Science of the Total Environment 647 (2019) 400–410

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

A comparison of factors affecting the small-scale distribution of mercury from artisanal small-scale gold mining in a Zimbabwean stream system

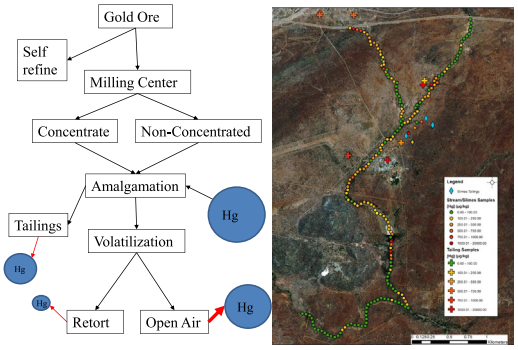
Corey S. Green [a,*], Patrick J. Lewis [b], Jeffery R. Wozniak [b], Paul E. Drevnick [c], Monte L. Thies [b]

[a] Raven Environmental Services, Inc., P.O. Box 6482, Huntsville, TX 77342, United States
[b] Sam Houston State University, 1900 Avenue I, Huntsville, TX 77340, United States
[c] Alberta Environment and Parks, 2938 11 Street NE, Calgary, AB T2E 7L7, Canada

HIGHLIGHTS

- Mercury concentrations fell within ranges of similar contamination studies.
- 60% of sample locations were above probable effect levels.
- Organic material had positive correlation with mercury concentrations.
- Distance downstream and from contamination source had negative correlation.
- Predictor variables provided adequate preliminary explanation of distribution.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 17 January 2018
Received in revised form 30 July 2018
Accepted 30 July 2018
Available online 31 July 2018

Editor: Xinbin Feng

Keywords:
Artisanal small-scale mining
Mercury
Zimbabwe

ABSTRACT

Artisanal small-scale gold mining (ASGM) operations use mercury liberally in the gold extraction process and account for approximately one quarter of the anthropogenic mercury consumption worldwide. ASGM activities are concentrated in many impoverished and poorly regulated countries such as Zimbabwe, resulting in a number of negative impacts to health and the environment. To examine levels of mercury contamination in one such geographic locality, sediment and tailing samples were collected in a heavily mined watershed in southern Zimbabwe from May–June 2015. Samples were collected from multiple points within the stream system, as well as from around six stamp mills and a single industrial mine in the watershed. GPS point location data were taken for mining operations and sampling sites to examine the spatial patterns of mercury concentration. Data were first analyzed using linear regression and development of a MARS model, followed by application of an ANCOVA model to assess the relationship among mercury concentrations and percent organic material, distance downstream, and distance from potential contamination source. Mercury concentrations within the study area ranged from 6 to 1541 μg/kg dw (mean 142 μg/kg dw). Analyses of mercury concentrations indicated a positive relationship with percent organic material but a negative relationship with distance downstream and distance from potential contamination source. Results from this study help elucidate the relationship between gold production and the spatial scale of mercury contamination in aquatic ecosystems in Africa. These data may lead to a better understanding of the relationship between mercury use and community health, which may aid both the local and global communities in regulating mercury contamination of the environment.

* Corresponding author.
E-mail address: csgreen@ravenenvironmental.com (C.S. Green).

https://doi.org/10.1016/j.scitotenv.2018.07.418
0048-9697/

1. Introduction

1.1. Mercury in mining

Although the use of mercury in large-scale mining operations has largely been eliminated, the practice has persisted in artisanal small-scale gold mining (ASGM), accounting for 37% of mercury emissions in 2010 and 24% of mercury demands in 2011 (UNEP, 2013). ASGM activities are largely concentrated in impoverished and poorly regulated countries such as Zimbabwe. Zimbabwe alone was conservatively estimated to have imported 21.8 tonnes of mercury in 2006, however, when an individual mercury dealer was interviewed in 2003 he claimed to have imported 20 tonnes of mercury himself leaving the exact amount of mercury used in Zimbabwe difficult to calculate (UNIDO, 2007). Mercury amalgamation has remained as the primary means of gold extraction for ASGM miners due to its ready availability, low cost, and the relative quickness of the gold extraction (Veiga et al., 2006). Depending on refinement technique, amalgamation process, and use of mercury recovery equipment such as retorts, as little as 50% of the mercury used in the amalgamation process is recovered (Cordy et al., 2011), with global estimates of 1–2 g of mercury lost for each gram of gold produced (Veiga and Baker, 2004; Spiegel and Veiga, 2005; Spiegel, 2009a; Spiegel, 2009b; Spiegel and Veiga, 2010).

When a retort is not used in the recovery process, mercury is released directly into the atmosphere during the volatilization process (Van Straaten, 2000a, 2000b; Velásquez-López et al., 2011). Unfortunately, this mercury loss is difficult to trace within the environment due to multiple factors, including variability in both wind conditions and deposition rates of mercury vapors. The second highest and most consistent source of mercury contamination from ASGM is through tailings (Veiga and Baker, 2004) with reports of as much as 66% of mercury being lost to tailings (Metcalf and Veiga, 2012).

Mercury within sediments and tailings is primarily associated with a fine particle size (<63 μm), which is largely dependent on water action for mobility (Pestana et al., 2000; Fernández-Martínez et al., 2006). While only a few distances were reported, Lacerda et al. (1991) demonstrated that mercury concentration in soil was positively correlated with proximity to tailing piles at a mine in Pocone, Brazil. van Straaten (2000a) demonstrated similar results in Tanzania and Zimbabwe. Despite this, numerous studies have documented mercury's ability to enter aquatic systems from ASGM sites (Ikingura and Akagi, 1996; Male et al., 2013; Tomiyasu et al., 2013; Ngure et al., 2014; Niane et al., 2014; Pinedo-Hernández et al., 2015). While mercury has been found primarily in sediment layers within aquatic systems (Ribeyre and Boudou, 1994; Tessier et al., 2007), studies within controlled natural water systems have demonstrated similar relationships between sediments and water column mercury concentrations (Rudd et al., 1983). Once mercury has entered aquatic systems, downstream travel distances and elevated mercury levels have been reported to range from 4 km at recent mining sites (Van Straaten, 2000a) to 20 km at historic mercury mines (Tomiyasu et al., 2012). In addition, mercury has been shown to have a strong positive association with organic material, which can affect its dispersion within stream systems by allowing pockets within these systems with high organic material to act as reservoirs for mercury (Guedron et al., 2009; Tomiyasu et al., 2012; Tomiyasu et al., 2013; Pinedo-Hernández et al., 2015).

Mercury is listed as one of the top 10 chemicals of major public health concern by the World Health Organization (WHO) and is most dangerous when it is within an aqueous environment where it can then be methylated to form methylmercury (Ullrich et al., 2001). Exposure to methylmercury can result in neurological damage and is especially toxic to mothers and their unborn children (Gibb and O'Leary, 2014; WHO, 2003; WHO, 2007). Understanding how mercury interacts with its environment once released is therefore tantamount to human health and safety.

1.2. Objectives/hypotheses

The primary objective of this study was to determine the impact of gold mining activities on mercury contamination in headwater streams in southern Zimbabwe that were directly associated with ASGM. The region possessed a high density of mining activities that includes industrial mines, small-scale artisanal mines, and stamp mill processing centers. Although the contribution of mercury contaminants from these mining activities have been well documented in other systems, the small scale distribution, levels of contamination, and subsequent fate of mercury once introduced into a watershed is not well known. The research questions and associated hypotheses that guided this study were:

Q1) Does mining activity within this study system contribute to mercury contamination in adjacent streams?

H1. We hypothesized that mining activities would serve as hot spots for mercury contamination and that mercury concentrations would be highest in stream locations closest to mining activities.

Q2) What is the downstream fate of mercury (e.g., concentration and distance) introduced into a headwater stream system?

H2. We hypothesized that mercury concentrations in sediments would decrease with increasing distance from the source of contamination and that local mercury contamination would not extend beyond 10 km.

Q3) Does percent organic material, distance downstream from the contamination source, or position within the stream influence the distribution of mercury after it has been introduced?

H3. We hypothesized that percent organic material of sediments and distance from mining operations would be significant predictors of mercury distributions but that distance downstream alone would not.

2. Materials and methods

2.1. Study area

The study area was located 170 km southeast of Bulawayo, Zimbabwe, and consisted of a single reservoir and four seasonally flowing streams that were subdivided into six segments for comparative analyses (Fig. 1). Flow through these streams is seasonally variable; however, all stream segments were completely dry during the time of collection for this study. Six stamp mills and a single industrial mine, the Farvic Mine, were located within the study area. Each stream and stamp mill within the study area was identified with a letter and number code to simplify references. The stream segments were labeled STR to denote stream, followed by numbers 1–6 to denote segment. The stamp mills were labeled with SM and individually number to differentiate them (SM-1, SM-2, etc.). Stream segment STR-5 continues downstream to the south for 9 km, with no mining activity known to occur beyond 1 km from the starting location along the stream. With the exception of stream segment STR-6, which flows to the east, all other stream segments flow in a southerly direction.