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Is mercury from small-scale gold mining prevalent in the southeastern Peruvian Amazon?☆

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ABSTRACT

There is an ongoing debate on the fate of mercury (Hg) in areas affected by artisanal and small-scale gold mining (ASGM). Over the last 30 years, ASGM has released 69 tons of Hg into the southeastern Peruvian Amazon. To investigate the role of suspended matter and hydrological factors on the fate of ASGM-Hg, we analysed riverbank sediments and suspended matter along the partially ASGM-affected Malinowski-Tambopata river system and examined Hg accumulation in fish. In addition, local impacts of atmospheric Hg emissions on aquatic systems were assessed by analysing a sediment core from an oxbow lake. Hg concentrations in riverbank sediments are lower (20–53 ng g^{-1}) than in suspended matter (~400 –4000 ng g^{-1}) due to differences in particle size. Elevated Hg concentrations in suspended matter from ASGM-affected river sections (~1400 *vs.* ~30–120 ng L^{-1} in unaffected sections) are mainly driven by the increased amount of suspended matter rather than increased Hg concentrations in the suspended matter. The oxbow lake sediment record shows low Hg concentrations (64–86 ng g^{-1}) without evidence of any ASGM-related increase in atmospheric Hg input. Hg flux variations are mostly an effect of variations in sediment accumulation rates. Moreover, only 5% of the analysed fish (only piscivores) exceed WHO recommendations for human consumption (500 ng g^{-1}). Our findings show that ASGM-affected river sections in the Malinowski-Tambopata system do not exhibit increased Hg accumulation, indicating that the released Hg is either retained at the spill site or transported to areas farther away from the ASGM areas. We suspect that the fate of ASGM-Hg in such tropical rivers is mainly linked to transport associated with the suspended matter, especially during high water situations. We assume that our findings are typical for ASGM-affected areas in tropical regions and could explain why aquatic systems in such ASGM regions often show comparatively modest enrichment in Hg levels.

1. Introduction

Artisanal and small-scale gold mining (ASGM) occurs in over 70 countries (Telmer and Veiga, 2009) and is the largest anthropogenic source of mercury (Hg) in the environment (UNEP, 2013). In the Brazilian Amazon alone, 2000–3000 tons of Hg has been released into the environment since the 1970s (Malm, 1998; Pfeiffer et al., 1993). In the Peruvian Amazon, the Madre de Dios (MDD) region accounted for ~70% of the national ASGM-gold production in 1990 (Kuramoto, 2002), and since then the land area used for ASGM activities has increased by 400% (Asner et al., 2013). Based on data from the Peruvian National Institute of Statistics and Informatics, it is estimated that ASGM in the MDD region used 273 tons of Hg during the period 1990–2003 (based on a Hg-to-gold ratio of 2:1) and that over 40 tons of Hg was used in 2006 alone (based on a Hg-to-gold ratio of 2.8:1; Brack et al. (2011)). These estimates, together with reports of high Hg levels in commercial fish species and environmental and human samples from ASGM regions (Ashe, 2012; Barbieri, 2004; Brack et al., 2011; CAMEP, 2013; Deza

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Arroyo, 1996; Diringer et al., 2015; Fernandez and Gonzalez, 2009; Gammons et al., 2006; Wade, 2013), have raised serious concerns among the local population and MDD authorities in terms of the potential ecological and public health issues related to the use of Hg in ASGM activities.

ASGM miners often use metallic Hg (Hg^0) for extracting gold particles by amalgamation. However, due to the lack of efficient recovery techniques, Hg is released into the environment both during the amalgam process (to soils, tailing, and water systems) and amalgam roasting (to the atmosphere). It is, however, uncertain to what extent Hg is actually being lost to the environment during these processes. Estimated emission factors per kilo of extracted gold vary from 0.1 to 10 depending on the type of ore and the extraction process (Pfeiffer et al., 1993). The fate of the released Hg is also uncertain, *e.g.*, Pfeiffer and de Lacerda (1988) estimated that 45% of the losses go to the hydrosphere and 55% go to the atmosphere, while Pfeiffer et al. (1993) reported that 65–83% of the total Hg losses go to the atmosphere.

Considering the large amount of Hg that is estimated to have been released by ASGM activities in the MDD region, both to the hydrosphere and the atmosphere, it should be possible to track the released Hg in soils and sediments. However, no apparent signs of elevated Hg levels have been found either locally in the MDD region (Diringer et al., 2015) or in the southeastern Andes (Beal et al., 2013). The scenario of ASGM-Hg release in the MDD region is similar to the one from preindustrial silver/gold mining in Spanish Colonial America; even though it has been estimated that 100,000–140,000 tons of Hg was released into the environment from 1570 to 1900 (Nriagu, 1994, 1993; Streets et al., 2011), there is little evidence of this massive amount of Hg in geoarchives from both hemispheres (Beal et al., 2014, 2013; Biester et al., 2003; Cooke et al., 2011, 2009; Engstrom et al., 2014; Hermanns and Biester, 2013; Conaway et al., 2012; Lamborg et al., 2002). This discrepancy is a manifestation of our lack of understanding regarding how much Hg is released by ASGM activities and what its fate is. In particular, the final sink of ASGM-Hg losses in aquatic environments is challenging to track not only because of the informal (sometimes illegal) character of the activity but also because Hg dispersion mechanisms, especially in the tropics, are still not well understood. Moreover, most of the theoretical estimates of Hg release have neglected the influence of hydrological and geochemical factors.

For the MDD region, Diringer et al. (2015) recently reported higher Hg concentrations in river sections downstream from ASGM activities compared to river sections upstream of ASGM activities. This result suggests that Hg concentrations can be directly linked to ASGM activities, and riverine communities located downstream from ASGM areas are exposed to an elevated risk through fish in their diet. Nevertheless, the Hg levels reported by Diringer et al. (2015), both in river sediments and suspended matter from upstream and downstream ASGM activities, are lower in comparison with findings in other ASGM-affected areas (Gammons et al., 2006; Lechler et al., 2000; Ouboter et al., 2012). It is also worth noting that ASGM is not the only possible source of Hg in the MDD region or in the rest of the Amazon; deforestation as well as forest burning and clearing – and important regional activity for different purposes including but not limited to ASGM – are responsible for perturbation and erosion of Hg-rich natural surface soils (Roulet et al., 2000; 2001).

The currently reported Hg concentrations in the aquatic systems of the MDD region do not agree with estimates based on regional ASGM-Hg losses. Thus, we chose to re-examine the area to characterize the local dispersion of Hg and elucidate the factors that control the distribution and transport of Hg in the system. We investigated riverbank sediments and suspended matter from the Malinowski-Tambopata river system, and compared ASGM-affected river sections with unaffected tributaries. In addition, we investigated atmospheric deposition of ASGM-related Hg on local lakes using down-core lake sediment profiles with the aim of ascertaining the effects of amalgam roasting and related atmospheric pollution on the local aquatic systems. Moreover, we investigated the Hg concentration in local fish species in both rivers and oxbow lakes of the Malinowski-Tambopata river system.

2. Materials and methods

2.1. Study area

The study focused on a 228 km stretch of the Malinowski-Tambopata river system, which forms the border between the Tambopata National Reserve (TNR) and its buffer zone (a managed forest used for agriculture, farming, ecotourism and forestry; Fig. 1). The studied river system flows into the heavily ASGM-affected MDD River. The three largest ASGM areas in the MDD region – Huepetuhe, Delta-1, and Guacamayo – are located on the Colorado and Inambari rivers, two major tributaries of the MDD River (Asner et al., 2013). Our studied river system is located south and east from those three ASGM areas. Annual precipitation ranges from 1600 to 2400 mm, with July being the driest (~30 mm) month and January being the wettest month (~260 mm). Annual average air temperature is 26 °C (10–38 °C), and the predominant wind direction is from northeast (Sernanp, 2011).

Both Malinowski and Tambopata rivers have a high load of suspended material (SI-Fig. 1). In Tambopata River, discharge is reported to be between 1132 and 2313 $m^3\ s^{-1}$ (MINAG, 2010). Annual average values for total suspended solids (TSS) in the Malinowski vary from 10 to 40 mg L^{-1} (Chang, 1998), but concentrations as high as 3342 mg L^{-1} have been recorded after a rain event (Barbieri, 2004). Such extreme values are likely a consequence of siltation caused by the intense bank erosion and sediment dredging related to ASGM activities along the Malinowski River. The Malinowski and Tambopata River lower section (*i.e.*, downstream the confluence with the Malinowski) have been affected by limited ASGM activities in the past, *i.e.*, prior to 1990 (Damonte et al., 2013). However; since ~2010, ASGM has drastically expanded with the easier accessibility after paving the Interoceanic Highway. Today, intense ASGM activities are confined to the Malinowski River, while in the Tambopata River lower section it is restricted to just downstream of the confluence with the Malinowski and close to Puerto Maldonado, capital city of the MDD region. Most of the regional gold shops, where amalgam roasting takes place, are located in Puerto Maldonado. Hereinafter, we define ASGM-affected based on if ASGM occurs along the river stretch, not based on upstream activities.

2.2. Sample collection

Field work was carried out between July and September (dry season) in 2012 and 2013. In 2012, sampling was also extended into the heavily ASGM-affected MDD River (Fig. 1). In 2013, the middle and upper sections of the Malinowski, as well as its tributaries, *i.e.*, Manuani, Azul, Malinowquillo, and Quebrada Yarinal, could not be accessed due to ongoing protests from ASGM miners that made the area unsecure at the time of the field campaign. Sampling within the TNR was approved by research permits SERNANP-JEG 036–2011 and 013–2013.

Riverbank sediments were collected from the top 10 cm on each side of the river using a plastic shovel in 18 locations (Fig. 1), and total suspended solids in river water were sampled in triplicate at eight locations by filtering known volumes of river water