Review of mercury pollution in Suriname

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Abstract
Since the 1980’th small-scale gold mining is on the increase in Suriname. Most mining occurs in the eastern part of the country. In the small-scale gold mining the gold is usually amalgamated to mercury. An estimated 1 kg of mercury enters the environment for every kg of gold extracted, which means at least 10,000 kg of mercury released annually in the atmosphere and the aquatic environment of Suriname. In the aquatic environment bacteria may transform mercury into the extremely poisonous methyl mercury, which bio-accumulates in the food chain. As a result predatory fish will usually have high levels of methyl mercury in their tissues. Mercury poisoning causes many defects in animals and neurological health problems in humans. This review gives an overview of mercury pollution results for the aquatic environment, in the atmosphere and in humans in communities in the interior. Mercury pollution is not limited to the gold mining areas, because mercury is transported by water and wind to downstream and downwind areas. As a result predatory fish in most of central and western Suriname show high mercury levels as well. A possible explanation for the mechanism of polluting of undisturbed areas is given. Many communities in the interior show increased levels of mercury. Of four villages tested along the Saramacca River, the most upstream community, also upstream of any gold mining, showed the highest mercury levels. Villages with easy access to the capital, show lower mercury pollution because people are less dependent on local fish as a protein source. Mercury pollution also occurs in Paramaribo in the vicinity of gold shops. An overview of the gaps in our knowledge of mercury pollution in Suriname is presented.

Keywords: Mercury, gold mining, Suriname

A history of gold mining in Suriname
A first gold rush occurred in Suriname between 1870 and 1910 (De Vletter & Hakstege 1998). This gold rush was of a limited extend and the gold production remained small (highest annual production 1,200 kg; Bosma et al. 1973). However, for those times the production was important enough to build the only railroad in the country, connecting the capital Paramaribo to the mining areas in the south. The mining methods used were mostly mechanical, although small-scale mining increased to the end of this period (De Vletter & Hakstege 1998). The extent of the use of mercury in those times is unknown. A second gold rush started in the 1980’th and continues till the present. It started with the finding of a large gold deposit at Serra Pelada in Brazil in 1980. From there the gold rush spread to all neighboring countries (Veiga 1997).

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In Suriname the start of the gold rush coincided with a deteriorating economic situation after the military coup in 1980. In 1986 a civil war started and continued till 1992. This war was mostly fought in the east of Suriname, but the unrest occasionally spread to the west following the road to Apoera. It caused the government to lose complete control over the interior, favoring the development of illegal gold mining.

The gold mining concentrates on the geological area where gold is most likely to be found, the Greenstone Belt. The greenstone is comprised of metamorphic rocks (De Vletter et al., 1988). This belt continues from the extreme southeastern point of Suriname to the northeast and north central part of Suriname (dark green area in fig. 2).

In land-based operations the creek bottom and shore sediments are made into a sludge using high-pressure water power. This sludge is pumped into a sluice box, where the gold is amalgamated to mercury and recovered between mats with spines. Usually the sludge is drained to the creek without the use of a tailing pond to have the sediment settle. River-based operations use a suction dredge to get to the gold-containing bottom sediment. Also here a sluice box with mercury is used to recover the gold.

The Geological and Mining Survey of Suriname (GMD) estimated in 2000 that 25,000-35,000 gold miners were active in the interior, producing 10,000-20,000 kg of gold annually (resp. Mol et al. 2001; Veiga 1997). Since 2000 the number of gold miners and the annual production of gold will only have increased. Veiga (1997) estimated that for every kilogram of gold, a kilogram of mercury is used. This means a minimum of 10,000 kilograms of mercury lost in the environment every year. From this amount an estimated 45% is lost in the water and 55% goes to the atmosphere (Pfeiffer & Lacerda 1988).

Since the 1990'th international gold mining companies started to show interest in Suriname. In 2004 the first large-scale gold mining operation started mining in the Gros-Rosebel area. This company changed ownership several times and is now part of the IamGold operations, a Canadian company. At the end of 2012 an agreement between the Suriname government and the US based Newmont was reached for a second large-scale gold operation at Merian Creek in the east of Suriname. Since the exploration and environmental impact phase have already been accomplished, it is likely that mining will start soon. The government of Suriname also announced the creation of a state-owned gold mine in the near future. Large-scale gold mining companies usually do not use mercury for amalgamation, but work with cyanide.

**Mercury in the environment**

Mercury has a complex cycle in the environment (fig. 1). Most environmental problems caused by mercury (as far as we know), occur in the aquatic environment.

The mercury in streams and lakes may have entered directly through the addition of mercury by gold miners. However, indirect and other sources are responsible for high mercury levels as well. During the mining process the soil is disturbed causing the additional release of mercury that is a small, natural component of the soil (Roulet et al., 1998). Mercury in the atmosphere may be deposited on the earth’s surface again by wet or dry depositing (Morel et al., 1998). Also the deposited mercury will finally, directly or indirectly, end up in the aquatic environment.

Mercury may occur in the environment in several forms (fig. 1). In the aquatic environment it occurs mostly as metallic mercury or Hg$^0$ (Jackson, 1998). Part of it may be bound to sediment particles, especially to the clayish fraction. Bacteria may transform anorganic mercury to organic mercury or methyl mercury (Morel et al. 1998). Especially at the anoxic bottom sediment-water interface methylation takes place (Jackson, 1998). Methyl mercury is the most poisonous form of mercury, and the form that bio-accumulates in the food chain (Morel et al., 1998). Aquatic predators in particular are prone to high mercury levels in their tissues. Mercury usually has a neuro-toxicological effect. In fish of temperate regions it is known to cause adverse impacts on behavior, gonadal development, production of sex hormones and reproduction (Scheuhammer et al. 2007).
Methyl mercury is extremely toxic for birds and mammals: behavioral, neurochemical, hormonal and reproductive changes have been shown (Scheuhammer et al. 2007).

Figure 1. Mercury cycling and transport via atmosphere and water.

Research on mercury pollution in Suriname
The increasing extent of the small-scale gold mining operations and the uncontrolled use of mercury have caused concern in the Surinamese society for many years. To investigate the possible pollution of air, water, soil, biota and the human population, several research projects have been executed.

Mercury in the aquatic environment
Pollack et al. (1998) reported some initial figures on mercury levels in water, sediment, fish and the human population, which indicated elevated levels in most compartments of the environment.

As far as the government of Suriname was interested in zoning the economic activities in the country, they usually did not take into account activities that can have a detrimental effect on each other. The right shore of the Lower Commewijne River was reserved for aquaculture, but despite this, gold mining concessions were issued at the Upper Commewijne River. Quik and Ouboter started a survey of mercury pollution of water, bottom sediment and fish of the Commewijne River in 1998. The results show elevated mercury levels in water and sediment, usually not surpassing international norms, but high levels in two species of predatory fish, well above the WHO norm of 0.5 µg/g muscle tissue (Quik & Ouboter, 2000). This project was finalized by a workshop on mercury pollution due to the small-scale gold mining. During this workshop the main criticism from government officials and gold miners on the conclusions of this research project, was that researchers blame high mercury levels on gold miners without knowing anything about mercury levels occurring in the environment naturally. This initiated a research project on background levels of mercury and the effect of atmospheric transportation of mercury in Western Suriname. Ouboter et al. (2003) reported elevated levels of mercury in many sites in Western Suriname and high levels in bottom sediments and fish tissue in the Lucie River (see fig. 2 and 3). Generally elevated levels of mercury were explained by atmospheric transportation of mercury by the Northeastern Trade Wind, while the much higher levels in the Lucie River were explained by possible high background levels in two geological formations that form the drainage area of this river (Curuni and Falawatra Formations).
This led to an MSc project looking at mercury levels in water, bottom sediment and fish tissue in the Falawatra Formation, and also upstream and downstream of this formation. High mercury levels were found in all three areas, indicating that the geological formation concerned was not the source of high mercury levels (Landburg, 2005).

In the mean time Mol et al. (2001), separately from Ouboter and co-workers, started a survey on mercury in fish in gold mining areas, west of gold mining areas and in the sea. Their findings were in agreement with former data: elevated to high mercury levels in gold mining areas, but also west of gold mining areas. The highest levels were recorded for the Brokopondo Reservoir. Also in marine predatory fish elevated levels of mercury were found (Mol et al., 2001).

Mol et al. (2001) looked at a limited number of localities. A very extensive survey on mercury pollution was carried out between 2003 and 2005 (Ouboter et al., 2007; Ouboter, 2007). The project included 23 localities in gold mining areas, 3 localities upstream of gold mining activities and 8 localities downstream (included in figs. 2 and 3). Water, bottom sediment and fish tissue were sampled following strict protocols and were analyzed on total mercury. For the first time the mercury analyses could be performed with a dedicated mercury analyzer in Suriname, in the NZCS/CMO laboratory. The results of this project emphasize earlier findings: elevated to high mercury levels in bottom sediments and tissues of predatory fish in most gold mining localities, as well as upstream. The highest levels were recorded for the Brokopondo Reservoir. Mercury levels in the downstream sections of the rivers were generally lower, although high mercury levels were found in the bottom sediments of Galibi (mouth Marowijne River).

Figure 2.

a. Average mercury levels found in sediments in different river systems in Suriname; Color codes: orange: Gold mining area (GMA); yellow: Upstream gold mining area (UGMA), brown: Downstream gold mining area (DGMA), blue: areas on the weather side of central west mountain range (PWS); black: areas on the lee side of central west mountain range, not draining the mountain range (PLS); green: West/South-west Suriname (WSW); pink: North West Suriname (NW).

b. Boxplot showing the distribution of mercury levels in sediment, measured in different areas. Codes for areas: 1= GMA; 2=DGMA; 3= UGMA; 4= Brokopondo Reservoir (BR); 5=WSW; 6=NW; 7=PLS; 8=PWS.

1 (Adapted from Ouboter et al., 2012, in Ambio 41(8). © Royal Swedish Academy of Sciences 2012)
This resulted in an extensive overview of mercury pollution in aquatic ecosystems in Suriname (Ouboter et al., 2012). The publication summarizes the results found so far (fig. 2 and 3; tab. 1), and explains the high mercury levels found in Western and Central Suriname by the following:

1. Atmospheric transportation of mercury from the gold mining areas to the southwest by the northeastern trade winds;

2. Wet deposition of atmospheric mercury, with the highest amounts polluting streams draining mountain ranges with high precipitation;

3. Mercury in pristine streams is freely available for methylation and bioaccumulation. In comparison, mercury in mining areas is to a large extent bound to fine sediment particles and therefore not freely available for bioaccumulation.
Table 1.

<table>
<thead>
<tr>
<th>Area</th>
<th>Number of localities</th>
<th>Water</th>
<th>Bottom sediment</th>
<th>Serrasalmus rhombeus</th>
<th>Hoplias aimara</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average Hg (µg/L)</td>
<td>Average Hg (µg/g)</td>
<td>Average size (cm)</td>
<td>Average Hg (µg/g)</td>
</tr>
<tr>
<td>Gold mining (GMA)</td>
<td>9</td>
<td>0.07±0.09</td>
<td>69 0.22±0.09</td>
<td>30 25.6 0.42±0.20</td>
<td>58 52.8 0.46±0.23</td>
</tr>
<tr>
<td>Brokopondo Reservoir (BR)</td>
<td>6</td>
<td>0.38±0.37</td>
<td>17 0.21±0.06</td>
<td>36 29.2 1.38±0.59</td>
<td>16 49.7 0.43±0.29</td>
</tr>
<tr>
<td>Downstream gold mining (DGMA)</td>
<td>9</td>
<td>0.06±0.06</td>
<td>50 0.13±0.08</td>
<td>9 24.2 0.23±0.13</td>
<td></td>
</tr>
<tr>
<td>Upstream gold mining (UGMA)</td>
<td>4</td>
<td>0.11±0.09</td>
<td>18 0.20±0.05</td>
<td>30 15.4 0.25±0.21</td>
<td>35 47.5 0.43±0.24</td>
</tr>
<tr>
<td>Upper Coppename Basin (PWS)</td>
<td>5</td>
<td>0.10±0.07</td>
<td>8 0.20±0.06</td>
<td>25 33.8 0.86±0.42</td>
<td>13 53.3 0.66±0.29</td>
</tr>
<tr>
<td>Western Suriname (WSW)</td>
<td>11</td>
<td>0.10±0.15</td>
<td>6 0.14±0.05</td>
<td>20 30.2 0.75±0.44</td>
<td>24 50.7 0.65±0.17</td>
</tr>
<tr>
<td>Northwestern Suriname (NW)</td>
<td>6</td>
<td>0.38±0.50</td>
<td>12 0.07±0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Predicted low level (PLS)</td>
<td>3</td>
<td>0.04±0.02</td>
<td>42 0.21±0.05</td>
<td>30 31.4 0.51±0.19</td>
<td>4 70.0 0.74±0.25</td>
</tr>
<tr>
<td>International standards</td>
<td></td>
<td>0.2</td>
<td>0.012 0.17</td>
<td>0.50 0.50 0.50</td>
<td></td>
</tr>
</tbody>
</table>

Another question touched in this publication is if the mercury is of an anthropogenic or natural origin. Soil cores from floodplain sediments (Kabalebo and Saramacca Rivers) were analyzed and showed that mercury levels decreased with depth, suggesting an anthropogenic source (Ouboter *et al.*, 2012; also Fig. 4).
Between October 2012 and March 2013 an MSc project was carried out at NZCS/CMO by S. Scholte to obtain more data on mercury in floodplain sediments, focusing on the Nickerie and Coppename Rivers draining undisturbed areas and the Saramacca River draining gold mining areas. The results confirm the result found earlier for other floodplains: the soil layers at the surface had higher mercury levels than deeper layers, indicating an anthropogenic source for the mercury pollution (fig. 4, numbered localities). Very strange are the much higher mercury levels in Coppename River floodplain soils, because this cannot be explained by the theory explaining high mercury levels in fish in pristine areas.

**Mercury in the human population**

Pollack *et al.* (1998) also measured workers in the gold mining and community members from communities in the vicinity of gold mining areas. Both groups showed elevated levels of mercury contamination. In 2005/2006 Peplow & Augustine (2007) re-measured the population of Kwakoeegrorn and confirmed slightly elevated levels of mercury in this population. Also de Kom *et al.* (1998) showed that small-scale gold miners had elevated levels of mercury in their urine.

A much more alarming publication came from Cordier *et al.* (1998), who reported that in some Wayana villages along the Lawa River up to 79% of the children had hair mercury levels above the NOAEL level of 10µg/g. These results were confirmed again in 2001 by Fréry *et al.* for other Wayana villages in the same area.

During the 2003-2005 surveys of Ouboter & co-workers a study on mercury pollution of local communities along the Saramacca River was included, looking at the gold mining village Njoeng Jacobkondre and the upstream village of Poesoegroenoe. In both villages several households were followed regarding their daily diet and hairs were sampled for mercury analysis. Despite several flaws in the methods used, the results showed that elevated levels of mercury occurred in both populations, and that levels were even slightly higher in the upstream village Poesoegroenoe (Ouboter *et al.*; 2007) (fig.5)
In 2010 and 2011 a dietary and mercury survey was carried out to compare the Maroon village of Kwakoebron with the Amerindian village of Pikin Saron, both downstream of the gold mining area of the Saramacca River. Also environmental measurements were performed. This project was carried out in cooperation with Tulane University. In both villages most people ate fish regularly, and these fish were often predatory species. Of the fish caught in the area 75% was above the WHO norm for human consumption. All hair samples analyzed were at or above the EPA reference dose for hair mercury concentration of 1.0 µg/g, but below the NOAEL value of 10 µg/g (e.g. Hawkins et al., 2011, 2014)(fig. 5).

On request of a foundation from the village of Brownsweg, a mercury, dietary and neuro-psychological survey was carried out here (Ouboter & Landburg, 2010). Most people (approx. 95%) seemed to get their proteins mostly from other sources then fish from the Brokopondo Reservoir (chicken, fish brought in from Paramaribo). Of 172 particpants, only 2 persons were above the NOAEL level of 10 µg/g (fig. 5). During the same project additional fish surveys were carried out in the lake, including all fish species caught. This provided a clear picture of the impact of the trophic level of the fish on mercury contamination (fig. 6).
Figure 6. Mercury levels in fish and shrimps of the Brokopondo Reservoir, organized in trophic groups.

Mohan et al. (2005) reported elevated levels of mercury in hair of mothers and their newborn children in 's Lands Hospital, Paramaribo. Eighty percent of the children had higher mercury levels than their mothers. Mothers from the suburbs of Paramaribo showed higher hair mercury levels than women living near the gold mining areas.

Mercury levels in the atmosphere
Only few observations are available on mercury levels in the atmosphere itself. A team of the University of Bremen, together with D. Wip of the Anton de Kom University of Suriname carried out measurements in Nieuw Nickerie in 2007, comparing both oceanic and continental air (Müller et al., 2012). Air coming from the northern ocean showed a slightly higher mercury concentration than from the southern hemisphere.

From the southern hemisphere continental air was slightly higher in mercury level than oceanic air. Müller et al. (2012) mainly attribute this difference to biomass burning, and do not seem to consider small-scale gold mining as a source.

Wip also did measurements on atmospheric mercury levels in and near gold shops in Paramaribo and found medium to high levels in many areas. These observations were published in a comparison with similar measurements in other South American countries (Cordy et al., 2013) and the world (Wip et al., 2013). Mercury levels were comparable with other world cities, but occurring spikes were much higher and longer in duration, although not posing any health risks. However measurements inside and nearby gold shops exceeded international minimal risk levels (Wip et al., 2013)
Overview of research results

- Mercury levels are elevated almost everywhere in Suriname, except for the Northwest:
- Most water samples had a mercury level above global background levels of 0.006 µg L\(^{-1}\).
- (Ayres & Hellier, 1998), the US EPA standard for freshwater chronic exposure of 0.012 µg L\(^{-1}\) (US EPA, 1994) and the US EPA wildlife criterion of 0.00091 µg/L (US EPA, 1997). The highest level measured (1.11 µg L\(^{-1}\) at the southern (upstream) side of Brokopondo Reservoir) is still below the EPA drinking water standard of 2 µg L\(^{-1}\) (US EPA, 1994).
- Most sediment samples have a mercury level well above global background levels of 0.01-0.05 µg g\(^{-1}\) (Anderson, 1979). Only few samples, mostly from northwestern Suriname were within global background levels. Sediments in the gold mining area are usually near or above the Canadian Interim Sediment Quality Guideline for Protection of Aquatic Life (Canadian Council of Ministers of the Environment, 1999) of 0.17 µg g\(^{-1}\) soil. The estuary of the Marowijne River (eastern border river) shows relatively high levels at its mouth (max. of 0.41 µg g\(^{-1}\)). Surprisingly, mercury levels of sediments in sites upstream of gold mining are all near or above the Canadian standard during the rainy season. Moreover in pristine areas of central, western and southern Suriname, levels often exceed this standard (average 0.20 µg g\(^{-1}\), max. 0.28 µg g\(^{-1}\)). This is especially the case in the Upper Coppename Basin. Levels in the most southwestern localities are high as well.
- Of the piscivores 41% had a mercury level above the European Union standard for human consumption of 0.5 µg g\(^{-1}\) (EC, 2002) and 15% above the US EPA standard for human consumption of 1 µg g\(^{-1}\) (US EPA, 1992).

In the gold mining areas levels are often above the European Union standard. Extreme high levels were measured in Brokopondo Reservoir where piranhas were sometimes six to seven times the norm for human consumption (on average two to three times). Downstream of the gold mining area, levels were usually much lower. Upstream of gold mining area, mercury values in piscivorous fish were generally below the norm, but in central and western Suriname levels were far above the norm.
- High mercury levels in undisturbed areas to the southwest of the gold mining areas are explained by the atmospheric transportation of mercury by the northeastern Trade Winds, wet depositing of mercury, especially in areas of high precipitation and the high bio-availability of mercury in unpolluted streams.
- The analysis of sediment samples from floodplains showed an increase of mercury levels nearer to the surface. This indicates an anthropogenic source of the mercury. The highest levels were found in Coppename River floodplain soils. Research is continuing.
- In local communities that are easily accessible by road, protein intake is more varied and includes, apart from local fish, chicken and fish imported from Paramaribo. Hair mercury levels in these communities are generally above the EPA reference dose for hair mercury concentration of 1.0 µg/g, but below the NOAEL of 10 µg/g. More alarming data and rumors come from Amerindian villages in the south. However, these data need confirmation. Research is continuing.
- Wip and co-workers showed that atmospheric mercury levels near gold shops in Paramaribo were very high and above international health norms inside or in close vicinity of the shops.
Gaps in our knowledge on mercury pollution

- What exactly happens with mercury in a stream and a lake? What determines bio-availability? What determines methylation rate?
- Is there a difference in sensitivity for mercury (accumulation) between different ethnic groups?
- What is the mercury pollution situation of various isolated communities in the interior in high-risk areas?
- We know that Western Suriname is polluted by mercury through atmospheric transportation and depositing. What effect has this downstream?
- How can the high mercury levels in floodplain soils of the lower Coppename River be explained?
- What is the impact of sediment from the Amazon River on mercury pollution in the estuarine zone of Suriname?
- What are the exact mercury sources in Suriname? We expect that a large part of the atmospheric mercury is coming from the gold mining. What is the contribution of global mercury pollution, of mercury evasion from water surfaces, especially the Brokopondo Reservoir, and of the industry in Suriname?
- Is it possible to model the risk of mercury pollution for local communities based on (recent) satellite images of turbidity of rivers?
- What is the impact of mercury pollution on (semi)aquatic wildlife populations?

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References


