally within a given country, including terrain characteristics, the actual presence of Hg-bearing veins and their depletion over time, and macroeconomic factors. The accurate analysis of these interactions will be the subject of future studies to assess the complex impacts of the different drivers, also within the context of climate change. In this regard, it is important not only to have a robust estimate of the current ASGM Hg emissions, but also their future projection.

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| Hg | Mercury |
| ASGM | Artisanal Small-scale Gold Mining |
| Au | Gold |
| CA | Concentration Amalgam |
| WOA | Whole Ore Amalgamation |
| GMA | Global Mercury Assessment |

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