Volume 102, Number 10, December 2020

# Toxicological and Environmental Chemistry

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ISSN 0277-2248

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# Toxicological and Environmental Chemistry

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United Kingdom

Universities and research institutions in United Kingdom

**SUBJECT AREA AND CATEGORY**

Environmental Science
- Environmental Chemistry
- Health, Toxicology and Mutagenesis
- Pollution

**PUBLISHER**

Taylor and Francis Ltd.

**H-INDEX**

38

**PUBLICATION TYPE**

Journals

**ISSN**

02772248

**COVERAGE**

1979-2020

**INFORMATION**

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ToxenChem@uni-bayreuth.de

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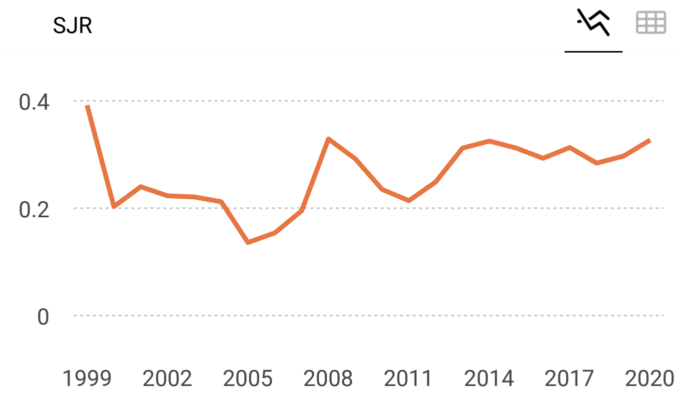
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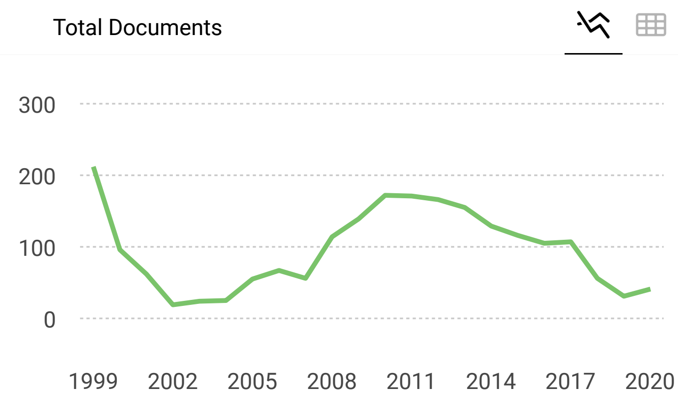
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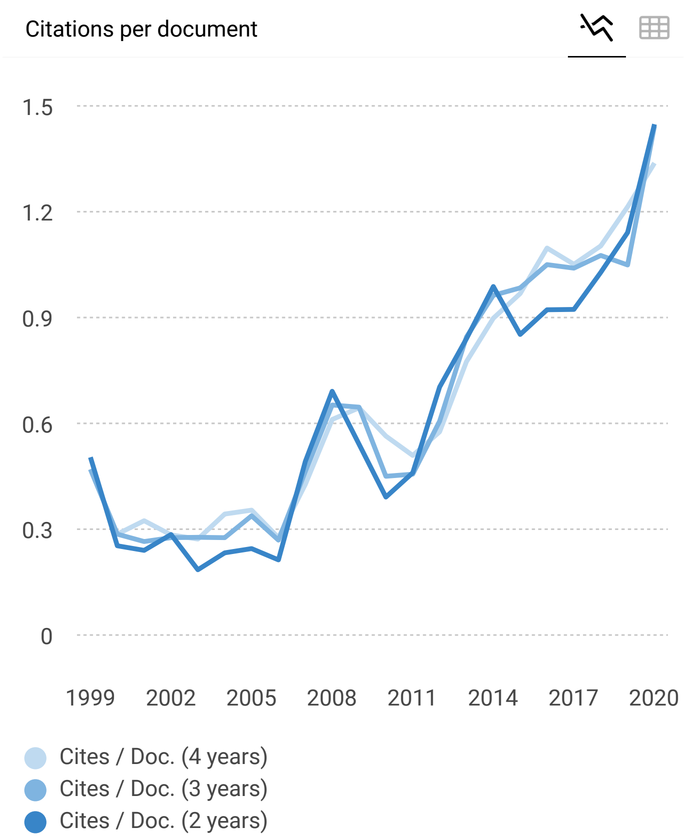
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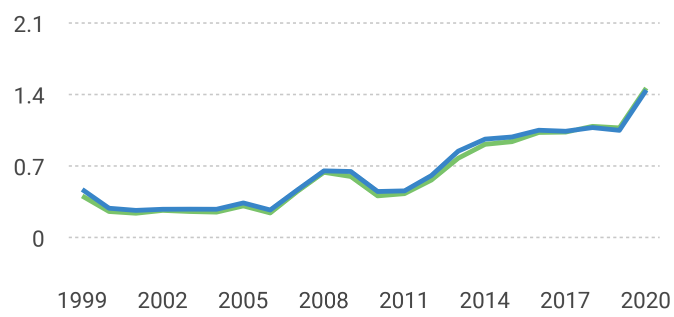


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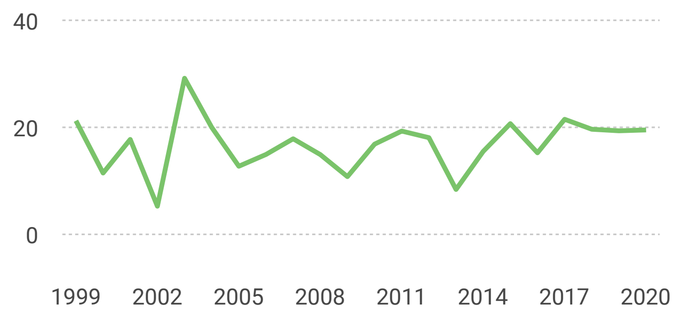


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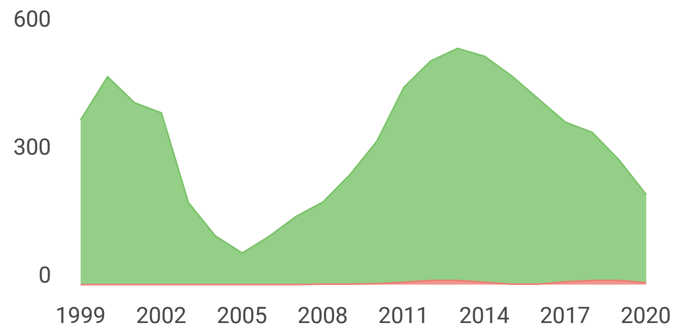


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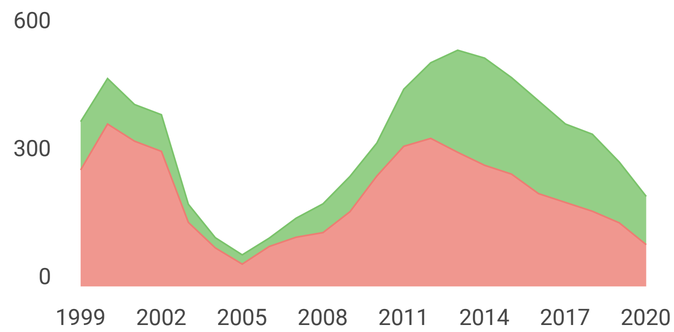


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# Artisanal and small-scale gold mining activities and mercury exposure in Gorontalo Utara Regency, Indonesia

Yayu Indriati Arifin, Masayuki Sakakibara, Sayaka Takakura, Mohamad Jahja, Fitryane Lihawa & Koichiro Sera

Pages 521-542 | Received 17 Oct 2019, Accepted 10 Oct 2020, Published online: 29 Nov 2020

Download citation https://doi.org/10.1080/02772248.2020.1839074 Check for updates



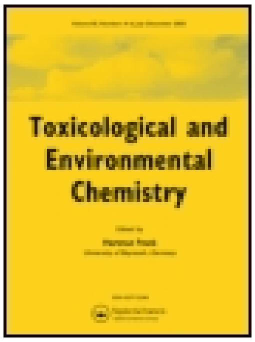
## Abstract

Small-scale gold mining activities and their mercury emissions in the Gorontalo Utara Regency of the Gorontalo Province, Sulawesi Island, Indonesia, have been studied. The mining occurs in many areas of this region, but especially in the three villages Hulawa, Ilangata and Ilangata Barat. Mining activities in the Hulawa village are the oldest (19th century) in the regency, whereas mining in the Ilangata village began just 15 years ago. The activity level changes rapidly from time to time depending on the fluctuations of the gold market. Women and children are involved in the gold mining process. Female workers crush ore, process sediment wastes, and pan for gold in rivers. Children assist their mothers in these activities and play around the mining sites. Gold mining in the Utara Regency is estimated to produce about 290 kg of gold and emits approximately 860 kg of mercury into the environment annually. The impact of such large mercury release into the environment have caused environmental degradation and contamination of fish as food for humans. Collaborative works of stakeholders are urgently needed to find solutions to the problems related to small-scale gold mining such as marginalization and environmental pollution.

# Artisanal and small-scale gold mining activities and mercury exposure in Gorontalo Utara Regency, Indonesia Artisanal and small-scale gold mining activities and mercury exposure in...

**Article** *in* Toxicological and Environmental Chemistry · November 2020

DOI: 10.1080/02772248.2020.1839074

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Toxicological & Environmental Chemistry

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/gtec20

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**To cite this article:** Yayu Indriati Arifin , Masayuki Sakakibara , Sayaka Takakura , Mohamad Jahja , Fitryane Lihawa & Koichiro Sera (2020): Artisanal and small-scale gold mining activities and mercury exposure in Gorontalo Utara Regency, Indonesia, Toxicological & Environmental Chemistry, DOI: 10.1080/02772248.2020.1839074

**To link to this article:** https://doi.org/10.1080/02772248.2020.1839074



Published online: 29 Nov 2020.

TOXICOLOGICAL & ENVIRONMENTAL CHEMISTRY
https://doi.org/10.1080/02772248.2020.1839074



# Artisanal and small-scale gold mining activities and mercury exposure in Gorontalo Utara Regency, Indonesia

Yayu Indriati Arifin[a,b], Masayuki Sakakibara[b,c], Sayaka Takakura[d], Mohamad Jahja[b,e], Fitryane Lihawa[f] and Koichiro Sera[g]

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**ABSTRACT**

Small-scale gold mining activities and their mercury emissions in the Gorontalo Utara Regency of the Gorontalo Province, Sulawesi Island, Indonesia, have been studied. The mining occurs in many areas of this region, but especially in the three villages Hulawa, Ilangata and Ilangata Barat. Mining activities in the Hulawa village are the oldest (19th century) in the regency, whereas mining in the Ilangata village began just 15 years ago. The activity level changes rapidly from time to time depending on the fluctuations of the gold market. Women and children are involved in the gold mining process. Female workers crush ore, process sediment wastes, and pan for gold in rivers. Children assist their mothers in these activities and play around the mining sites. Gold mining in the Utara Regency is estimated to produce about 290 kg of gold and emits approximately 860 kg of mercury into the environment annually. The impact of such large mercury release into the environment have caused environmental degradation and contamination of fish as food for humans. Collaborative works of stakeholders are urgently needed to find solutions to the problems related to small-scale gold mining such as marginalization and environmental pollution.

**ARTICLE HISTORY**
Received 17 October 2019
Accepted 10 October 2020

**KEYWORDS**
Artisanal and small-scale gold mining; mercury exposure; human health problems; Gorontalo Utara; Indonesia

## 1. Introduction

Indonesia is the world's second-largest source of mercury emissions from artisanal and small-scale gold mining (ASGM) after China (Veiga,

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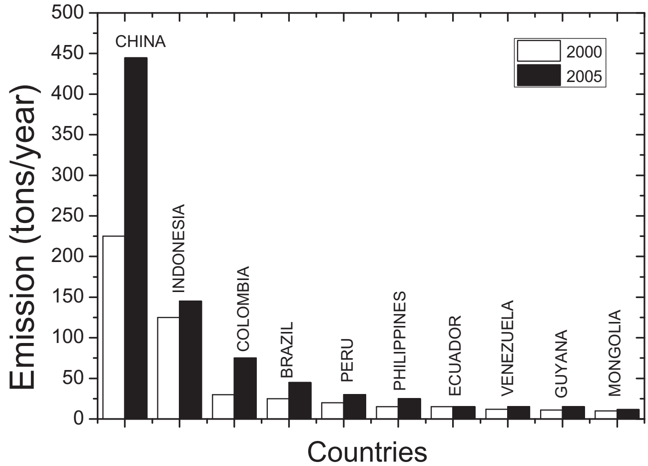


**Figure 1.** The top ten of mercury emitter countries from ASGM in the World.

Maxson, and Hylander 2006; Pacyna et al. 2010; Ismawati 2014). The top 10 global ASGM mercury emitters in 2000 and 2005 are shown in Figure 1 (Veiga, Maxson, and Hylander 2006; Telmer and Veiga 2009; Pacyna et al. 2010; Cordy et al. 2011; Ismawati 2014). Annual mercury emissions from ASGM in Indonesia in 2000, 2005, and 2013 were approximately 125, 150, and 175 tons, respectively. In a five-year period (from 2000 to 2005), Indonesia's ASGM mercury emissions were increased by approximately 20%.

According to UNEP (2008), there are 115 ASGM industries distributed evenly throughout Indonesia that collectively produce 60 tons of gold per annum. The number of ASGM sites in Indonesia is estimated to be ca. 900 involving about 250,000 miners (Purwana 2013). The largest gold mining site in Indonesia is located near Puncak Jaya in Papua. Tailings from this site are dumped in Timika in eastern Indonesia (Nakagawa 2008; Vogt 2012). Here ASGM activities can be found in several places, for example,: Jayapura, Nabire, Paniai and Manokwari. ASGM activities also occur in Maluku Province, Gunung Botak and Gogorea on Buru Island, Maluku Province (Male et al. 2013; Idrus et al. 2014).

Several ASGM locations have also been reported in Sulawesi, including Poboya in Palu (Basir-Cyio et al. 2012). According to Ismawati, Petrlik, and DiGangi (2013), ASGM miners' activities in Poboya use 100 tons of mercury annually (Nakazawa et al. 2016). Basir-Cyio et al. (2012) estimate that about 34 tons of mercury are used daily and produce 22.4–45 kg gold daily. High concentrations above 1000 ng $m^{-3}$ the limit of air-quality guideline for annual mercury exposure by the World Health Organization) of mercury vapor from ASGM were detected in Palu City, and almost all residents of the city are exposed (Nakazawa et al. 2016). Several ASGM has been reported in Mamuju of Sulawesi Barat Province, Tana Toraja and Luwu of Sulawesi Selatan Province and the Bombana of Sulawesi Tenggara Province. The Bombana ASGM has been reported to have negative impact on social, economic and cultural status of the people around the ASGM (Rianse et al. 2015).

There are four other ASGM locations in Sulawesi Utara Province (Basir-Cyio et al. 2012), at Talawaan (Filho and Villas-Bôas 2004; Bose-O'Reilly et al. 2010), Buyat (Kambey, Farrell, and Bendell-Young 2001; Limbong et al. 2005), Tobongon and Tanoyan in the Bolaang Mongondow Regency. Mercury emissions from Talawaan alone are 70 t per annum (Lasut et al. 2010), which is seven times thevalue reported earlier by Telmer and Veiga (2009).

At least there is one ASGM site in each regency of the Gorontalo Province: (1) Pohuwato Regency: Gunung Pani and Bulontio; (2) Boalemo Regency: Bilato; (3) Gorontalo Regency: Bumela (Lihawa and Mahmud 2019) (4) Bonebolango Regency: Tulabolo and Mopuya; and (5) Gorontalo Utara Regency: Hulawa and Ilangata villages.

Gold deposits in the Gorontalo Utara Regency have existed in Wubudubreccias within Boliyohuto diorite of the middle Miocene age (Carlile, Digdowirogo, and Darius 1990). Gold in hydrothermal breccias and quartz veinlets has been reported in Sumalata and Boliyohuto sub-districts (Carlile, Digdowirogo, and Darius 1990). Gold mining in the Hulawa village is considered to date back to Indonesia Dutch era (Henley 2005).

This study describes mercury pollution from ASGM sites in the Gorontalo Utara Regency where gold mining activity is intense, but information is scarce. The report describes how miners work and what the mercury emission situation is, as a basis for further discourse on health risks in and around these mining sites.

## 2. Materials and methods

### 2.1. Study area

The Hulawa (meaning 'gold' in the Gorontalo language) mining area (Figure 2) is also known as the Buladu mining area in Sumalata. This area lies within the Buladu River watershed, between the Pasolo and Padengo villages, approximately 109 km northeast of Gorontalo City, the capital of Gorontalo Province. From Gorontalo City, the area can be reached by car in approximately four hours. Buladu has a typical equatorial climate with two seasons (rainy: November–April; dry: May–October), with the highest rainfall occurring in December (annual average 1,210 mm). The temperature is 27 °C on average. The Buladu

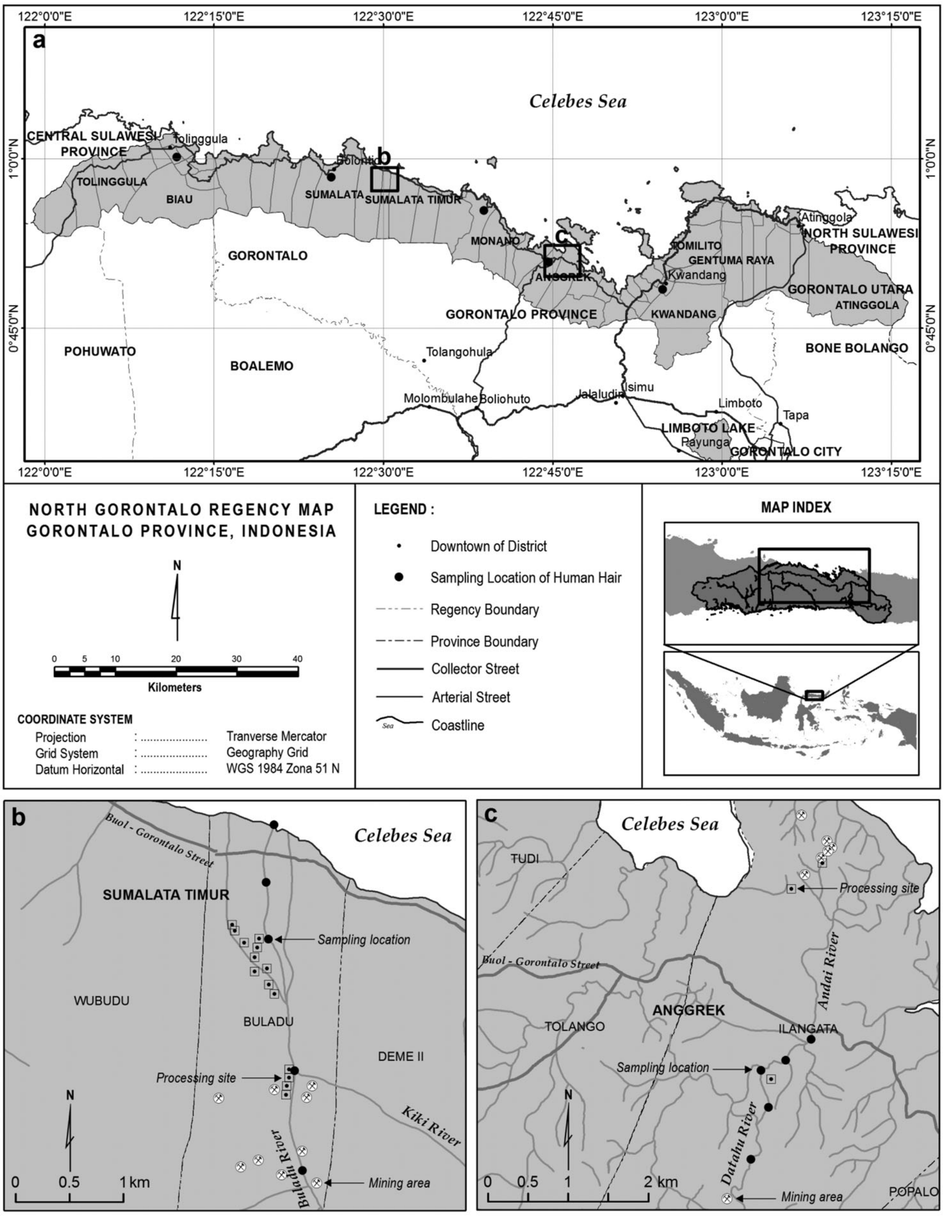


**Figure 2.** Map of the Gorontalo Utara Regency showing the location of Sumalata sub district, where the Hulawa mining area is, and the Anggrek sub district where the Ilangata and Ilangata Barat mining areas are located.

River watershed drains from the mountain peaks with the highest point being 2,000 m, on the northern coast of the Sumalata district. The distance from the mountain peaks to the Sulawesi Sea is approximately 10 km. Several rivers run through this watershed, including the Buladu and Wubudu rivers.

The Ilangata and Ilangata Barat mining areas (Figure 2) comprise the Anggrek mining area. The area lies within the Anggrek River watershed between the Diata, Lunggulo, and Lantolo villages, which are approximately 68 km northwest of Gorontalo City. It is three hours by car from Gorontalo City. The Anggrek River watershed drains from the peaks of several hills with elevations of 300 m at most. The distance from the peaks to the sea is approximately 5 km. Number of rivers, including the Anggrek and Ilangata rivers, flow through the Anggrek watershed.

Residents of Hulawa, Ilangata and Ilangata Barat are exposed directly and indirectly to mercury from mercury vapor of ASGM process and sea fish consumption, while residents of other subdistricts (Kwandang, Monano and Tolinggula) are treated as control group since they might only be exposed to mercury through sea fish consumption.

### 2.2. Sample and data collection

The ASGM locations within Gorontalo Utara regency have been visited many times over the course of one month each year, from 2012 to 2014. Data on mercury use during ASGM and the activities of miners and their families were obtained via direct interviews with miners, mine owners, and local government officials. These interviews were conducted onsite at the mining locations in the Gorontalo Utara Regency (Figure 2). The simple questionnaire consisted of number of workers, number of gold trommels, amount of ore filled into trommels, and amount of mercury consumed and gold produced ina single mill process. This was done in Hulawa, Ilangata and Ilangata Barat ASGM sites ($n = 23$): 6 ASGM operators, 2 panners, 3 villagers in Hulawa, 6 ASGM operators, 4 villagers and 2 gold shop workers in Ilangata and Ilangata Barat, 2 officers in Kwandang). The interviewed were key-actors, including mine site managers, head of villages, and elderly people who were working as ASGM miners 20 to 40 years ago.

Data obtained from different sources were compared with each other via triangulation procedure, for example, number of miners from the owner, from direct investigation and from local officers were confronted other to keep accountable. Any information obtained from participants was recorded and is used in triangulation process. For instance, we recorded the following information while communicating with villagers who have a motorcycle repair kiosk in Ilangata, his friend said that: "he started that business after he earned about 6000 US-$ for a week from ASGM one year ago". Once we were in Hulawa village, a man who got training on the Minamata disease problem informed us that in nearby villages live three people who were suspected to have tremor disturbance related to their former activities as ASGM miners in Hulawa. The first person showed tremor during our conversation and he has a problem on oral communication already. The second one, also showing tremor with a lesser degree, said that: 'We were working as ASGM miners, dealing with mercury without safety equipment during smelting; sometimes they put gold amalgam in their mouths to sell later on'. They also consumed fish from contaminated rivers, the estuary, and the sea.

Information on the economy and social life in ASGM were also obtained from interviews with miners, managers of ASGM businesses, and villagers. Compared to large-scale mining, ASGM activities have more positive economic impacts on local communities, since the capital is shared within local investors, miners, and villagers (Langston et al. 2015). Economy and social life information, in this case, will enrich our understanding on ASGM activities, its impacts on the environment and human health, and ongoing struggles against social marginalization in Indonesia's gold mining sector (Spiegel and Veiga 2010).

### 2.3. Analytical procedure

The health effects on ASGM miners and villagers were examined by collecting scalp hair strands from 115 donors from five subdistricts. The hair strand from the occipital region was cut close to the skull, collected, put in a clear plastic bag, and labeled accordingly. Mercury content in hair was determined using proton induced X-ray emission (PIXE) at Iwate Medical University, Japan, as reported elsewhere(Sera, Futatsugawa, and Murao 2002; Arifin, Sakakibara, and Sera 2015; Basri, Sakakibara, and Sera 2017). The procedure is known as a standard-free method for hair without powdering and acid treatment as reported in previous studies (Sera, Futatsugawa, and Matsuda 1999; Sera, Futatsugawa, and Murao 2002; Arifin, Sakakibara, and Sera 2015; Basri, Sakakibara, and Sera 2017). The widely accepted exposure limit values for mercury concentration in hair (μg/g) as suggested by the German Human Biomonitoring Commission (HBM) as the following categories are adopted: concentration (μg/g) below 1.0 are considered normal, 1.0 – 5.0 are an alert level, and above 5.0 are indicative of a serious risk of health effects.

### 2.4. Neurological assessment

The participants with elevated hair mercury concentration were assessed clinically according to a questionnaire specifically for subjective symptoms and a neurological examination, and the use of mercury-containing soap (for female only). Neurological examination was performed by a medical doctor on participants, using a UNIDO protocol which consists of 10 symptoms: (1) rigidity and ataxia (walking and standing); (2) tremor: tongue, eyelids, finger to nose, pouring, posture holding, and the Romberg test; (3) signs of bluish discoloration of gums; (4) irregular eye movements or nystagmus; (5) salivation and dysarthria; (6) field of vision; (7) alternating movements or dysdiadochokinesia; (8) knee jerk reflex and biceps reflex; (9) sensory examination and (10) Babinski reflex and labial reflex. Score 1 was given for positively-observed symptoms, and 0 for negatively-observed symptoms. The sum of score for every participant is calculated and analyzed.

### 2.5. Description of sites and processes in of ASGM

Ore is manually excavated from nearby hills or mountains (Figure 3(a)) using vertical holes in the ground (Figure 3(b)). Traditional tools such as broad hoes, bars and simple pulleys are used for the ore excavation (Figure 3(c)). The ore is manually crushed (Figure 3(d)) using hammers or other percussion tools (Figure 3(e)). Some processing plants use homemade mechanical crushers. The ore is then packed into sacks and manually transported to the processing plant (Figure 3(f)).

At the processing plant, crushed ore (30–40 kg) is fed into a trommel (known as 'Tromol' in the local language (James 1994), a steel mill grinder where gold is extracted from ore (Male et al. 2013) (Figure 4(a)) with water (Figure 4(b)) and several decimeter-sized rocks (Figure 4(c)) and milled for 3–4 hours until the material is fine enough to release the gold. Subsequently, approximately 500 g of mercury are added to the trommel (Figure 4(d)), which then rotates for 30 minutes until the amalgamation has completed. This amalgamation process is the major gold production method for ASGM miners in Gorontalo Province.

After 30 minutes, the material is discharged (Figure 4(e)), and the tailings are manually separated using bare hands (Figure 4(f)). The tailings are washed and rinsed several times (Figure 4(g–j)) to separate the gold from the unamalgamated mercury. The mixture is filtered using a fine cloth to separate the mercury amalgam (Figure 4(k)). The gold amalgam is recovered from this process as shown in Figure 4(l).

After milling the gold, the amalgam is recovered, and the waste sediment is kept (Figure 4(m)) for a second recovery process. Then, mercury-contaminated water is released into the environment (Figure 4(n)). The amalgams are then smelted to obtain gold bullion. Gold smelters with simple tools smelt the gold outdoors (Figure 4(o)) or inside houses

**Figure 3.** ASGM in the Gorontalo Utara Regency: (a) An artisanal mine shaft on a slope. (b) A hole where the miners are working. (c) A sack of ore is being pulled from the base of the hole. (d) The ore is manually crushed using simple tools. (e) The percussion tools used to crush the ore. (f) Raw crushed ore is manually transported to the processing plant.

and gold shops. Gold bullion is recovered from the smelting process (Figure 4(p)).

The secondary process begins when miners, usually women, and children, wash sediment wastes from the primary milling process in running water. The milling process is then repeated, as shown in Figure 4(a) through Figure 4(l), with the difference being that the trommel is generally rotated by a wheel powered with river water (Figure 4(n)).

Tertiary processing involves bagging the waste from the secondary processing and sending it to another processing plant to undergo cyanidation. There is no cyanidation plant in the Gorontalo Utara Regency.

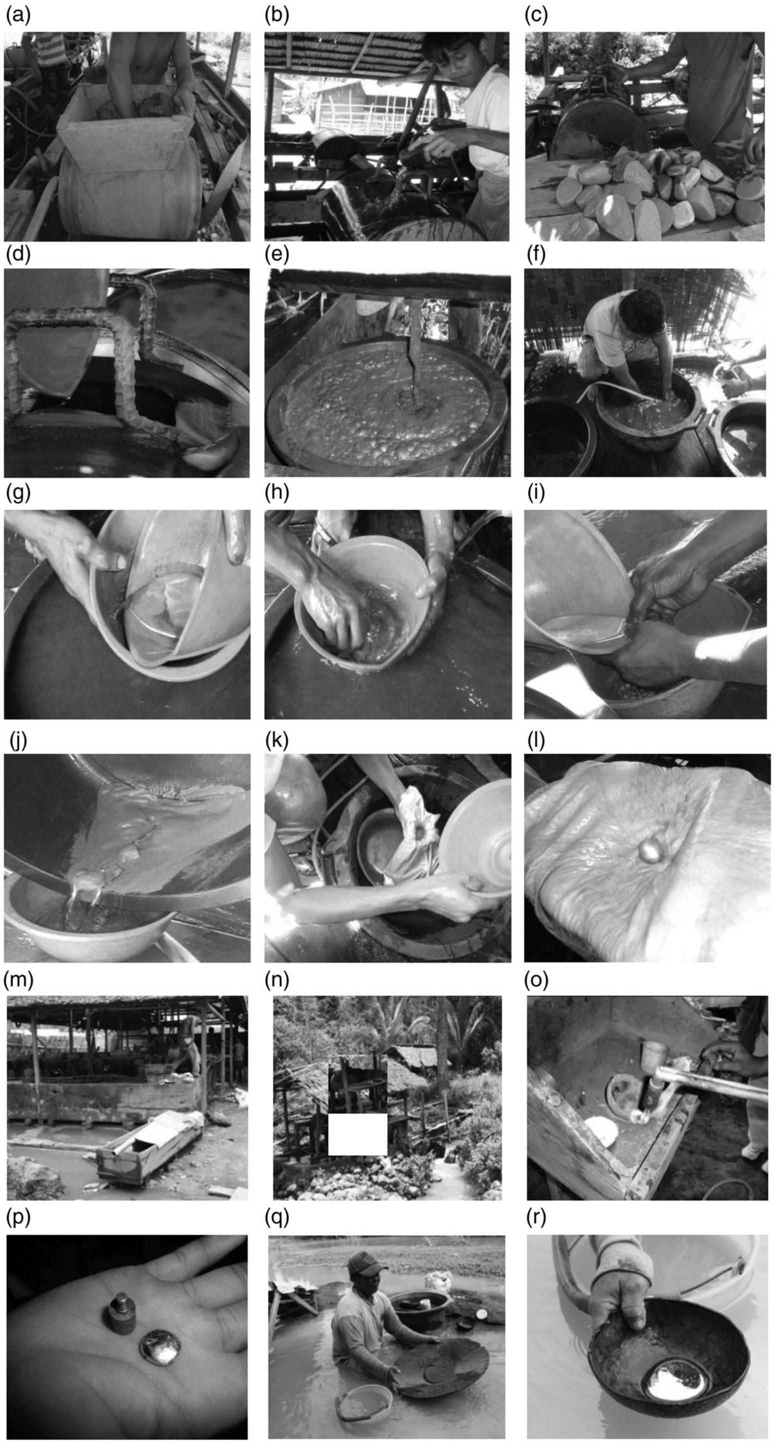


**Figure 4.** Artisanal and Small-scale mining (ASGM) activities in three locations in the Gorontalo Utara Regency. (a) Crushed ore is inserted into the ball mill (b) Water is poured into the trommel (c) The softball size rocks used to mill the ore inside the trommel (d) Where mercury is poured into the trommel mill (e) Discharging the trommel. (f) Separating

**Figure 4.** (*Continued*)
the gold amalgam from tailing (g–j) Extracting the gold-containing mercury (k) Separating amalgam from mercury (l) The amalgam is recovered (m) Tailing waste is kept into wooden boxes for secondary processing (n) Wastewater flows into the rivers stream directly (o) Smelting the amalgam (p) Gold bullion (q) A woman panning the sediment for gold (r) Extracting gold from sediment using mercury.

**Table 1.** Number of mining workers, population, trommel mills and mercury needed per milling process at several locations in the Gorontalo Utara Regency.

| Subdistrict | Village | Number of Workers | Population | Number of Trommel Mills | Mercury/Milling Process (kg) |
|---|---|---|---|---|---|
| Ilangata Barat | Diata | 10 | 382 | 35 | 23 |
| | Lunggulo | 6 | 247 | 43 | 23 |
| Ilangata | Lantolo | 8 | 248 | 60 | 71 |
| Hulawa | Pasolo | 29 | 558 | 164 | 105 |
| | Padengo | 14 | 0 | 76 | 54 |
| Total | – | 67 | 1435 | 378 | 275 |

However, there is a cyanidation plant in the other Regency of Gorontalo Province. Numerous miners pan in the Wubudu River estuary (Figure 4(q)) and (Figure 4(r)) where the mercury enters the environment (air, soil, and water) directly.

Smelting activities occur in gold shops in the Ilangata Barat village. The owners of these gold shops determine the gold quality (amount of gold in 'dore') via these processes. The amount of gold in a dore varies from 40—80% of the weight. A dore with 80% quality can be purchased for approximately US $30,-/gram. Mining wastes have solid and liquid forms that contaminate river waters and soils. Gold bullion is extracted after smelting the amalgam, which emits mercury vapor.

## 3. Results

### *3.1. Mercury emissions*

Because ASGM activities are unregistered, no exact data were available on the number of workers; therefore, it is difficult to estimate the amount of gold produced, and mercury used, for ASGM activities throughout Indonesia and its local provinces or regencies. This difficulty in estimating amounts of gold produced and mercury used by ASGM throughout the world is described elsewhere (Seccatore et al. 2014). We used direct observation and interviews to get information and compared it with data reported by several researchers. Data on mercury imported to Indonesia will be used as the upper limit of mercury lost to ASGM. Socio-economic factors which should be considered when dealing with ASGM (Sulaiman et al. 2007; Spiegel and Veiga 2010; Spiegel 2012; Langston et al. 2015), will be elaborated further to discuss any possible scenario or solutions on sustainable development in local ASGM site areas.

Data on the number of mine workers, population and mercury used during the milling process in each village are listed in Table 1. These figures were estimated based on each milling process requiring 0.5 kg mercury for one trommel mill to extract gold from ca. 30–40 kg of crushed ore. Assuming all trommel mills are operating during the milling process, a maximum of 275 kg of mercury is needed (these data and the amount of mercury emitted per gram of gold produced allows us to estimate the mercury emitted into the environment). Each primary process produced ca. 3 g of gold per trommel mill. The secondary processing of waste produces ca. 0.5 g of gold per trommel mill. We also assume the miners only work five days a week and sell the gold on Saturday. The ratio of mercury emissions to gold produced is ca. 2:1 (Darmutji 2003). The amount of gold produced by the process is ca. 1134 g. Thus, the mercury emissions are ca. 2.2 kg per milling process. The total annual mercury emission in the Gorontalo Utara Regency is approximately 572 kg. If we used 1-3 grams of mercury lost per gram of gold produced, the mercury emission ranges from 286–858 kg (Veiga et al. 2009).

### 3.2. Mercury concentration in hair samples according to geographic location

The distributions and range of mercury levels in 115 hair samples collected from the five subdistricts are shown in Figure 5. Mercury concentrations in all hair donors are more than 1 µg/g, which indicates the

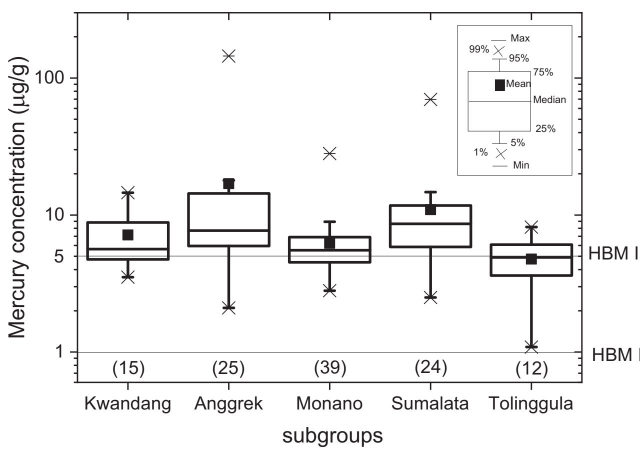


**Figure 5.** Mercury in hair data among the population of Gorontalo Utara regency as box plot, two threshold lines (HBM I and HBM II) according to German Human Biomonitoring (HBM) Commission are shown, number of sample of each group is presented in the bracket.

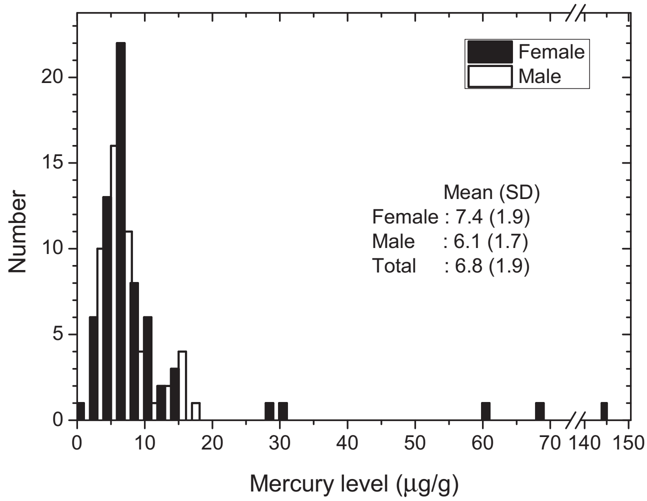


**Figure 6.** The hair mercury levels among females and males are lognormally distributed. Solid and open bar indicate female and male, respectively. Geometric mean and Standard Deviation (SD) are shown for female, male and total.

concentrations are already within the alert level range according to HBM (Schulz et al. 2007). The number of subjects with high mercury levels over 10 µg/g was 10 (40%), 7(30%), and 4 (8.5%) in Anggrek, Sumalata, and the control group (Kwandang, Monano and Tolinggula), respectively.

According to the Kolmogorov-Smirnov test, the distribution of mercury in the hair data from the Gorontalo Utara Regency was not normal; instead, it had a log normal distribution (Figure 6). The geometric mean is more suitable for log normal distribution data. Mean mercury level (+/− standard deviation) of Gorontalo Utara regency is 6.7 (2.0) µg/g and is higher than minimum limit for danger level (5.0 µg/g) according to HBM. Only residents of Tolinggula has average hair mercury level less than 5.0 µg/g. This may due to their residence away from the seaside; their common diet along with rice is chicken. Even though one male and two females have mercury higher than 6.0 µg/g, the Tolinggula group could be considered as a control group in Gorontalo Utara regency.

The data were plotted using a box-and-whisker plot to make a clear view of data distribution in each residence and among Gorontalo Utara regency data. Each Box is filled with the horizontal line representing the position of the median. The position of the median and mean relative to HBM was used to put the population into three categories according to HBM. Box plot of mercury distribution according to geographical location is shown in Figure 5, the results of Sumalata and Anggrek are positioned higher than others, which means that their hair average mercury is elevated in the regency. Other subdistricts (Tolinggula and Kwandang) have no known ASGM activities, but the population lives close to seashore (their common diet is fish from Sulawesi sea, same as the population of Anggrek and Sumalata).

### 3.3. Mercury concentration for male and female

The hair mercury levels among females and males are lognormally distributed is shown in Figure 6. Three females had mercury levels greater than 50 µg/g, and none of them worked as ASGM miners. Those three females may have been exposed to mercury from another source. The elevated hair mercury levels that were above average (6.8 µg/g) and even the highest (17.9 µg/g) mercury level were found among the ASGM miners. The average hair mercury levels for all, male and female inhabitants in the Kwandang subdistrict are 6.5, 6.1 and 6.9 µg/g, respectively. These levels show that there are no significant differences between the mean hair mercury of males and females in that subdistrict. While the average of all mercury hair content for females is 7.4 µg/g (only more than 11 percent higher than males (6.1 µg/g), such conditions were also found for the subgroups of Monano and Sumalata. The condition in Anggrek and Sumalata are even higher (the average mercury for females is 50 percent higher than the males). The large discrepancy of mercury levels between female and male inhabitants suggests that female inhabitants may receiving mercury from another source (e.g. whitening cream, soap, etc).

The clinical symptoms were observed in most of the females with mercury higher than 50 µg/g (the minimum level at which Minamata disease symptoms are seen (Harada 1995)) are listed in Table 2, indicative of inorganic-mercury poisoning only. All the subjects have habitual use of whitening cream that are common in Gorontalo Utara regency. The mercury concentration on the whitening creams are shown in Table 3. It seems that elevated mercury concentration among female inhabitants of

**Table 2.** Females with hair mercury level more than 50 µg/g.

| Subdistricts | Age (years) | Mercury level (µg/g) | Duration of use | Clinical symptoms | Occupation | Notes on ASGM activities |
|---|---|---|---|---|---|---|
| Ilangata | 45 | 144.8 | 10 years | Headache, tremor | Housewife | not active |
| | 13 | 61.3 | 2 years | Headache | Student | not active |
| Hulawa | 36 | 69.8 | 8 years | Headache, tremor | Housewife and owner of local ASGM industry | Burning Amalgam at home |

**Table 3.** Mercury concentration in common whitening cream used among female in the ASGM.

| Whitening cream | Mercury level (µg/g) |
|---|---|
| A | 11.9 |
| B | 7.2 |
| C | 4.1 |
| D | 3.3 |

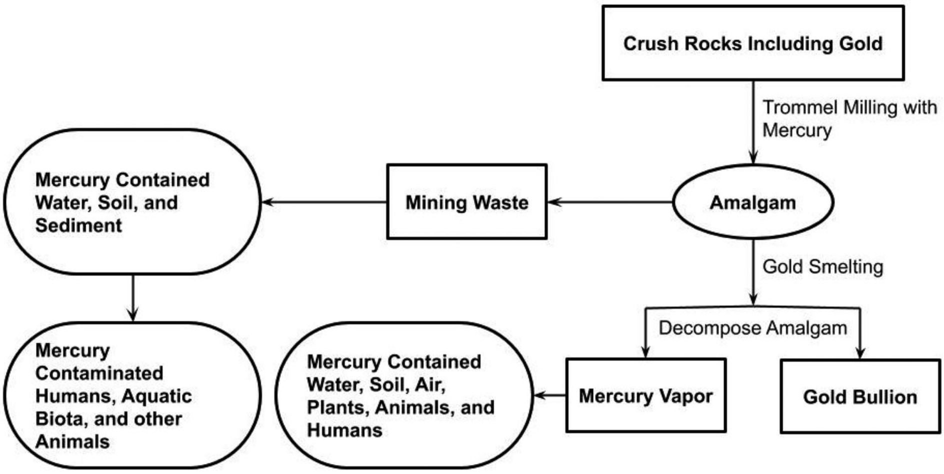


**Figure 7.** Flowchart showing artisanal mining operations to extract gold using mercury and mercury contamination pathways to humans and the environment.

Hulawa and Ilangata may caused by direct mercury contact from habitual use of whitening creams. Harada et al. (2001) found the similar cases in Kenya which were caused by female were elevated hair mercury levels were using soaps with high mercury concentrations.

## 4. Discussion

### 4.1. ASGM operation system and mercury losses

Figure 7 shows the ASGM operation system which is used in Gorontalo Utara Regency; the system used in North Gorontalo is similar to those reported elsewhere (Veiga et al. 2009). Gold recovery systems is based on whole ore amalgamation using trommel, gravitation and panning methods were found in Wobudu river estuary and Anggrek river banks. There are two possible routes for mercury contamination from ASGM into the environment and humans. During the milling process, liquid mercury could contaminate miners and the environment. Working with mining wastes (tailings), and direct exposure to liquid mercury during panning, are also contamination routes. Mercury vapor could contaminate the smelters and environment during smelting.

For comparison, we also estimated the total annual mercury emissions in the Gorontalo Utara Regency from ASGM using data on Indonesian mercury emissions (Pacyna et al. 2010) and the number of known ASGM sites (Kocman et al. 2013). The rate for Indonesian mercury emissions from ASGM may be close to 200 t annually. The average emission from each mining site is approximately 200 kg/year based on the 900 known ASGM sites (Kocman et al. 2013). The three mining sites in the Gorontalo Utara Regency emit approximately 600 kg/year. Ismawati (2014) estimated the ASGM production ranged from 65–130 t in 2012 (Ismawati 2014). Thus, approximately 170−260 t of mercury was lost to the environment based on the multiplication factor from Darmutji (2003). Using the 1:1 to 3:1 ratio proposed by Ismawati (2014), the amount of mercury lost was 65−390 t. These estimates agree with the total mercury import data for Indonesia in 2012, which was approximately 368 t.

### 4.2. Health issues

The involvement of women and children workers is unique to the Hulawa mining site. These women and children come from the Buladu area. They work with waste stored in wooden boxes, and sluice and pan in the Wubudu River estuary. Women and children typically work on mercury-bearing mining wastes during the secondary processing stage (Figure 8(a,b)). Their bare hands and feet are directly exposed to the mining waste, which allows mercury to enter their body via dermal absorption.

Health problems in miners and inhabitants were documented by medical doctors using a standard questionnaire and neurological test tools (Figure 9(a,b)). Ten neurological disorder indicators/symptoms were observed. Bluish gums and tremors are major symptoms observed in the

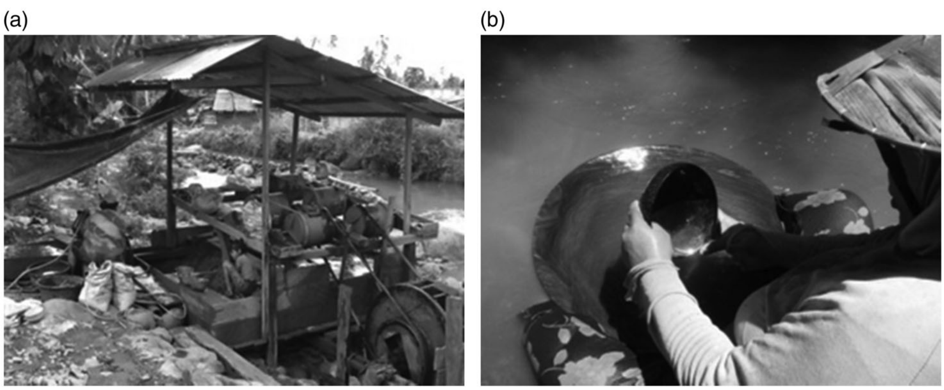


**Figure 8.** The wastewater discharge goes directly into the river. (a) A small child working with her mother handling tailings (solid waste) at the water-powered mill. (b) A woman extracting gold from sediment using mercury.

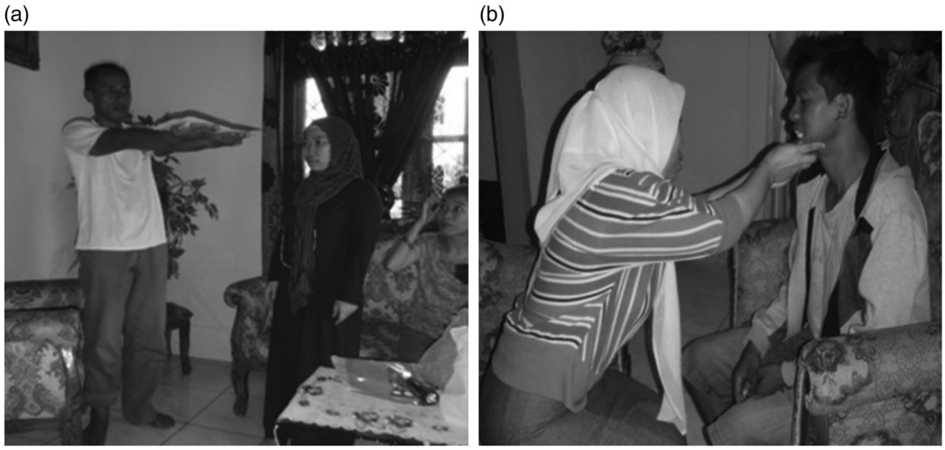

**Figure 9.** A medical doctor observing the inhabitants' symptoms during a neurological examination. (a) Observation of tremor symptoms. (b) Observation of bluish gum symptoms.

miners and inhabitants of the Gorontalo Utara Regency. Several explanations could be addressed based on the evidence; first, they have experienced prolonged contact with mercury, and second, the mercury has entered their body via the food chain (Bose-O'Reilly et al. 2010; Basir-Cyio et al. 2012; Nakazawa et al. 2016). Both can happen simultaneously for the miners and inhabitants of these mining sites. Further investigations are needed to explain the evidence and determine the most probable mercury contamination routes in the Gorontalo Utara Regency.

Without pollution controls and environmental cleanup, further mercury contamination of the environment (bottom sediments, water, and fish) and human population around ASGM sites within the Gorontalo Utara Regency is inevitable (Arifin, Sakakibara, and Sera 2015). Veiga and Hinton (Seccatore et al. 2014) reported that gold bullion contains two to five percent mercury just after smelting, and such gold bullion is refined at gold shops in towns within the Gorontalo Utara Regency with few emission controls. Mercury pollution from gold shops, like those observed in Colombian cities, is of great concern (Cordy et al. 2013).

### *4.3. Socio-economic aspects of ASGM system in gorontalo utara regency*

The intensification of ASGM activities at the historical gold mining site (hulawa village) and expansion to the new gold mining site (Ilangata and Ilangata Barat villages) has been seen as advantage of ASGM over large scale gold mining (LSGM) (Adler Miserendino et al. 2013). The ability of ASGM activities to cut down production cost through their reliance on flexible informal labor. The ASGM activities are driven by local investors which are intimately entangled with socio-political structures and land tenure systems (Verbrugge and Geenen 2019).

The hierarchy of people working in ASGM system in Gorontalo Utara regency can be explained using the network chart introduced by Langston et al. (2015), with slight modification mainly related to the number of ASGM miners. In general, a small number of miners (up to 3 to 4 people) work at the excavating site or processing site; these miners may be family members or friends. Hence supervisor, landowner position, and even investor itself can be the same person.

Local miners are formerly farmers or fisherman and live nearby in their houses, while migrants usually live inside the processing site camps, which are very simple structures and lack sanitation facilities. The basic needs (foods, drinks, cigarettes) were available in kiosk/gold shops which may belong to cooperation or investor/landowner/supervisor.

Positive economic impacts of ASGM activities to miners and inhabitants were not easily seen in Gorontalo Utara regency since there is no significant difference in economic activities in ASGM sites and non ASGM sites. In a stakeholder meeting, ASGM miners, local government, and investor seem to have opposing viewpoints on issues such as sustainable development, environmental protection,and negative impacts of ASGM on health.

Local governments and inhabitants would like to embrace long-term economic solution such as farming, fishery, and tourism, which could eventually replace ASGM. There is ongoing research on finding the ultimate solutions which fit to Gorontalo Utara Regency cases. The multidisciplinary research approach is being taken to help young local students who were living in the ASGM area to find solutions to their local problems. A transdisciplinary approach could facilitate the stakeholders in ASGM area together with the researcher to develop the ideas on sustainable development (Sippl and Selin 2012).

## 5. Conclusions

ASGM activities in the Gorontalo Utara Regency are dangerous to the environment, miners, and the local population. The amount of mercury used per mining cycle is approximately 275 kg, and approximately 2.2 kg of mercury is lost per cycle. Annually, ASGM in the Gorontalo Utara Regency produces approximately 286 kg of gold and emits approximately 572 kg of mercury. This estimate is probably conservative given the limited mining data available. The impact of such a large mercury loss into the environment and human population has been to degrade the environmental conditions and contaminating humans and fish as demonstrated by Arifin, Sakakibara, and Sera (2015).

Gorontalo Utara Regency is an essential agricultural (rice) and horticultural (dairy) production area in the Gorontalo Province and Indonesia. The ASGM driven economy did not bring sustainable development in the vicinity of ASGM sites and Gorontalo Utara regency as a whole. Solutions to the problem are being developed using ongoing multi and trans-disciplinary research approach through the collaboration of Indonesian and Japanese researchers.

## Acknowledgments

The authors thank the regent of Gorontalo Utara and its officers, and the owners of mining plants for allowing us to conduct interviews and take photographs.

## Author contributions

All authors contributed to the work presented in the manuscript.

## Disclosure statement

The authors declare no conflict of interest.

## Funding

This research was supported by The Research Institute for Humanity and Nature (RIHN: a constituent member of NIHU), Project No.14200102.

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