



Mapping the Spread of Mercury from Artisanal Mining Activities in Aceh Jaya

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Abstract

Illegal gold mining, carried out using amalgamation techniques, produces mercury waste which damages the environment and the health of residents. The negative impact due to the use of mercury is contaminated fish, polluted river, and low standard of water quality. This has caused environmental damages, particularly in terms of land and water. Thus, this research was conducted to obtain deeper understanding on environmental damage by mercury, especially in terms of soil and water in the district of Aceh Jaya, Indonesia. The method for this research was the geochemical method. In this case, the samples used were soil and water, samples which were subsequently tested by the Atomic Absorption Spectrophotometry (AAS) and X-ray Fluorescence (XRF) methods to see the mercury levels. The distribution of scattered mercury levels in the research location were mapped through QGIS software. Based on the study conducted, it was found that the distance from the traditional gold mining processing location determines the concentration level of mercury. Analysis using AAS shows that there were 13 samples having mercury concentrations above the critical threshold. According to the analysis made, it is also known that AAS could not detect mercury levels in soil samples, except using XRF analysis. The XRF analysis shows 6 soil samples exceeding the critical threshold and confirms the result of AAS that the high level of mercury was due to the direct dispose around the processing area.

Keywords: Environmental damage, geochemical analysis, illegal gold mining, mercury, soil

1. Introduction

Illegal gold mining is a community activity in the mining sector in an area that does not have a permit from the local government (Muslihudin et al., 2020). Illegal gold miners use simple and rudimentary tools (Aslam et al., 2022). Illegal gold mining or artisanal mining activities generally process gold by extraction using mercury. Mercury itself has been known since humans knew civilization. Mercury forms various compounds, both inorganic (such as oxides, chlorides, and nitrates) and organic. Three forms of mercury are toxic to humans, namely elemental mercury (pure mercury) as well as ionic salt of mercury in the form of mercury (I) (Hg⁺) and mercury (II) (Hg²⁺) (Saturday, 2018). Mercury harms health when consumed. The impact of mercury on human health mostly

occurs in the neuron system (Esdaile and Chalker, 2018). Mercury contamination can cause symptoms in the form of headaches, tremors, tingling especially around the hands and feet, impaired vision, mild shaking, and muscle weakness. In the long term, mercury can cause disorders of the nervous system, parkinsonism, speech and hearing disorders, walking difficulty, and memory loss (Taux et al., 2022).

Mercury is a heavy metal that is very dangerous also for the environment. American Food and Administration (FDA) sets a threshold value for mercury levels in the environment, which is 0.005 ppm (Rosanti et al., 2020). For the consumption of drinking water, the mercury limit set by the government of the Republic of Indonesia

through the Decree of the Minister of Health No. 907 of 2002 is 0.001 mg/l. Therefore, if it exceeds these two thresholds, community gold mining activities can be classified as an anthropogenic source of mercury pollution in the environment.

In Aceh, the practice of gold mining without a permit is very common, such as in Kreung Sabee District, Aceh Jaya Regency. The area, which is in the southwest of Aceh Province, is an area that has an abundant resource of gold. However, the gold processing is carried out simply and even illegally by the local community causing environmental damage due to the lack of knowledge of the miners. The effect even is not only in form of environmental damage but also contamination of mercury to grass as well as agricultural products and fishes consumed by cattles and surrounding people, respectively (Zulfahmi et al., 2021).

The environmental damage that occurred in the Krueng Sabee area was caused by the direct discharge of mercury into the environment. Unfortunately, the mercury waste or tailing discharge point is very close to residential areas. This is because the machines used to extract gold, which is often called 'Gelundung' or 'Glundung', are designed to be placed in such a way as to be close to where the workers live (Brata and Rochana, 2017; Kristianingsih, 2018).

Generally, the tailing containing mercury is directly discharged into the ground and rivers. As a result, the mercury-containing tailing flows below the ground surface creating difficulties in observing how far the tailing will flow (Macabuhay et al., 2018). The mercury also often seeps directly into groundwater that is consumed by residents (Daso et al., 2019). Therefore, before determining the appropriate method and way to deal with the issue, a preliminary study that can map the distribution or movement of mercury is urgently needed. Through this preliminary study, specific contaminated areas can be mapped which later may be continued to the mitigation actions such as reducing mercury contamination or relocating residences to a safer place.

Among the methods used to analyze the distribution of mercury, the geochemical method is the most used one (Srivastava and Ramanathan, 2018). The geochemical method tends to apply theoretical principles to mineral exploration. This method is often used to obtain new mineral deposits during prospecting (Zuo et al., 2019).

The geochemical method includes the systematic measurement of one or more chemical elements in sedimentary rock, soil, water, vegetation, and air (Filella et al., 2019). Thus, the mineralization process that occurs can be well known. Two types of geochemical analysis are often used, namely soil and water analysis. This analysis is very relevant to be used in the case of mapping the distribution or movement of mercury waste, which has not been done before for artisanal gold mining in Aceh.

In addition, compared to other methods such as geoelectrical/geophysical or geological methods, geochemical method can be carried out on surface areas such as surface water, surface wells, rivers, or soil at shallow depth. This is considered more suitable considering that the mercury discharged from processing sites tends to flow on the surface of the ground or surface water. Furthermore, the geochemical method tends to directly show the level or concentration of chemical contaminants which is not shown in geoelectrical/geophysical or geological analysis.

Therefore, by using the geochemical method, this study was done to determine the distribution of mercury waste in the Krueng Sabee, Aceh Jaya, in which illegal gold mining has been conducted. The results obtained were then interpreted in the form of a map of the distribution of mercury in the soil and water body.

2. Methodology

2.1. Materials

Materials used in this study were only soil and water, which were obtained from several areas around Krueng Sabee river, Krueng Sabee sub-district, Aceh Jaya district, Aceh, Indonesia. No chemicals or other materials were used in this study as sample analysis was carried out by analytical laboratory.

2.2. Water/Soil Sampling

Initially, water/soil sampling was conducted by identifying the sampling locations. These locations were determined based on different range of environmental conditions. The samples taken were 20 water samples and 10 soil samples, respectively. For the water samples, appropriate containers (bottles) were used to store the samples. The water sampling method followed the requirements and procedures for taking water quality samples for the purposes of water quality

analysis according to SNI 06-2412-1991. Meanwhile for the soil samples, shovel and plastic bags were used to pick and store the samples. Before using equipment or storing the samples, appropriate protocols were conducted to avoid cross-contamination between samples. Once each sample was collected, the sample was labelled according to the sample code. The soil sampling method referred to the free grid method, that the mapper is 'free' to choose the location of observation points to systematically confirm drawing boundaries and determine the composition of map units.

2.3. Mercury Analysis

The geochemical samples were tested in the laboratory to measure mercury levels. Testing for water and soil samples was carried out using high-performance laboratory Thermo Scientific iCE 3000 Series Atomic Absorption Spectroscopy (AAS) at the Chemistry Laboratory, Faculty of Mathematics and Science, Universitas Syiah Kuala. The instrument can provide wide detection capability for over 60 elements with automatic gas control, flame optimization, and intelligent Spectrometer Qualification (iSQ).

In addition to Atomic Absorption Spectroscopy, testing for soil samples was also conducted using S1 TITAN Series handheld X-ray Fluorescence Spectroscopy (XRF) Analyzer. The instrument allows measurements of light elements such as magnesium, aluminum, and silicon with good precision and accuracy.

2.4. Determining Mercury Distribution

The results of sample testing and data processing were carried out using QGIS and Saga GIS software to determine the distribution of mercury in the study area according to the coordinate input. Mercury distribution modelling using geochemical methods was performed using simple kriging and Inverse Distance Weight (IDW).

In detail, data analysis for the distribution mapping process was carried out using 70% training data and 30% testing data. The training data represents the results of the interpolation using the IDW method while testing data is a representative of the sample to determine the power value to be used. The calculation for the optimum power value was conducted by using power value in the range 1 to 5. When the interpolation was carried out, the Root Mean Square Error (RMSE) value will

be obtained for each power, so that the RMSE value which had the smallest error for each power could be used as the optimum power value. Afterwards, distribution maps with the Inverse Distance Weighted (IDW) interpolation method was done using QGIS Software by inputting the optimum power value.

3. Results and Discussion

3.1. Mercury Content in Water Samples

Table 1 shows the results of the analysis of 20 laboratory water samples obtained using Atomic Absorption Spectroscopy. Based on the results of laboratory examinations of 20 water samples, it was found that there were 6 samples of wastewater from gold processing that contained mercury. Of the six samples, sample PS-05 had the highest mercury content of 0.040 mg/L. The results of laboratory tests for 5 samples of community well water showed that the highest mercury content was found in wells with sample code RP-02, namely 0.011 mg/L.

Meanwhile, the results of laboratory tests for 5 samples of river water indicated that the highest mercury content was found in sample RP-05, with a mercury concentration of 0.011 mg/L. Mercury levels in other river waters were 0.0005 mg/l. In the wastewater disposal channel, the mercury level detected was 0.01 mg/L, while the results of the examination of 2 samples of rice field water showed mercury concentrations of 0.031 and 0.015 mg/L, respectively. The results of the analysis also showed that the mercury content in community groundwater was 0.010 mg/L.

Based on these results, it is known that there were 13 samples that mercury concentration was above the critical threshold and 7 samples that mercury concentration was below the critical threshold. Referring to the standard concentration of mercury discharges in the environment set by the USFDA, all these samples are not suitable for disposal in the environment. In this case, all the contaminated water cannot be consumed by the public because it exceeds the threshold set by the Ministry of Health of the Republic of Indonesia.

According to Table 1, it is also interesting to discuss all samples showing mercury contamination are rooted from the gold processing points. The pollution has spread to well water, rice fields, and community groundwater even though they were located

Table 1. The Result of the analysis for 20 water samples using atomic absorption spectroscopy

No	Sample Code	Latitude and Longitude	Location	Mercury Content (mg/L)	Remark
1	PA-01	4° 41' 15.30" N 95° 41' 08.66" E	Panggong Village River ($\pm$ 100 meters from the gold processing site)	0.0005	Unpolluted
2	PA-02	4° 41' 07.16" N 95° 41' 21.94" E	Gold processing site at Panggong Village	0.0085	Polluted
3	PA-03	4° 41' 09.77" N 95° 41' 09.74" E	A school well at Panggong Village	0.0005	Unpolluted
4	PA-04	4° 40' 58.08" N 95° 40' 53.86" E	Currently operating gold processing site at Panggong Village	0.0082	Polluted
5	PA-05	4° 40' 55.74" N 95° 40' 41.81" E	A mosque well in Panggong Village	0.0005	Unpolluted
6	PA-06	4° 40' 23.28" N 95° 40' 26.29" E	Currently operating gold processing site at Panggong Village	0.0085	Polluted
7	PA-07	4° 40' 17.40" N 95° 40' 24.83" E	Panggong Village River	0.0005	Unpolluted
8	PS-05	4° 37' 20.80" N 95° 39' 23.22" E	Currently operating gold processing site at Paya Seumantok Village	0.0400	Polluted
9	DL-01	4° 36' 42.72" N 95° 39' 10.34" E	Residents' rice fields ($\pm$ 200 meters from the gold processing site)	0.0150	Polluted
10	DL-02	4° 36' 39.59" N 95° 39' 06.18" E	Flow of wastewater disposal at Datar Luas Village	0.0100	Polluted
11	DL-03	4° 36' 11.15" N 95° 39' 14.81" E	Residents' rice fields ($\pm$ 500 meters from the gold processing site)	0.0310	Polluted
12	DL-04	4° 36' 44.88" N 95° 39' 29.20" E	Groundwater at the houses of the villagers of Datar Luas	0.0100	Polluted
13	RP-01	4° 38' 43.20" N 95° 39' 23.53" E	Resident's well at Ranto Panyang Village	0.0100	Polluted
14	RP-02	4° 38' 24.69" N 95° 39' 04.00" E	Resident's well at Ranto Panyang Village	0.0110	Polluted
15	RP-04	4° 38' 21.21" N 95° 39' 06.76" E	Gold processing at Ranto Panyang Village	0.0110	Polluted
16	RP-05	4° 38' 32.34" N 95° 39' 11.73" E	River of Ranto Panyang Village	0.0110	Polluted
17	RP-06	4° 37' 33.91" N 95° 40' 01.16" E	Currently operating gold processing site at Ranto Panyang Village	0.0170	Polluted
18	BU-01	4° 39' 55.37" N 95° 40' 23.94" E	Community well at Buntha Village	0.0005	Unpolluted
19	BU-02	4° 39' 48.08" N 95° 40' 14.11" E	Buntha Village River	0.0005	Unpolluted
20	BU-03	4° 39' 36.60" N 95° 39' 36.60" E	Buntha Village River	0.0005	Unpolluted

200 – 500 m from the gold processing points at the villages of Ranto Panyang and Datar Luas. On the other hand, although the river sampling point in Panggong village was 100 m from the gold processing centre, the rivers and even the community wells were still safe and have not shown significant levels of pollution

(below the threshold set by the Ministry of Health of the Republic of Indonesia).

However, if the former gold processing in Panggong village was more intensive and massive than it is now, mercury pollution might have reached the residents' rivers and

wells. Thus, it can be said that the distance from the traditional gold mining processing location determines the level of mercury concentration, where the closer the distance and the mining processing location, the higher the concentration when compared to locations far from traditional gold mining processing sites (Langeland et al., 2017).

According to Tomiyasu et al. (2017), the slope of the soil affects the deposition of mercury levels in the water. A large enough slope will result in turbulent water flow while a small flow will cause the river flow to become laminar. The type of flow will affect the mercury deposition process in the water. The flow of water tends to be flat, and the low speed of river flow will result in mud and sediment. One that affects the quality of well water is the distance to the pollutant source. According to Li et al. (2017); Olagunju et al. (2017); Yahaya et al. (2022), the permissible distance from the source of chemical pollution to well water is 200 meters. In Ranto Panyang Village, two well water samples were taken, and, in both samples, the mercury concentration was above the threshold. Therefore, the residents' well water is still not safe to use for their daily needs.

According to Widyaningrum and Sinaga (2018), dug well walls that meet sanitary requirements are well walls made of waterproof material. The aim is to protect against pathogenic and non-pathogenic bacteria in the soil so that water quality can be maintained and not polluted. In the Regulation of the Minister of the Environment Number 23 of 2008 concerning Technical Guidelines for the Prevention of Pollution or Environmental Damage affected by Artisanal Gold Mining, it is stated that mining activities must limit the rate of land clearing. However traditional gold mining processing has been already in residential areas and even in the yards of residents' houses. This then causes contamination of groundwater which is a source of water used by the community. As shown in Figure 1, the technique of interpolating the distribution of mercury in water is carried out using Inverse Distance Weight (IDW).

This interpolation technique assumes that each plot has a local effect, and the value of the plot will decrease with distance. The distance referred to here is the distance (flat) from the data point (sample) to the block to be estimated. The IDW method directly implements the assumption that things that are close together will be more similar than those that are far apart. To estimate a value

at each measured location, IDW will use the size values surrounding the location to be estimated. In the IDW method, it is assumed that the degree of correlation and similarity between the estimated point and the estimator data is proportional to the distance. The weights will change linearly as a function of distance according to their distance to the estimator data (Lepot et al., 2017).

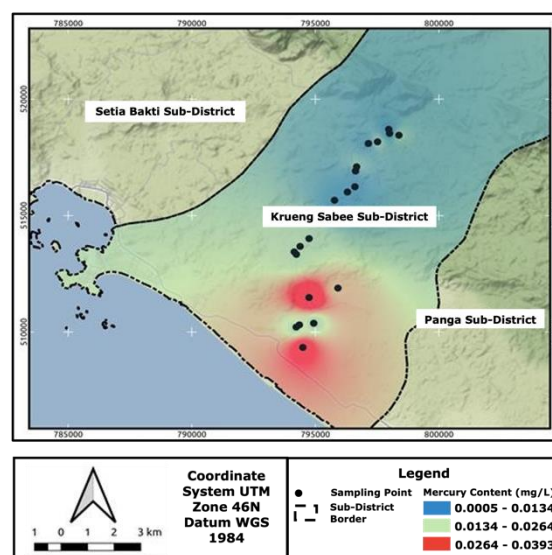


Figure 1. Map of mercury distribution in water using Inverse Distance Weighted (IDW)

The results of mapping the values show that important factors that can affect the results of the assessment include actor power and the surrounding radius (neighbouring radius) or the amount of estimator data (Almodaresi et al., 2019). The main actor that affects the accuracy of the assessment results is the value of the power parameter. The power parameter value used in the water data interpolation based on Table 1 was 2.6 with a Root Mean Square Error (RMSE) value of 0.011356153.

3.2. Mercury Content in Soil Samples (Result of Atomic Absorption Spectroscopy Analysis)

Based on the results of the examination of 10 soil samples taken from four different locations, namely around the gold processing plant, gardens, rice fields and land in the yards of residents' homes, each sample has been analyzed to determine the mercury content in the soil. The analysis in the laboratory using AAS showed that there was no soil sample with mercury concentrations above the critical threshold as shown in Table 2.

Table 2. The Result of the analysis for 10 soil samples using atomic absorption spectroscopy

No	Sample Code	Latitude and Longitude	Location	Mercury Content (mg/L)	Remark
1	PA-01	4° 41' 07.15" N 95° 41' 21.74" E	Currently operating gold processing site at Panggong Village	0.0959	Unpolluted
2	PA-02	4° 41' 10.13" N 95° 41' 07.37" E	Former gold processing site at Panggong Village	0.0147	Unpolluted
3	PA-03	4° 40' 58.07" N 95° 40' 53.96" E	Resident's home at Panggong Village	0.0118	Unpolluted
4	PS-01	4° 37' 20.16" N 95° 39' 23.19" E	Gold processing site at Paya Seumantok Village	0.0430	Unpolluted
5	PS-02	4° 37' 09.57" N 95° 39' 40.76" E	Rice fields of residents near the processing site	0.0464	Unpolluted
6	PS-03	4° 37' 05.11" N 95° 39' 47.03" E	Former gold processing site at palm oil plantation	0.0085	Unpolluted
7	PS-04	4° 36' 50.73" N 95° 39' 12.64" E	Gold processing at Paya Seumantok Village	0.0613	Unpolluted
8	RP-01	4° 38' 43.26" N 95° 39' 23.48" E	Resident's home at Ranto Panyang Village	0.0074	Unpolluted
9	RP-02	4° 38' 24.51" N 95° 39' 03.74" E	Resident's home near the river at Ranto Panyang Village	0.0544	Unpolluted
10	RP-03	4° 38' 21.39" N 95° 39' 07.09" E	Gold processing site at Ranto Panyang Village	0.0023	Unpolluted

Table 3. The result of the analysis for 6 soil samples using x-ray fluorescence

No	Sample Code	Latitude and Longitude	Location	Mercury Content (mg/L)	Remark
1	PA-01	4° 41' 07.15" N 95° 41' 21.74" E	Currently operating gold processing site at Panggong Village	149.0000	Polluted
2	PA-02	4° 41' 10.13" N 95° 41' 07.37" E	Former gold processing site at Panggong Village	127.0000	Polluted
3	PS-01	4° 37' 20.16" N 95° 39' 23.19" E	Currently operating gold processing site at the Paya Semantok Village	99.0000	Polluted
4	PS-03	4° 37' 05.11" N 95° 39' 47.03" E	Former gold processing site at palm oil plantation	79.0000	Polluted
5	PS-04	4° 36' 50.73" N 95° 39' 12.64" E	Currently operating gold processing site at the Paya Semantok Village.	129.0000	Polluted
6	RP-03	4° 38' 21.39" N 95° 39' 07.09" E	Currently operating gold processing site at Ranto Panyang Village.	66.0000	Polluted

This is because of the low retention or binding capacity of the soil to mercury affected by the low clay content in the soil (O'Connor et al., 2019). Similarly, Xiao et al. (2019) also stated that clay fraction is an important soil property in absorbing heavy metal ions. In addition to clay content, according to Zhang et al. (2020), the absorption of heavy metal mercury is also influenced by several factors, namely soil pH,

soil organic contents, and redox potential. Changes in condition such as a decrease in pH, an increase in the concentration of organic acids, or a decrease in the redox potential drastically reduce the strength of heavy metal bonds and increase their mobility (Jacob et al., 2018).

The mapping carried out based on the results

obtained in Table 2 produces Figure 2. From Figure 2, the IDW method used gave values close to the minimum and maximum values of the data sample. The power parameter value used in the soil data interpolation was 0.2 with a Root Mean Square Error (RMSE) value of 0.024250875.

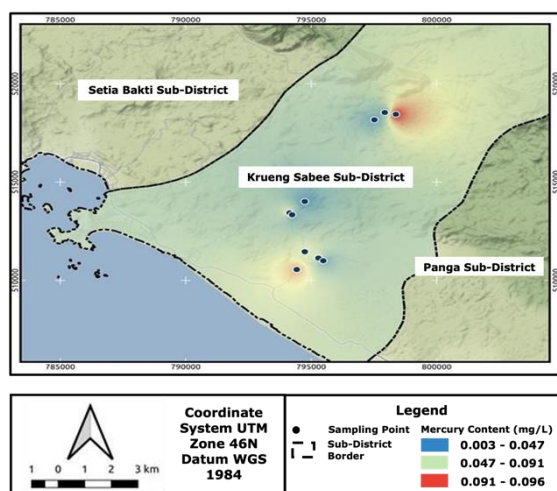


Figure 2. Map of mercury distribution in soil using Inverse Distance Weighted (IDW interpolation)

3.3. Mercury Content Analysis in Soil Samples (Result of X-ray Fluorescence Analysis)

According to Table 3, The XRF test results on soil samples showed that the highest mercury content was found at the PA-01 sample point, which was 149 ppm. According to Nasir et al. (2021), the normal range of heavy metal mercury (Hg) in the soil is between 0.01 and 0.3 ppm and the critical concentration is in the range of 0.3-0.5 ppm. The high mercury content at this observation point was due to of the soil taken at the location of amalgamation of gold processing. As shown in Table 3, the Hg content of the PS-03 in which the sample was taken at the oil palm plantation area was 79 ppm.

The mercury content of Hg in oil palm plantations was relatively high because the location is a former location for gold processing. If there is no serious attention, the plant will absorb more mercury in the soil and will endanger human health. Thus, the land taken at the processing site and the former processing sites contains much higher mercury which in turn has an impact on the surrounding land. The high mercury content in the soil is because it is close to the amalgamation of gold processing, so the soil may have been contaminated with waste in the holding pond.

The results of laboratory analysis showed that the mercury content in the soil at the processing location, namely the PA-01 sample showed a very critical value of 149 ppm, the PA-02 sample was 127 ppm, the PS-01 sample was 99 ppm, the PS-01 sample was 129 ppm, and the sample RP-03 was 66 ppm. The high content of mercury in the processing area was because of the mercury used during processing which is directly disposed of in the area around the processing.

According to Azizsoltani et al. (2019), soil dominated by sand will have a lot of macropores (large), soil dominated by dust (silt) will have a lot of mesopores (medium), and clay dominated will have a lot of micropores (small). Silt is a grain of soil that is between the size of sand and clay. The dominance of the dust fraction in the soil will cause the formation of mesopores (medium) so that the coverage is quite wide and produces a strong enough absorption capacity for water. This causes water and air to enter and leave the soil quite easily, and some of the water will be retained.

The silt-type soil has moderate permeability (soil ability to pass water), which has an absorption capacity of 2.0-6.5 cm/hour (Pranoto et al., 2022). That is, in 1 hour the depth of water absorption in the soil is 2.0-6.5 cm. This is one of the causes of the high concentration of mercury in the soil because the soil in the study area is of a silt type so the absorption of water from gold processing waste is high.

4. Conclusion

The result of this study indicates that the distance from the traditional gold mining processing location determines the concentration level (Hg), where the closer the distance and the mining processing location, the higher the concentration. According to the laboratory tests, 13 of 20 water samples had mercury concentrations above the critical threshold, that are not suitable for disposal in the environment according to USFDA and cannot be consumed by the public the Ministry of Health of the Republic of Indonesia. Examination of 10 soil samples using Atomic Absorption Spectroscopy (AAS) showed that none of the soil samples had mercury concentrations above the critical threshold. In this case, the low retention or binding capacity of the soil to mercury and the low clay content in the soil were the two causes found. Meanwhile, examination of 6 soil samples using XRF (X-Ray Fluorescence) analysis showed that the mercury content in all

samples had exceeded the critical threshold. The high content of mercury in the processing area is because the mercury was used during processing and was directly disposed around the processing area. It is recommended that further study can be conducted with a larger number of samples to improve the map of mercury distribution. Additionally, it is also recommended that the mercury waste disposal or drainage be constructed of solid concrete and not by trenches. The location of mercury waste disposal must also be in a watertight area such as clay.

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