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Total mercury loadings in sediment from gold mining and conservation areas in Guyana

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Abstract The Low Carbon Development Strategy proposed in June 2009 by the government of Guyana in response to the Reducing Emissions from Deforestation and Forest Degradation in Developing Countries program has triggered evaluation of forest-related activities, thereby acting as a catalyst for improvements in Guyana's small- to medium-scale gold mining industry. This has also shed light on areas committed to conservation, something that has also been handled by Non Governmental Organizations. This paper compares water quality and mercury concentrations in sediment from four main areas in Guyana, two that are heavily mined for gold using mercury amalgamation methods (Arakaka and Mahdia) and two that are considered conservation areas (Iwokrama and Konashen). Fifty-three sediment and soil mercury loadings ranged from 29 to 1,200 ng/g and averaged 215 ± 187 ng/g for all sites with similar averages in conservation and mining areas. Sediment loadings are within the range seen in French Guiana and Suriname, but conservation area samples had higher loadings than the corresponding uncontaminated baselines. Type of ore and location in the mining process seemed to influence mercury loadings. Mercury sediment loadings were slightly positively correlated with pH (correlation coefficient = 0.2; p value < 0.001) whereas no significant correlations were found with dissolved oxygen or turbidity.

Keywords Mercury · Guyana · Sediment · Gold · Mining · Tropical forest · Guianas

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Introduction

The Guiana Shield refers to a belt of greenstone underlying 21% of the total land area of Brazil, Colombia, French Guiana, Guyana, Suriname, and Venezuela combined (Table 1). The area is bounded by the Amazon River and Japura-Caqueta River in the south, the Sierra de Chiribiquere to the west, the Orinoco and Guaviare rivers to the north, and the Atlantic Ocean to the east. Sixty-three percent of the

Table 1 Land and forestry coverage and gold production of countries of the Guiana Shield

Country	Total land (km^2)	Land in GS%	Land as IF%	Gold prod. kg (2006)
Brazil	8,456,510	14	64	45,000
Colombia	1,038,710	16	47	15,700
French Guiana	88,150	100	90	2,000
Guyana	214,980	100	79	6,406
Suriname	156,000	100	90	9,362
Venezuela	882,060	51	56	12,400
Total	10,836,410	21	63	90,868

Adapted from Hammond (2005) and USGS (2008)
GS Guiana Shield, *IF* Intact Forest

total land in these six South American countries remains as intact forests (76% of which are tropical forests), with the smaller Guianas—French Guiana, Guyana, and Suriname showing the least amount of deforestation (Hammond 2005).

Biological diversity, especially of endemic species, has driven the establishment of conservation areas in the region, including World Heritage Sites like the Central Suriname Nature Reserve that covers 10% of Suriname's land. Larger efforts are underway to protect the standing forests through international payment mechanisms established to combat global climate change (see Guyana's Low Carbon Development Strategy). The Guiana Shield is also rich in gold, having one of the largest lower-grade deposits, and it ranks one of the fastest growing regions of gold production where the scale of mining ranges from large (>500,000 t ore/year) to medium (50–500,000 t ore/year) to small (<50 t ore/year) (Hammond et al. 2007). In the case of Guyana, classifications are made according to property size—2–52 km^2 (large), 0.6–4.9 km^2 (medium), and 0.1 km^2 (small) (Hilson and Vieira 2007).

Rising gold prices has led to the spread of mining activities throughout areas of the Guiana Shield which have had, and continue to have detrimental social and environmental impacts, many times in, or close to areas considered protected or inhabited by indigenous groups (Hammond et al. 2007; Hilson and Vieira 2007; Paterson and Heemskerk 2001; Colchester et al. 2002). In countries like Guyana which experienced significant increases in gold exports from the large OMAI mine which used the cyanide heap leaching procedure and operated there for 10 years, gold production from small- and medium-scale mines which use mercury amalgamation procedures are rising sharply as are the number of mining permits disbursed versus the use of more efficient procedures and safe practices or the discovery of richer deposits (Fig. 1). As of 2005, Guyana had 3,715 medium-scale prospecting permits and 41 prospecting licenses for large-scale operations (Fong-Sam 2009). Gold mining, logging, and the opening of new roads threaten biodiversity and mined areas have shown extremely slow rates of recovery under current practices (Funk et al. 1999; Paterson and Heemskerk 2001).

In June 2009, the Government of Guyana (GOG) released a Low Carbon Development Strategy (LCDS, http://www.lcds.gov.gy/) that would limit deforestation throughout Guyana. An initial bilateral agreement with Norway is being

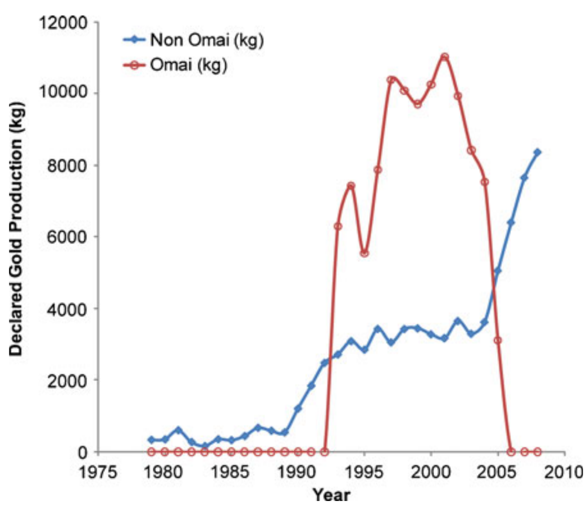


Fig. 1 Guyana declared gold production 1979–2008 from large scale OMAI mine and small to medium scale mines (non Omai) (GGMC 2009)

watched for its ability to develop a model upon which the World Bank's Forest Carbon Partnership Facility can build its Reducing Emissions from Deforestation and Forest Degradation program in developing countries. The attention to the LCDS has rapidly moved local Guyanese discussions on improvements in the gold mining sector which would retain its mining concessions (Office of the President Republic of Guyana 2009). In August 2009, the Guyana Geology and Mines Commission announced that it would eventually seek to ban mercury use in gold mining from 2011 (Stabroek News 2009).

In 1989, Brazil became the first country in the Guiana shield to ban mercury use in gold mining (UNEP 2000), and the miners and their excessive mining habits have migrated to the Guianas where environmental regulation on mercury use is lacking or lacks proper enforcement mechanisms (Hilson and Vieira 2007; Colchester et al. 2002). In 2006, French Guiana also outlawed the use of mercury in gold mining activities (WWF 2008). Small-scale gold mining was estimated to contribute more than 10% of annual global anthropogenic mercury loading to the atmosphere in 2005 (Swain et al. 2007). Mercury is recognized as a global contaminant known to cause deleterious neurological, developmental and other health effects (US Department of Health and Human Services 1999). Based on toxicological studies, the following guidelines have been established for mercury: 1 μg/L for drinking water (WHO 2004), 1 $\mu g/m^3$ for air (WHO 2000), 0.77 μg/L for the protection of aquatic life through chronic exposure (EPA 2009), and 0.3 mg methyl mercury/kg wet weight of fish for human consumption (EPA 2009). Epidemiological studies indicate neurological damage when total mercury concentrations are greater than 50 μg/g in adult hair or 10–20 μg/g in maternal hair (WHO 1990). Higher mercury concentrations in hair and urine samples have been found in or close to small to medium scale mining communities in the Guiana Shield (De Kom et al. 1998; Singh et al. 1999) and in some instances correlated with neurocognitive outcomes (Chevrier et al. 2009). Higher hair mercury loadings seen in indigenous populations, many times in areas upstream from mining, have been linked to fish consumption habits (Cordier et al. 1998; Frery et al. 2001) although very little work has looked at contributions from thiomersal (an organomercury compound) preserved vaccinations or nutritional deficiencies (Dorea 2009) or other local environmental conditions (e.g., slash and burn agriculture or wood fires in homes).

An ensuing debate remains over whether small-scale gold mining use of mercury is the most significant source contributing to elevated levels in the Guiana shield. Early work in Brazil found higher concentrations of mercury in fish, sediment, and water around small- and medium-scale gold mining communities when compared to non mining areas (Lacerda et al. 1991; Nriagu et al. 1992; Akagi et al. 1995a, b; Mol et al. 2001). Hilson (2006) summarizes other studies that support these observations around the world. Others have also found some upstream non-mined environments to have higher loadings in Brazil (Lechler et al. 2000) and Wasserman et al. (2003) argues that mercury releases from actual amalgamation are too insignificant to be the cause of loadings seen in soils in the Amazonian environment and that it is human induced activity, some from gold mining like land clearing, that releases mercury from soils into aquatic systems (Roulet et al. 1998a, b). Though limited by its exclusion of the impact of mercury deposition, Beliveau et al. (2009) found that slash and burn agriculture altered the fractions that soil mercury was associated with, but did not result in any major loss of mercury to waterways. Deforestation and other land use changes are indeed being used as indicators for increased mercury levels in carnivorous fish (da Silva et al. 2009). Miller et al. (2003) describes the ensuing debate within the scientific journals on whether the high mercury levels seen in Brazil resulted from gold mining or deforestation (and soil erosion) since both activities were prevalent and the soils from the area naturally had high background mercury levels compared to other parts of the world (Fostier et al. 2000). Some studies in the less deforested Guianas also found higher mercury loadings closer to or downstream from mining although localized deforestation would have been an issue at mining sites (Spadini and Charlet 2003; Charlet et al. 2003; Gray et al. 2002; Miller et al. 2003). Mercury loadings in forest soils, river sediment, and lateritic soils along the Sinnamary River in French Guiana did not show any significant variations around mining sites (Richard et al. 2000) whilst the type of soil (oxisol versus utisol) found in the ECEREX reserve in French Guiana influenced mercury loadings, with oxisols having higher values (Grimaldi et al. 2008).

While the environmental and health impacts from mercury used by the small-scale mining sector are undesirable (Hilson and Vieira 2007), little is still known on mercury mobilization and exposure in unmined parts of Guyana, especially those that will fall under the "sustainable forest" type management vision as proposed by the LCDS. Non-mining areas in Guyana have had the least monitoring and least public awareness on mercury exposure but may have the most vulnerable communities, if background mercury levels are high and mercury bioaccumulates in food sources, as suggested by other researchers (Singh et al. 1999 and Richard Couture, personal communication).

This paper presents mercury concentrations in sediment from four main areas in Guyana, two that are heavily mined for gold using mercury amalgamation methods (Arakaka and Mahdia) and two that are considered conservation areas (Iwokrama and Konashen) where illegal gold mining may happen or may have happened within or on the periphery but to a very small extent. Environmental monitoring programs looking at water quality recently started in the conservation areas and this work provides baseline data for those communities. Sediment and soil total mercury loadings are compared by site type and location in the mining process. Field and historical observations and rudimentary sediment and soil characterization are used to interpret data and discuss its significance in the context of both potential mining regulation and management and sustainable forest livelihoods.

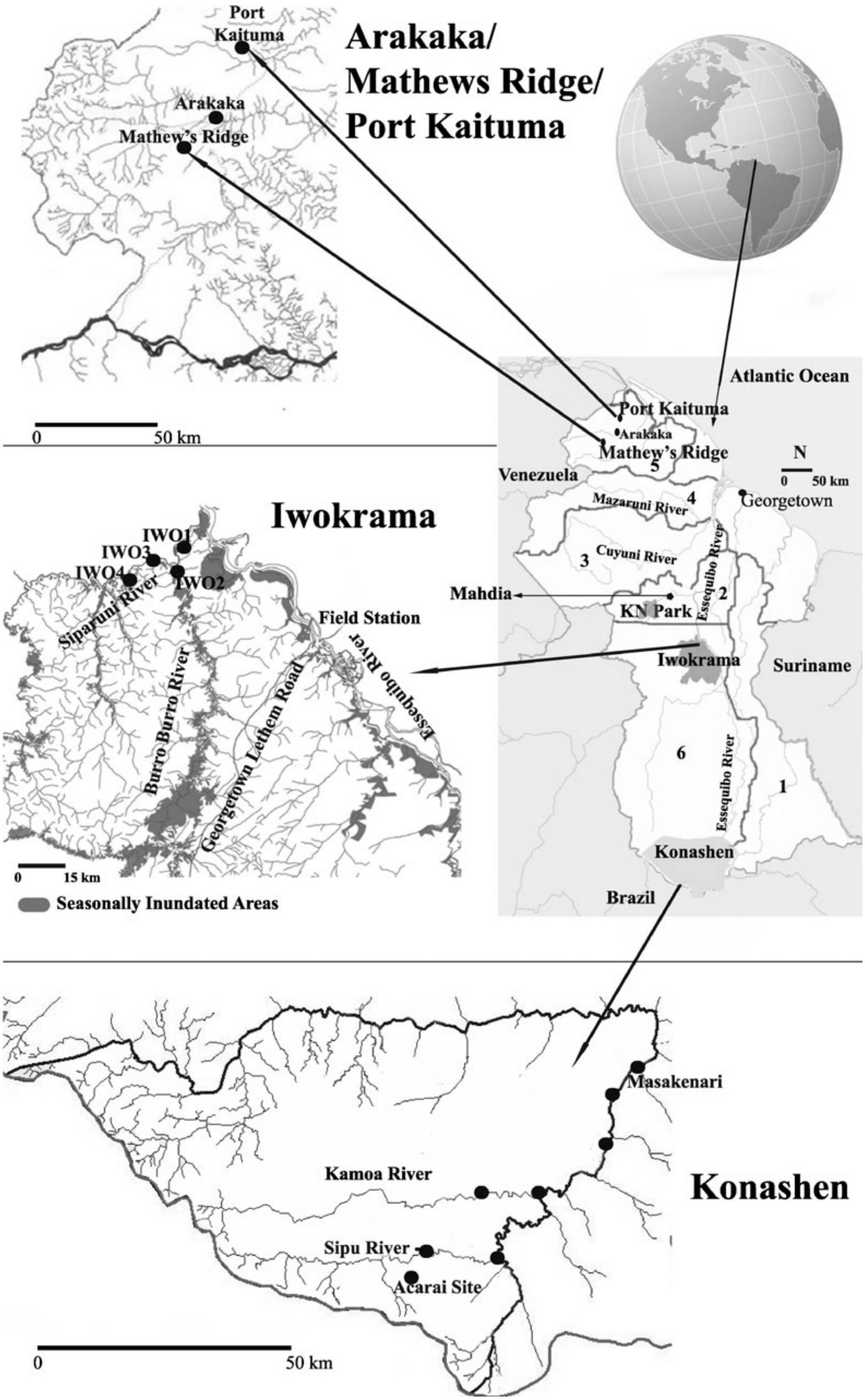
Materials and methods

Study sites

Guyana, the only English speaking country in South America is a tropical climatic region with a population of about 772,298. Ninety percent of the population resides on the Atlantic coastal region which has most of the arable land (2% of total land area). Apart from agriculture, major exports include timber, bauxite, gold, and diamond (CIA 2009). Figure 2 shows the location of the sample sites and the delineations for the mining districts. There are six mining districts in Guyana: Berbice Mining District 1, Potaro Mining District 2, Mazaruni Mining District 3, Cuyuni Mining District 4, Northwest Mining District 5, and Rupununi Mining District 6, with the bulk of gold mining currently occurring in Districts 2 to 4. The approximately 960 km long Essequibo river starts in the Acarai Range located in the southernmost part of the country (on the border with Brazil) in District 6's Konashen area and passes through Districts 2, 3, and 4 prior to emptying into the Atlantic ocean. The Essequibo drainage basin is approximately 50,000 km^2 and has a maximum depth of about 40 m with an average annual rainfall of 3,000 mm/year (Watkins et al. 2005; Vari and Ferraris 2009). The Essequibo River and its tributaries drain two current protected areas in central Guyana, the Kaieteur National Park and Iwokrama International Centre for Rain Forest Conservation and are the main surface waters of an even larger biodiversity conservation corridor proposed by Conservation International-Guyana.

As depicted in Fig. 2, sediment sampling was conducted along the Essequibo river and in tributaries at its main northern and southern watersheds. The areas covered included (1) unmined land (Konashen and Iwokrama), and (2) actively mined areas (Arakaka and Mahdia). Mathew's Ridge and Port Kaituma were also sampled because of their close proximity to Arakaka in an

Fig. 2 Map of Guyana and sample sites with Mining Districts labeled (for illustration purposes only). The Mining Districts are: *1* Berbice, *2* Potaro, *3* Mazaruni, *4* Cuyuni, *5* Northwest, *6* Rupununi. Iwokrama insert adapted from The Iwokrama Forest Hydrology Map (Iwokrama 2009). Konashen and Arakaka/Mathew's Ridge/Port Kaituma insert adapted from Guyana National Protected Areas, Consensus Areas for Conservation, and CI-Guyana's Vision (Eustace Alexander, Personal Communication). KN refers to Kaieteur National Park, the second largest of four protected areas in Guyana ▶


Arakaka/
Mathews Ridge/
Port Kaituma
Port Kaituma
Arakaka
Mathew's Ridge
0 50 km
Atlantic Ocean
Venezuela
N
0 50 km
Georgetown
Mazaruni River
Cuyuni River
Esequibo River
Mahdia
KN Park
Iwokrama
Suriname
Esequibo River
Konashen
Brazil
1
2
3
4
5
6
Iwokrama
IWO1
IWO3
IWO4
IWO2
Siparuni River
Field Station
Esequibo River
Burro Burro River
Georgetown Lethem Road
0 15 km
Seasonally Inundated Areas
Masakenari
Kamoa River
Konashen
Sipu River
Acarai Site
0 50 km

effort to get background levels for that northern part of the country.

Arakaka/Mathew's Ridge/Port Kaituma

The 21,755 km^2 area of the Northwest district towns of Arakaka and Matthew's Ridge with populations less than 1,000 persons, have been mined extensively for manganese, diamond, and gold; however, the dominant commerce today is gold mining (Vieira 2006). This area is a part of Mining District 5 and small–medium-scale gold mining occurs in Arakaka while Matthew's Ridge serves as the central location of residency for many of the miners and their families. Port Kaituma served as the port for manganese cargo when the mine was operating and is now another residence for many in the gold mining industry. Residents and workers surveyed within this area depend extensively on rain catchments and springs for potable water, consume fish from the rivers, and the majority of those involved in the mining business used mercury (Bera 2005). Hair and fish samples have also been found to have high levels of mercury (Bera 2005; IAST 2006). Sediment and soil samples were collected from Port Kaituma, Pakera Creek located in Matthew's Ridge and various water bodies in Arakaka as well as from an active gold mine in Arakaka in April 2005 in conjunction with the Institute of Applied Science and Technology under a WWF-Guianas sponsored project.

Mahdia

Mahdia is the central town of the Mining District 2 and is currently the largest mining area in Guyana today, making mining the main source of income for local and migrating residents. As with most small- and medium-scale operations in Guyana, the mining process involves clear cutting of the concession, dredging of the land, and loosening of the low-grade gold-bearing ore via spraying with water from high-pressured hydraulic pumps, collection of gold bearing ore on a specially designed mat located in a sluice box, and recovery of the gold by mixing mercury with the ore collected on the mat and finally burning off the mercury. The place of mercury application in the process (in mat or after mat is shaken) and the precautions employed during burning of the amalgam to recover gold (e.g. use of retorts to limit atmospheric releases) varies among mines. In March 2009, five different mining sites were visited and sampled for sediment and water at various locations in and around the mine.

Konashen

The Konashen Community Conservation Area (COCA) is comprised of 6,250 km^2 of some of the most pristine expanses of evergreen forests in the northern part of South America with over 319 species of birds, and 119 species of fish, including four that may be new to science (Alonso et al. 2008). The area is primarily underlain by sedimentary rocks and sand and houses the headwaters of the Essequibo River, and drains the Kassikaityu, Kamoa, Sipu, and Chodikar rivers. The area's main mountains include the Acarai, Wassarai, Yashore, Kamoa, and Kaiawakua with elevations reaching 1,200 m above mean sea level. The Konashen District supports 200 Amerindians known as the Wai Wai who rely heavily on the Essequibo and its tributaries for daily water activities (i.e., drinking, bathing, eating, and cultivating the land) and who have teamed up with the GOG via the Ministry of Amerindian Affairs and Conservation International Guyana (CI-Guyana) to develop and implement a sustainable management plan for the area. It is the second largest out of five "consensus areas" in Guyana. Apart from slash and burn agriculture there is no current mining or industrial development in the area COCA; however, the local population speculated on certain areas being old mining sites and also on the existence of illegal mining activities. Hammond et al. (2007) indicates that registered mines exist less than 200 km east of the COCA along the Brazilian border in Mining District 1. In October 2006, during the dry season, sediment samples were collected from the banks of the Sipu river (SR), Acarai Mountain creek (AM), Kamoa river (KR), and Essequibo river (ER), the sites of which have been described in more detail elsewhere (Trotz 2008). Samples were also collected in creeks and swamps in these areas. This sampling was done during a Conservation International Rapid Assessment Program (Alonso et al.

2008) and sample sites coincided with the various camp locations. In 2007, a COCA-managed water-quality monitoring program was established using a subset of the sampling sites identified in this study.

Iwokrama

The Iwokrama International Centre for Rain Forest Conservation and Development (IIC) was established following the IIC Act (1996) to provide for the sustainable management and utilization of the rainforest. It is one of four protected areas in Guyana and by far the largest. Encompassing 3,710 km^2 the IIC borders, the Pakaraima Mountains to the west, the Essequibo River to the east, the Siparuni River to the north, while the Burro-Burro River runs through its center. The highest point on the Iwokrama Mountain is close to 1,000 m. In addition to being the home of the Makushi indigenous group totaling roughly 250 people in Fairview Village (15 communities south of the Iwokrama forest combine to give a total indigenous population greater than 5,000 people), IIC is known for its extensive biodiversity which includes 475 species of birds, over 400 species of fish, and over 90 species of bats (Lim and Engstrom 2005). As one of the few protected lowland tropical rainforests in the Amazon, IIC serves as an ecotourism site and research area for sustainable livelihoods, biodiversity, and ecosystems services research. The site supports a sustainable utilization area which includes certified logging operations under the Forest Stewardship Council. The Iwokrama Reserve is partly bordered by rivers and more in the north is surrounded by areas designated for small to medium-scale gold mining (land mining on opposite side of rivers) although regulations are in place preventing this activity given its proximity to Iwokrama. Sampling occurred in March 2009 on the Siparuni and Burro Burro rivers, although not as far as the mining creeks. Based on observations and recollections of Iwokrama staff, sampling was done at areas that may have been illegally mined and at areas that will be consistently monitored for water quality under an environmental monitoring program established in 2009.

Reagents and equipment

All reagents and lab instrument calibration standards were prepared with trace metal grade (TMG) solutions supplied from Fisher Scientific. Mercury soil standard reference material (NIST SRM 1944, 3.40 mg/kg dry wt.), and freshwater standard reference material (NIST-1641d, ×200 dilution; 8,010 ng/L THg) were used for quality control and quality assurance. Stock solutions for mercury calibration were made from a 10 mg/L mercury nitrate standard preserved in 5% nitric acid (Fisher Scientific). A Quanta HYDROLAB multi-sensing system was used to measure depth (±0.003 m), pH (±0.2 pH units), dissolved oxygen (±0.2 mg/L), specific conductance (±1% of reading ±1 count), temperature (±0.2°C), and turbidity (±5% of reading ±1 NTU) in the field and was calibrated using Fisher Scientific standards for pH, conductivity, and turbidity and temperature-stable air-saturated water for 100% DO_{sat}.

In Iwokrama, sediment samples were collected using a Wildco 196-B15 standard Ekman bottom-grab sampler and transferred to Ziploc bags. In Konashen, Arakaka/Mathew's Ridge, and Mahdia, sediments from the edge of rivers or from areas within a mining site were collected in Ziploc bags using either a stainless steel or plastic scoop. All of the samples were stored on ice or refrigerated in the field and shipped on ice to the USF laboratory. The sediment was dried at 35°C in a THELCO Laboratory oven prior to homogenization using a pestle and mortar and stored in Ziploc bags in the laboratory. The Arakaka/Mathew's Ridge samples were air dried and homogenized using a mortar and pestle at the Institute of Applied Science and Technology laboratory in Guyana prior to shipment to USF where analyses for total mercury were done by Advanced Environmental Laboratory in Tampa, Florida. All other sediment samples were analyzed on a 240FS VARIAN DUO Atomic Absorption Spectrometer (CVAAS) coupled to a VGA77 Cold Vapor Accessory following the digestion procedure described below.

Approximately 1 g of the dried homogenized sediment was placed into 125 mL digestion vessels from Environmental Express. Digestion and analysis followed various versions of the latest

FDEP SOP # HG-020–5.12 (Florida Department of Environmental Protection 2008) and HG-008–3.16 (Florida Department of Environmental Protection 2009) which is based on US EPA Method 245.5/7471 (EPA 1994) for total mercury concentrations in sediment and waste by CVAAS. Samples were predigested by adding 5 ml TMG nitric acid and 2 ml 30% hydrogen peroxide and allowed to react for 15 min and then heated at 95°C for 5 min. After cooling, 40 ml of ultrapure water (resistivity > 18.2 mΩ cm) was added to each sample. Ten ml of 6% (*w*/*v*) potassium permanganate and then 4 ml of 6% (*w*/*v*) potassium persulfate were then added to each sample and allowed to heat for 1 h at 95°C. After cooling, 4 ml of 12% (*w*/*v*) hydroxylamine hydrochloride were added to each sample to fully reduce any excess potassium permanganate. Sediment duplicates, spikes, blanks, and reference standards were prepared and total sediment mercury loading (sTHg) was expressed as nanograms per gram dry weight of sediment. The method detection limit was 1 ng/g. Recovery from the reference standard was between 85% and 115% and duplicates had less than a 5% difference which met QA/QC requirements.

Results and discussion

Total mercury loadings in sediment and soil samples and surface water quality data are provided in Table 2 with averages for the different areas given in Table 3 (value ± SD). Fifty-three sediment and soil concentrations ranged from 29 to 1,200 ng/g and averaged 215 ± 187 ng/g for all sites. Twenty-seven samples taken from active gold mining areas (Arakaka and Mahdia) had sediment and soil concentrations that ranged from 29 to 601 ng/g and averaged 226 ± 171 ng/g. Thirty-five samples taken from active gold mining areas plus Mathew's Ridge and Port Kaituma had sediment and soil concentrations that ranged from 29 to 1,200 ng/g and averaged 229 ± 223 ng/g. Eighteen sediment and soil samples taken from conservation areas (Iwokrama and Konashen) had mercury loadings that ranged from 53 to 301 ng/g and averaged 187 ± 77 ng/g. The highest loadings seen in the Iwokrama samples (IWO2, IWO3, and IWO4) were actually taken at locations which local staff suggested might be old mining camps which might explain why sample IWO1 was only 53 ng/g.

Some soil and sediment samples were taken from places which prevented the collection of water quality data because of high solids density. For the water quality data collected, pH values ranged from 3.9 to 7.3 pH units with lowest values observed around tailings ponds in Mahdia. The pH of water samples in Iwokrama and Konashen ranged from 4.8 to 6.3 pH units with the lower values observed in small creeks and swamp environments. The average pH for these conservation areas was 5.7 ± 0.5 pH units. In the Mahdia mining samples, pH ranged from 3.9 to 7.3 pH units and averaged 6.6 ± 1.1 pH units. Dissolved oxygen levels for Iwokrama and Konashen varied between 1.2 and 10 mg/L and averaged 6.5 ± 1.7 mg/L. The lower value of 1.2 mg/L dissolved oxygen was associated with a seasonal pool in Konashen. Dissolved oxygen levels measured in Mahdia varied from 3.5 to 5.7 mg/L and averaged 4.7 ± 0.8 mg/L. Turbidity values for Iwokrama and Konashen varied from 0 to 51 NTU and averaged 14 ± 15 NTU, and for Mahdia, it ranged from 12 to 178 NTU and averaged 70 ± 55 NTU. Mercury sediment and soil loadings were slightly positively correlated with pH (correlation coefficient = 0.2; $p < 0.001$) whereas no significant correlations were found with dissolved oxygen or turbidity. Mercury (II) sorption to clays and mineral oxides of iron, aluminum, and silicon, some of the most common sediment constituents, typically increases as a function of pH until it reaches a maxima then decreases in the higher pH regions (Sarkar et al. 1999, 2000; Kim et al. 2004; Mac Naughton and James 1974) and may explain the observed correlation. The presence of competing ions and natural organic matter, especially for the river sediments, likely play a role in loading behavior observed (de Diego et al. 2001; Benoit et al. 2002; Drexel et al. 2002).

Figure 3 shows a box plot of the sediment and soil total mercury loadings by site. The highest sediment loading of 1,200 ng/g was actually observed in Mathew's Ridge at a water source for the area. No active gold mines existed in Mathew's Ridge at the time of sampling; however, Mathew's Ridge was once a manganese mine and

Table 2 Sediment total mercury loadings (sTHg in ng/g dry weight) and water quality parameters

Area			sTHg (ng/g)	Surface water			Longitude	Latitude
				pH	DO (mg/L)	TURB (NTU)		
For samples taken at Iwokrama, Konashen, Arakaka/Matthew's Ridge/Port Kaituma								
Iwokrama	Iwokrama	IWO1	53	5.4	6.9	19	N04.78912	W058.87139
		IWO2	225	5.6	6.9	13	N04.73200	W058.85048
		IWO3	298	5.7	7.69	32	N04.76645	W058.88126
		IWO4	120	6.0	10.0	29	N04.74021	W058.92834
Konashen	Essequibo River	GR-ER-11	209	6.3	5.3	12	N01.62.976	W058.62.447
		GR-ER-12	176	6.3	6.0	12	N01.64.733	W058.61.826
		GR-ER-16	198	6.0	5.7	0	N01.68.102	W058.62.934
	Acarai Creek	GR-AM-01	290	4.7	1.2	0	N01.42.180	W058.95.221
		GR-AM-02	131	5.7	7.6	11		
		GR-AM-03	121	5.5	7.5	0		
		GR-AM-04	301	5.2	8.3	3	N01.38.989	W058.94.489
	Kamoa River	GR-KR-02	220	6.0	6.5	28	N01.53.189	W058.82.967
		GR-KR-04	121	6.1	6.9	51		
		GR-KR-05	163	6.1	6.6	34		
		GR-KR-06	92	5.2	6.4	6	N01.53.427	W058.82.692
		GR-KR-07	262	4.8	6.2	9		
		GR-KR-12	115				N01.53.193	W058.81.922
	Sipu River	GR-SR-06	271	5.7	7.43	5	N01.43.072	W058.92.941
Arakaka/ Mathew's Ridge/ Port Kaituma	Arakaka	S270405–0103	130	–	–	–	N0735.431	W059.58.714
		S270405–0401	180	–	–	–	N07.35.761	W060.00.260
		S270405–0805	61	–	–	–	N07.34.784	W060.00.186
		S270405–0704	98	–	–	–	N07.35.193	W060.01.188
		S270405	110	–	–	–	N07.35.574	W059.59.378
		S270405–0302	41	–	–	–	N07.34.799	W060.00.130
		Mine tailings	300	–	–	–	–	–
	Mathew's Ridge	S030505–2107	1,200	–	–	–	–	–
		S020505–1804	200	–	–	–	N07.29.448	W060.08.452
		S020505–1602	190	–	–	–	N07.29.359	W060.11.120
		S040505–2309	200	–	–	–	N07.28.956	W060.09.238
		S030505–2006	290	–	–	–	N07.30.129	W060.08.044
		S020505–1703	583	–	–	–	N07.29.448	W060.09.214
	Port Kaituma	S050507–2502	168	–	–	–	N07.41.881	W059.55.450
		S050507–2704	364	–	–	–	N07.41.917	W059.53.559
		S070505	142	–	–	–	N07.42.517	W059.53.223

Table 2 (continued)

Area			sTHg (ng/g)	Surface water			Longitude	Latitude
				pH	DO (mg/L)	TURB (NTU)		
For samples taken at Mahdia								
Mahdia	Mine 1	11, by pump	331	6.6	4.3	48	N05.380.23	W059.13596
		12, sluice box	127	–	–	–	–	–
		12B, LHS, sluice box	143	–	–	–	–	–
		12C, RHS, sluice box	81	–	–	–	–	–
		12D, camp	134	–	–	–	–	–
		Diosmp	114	–	–	–	–	–
		Topsoil	253	–	–	–	–	–
		Topsoil B	111	–	–	–	–	–
	Mine 2	14, pit	29	7.3	3.9	15	N05.29134	W059.13186
		14B, tailings 2	150	7.3	4.1	12	N05.29117	W059.13206
		15, tailings 1	222	3.9	3.5	178	N05.28982	W059.13229
		16, sluice box	49	6.0	4.3	15	N05.29007	W059.13061
		17, tailings 3	66	7.1	5.0	34	N05.26475	W059.13805
	Mine 3	18, tailings	409	7.3	5.7	116	N05.26437	W059.13745
		19, by pump	443	–	–	–	–	–
	Mine 4	20	508	6.7	5.5	80	N05.26443	W059.13791
		21, by pump	471	7.1	5.5	95	N05.25819	W059.13311
		Tailings	601	7.2	5.6	104	N05.25814	W059.13308
	Mine 5	22, by pump	72	–	–	–	N05.27391	W059.13372
		22b, sluice box	127	–	–	–	–	–

Table 3 Average values of total mercury loading, sTHg (ng/g dry weight), pH, DO (mg/L), and turbidity (NTU) found in each study area

Location (# samples)	sTHg ± SD (ng/g)	Surface water		
		pH±SD	DO±SD (mg/L)	TURB±SD (NTU)
Iwokrama (4)	174 ± 109	5.7 ± 0.2	7.8 ± 1.5	23 ± 9
Essequibo River (3)	194 ± 17	6.2 ± 0.1	5.6 ± 0.3	6 ± 7
Acaria Creek (4)	211 ± 98	5.3 ± 0.4	6.1 ± 3.3	3 ± 5
Kamoa River (6)	162 ± 67	5.6 ± 0.6	6.5 ± 0.3	25 ± 19
Sipu River (1)	271	5.7	7.4	5
Arakaka (7)	116 ± 87	–	–	–
Mathew's Ridge (5)	416 ± 440	–	–	–
Port Kaituma (3)	225 ± 128	–	–	–
Mine 1 (8)	162 ± 85	6.6	4.3	47.7
Mine 2 (5)	103 ± 81	6.3 ± 1.5	4.1 ± 0.6	72 ± 116
Mine 3 (2)	426 ± 24	7.3	5.7	116
Mine 4 (3)	527 ± 92	7.0 ± 0.1	5.5 ± 1.7	93 ± 6
Mine 5 (2)	100 ± 39	–	–	–
All sites (53)	215 ± 187			
Conservation Areas (18)[a]	187 ± 77	5.7 ± 0.5	6.5 ± 1.7	15 ± 14
Gold Mining Areas (27)[b]	226 ± 171	6.6 ± 1.1	4.7 ± 0.8	70 ± 55
Mining Areas (35)[c]	229 ± 223			

[a]Conservation areas include Iwokrama and Konashen only
[b]Mining areas include Arakaka and Mahdia (Mines 1–5)
[c]Mining areas include Arakaka, Mathew's Ridge, Port Kaituma, and Mahdia (Mines 1–5)

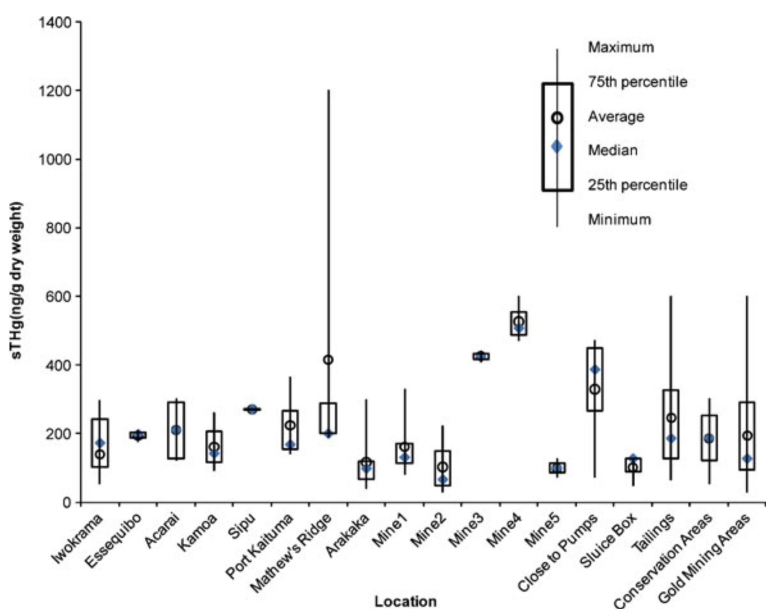


Fig. 3 Box plot of total mercury loading on sediments and soils, sTHg (ng/g dry weight), by area sampled showing values that fall within the 25th and 75th percentile (*box*), the minimum and maximum loading (*line*), and the median (*diamond*). Close to pumps, Sluice box, and Tailings are averages for samples from active gold mining areas (Arakaka and Mines 1–5 in Mahdia). Conservation Areas include Iwokrama, Konashen (Essequibo, Acarai, Kamoa, and Sipu), and Gold Mining Areas include Arakaka and Mahdia (Mines 1–5)

it is possible that the manganese oxides in the soil and sediment serve as sorption sites or sinks for mercury (Thanabalasingam and Pickering 1986). Aside from Mines 3, 4, and the high Mathew's Ridge sample, the loadings seen at mining and non-mining areas in this study all lie between 29 and 364 ng/g with no significant difference seen between loadings found in conservation areas versus mining areas or areas close to mining. If only active gold mining areas are compared with the conservation areas higher loadings are seen in the gold mining areas.

Arakaka and Mines 1–5 were the sites with active gold mining and samples were taken from the sluice boxes and/or other areas around each of those sites. Mines 3 and 4 had the highest sediment loadings for the active gold mining sites studied in Mahdia. Figure 4 shows an image of the sediments representative of these mines as well as the average mercury loadings observed. The iron oxides were clearly prevalent in Mines 3 and 4 and to a lesser degree in Mine 5. Further spectroscopic analyses of collected samples are currently under investigation. In Thailand, Pataranawat et al. (2007) surveyed areas around an active gold mining site that uses mercury amalgamation methods and found extremely high localized levels in soils, especially close to recovery areas (∼10,000 ng/g) which they attributed to volatilization of Hg and dry deposition nearby. The mine sampled in Arakaka, and Mines 1, 2, and 5 in Mahdia, were also larger than Mines 3 and 4 and hence the recovery process was done fairly far from the pits and sluice boxes sampled. In addition to ore type and mine size, other factors like mercury handling and practices could influence the loadings observed. Surveys performed at each mining site indicate varying degrees of management and worker awareness and attention to handling of mercury, though the mine managers and/or owners in Mahdia interviewed all stated that retorts were used during recovery (survey results are currently being analyzed for separate publication). Soil samples were not taken in the areas where gold recovery was conducted because this activity was not underway during our visit and the miners did not readily identify these locations.

Fig. 4 Photographs of sediment samples collected in Mahdia from five different mines. The average sediment loadings of the various sites at Mines 1–5 were 162 ± 85, 103 ± 81, 426 ± 24, 527 ± 92, and 100 ± 39 ng/g, respectively

Figure 3 also plots data for specific areas around the mining sites, directly under the sluice box, in various tailings ponds, and close to hydraulic pumps. The sediment close to the sluice box had the lowest average mercury loadings of these three categories and the sediment close to the diesel powered hydraulic pumps had the highest average loadings. The pump samples were taken at the points where water was first pumped into the mining pit and included water recycled from tailings areas and water collected in flooded forest floors or creeks. Hence, the higher loadings seen close to the pump samples could be due to the fact that (1) they burned diesel which could be a local source of mercury; (2) they received water and likely fines from tailings which may have been exposed to mercury during the mining process; and (3) they inundate a forest floor which could provide an environment conducive to mercury release from topsoil.

For one mine in Mahdia, samples were taken from the pit, sluice box, and tailings ponds, and the sediment total mercury loading increased at each stage as shown in Fig. 5. The designations used here to identify different tailings areas may not match those designations used by miners; however, it reflects various locations within the mine site that are separated by some type of makeshift boundary/earthen dam. Researchers have found that forest soils in the Guianas have total mercury loadings in the range of 30 to 800 ng/g (Richard et al. 2000; Grimaldi et al. 2008). Forest and overburden removal constitutes one of the first steps in the mining process and the low loading seen in the pit (29 ng/g) likely reflects the low background concentration of mercury in the ore. Between the sluice box and the first tailings pond area, the loading increased from 49 to 222 ng/g, and this could be due to inputs of mercury from the sluice

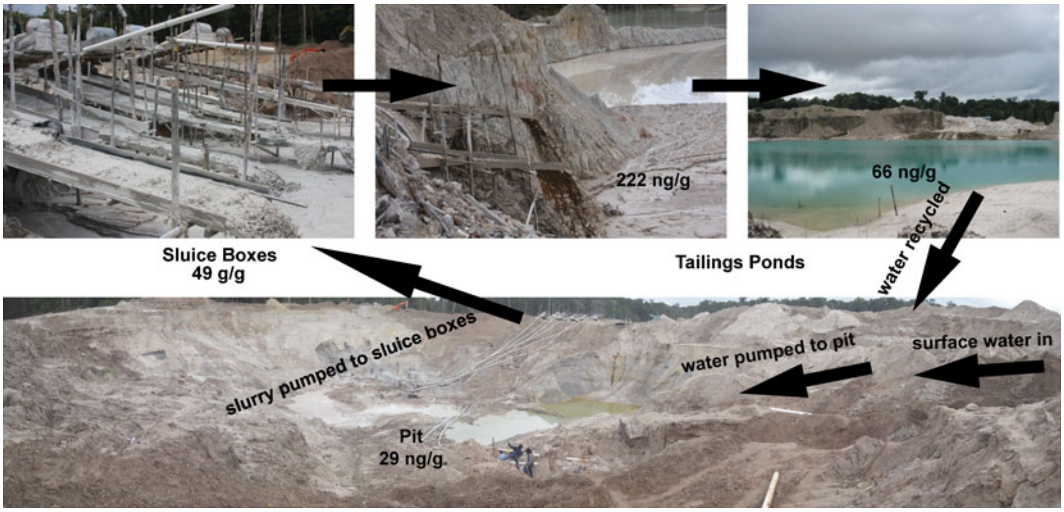


Fig. 5 Diagram of Mine 2 in Mahdia, showing main mining processes and areas sampled including: (1) the Pit where high pressure water is used to make a slurry with the ore; (2) Sluice Boxes fitted with mats that trap gold bearing ore as slurry passes over; and (3) Tailings Ponds where sediment is allowed to settle, sometimes with the help of flocculants

box, atmospheric deposition, or an increase in the concentration of finer particles. The sample from the sluice box was taken prior to passing over the black mat which collects denser gold bearing ore. Although the application of mercury to this mat is illegal in Guyana, miners sometimes apply mercury to increase gold recovery. However, surveys of miners done simultaneously with this sampling exercise did not reveal this practice in Mahdia.

The turbidity of the water sampled in the first ponded area was high (178 NTU) indicating a high percentage of fines which have been positively correlated with mercury loadings downstream from artisinal gold mines in Suriname and Guyana (Paktunc et al. 2004; Gray et al. 2002). Miners are encouraged to apply flocculating agents to their tailings and this likely occurred at Mine 2, prior to the last two tailings pond locations (Guyana Geology and Mines Field Officer, Colin Mathis, personal communication). This could explain the observation that as the tailings moved further away from the sluice box, from one ponded area to the next, the mercury loading decreased as did the turbidity.

Table 4 summarizes the more recent studies on mercury loadings in the less deforested Guianas where the highest sediment loadings observed have been in tributaries of small or medium scale mining activity (Gray et al. 2002; Spadini and Charlet 2003; Charlet et al. 2003; Miller et al. 2003), but where high levels have also been recorded at remote areas (Spadini and Charlet 2003). For the most part, the higher end of the range of sediment loadings in US streams (Scudder et al. 2009) and in Brazil (as summarized by Miller et al. 2003) are greater than values observed in the sediments from the Guianas, even in active gold mining sites that use mercury. The upstream sediments and unmined baselines found in other studies of the Guianas in Table 4 includes coastal areas and the range of loadings varies from 14 to 150 ng/g whereas the sediments from mining sites or tributaries downstream from mining sites ranged from 5.5 to 6,200 ng/g (Spadini and Charlet 2003; Charlet et al. 2003; Gray et al. 2002; Miller et al. 2003). Soil loadings in the ECEREX reserve area and Sinmarry river in French Guiana ranged from 30 to 800 ng/g with higher loadings seen in forest soils and more specifically in oxisols (Richard et al. 2000; Grimaldi et al. 2008).

The mercury loadings of sediment and mine tailings observed in this study fall within the range of loadings observed in similar sites throughout the Guianas (Richard et al. 2000; Gray et al. 2002; Spadini and Charlet 2003; Charlet et al. 2003;

Table 4 Range of mercury concentrations seen in sediment from this and other studies

Location	sTHg (ng/g)
Arakaka (this study)	41–300
Mathews Ridge (this study)	190–1,200
Port Kaituma (this study)	142–364
Mahdia mine wastes (this study)	29–601
Konashen river and creek sediments (this study)	92–301
Iwokrama river sediments (this study)	53–298
US Streams (Scudder et al. 2009)	
Unmined basins	0.90–2480
Mined basins	0.84–4520
Brazil Summary (Miller et al. 2003)	
Channel sediments[a]	<20–19,800
Soils[b]	30–406
French Guiana Sinnamary River (Richard et al. 2000)	
Forest soils	50–480
River sediment	10–1550
Lateritic soils	40–180
French Guiana (Grimaldi et al. 2008)	
Oxisol at ECEREX reserve	300–800
Utisol at ECEREX reserve	30–300
French Guiana (Spadini and Charlet 2003)	
Coastal and ECEREX non mining area	<150
Upstream from mines	<400
Streams below mines	50–6200
French Guyana (Charlet et al. 2003)	
Litany river (uncontaminated)	74–150
Mining tributaries	254–350
Artisinal Au mines Suriname (Gray et al. 2002)	
Mine wastes	5.5–200
Streams below mines	110–150
Uncontaminated baselines	14–48
Essequibo and Mazaruni rivers, Guyana (Miller et al. 2003)	
Essequibo river (mining)	4–225
Mazaruni river (mining)	5–707

[a]Summary of studies done up to 1995
[b]Summary of studies done up to 2000

Miller et al. 2003); however, the loadings observed at the conservation areas were not as low as those seen in some baselines for river sediments in this region (Spadini and Charlet 2003; Charlet et al. 2003; Gray et al. 2002). The Iwokrama samples were taken from the rivers on its periphery where mining likely occurs on lands outside its jurisdiction. The three highest samples were identified by staff as areas where they thought may be impacted by some sort of historical mining activity. Hence, it is very likely that the levels reflect mining and it may be unfair to classify those samples as representative of an uncontaminated baseline. It does serve as a baseline from which future and more extensive monitoring programs can reference. Sampling for mercury within the site itself will provide important information on the impact of various income generating activities like sustainable logging and can be used to better understand the dynamics of coupled human natural systems.

Samples in Konashen were taken from areas where the Wai Wai had relatively little recollection of mining activity and in the Essequibo headwater region with low population density (0.032 persons/km^2) and not much through traffic. Using published geospatial data on registered gold mines and logging activity in Guyana, Konashen is the farthest from registered gold mines and logging activity of all sites sampled in this study (Hammond et al. 2007). The Wai Wai practice slash and burn agriculture which also could release mercury rich topsoil to the rivers, but most of the sample sites were taken upstream of village plots in areas considered amongst the most pristine in the world (see Conservation International's Rapid Assessment Program). Konashen borders the Brazilian gold producing state of Para (mining activity concentrated some distance away) and also lies approximately 200 km west of registered, but not necessarily active, mines in Guyana, and the influence of atmospheric releases from those areas on Konashen is unknown.

Conclusion

The mercury loadings observed in sediments and soils in Guyana fall within the range of loadings seen in French Guiana and Suriname. The active gold mining areas studied in Guyana had average mercury loadings (226 ± 171 ng/g) that were similar to that of the two conservation areas (187 ± 77 ng/g). The two conservation areas are Konashen, the southernmost part of Guyana and source of the Essequibo river which drains the entire country, and Iwokrama, located closer to heavily mined areas around the middle of the Essequibo river. Further studies are needed to elucidate the reasons for these similarities which could include: nature of sediment in these areas, atmospheric deposition patterns for this region, and historical and illegal (i.e., non-registered mining activity) use of mercury in these areas.

The maximum mercury loadings in sediment were observed around mining sites which visually appeared to have higher iron deposits (Mines 3 and 4 in Mahdia). Surveys of miners conducted along with media sampling (to be published elsewhere) did not clearly reveal substantial differences in mercury management practices or awareness amongst the five different mining sites studied in Mahdia. The differences in loadings between these mines could be due to the nature of the ore (mercury already present in ore, mercury retained after ore is mined through addition by miners or atmospheric deposition); management practices; or atmospheric deposition patterns. If management practices (no mercury added to sluice boxes, retorts used, flocculants added to control fines, tailings areas designed to reduce runoff to creeks, etc.) result in the differences observed, then awareness and regulation could reduce the kind of mercury loads seen at Mines 3 and 4. If mercury is either already present in ore or atmospheric deposition patterns favor a specific area, then regulating mercury application during the mining process may not have a significant impact on reducing mercury loads in tailings areas. Instead, emphasis would have to be placed on ways to reduce sediment loss from the mining site and treatment of any runoff. Further studies should try to establish the reasons for the differences between these mining sites. Regardless of the results from such studies, however, improved management of tailings are needed which include mine restoration efforts.

The small to medium scale gold mining industry is currently the largest contributor to Guyana's GNP, larger than even agricultural exports. Yet, very little has been done in terms of local research and development to improve this industry and implement safety and environmental standards that protect both miners and surrounding communities. Better industry practices (retorts, public awareness, mercury free technology, proper tailings management) for small- to medium-scale miners are definitely needed; however, implementation has remained a challenge in places like Guyana (Hilson 2006; Hilson et al. 2007; Hilson and Vieira 2007). The LCDS has triggered internal and external evaluation of the sustainability of all forest related activities, thereby acting as a catalyst for improvements in the gold mining industry. Not only is a ban on mercury use likely to occur by 2011, but also tailings management pilot projects have started in Mahdia since the sampling in March 2009 reported in this paper.

The conservation areas are home to different indigenous populations whose diet consists of a range of locally caught fish and protection of their health requires fish sampling, advisory development, and capacity building. Whilst this also applies to mining areas, it is a less pressing issue in those communities as they have more access to other meats like chicken. IIC, CI-Guyana and WWF-Guianas have all independently established water quality monitoring programs with local communities at various conservation sites in Guyana's forested regions. Mercury monitoring is expensive and not included in most of their current data collection activities which is limited to basic water quality parameters and some Total/Fecal coliform analyses. WWF-Guianas has invested in analytical equipment to measure mercury which has been placed at the University of Guyana and the Guyana Gold Mining Commission (GGMC); however, much more support is needed to mainstream their use and application. The LCDS can potentially provide funding for organizations like WWF-Guianas and the local governmental agencies to also monitor mercury levels of fish and develop advisory limits that protect health of the populations in these areas. Investment will have to be made to build local capacity to undertake these tasks.

Given that the measured baselines for conservation areas of Guyana have average mercury sediment and soil loadings similar to active gold mining areas, what does this mean from a regulatory standpoint and from an environmental monitoring perspective aimed at protecting human health? If mercury use is banned, will levels seen in tailings from sites like Mines 3 and 4 decrease or will these sites continue to exhibit high loadings, either because it naturally occurs in the ore, or because the ore acts as a sink for atmospherically deposited mercury? This poses challenges for tailings management and as the LCDS discussions continue, it may even be possible that some miners find more sustainable alternative livelihoods in the forested regions. Out of a score of 10 on the Corruption Perception Index in 2008, where the least corrupt scored 10, Guyana got 2.6 which made it the 126th least corrupt of 180 countries ranked (Transparency International 2009). This emphasizes that the proposed LCDS should be monitored closely to ensure that visions for more sustainable forest livelihoods are translated into support and resources actually needed to properly engage and protect local communities.

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