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An estimation of the artisanal small-scale production of gold in the world

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HIGHLIGHTS

- Artisanal Au Mining releases ~727 t/y of Hg to the environment.
- From 2003 to 2011 Au price increased 417% and ASM population doubled.
- 380 to 450 t of gold are produced annually by ~16 million artisanal miners.
- Au recovery: South America > Asia and Central America > Africa
- Hg:Au: South America < Asia = Central America < Africa

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ABSTRACT

The increase in gold price of over 400% between 2002 and 2012, due to a shift towards safe investments in a period of crisis in the global economy, created a rapid increase in gold production. A response to this shift in production was observed for artisanal and small-scale mining (ASM) units in remote locations of the world, but this phenomenon has not been quantified yet. The work presented here was done to provide a quantitative tool for estimation of the gold (Au) produced by ASM and the population of workers involved in the production process, and assessment of mercury (Hg) consumed. The following hypotheses were addressed: i) It is possible to estimate, on first approximation, the amount of Au production in the world by artisanal mining; ii) Au production by artisanal mining varies by country and continent and iii) Hg consumption due to ASM can be correlated with the methods applied in the different countries and continents for the production of Au. To do this we estimated the number of miners, calculated the change in Au price and production and then applied an adjustment factor to calculate Hg production by country and continent. The amount of Au produced depends on technology of the miners by continents (highest in South America, medium in Asia and Central America, and lowest in Africa), and the geologic setting (not investigated here). The results of the estimation show that, as of 2011, over 16 million Artisanal Miners, in the world, were involved in gold extraction (mining or treatment), producing between 380 and 450 t of gold per year, with clear global behavior between the continents in terms of recovery efficiency, confirmed by data on Hg release that is higher in countries with lower technology.

1. Introduction

Artisanal and small-scale mining (ASM) of gold (Au) has been studied worldwide due to the use and release of mercury (Hg) to the environment (Veiga, 1997; Veiga et al., 2006, 2009; Shandro et al., 2009; Spiegel and Veiga, 2010; Velasquez-Lopez et al., 2010). The Global Mercury Assessment (UNEP, 2013) estimated that ASM of gold released ~727 t (metric tonnes) of Hg to the environment per year. This is 37% of the global 1960 t of Hg released annually by anthropogenic sources to the environment (UNEP, 2013). Such numbers are corroborated by various studies specifically on ASM of Au (Cordy et al., 2011; Bose-O'Reilly et al., 2010; Paruchuri et al., 2010; Castilhos et al., 2006). It was estimated that as many as 15 million individuals in developing countries are involved in extracting gold using rudimentary techniques ~10 years ago (Veiga and Baker, 2004). In 2004, the Au production by ASM was estimated at 20 to 30% (500–800 tonnes) of total global production (Swain et al, 2007). Telmer and Veiga (2008) suggested, based on investigation of the Hg consumption in ASM, that the Au production by these individuals might be around 350 t/a. In fact it is very difficult to obtain accurate estimates of the Au production from ASM since governments do not have reliable data on gold production and miners do not freely disclose recoveries. The most reliable information can be obtained from field surveys with miners and Artisanal Mining Associations, and from Au shops that buy Au directly from miners.

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This work was focused on fulfilling a lack of information regarding Au production and Hg release by investigating the following hypotheses. Through knowledge regarding changes in the price of Au and mining technology, and the relationship of number of artisanal miners with changes in prices in Au it is possible to: i) estimate, on first approximation, the amount of Au production in the world by artisanal mining; ii) quantify Au production through artisanal mining globally; and iii) determine Hg consumption.

1.1. Definitions

The definition of "artisanal and small-scale" mining is not uniform in many jurisdictions. The term "artisanal" refers to the rudimentary type of the operation, independently whether the mine is small or large, while small scale mining refers only to the size of the operation, and these can operate in a conventional or in a rudimentary fashion (Veiga, 1997). Very often the legislations of developing countries refer to "artisanal and small-scale mining" as "individuals, groups, families or cooperatives mining with minimal or no mechanization, often in the informal (illegal) sector of the market" (Hentschel et al., 2002). Nonetheless, a more precise definition is needed when dealing with the technical aspect of the problem. In 1972, the United Nations (UN) attempted a first definition of small-scale mining: "Any single mining operation having an annual production of unprocessed materials of 50,000 metric tons or less as measured at the entrance of the mine". In Brazil, the National Mineral Research Department (DNPM) defines small-scale mining as an operation producing between 10,000 t/a (t per year) and 100,000 t/a of ore (CPRM, 2002). A similar definition is given in Ecuador where a small-scale mine is one producing less than 300 t/d ROM (t per day in the Run-of-Mine production) of metallic ore or 800 t/d ROM of non-metallic ore (Vergara, 2009). In a mining process, the Run-of-Mine (ROM), also called "tout-venant", is defined as the ore mined-out and still unprocessed. The ROM is an operational parameter that characterizes both the mine and processing plant: it can be seen either as the volume or mass extracted at the mining site, or as the volume or mass feeding the plant. These data are summarized in Table 1.

Hilson (2002) described that an artisanal mining operation is that one with "intense labor activity located in remote and isolated sites using rudimentary techniques and low technological knowledge, low degree of mechanization, and low levels of environmental, health and safety awareness". Many definitions of artisanal miners mix up the term with "micro-miners" i.e. those who pan the river banks to produce 0.1 to 0.5 g of Au per day (Veiga, 2013). These individuals are usually spread over a large area, they are seasonal and/or they mine to complement their low income from agricultural activities. It must be highlighted here that micro-miners belong to the category of "artisanal miners", nonetheless they are not the major polluters. The large dredges, the processing centers, and those operations producing 0.3 to 3 kg of Au per day are responsible for a much larger environmental contamination (Veiga, 2013).

Considering the above definitions we propose the following general definition:

> *Small-Scale Mining (SSM) is a mining activity producing less than 100,000 t/a ROM for profit. Artisanal Mining is a subset of the previous, where operation does not follow the conventional ecological and engineering principles of mining and uses rudimentary or basic simple techniques to extract minerals.*

In this article, the term ASM (artisanal and small-scale mining) is broadly used to refer to those small or large operations that use rudimentary techniques to extract Au operating in a legal or illegal fashion that are not on the radar of many mining companies, governments, and international environmental agencies.

2. Materials and methods

2.1. Estimation of the ASM population in the world

Data show that a close relationship exists between the price of Au and the population of ASM operators in the world. Quiroga (2002) estimated a population of 13 million ASM operators at the time of publication. The same number is estimated by Hentschel et al. (2003) and Hinton et al. (2003). Eight years later Hruschka and Echavarría (2011) estimate an ASM population of 25 million. The World Bank (2012) estimated a population of 20 million. In the same years AU price increased 417%: from an average of 310 US$/oz (dollars per ounce) in 2002 to an average of 1600 US$/oz in 2012, with a peak of 1700 US$/oz in 2011 (GoldPrice, 2014). The data cited here are rough estimates, but a common trend is clear between Au price and ASM population. Based on this observation, it is possible to calculate the shift in ASM population during a given time, considering it directly proportional to the shift in Au price in the same period. This is shown in Eqs. (1) and (2).

References are available for general numbers of artisanal and small-scale miners (ASM) by country, regardless of mineral production. ASM of Au is a percentage that can vary from almost 100% to none, depending on the country. The proportion of Au miners versus population influences the Au productivity per miner. This is taken into account when dealing with the adjustment factors described in Section 2.3.

The calculation of the ASM population can be based on a relationship developed using the number of ASM population per country using data obtained from reliable available sources, such as the *Report on Mining, Minerals and Sustainable Development* (MMSD, 2002) and the *Communities and Small-scale Mining* (CASM, 2012) online database. The complete list of sources is reported in the caption of Table 3. The variation (percentage) in the price of Au can be calculated between the year of the reference (per each country) and the 2011 average Au price, updated to January 2012, as in Eq. (1):

$$\Delta_{\text{Au price}}[\%] = \frac{\text{Price}^{\text{Au}}_{2011} - \text{Price}^{\text{Au}}_{\text{year of reference}}}{\text{Price}^{\text{Au}}_{\text{year of reference}}} \cdot 100. \quad (1)$$

The same percentage shift, per country, can subsequently be applied to the ASM population, obtained the updated current value, as in Eq. (2):

$$n^{\mathit{COUNTRY}\ x}_{2011} = n_{\mathit{year\ of\ reference}} \times \Delta_{\text{Au price}} \quad (2)$$

where n is the number of artisanal miners operating in country x.

The analysis has been conducted using two different scenarios. *Scenario* 1: the "low-number scenario": when two references with the same credibility were available per country, the lower number has been chosen to feed Scenario 1. *Scenario* 2: the "high-number scenario" when two references with the same credibility were available per country, the higher number has been chosen to feed Scenario 2.

Table 1
Summary of production and investment features that define small scale mining. ROM = Run of mine and CAPEX = Capital Expenditure.

Source	ROM [t/y]	Daily ROM [t/d]	CAPEX [$]	Revenues [$/y]	Human resources
ONU	$<50 \times 10^3$	<200	$<1 \times 10^6$	$<1.5 \times 10^6$	40
DNPM (Brazil)	$10 \times 10^3 < \text{ROM} < 100 \times 10^3$	–	–	–	–
Ley de Mineria (Ecuador)		<300 (metallic ore) <800 (nonmetallic ore)			

2.2. Estimation of gold produced by ASM

In an extensive study elaborated for United Nations Industrial Development Organization (UNIDO) about the ASM scenery in Latin America, Veiga (1997) observed a correlation between Au production and number of miners. An analysis conducted using these data showed two trends. A parabolic trend fits lower values of ASM population (n. ASM < 300,000), as in Eq. (3):

$$P_u = -2 \cdot 10^{-10} n^2 + 0.002 \cdot n + 2.1793. \quad (3)$$

A linear trend fitting higher values of ASM population (n. ASM > 300,000), as in Eq. (4):

$$P_u = 0.0001 \cdot n + 9 \quad (4)$$

where P_u is the uncorrected production of Au of a given country [t] and n is the number of artisanal miners operating in that country. The two regression formulations can be applied to calculate the ASM Au production by country. Nevertheless, using roughly these correlations on world ASM populations would generate a heavy bias, since Veiga (1997) numbers came only from Latin American Countries. The correlation between the number of Au miners and their production depends on the type of ore (alluvial or hard rock), on the mining grade, the technology used, the level of mechanization, the level of instruction of the miners, the accessibility, and social and geopolitical conditions, among other factors. ASM in Latin America is characterized by a higher technological level, and better access to ore, than in Asia and Africa. Thus, the production of Au per miner in other continents is expected to be lower. This estimation needs, hence, to be corrected.

The proposed correction was performed to estimate, for each continent, an adjustment factor, using ratios of technological impact factors in ASM between Latin America and other continents. This is done as follows:

1. Eqs. (1) and (2) are used to calculate the population of ASM in a given country.
2. Either Eq. (3) or (4) (depending on the ASM population of the given country) is applied to these results to calculate the uncorrected production of Au for the considered country.
3. An adjustment factor is calculated by continent, and applied by country according to its geographical position, according to Eqs. (6) and (7). Such factors take into account the different technological levels of the ASM operations in the various continents. The method of determination of these factors is described in Paragraph 2.3.
4. The factors are then applied according to Eq. (5). The final output is the estimated amount of Au produced by ASM per country in 2011.

$$P_{country\ i} = P_u \times C_{continent\ k} \quad (5)$$

where $country\ i \in continent\ k$. $P_{country\ i}$ is the corrected production of Au in country x in 2011 [t], P_u is the uncorrected production of Au [t] and C is the adjustment factor for the continent k.

When available, an official reliable estimate of Au produced by ASM has been inserted in Table 3 instead of the result of the calculations.

2.3. Determination of the adjustment factors

When looking at the ASM productivity (grams of Au per ASM capita) versus the ASM population (Fig. 1), a clear tendency appears between ASM population and quantity of Au produced per capita: higher ASM population corresponds to lower productivity per capita. This indicates, in general, that when fewer numbers of ASM are operating, they possess a higher technological level for Au extraction. Nevertheless, even if the tendency is common when considering the world scenario, when

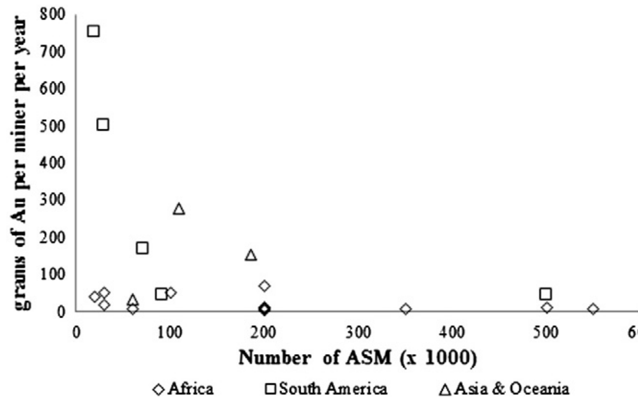

Fig. 1. Number of ASM population vs Au produced, by continent. The point for South America with high ASM population and low productivity refers to Brazil that has the largest ASM population in the continent characterized by a lower technological level compared to other neighbor states. (References in Table 3). Note: overlapping diamonds at y ≈ 0 and x = 200.

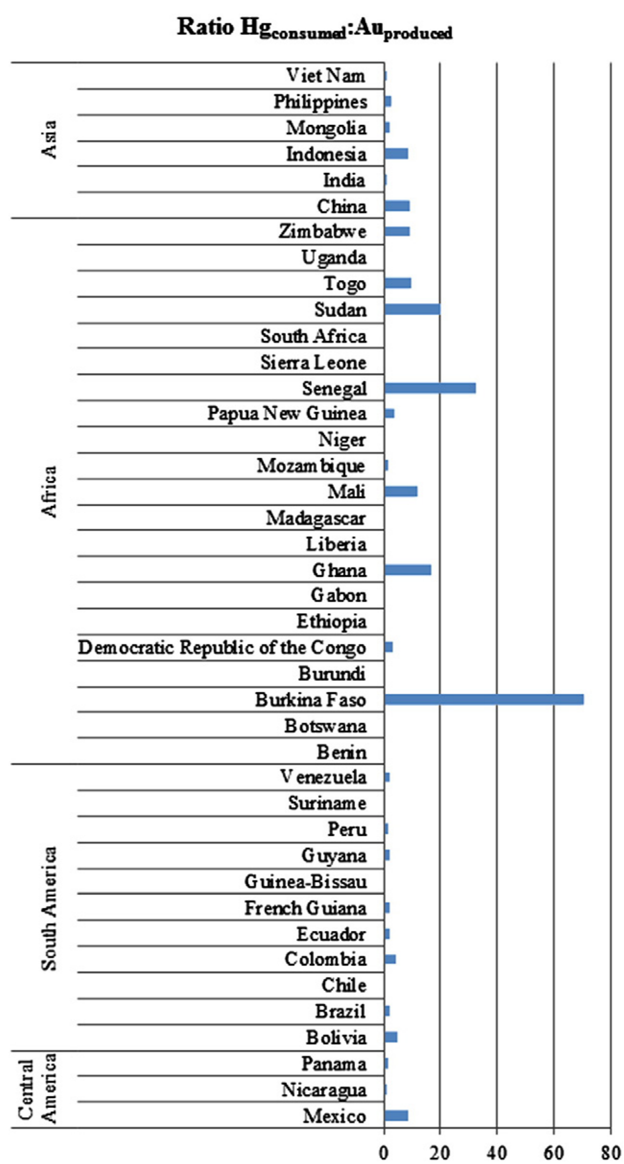

Fig. 2. Ratio of Hg*consumed*:Au*produced*, by country per continent.

looking at a sub-division by continent it appears clearly that each continent presents a different trend. South America has higher values, followed by lower values for Asia and much lower for Africa. (See Fig. 2.)

It must be considered that: a) data on ASM productivity (grams extracted per miner) can be obtained only from sources that report both the population of ASM and amount of Au produced; and b) the number of sources containing reliable information about this is quite scarce. Therefore, it is necessary to find an average value per continent and apply this adjustment factor to every country for which information is not available.

The adjustment factor per each continent, hence, can be calculated comparing the average productivity per capita to the one of South America (on whose data Eqs. (3) and (4) were determined).

The average production of Au per miner is calculated per continent, based on the available information in literature, according to Eq. (6).

$$\overline{P}_{continent\ k} = \frac{1}{m}\sum_{i=1}^{m} P_{country\ i} \tag{6}$$

where country i is in continent k. $\overline{P}$ is the average production of Au per miner per year in the continent k [g_{Au}/miner/year], $P_{country\ i}$ is the production of Au in the country i, and m is the number of countries analyzed for the given continent.

The adjustment factor of each continent is calculated according to Eq. (7), based on the relationship between the average productivity and the highest one (the one from South America):

$$C_{CONTINENT\ k} = \frac{\overline{P}_{CONTINENT\ k}}{\overline{P}_{SOUTH\ AMERICA}}. \tag{7}$$

All the data used to determine the coefficients come from the references marked from [1] to [9] in the capture of Table 3.

The adjustment factors obtained are reported in Table 2.

The same coefficient for Central America was also applied to Asia, despite the fact that Central America's technological level is similar to South America, the number of ASM actually extracting Au is a lower percentage than the rest of Latin American countries. This is an assumption based on the field experience of the authors, and is not based on literature references.

These coefficients are then applied in Eq. (5), to obtain the amount of Au produced in 2011 per each country without a reliable source for Au production.

3. Results

The results for the two scenarios are reported in Table 3. In this table "Estimate" means that the result came from the model above described, and not from a direct source. The coefficients calculated according to Eq. (7) have been applied in Eq. (5) by country according to its geographical position. Those countries with no reliable information about ASM were not included in this evaluation.

4. Influence with Hg consumption

Hg consumption data analyzed in this section was taken from the online database Mercury Watch (2014). The present work refers to the "Hg consumed" ($Hg_{consumed}$ or Hg_{lost}) by artisanal miners. This is the mercury consumed during processing and lost to the environment (air, water, and soil). This is different from the "Hg used" (Hg_{used}) as it is often employed in large excess and then recovered by means of retorts, squeezing through clothes or other ways. Hg "consumed" depends on the processing technique adopted by artisanal miners as well as on the type of ore being processed, and has a strong relationship with the technological level of the ASM process. Here, the results of the high-number scenario (Scenario 2) are compared to the values of Hg consumption from the online database to generate a $Hg_{consumed}$:$Au_{produced}$ ratio (often referred to as Hg_{lost}:$Au_{produced}$, it is written as "consumed" in this discussion to highlight its role of technological indicator more than of environmental hazard). It is used for the high-number scenario because it is the one where Au production is considered higher, and therefore gives a more conservative Hg:Au ratio.

The highest Hg:Au ratios are calculated for Africa, and the lowest in South America. Table 4 shows the comparison between the mean of the ratio $Hg_{consumed}$:$Au_{produced}$ and the adjustment factors described in Section 2.3. As said, such factors reflect the technological level (therefore the efficiency) of the ASM process. These results indicate a higher level of ore processing efficiency in South America > Asia = Central America > Africa.

Table 2
Productivity per ASM capita and adjustment factors by continent.

Continent	Average grams of Au per miner per year	Adjustment factor
South America	300.4	1
Africa	20.6	0.069
Asia & Oceania	153.3	0.511

5. Discussion

The results reported in Table 3 are summarized by continent, in Table 5. The Au produced by ASM is approximately between 17% and 20% of the official Au production in the world, in 2011, 2660 t (U.S. Geological Survey, 2013).

It is important to reiterate that formal and reliable sources on occupation and production of artisanal mining of Au in the world are very scarce. Therefore, the aim of the present model is to provide an estimate. Field research, census, and control over the ASM phenomenon would reduce the uncertainty.

The global characteristic of artisanal Au production that may be governed either by the level of the technology available, or type of ore mined and treated is evident based on percent production by continent (Table 5).

This model, for its very nature, is not precise, but a first approximation. The results here reported give a reliable order of magnitude of the production of artisanal mining in the world, of the people involved in such production, and the technological levels employed in the different parties of the world. The comparison with Hg consumption reported by independent sources confirms the assumptions made to create this model.

This model must be still validated by comparing the results with consistent and reliable data coming from on-field census, and eventually adjusted accordingly.

6. Conclusions

Based on a first approximation, between 380 and 450 t of Au are produced annually by ~16 million artisanal miners in the world. A global trend in Au recovery was observed. As a consequence, adjustment factors were introduced to account for the different technological levels of the ASM process across continents: higher for Latin America, lower for Asia and Central America, and lowest for Africa. The comparison with Hg consumption reported by independent sources confirms such assumption.

The correlation of Au production with Hg consumption shows a correspondence between the adjustment factors adopted and the Hg:Au ratio: the ASM process is more efficient in South America, less efficient in Asia and Central America, and least efficient in Africa. The relationship with Hg release and contamination and technology is direct.

As said above, other factors such as the geological differences between the countries and continents can be influential, but at this stage

Table 3
Results of the estimation model, by nation. List of sources: [1] DNPM (2010), [2] Infomine (2012), [3] Encyclopedia of the Nations (2012), [4] CASM (2012), [5] Mesfin (2012), [6] Hilson (2003), [7] Gold in South Africa (2004), [8] UNEP (2010), [9] Veiga (2012).

Continent	Country	Scenario 1		Scenario 2		
		Expected ASM population [×1000]	Estimated gold production [t]	Expected ASM population [×1000]	Estimated gold production [t]	Source for gold production values
Central America	Cuba	7	0.2	7	0.2	Estimate
	Mexico	56	0.9	56	0.9	Estimate
	Nicaragua	20	1.2	30	1.2	[9]
	Panama	63	1	63	1	Estimate
South America	Bolivia	130	24.8	130	24.8	Estimate
	Brazil	861	21	861	64.9	[1] + Estimate
	Chile	17	5.5	17	5.5	Estimate
	Colombia	268	41.4	418	50.8	Estimate
	Ecuador	128	24.5	128	24.5	Estimate
	French Guyana	7	3.6	7	3.6	Estimate
	Guyana	28	7.6	28	7.6	Estimate
	Peru	70	40	70	40	[2]
	Suriname	28	15	28	15	Estimate
	Venezuela	25	7	70	15.1	Estimate
Africa	Algeria	7	0.3	7	0.27	Estimate
	Angola	218	2.5	218	2.5	Estimate
	Benin	15	0.3	15	0.3	Estimate
	Botswana	15	0.3	15	0.3	Estimate
	Burkina	–	0.5	–	1	[3]
	Burundi	91	1.3	91	1.3	Estimate
	Cameroon	44	1.5	44	1.5	[4]
	Central African Rep.	291	3	291	3	Estimate
	Chad	146	1.9	146	1.9	[4]
	Congo Dem. Rep.	2910	5	2910	5	[4]
	Equat. Guinea	15	0.3	15	0.3	Estimate
	Ethiopia	728	5	728	5	[5]
	Gabon	36	0.6	36	0.6	Estimate
	Ghana	406	4.1	406	4.1	[6]
	Guinea	200	6	300	9	Estimate
	Guinea Bissau	7	0.3	7	0.3	Estimate
	Kenya	146	5	146	5	[4]
	Liberia	146	1.9	146	1.9	Estimate
	Lybia	7	0.3	7	0.3	Estimate
	Madagascar	437	3.5	437	3.5	Estimate
	Mali	361	1.7	361	1.7	[4]
	Morocco	73	1.1	73	1.1	Estimate
	Mozambique	291	3	291	3	Estimate
	Namibia	29	0.5	29	0.5	Estimate
	Niger	291	1	291	1	[4]
	Ruwanda	73	1.2	73	1.2	Estimate
	Senegal	15	0.3	15	0.3	Estimate
	Sierra Leone	437	3.5	437	3.5	Estimate
	Somalia	15	0.4	15	0.4	Estimate
	South Africa	37	17	37	17	[7]
	Sudan	291	3	291	3	Estimate
	Tanzania	994	2	994	3.5	[5]
	Togo	20	0.4	15	0.3	Estimate
	Uganda	218	2.5	218	2.5	Estimate
	Zambia	87	1.4	87	1.4	Estimate
	Zimbabwe	509	2.8	509	2.8	Estimate
Asia	Mongolia		5		5	[8]
	China	2746	48.2	2746	48.2	Estimate
	India	915	1.2	915	1.2	Estimate
	Indonesia	250	20.0	250	20.0	[3]
	Pakistan	515	8.9	515	8.9	Estimate
	Papua N.G.	108	2	108	5	[4]
	Philippines	366	28	366	28	[8]
	Vietnam	63	7.1	63	7.1	Estimate
Total		16,027	379.4	16,327	448.7	

Table 4
Comparison between the adjustment factors used in the model and ratio of Hg used over Au produced by continent.

Continent	Adjustment factor	Ratio Hg*consumed*:Au*produced*
South America	1	2.0
Africa	0.069	8.5
Asia& Oceania	0.511	3.3
Central America	0.511	3.8

of the research there is no way of quantifying such influence. It must be assumed that the technological level, represented by the key indicator Hg:Au ratio, is the most influential factor. A dedicated study should address the influence of mineralogy in artisanal Au recovery, among other factors.

The present model is a reliable tool for a first approximation, but it must be still validated comparing the results with consistent and reliable data, and eventually adjusted accordingly. Field research and census must be strongly encouraged with this purpose.

Table 5
Estimated values of Au produced by ASM by continent.

Continent	Scenario 1		Scenario 2	
	Estimated ASM Au production [t]	% of world production	Estimated ASM Au production [t]	% of world production
Central America	3	0.1%	3	0.1%
South America	190	8.4%	252	11.2%
Africa	85	3.8%	90	4.0%
Asia	100	4.4%	103	4.6%
Total	379	16.8%	449	19.9%

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