Impacts of Artisanal Small-Scale Gold Mining on Water Quality of a Tropical River (Surow River, Ghana)

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ABSTRACT

Rivers in Ghana provide environmental and economic services such as fishery and farming, and are also the main sources of clean drinking water. Artisanal small-scale gold mining (ASGM), a significant industry in Ghana, typically occurs near streams and rivers in order to obtain a source of water for processing and waste discharge. ASGM is subsistence mining carried out by individuals or small collectives using rudimentary technologies for both extraction and processing of ore. Using small quantities of mercury for gold extraction, ASGM also releases high quantities of sediment, (along with metals and other contaminants) into local water bodies, posing environmental and downstream human health risks. In Ahafo, Ghana, we undertook a detailed assessment of the effect of ASGM on the water quality of the Surow River over one year (January 2013 to April 2014). Physico-chemical properties of the water at 11 sites along the river (above and below ASGM sites) were measured monthly. Our research indicates that the impacts of ASGM extend beyond Hg contamination, with the main effects of ASGM on river systems being changes in water conductivity, sediment loads, and metals, as well as alteration of river morphology. Dewatering water was responsible for significant increases in conductivity. We did not detect mercury above drinking water standards, with the exception being at the headwaters, presumably from natural sources. In general, we found that sites with associated ASGM activities had water qualities that did not meet Ghanaian national standards for drinking water, with manganese at particularly high concentrations. We also saw temporal variability in water quality parameters, likely due to the combination of fluctuating ASGM activities and the natural seasonal hydrology of tropical river systems.

Keywords: ASGM, sedimentation, mine dewatering, river ecosystems

INTRODUCTION

Rivers in Ghana provide not only environmental and economic services such as fishery and farming, but are also the main source of clean drinking water. Rural communities, particularly in areas where access to clean water is limited, often use untreated river water for domestic purposes including drinking. Where water is treated before consumption, declines in water quality within the rivers from pollutants and sediment loads from agriculture, industry, mining and forestry increase treatment costs (Fianko et al. 2010; Gyau-Boakye and Biney 2002). Coupled with declines in water quality, increasing demand (Gyau-Boakye and Biney 2002), and declining rainfall (Gyau-Boakye and Tumbulto 2000; Owusu and Waylen 2009), rivers in Ghana are under pressure.

Artisanal small-scale gold mining (ASGM) is a globally-significant industry, providing rural employment directly to at least 15 million people and indirectly to over 100 million in more than 70 countries (WHO 2013). Many ASGM operations occur near streams and rivers for easy access to alluvial ores, but also to supply water used in processing and as a receiving environment for mine waters. Although ASGM contributes to rural economies, it often results in degraded environmental, safety and social conditions due to the rudimentary mining and processing techniques used (Hilson 2002; Telmer and Veiga 2009). ASGM traditionally relied upon secondary and tertiary materials easily found near to the surface or river banks. However, due to depletion of alluvial resources and increased technical and financial capacities, contemporary operators are increasingly mining primary ore found underground, by manually digging vertical shafts or tunnels up to 30 to 35 m deep. These shafts and tunnels often require dewatering, with large volumes of untreated dewatering water often pumped out of these underground operations into nearby rivers and streams. Metal released from processing, dewatering or acid rock drainage can further degrade river water quality. Particularly concerning in ASGM is the widespread use of mercury amalgamation techniques in processing, although cyanide processing is increasingly being used in reprocessing of tailings (de Andrade Lima et al. 2008; Velásquez-López et al. 2011). Mercury processing emits toxic vapours, with predicted global mercury emission by ASGM to be 727 tonnes: 35% of the total world anthropogenic emission of mercury (UNEP 2013). The toxicity of mercury derived from ASGM operations to people and, to a lesser extent, the environment, has been well studied (Bose-O'Reilly et al. 2010; Castilhos et al. 2006; Donkor et al. 2006). However, the impact of AGSM operations on the broader water quality of these river and streams has been largely overlooked.

Previously, we identified a range of potential environmental impacts of ASGM on rivers, such as changes in hydrology and water quality (particularly increased turbidity), as a result of land clearing, erosion, mining and processing (Macdonald et al. 2014). Hydrological changes in rivers can alter available hydrological habitat for aquatic biota (Blanchette and Pearson 2013), and increased turbidity may lead to smothering of aquatic plants, habitats, and biota. Clearing of riparian vegetation, unregulated sewage from mining camps and rubbish disposal can impact on the rivers nutrient concentrations and habitats. In Ghana, these environmental impacts are temporally variable, with ASGM demands for water during dry seasons and excess water in wet seasons altering the flow of the river/stream (pers. obs.). Further, degradation of the river water quality and ecology can have flow-on impacts to cultural values associated with the river, as well as fishing and suitability for drinking.

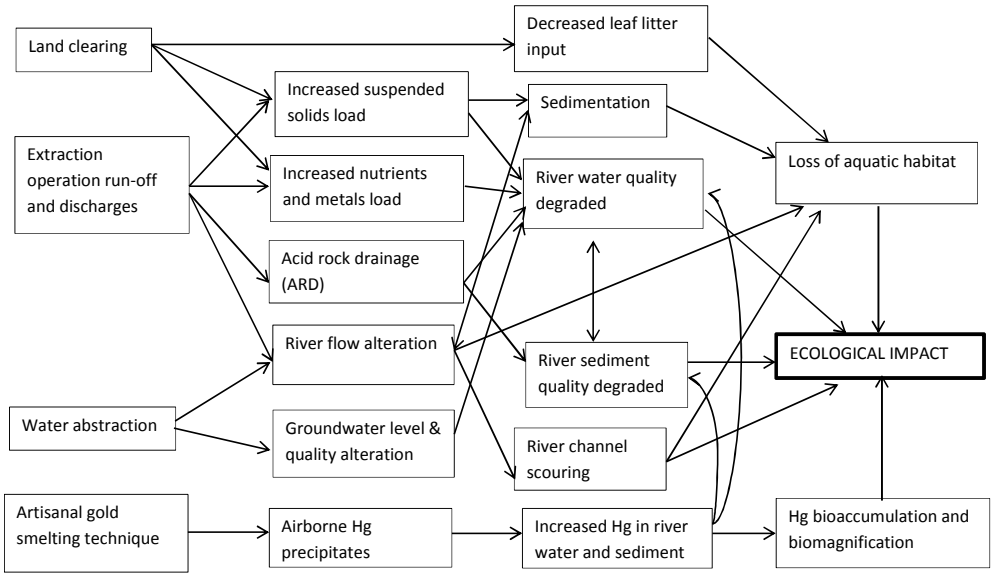


Figure 1 The impacts of artisanal small-scale gold mining (ASGM) on riverine systems (from Macdonald et al., 2014)

The impact of ASGM on tropical rivers has been investigated in Ghana, the Philippines, and Brazil, but the focus of these studies has been on elevated mercury concentrations and mercury cycling as a result of rudimentary processing techniques (Appleton et al. 2006; Bastos et al. 2007; Brabo et al. 2003). These studies were conducted on large river systems such as the Amazon in Brazil (Santos et al. 2000; Telmer et al. 2006) or the Pra (Donkor et al. 2005)and Ankobra Rivers in Ghana (Akabzaa et al. 2009) which have extensive and long-established ASGM operations with chronic mercury inputs. However, the scale and age of these systems prevents identification of other possible impacts besides mercury contamination. In contrast, ASGM activities in smaller rivers are easier to trace due to acutely concentrated nature of measurable impacts (see Webster et al. 1992). Therefore, this study is different from previously published research because of the focus on a smaller river, with the intention of more clearly defining the suite of impacts from ASGM operations.

The aim of this study was to identify the possible impacts of ASGM operations on water quality in the Surow River, a small tributary of the Tano River in Brong Ahafo, Ghana.

METHODOLOGY

Study site background

The Surow River catchment is located in the upper Tano River Basin in the Brong Ahafo region, Ghana, approximately 300 km northwest of the capital city of Accra (Figure 2). Major land uses in the Surow catchment are ASGM and agriculture among tracts of natural forest. Farming activities in the area include cash crop (cocoa), ranching and subsistence farming (vegetables and tubers). The Tano River (400 km long and 15,000 km^2 of catchment) is a major source of potable and domestic water for south west Ghana, and the Surow River is approximately 16 km long with a 3,500 ha. catchment. Located in a wet tropical region, the major rains occur during April to June (average

precipitation 294 mm/month) with minor rains from September to November (average precipitation 234 mm/month) and the driest months are from December to February (average precipitation 16 mm/month and evaporation 105 mm/month) (unpublished meteorological report NGGL, 2013). Therefore, rivers in the Tano Basin exhibit classical wet-dry hydrological patterns, driven by rainfall.

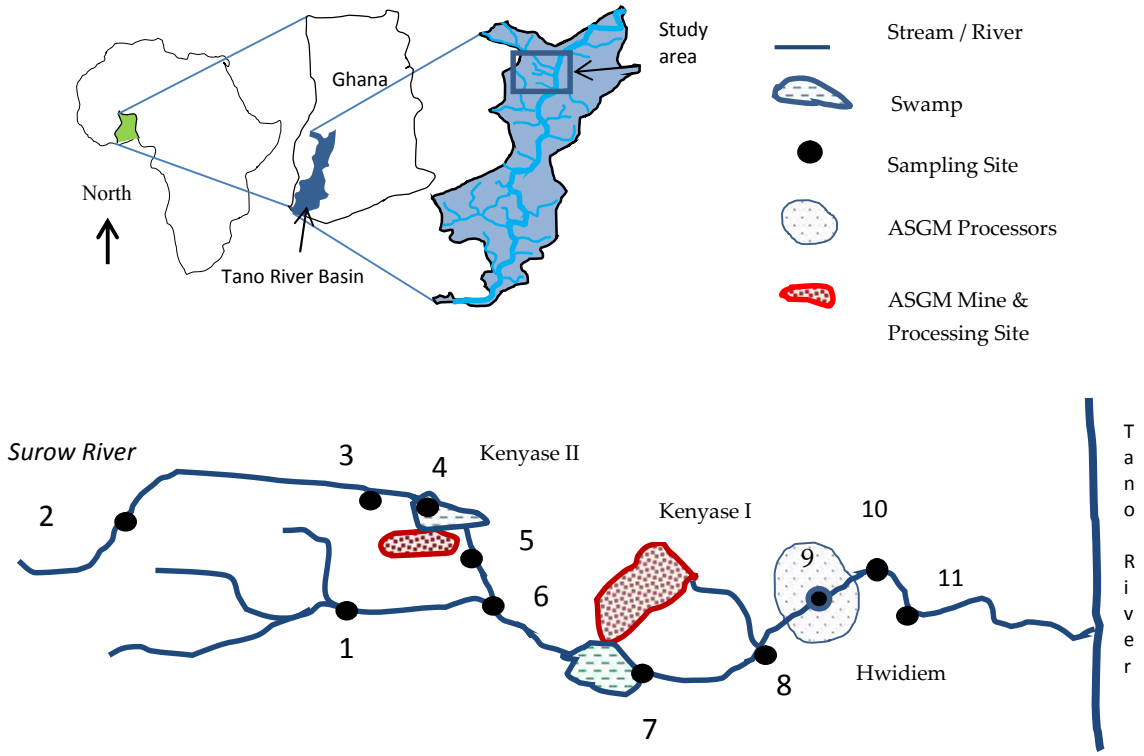


Figure 2 Location of sampling sites (1-11) along the Surow River, Ghana (not to scale)

ASGM has been practiced in many parts of Ghana for hundreds of years (Donkor, et al. 2005). However, operations are relatively new (9 years) to the Surow River catchment. ASGM in this area was started in 2005, following the commencement of a large multi-national gold mining project that discovered gold in the region. During the study period (February 2013 to April 2014), ASGM communities operated along the river at Kenyase I, Kenyase II and Hwidiem townships (Figure 2). At Kenyase I and II, small operators extracted secondary or tertiary alluvial ores easily found in the river banks, while larger operators extracted primary ore mined underground. Ores from these two sites are processed on site as well as sold to other processors mainly scattered near to the river at Hwidiem township. Loose gravel, sands and milled ores are processed via mechanical crushing, elutriation and, in most cases, mercury amalgamation followed by gold smelting and refining (see Macdonald et al. 2014).

Ghanaian legal provisions on mining exclude foreigners and foreign investments in ASGM operations. The sector, nevertheless, received foreign investments at least until March/April 2013 when the Ghanaian government deported as many as 4000 foreigners involved in the industry. As a result, many ASGM operators across the country (including those in Kenyase I and II) ceased most of their operations in May 2013, mostly due to lack of financial support previously provided by

foreign investors. Although underground mining activity was substantially reduced, dewatering of existing mine pits continued, especially during the wetter months. Smaller mining operators and processors, comprised of local citizens, continued to operate after the deportation.

Sampling program

Eleven sites on the Surow River were sampled monthly for 14 months from February 2013 to April 2014, typically within a 12 h period. Sites were chosen based on access, safety, and representativeness of catchment land use (Table 1). In addition, direct sampling of dewatering water at the Kenyase I ASGM site (sample site 8) was conducted once in April 2014.

Table 1 Hydrology and land use of sites (numbered upstream to downstream) on the Surow River, Ghana (February 2013-April 2014)

Sample site	Dominant site hydrology	Major land use
1	Riffle/run	Minimal use
2	Riffle/run	Minimal use
3	Pool/slow run	Minimal use, rural dwelling
4	Swamp	Mining, processing waste
5	Riffle/run	Minimal use
6	Run	Minimal use
7	Swamp	Mining, processing waste
8	Rifle/Run	Dewatering water
9	Riffle/Run	Processing
10	Riffle/Run	Cattle, cocoa farming
11	Pool/slow run	Rural dwelling

On each sampling occasion, and at each site, water depth and velocity (Marsh-McBirney Flowmeter, USA) were measured. Physico-chemical parameters of pH, oxygen reduction potential, dissolved oxygen (DO), temperature, electrical conductivity (EC), and turbidity were measured *in situ* using a Quanta Multimeter (Hach, USA). Water samples were collected 0.1 m below water surface and immediately divided into unfiltered and filtered (through 0.5 μm GF/C; Pall Ltd Metrigard) aliquots. All samples were stored at <4°C prior to analysis.

Aluminum, As, Cd, Cu, Cr, Mn, Pb, Zn in filtered water was analyzed using inductively coupled plasma mass spectrometry (ICP-MS) following USEPA Method 200.8; Fe and Mg were analyzed using ICP (USEPA Method 200.7), and Hg was quantified using cold vapour atomic absorption (CVAA; USEPA Method 245.1,detection limit of 0.0002 mg/L). Dissolved organic carbon was analyzed following USEPA Method 5310B. On unfiltered samples, total Kjeldahl nitrogen (TKN)

was analyzed via block digester method (USEPA M351.2); and total phosphorus was analysed with an auto ascorbic acid method (USEPA M365.1). The above samples were airfreighted to ACZ Laboratory in Colorado, USA.

Analysis of ammonia/ammonium (NH_3-N), nitrate/nitrite (NOx-N) and sulfate (SO_4) on filtered water were performed at the Newmont Ghana Ltd. environmental laboratory at Ahafo using a Hach DR 2800 spectrophotometer following APHA (2005) methods 4500B&C, USEPA Method 375.4; and USEPA Method 365.2 respectively.

Data Analysis

Water quality data was ordinated using principal components analysis (PCA) to illustrate patterns in the data, then compared among sites using permutational ANOVA (PERMANOVA). Data were prepared for ordination and analysis by selecting parameters where more than half of the samples were above detection; values below detection were replaced with half the detection limit, missing data were replaced by the average of any other data for that time and treatment, and auto-correlated parameters were reduced to a single representative parameter. Data were also normalized in Primer v6 prior to ordination and analysis. Significance testing of the multivariate data among sites was undertaken on PERMANOVA, using a two-way, unreplicated design with time (fixed) and site (random) as factors, followed by pairwise comparisons between sites. All analyses were performed on Primer v6 (Primer-E; Clarke and Gorley 2006).

RESULTS AND DISCUSSION

Water quality varied among sites (pseudo-F 2.36, $P<0.01$) and over time (pseudo-F 3.92, $P<0.01$), reflecting stochastic events, seasonal trends, and anthropogenic impacts. A PCA of water quality data, separated by month, illustrates the effect of seasonal trends on the data is presented in Figure 3 (note different axis scales). On most occasions, water quality at the headwater sites (1, 2, 3), and minimal land use sites (5, 6) were closely associated with each other, with the exception of site 6 in September and October 2013. Water quality at sites 1, 2 and 6 were not significantly different to each other, but were different to 5 (Table 2). Water from sites 1, 2 and 3 (headwaters) had low EC (0.11-0.35 mS cm^{-1}), turbidity levels generally below the Ghanaian EPA standard of 75 NTU (except on one occasion at site 2, and six occasions for site 3 where turbidity peaked at 247 NTU), and pH levels between 6.03 to 7.81. Water quality at the headwater sites reflects catchment mineralization (NGGL 2005), with silicate and carbonate mineral weathering, precipitation, and agricultural activities the most significant processes influencing the water quality in the area (Banoeng-Yakubo et al. 2009; Yidana 2009).

In March 2013, Hg concentrations at sites 1 and 3 exceeded the Ghanaian drinking water standards of 0.002 mg L^{-1}, reaching 0.003 mg L^{-1} – at no other time or site were standards exceeded. Mean (±SE) Fe concentrations declined downstream from 1.07±0.35 at site 1, to 0.25±0.10 by site 9. The Ghanaian drinking water standard for Fe is 0.3 mg L^{-1} and the EPA standard is 1 mg L^{-1}; essentially, exceedances occurred at headwater sites. Manganese exceeded the Ghanaian drinking water standards (0.05 mg L^{-1}) in 93 out of 130 samples, and the EPA standard (0.1 mg L^{-1}) in 67 samples across all sites and times (Figure 4). Although there were exceedances of both standards at sites 1 and 2, at site 3 every sample exceeded the drinking water standard. Sites 4, 5 and 6 (further downstream) had progressively fewer exceedances of the drinking water standard for Mn.

Therefore, Hg, Fe, and Mn concentrations in the Surow River do not appear to be directly related to ASGM operations, instead reflecting local geologies.

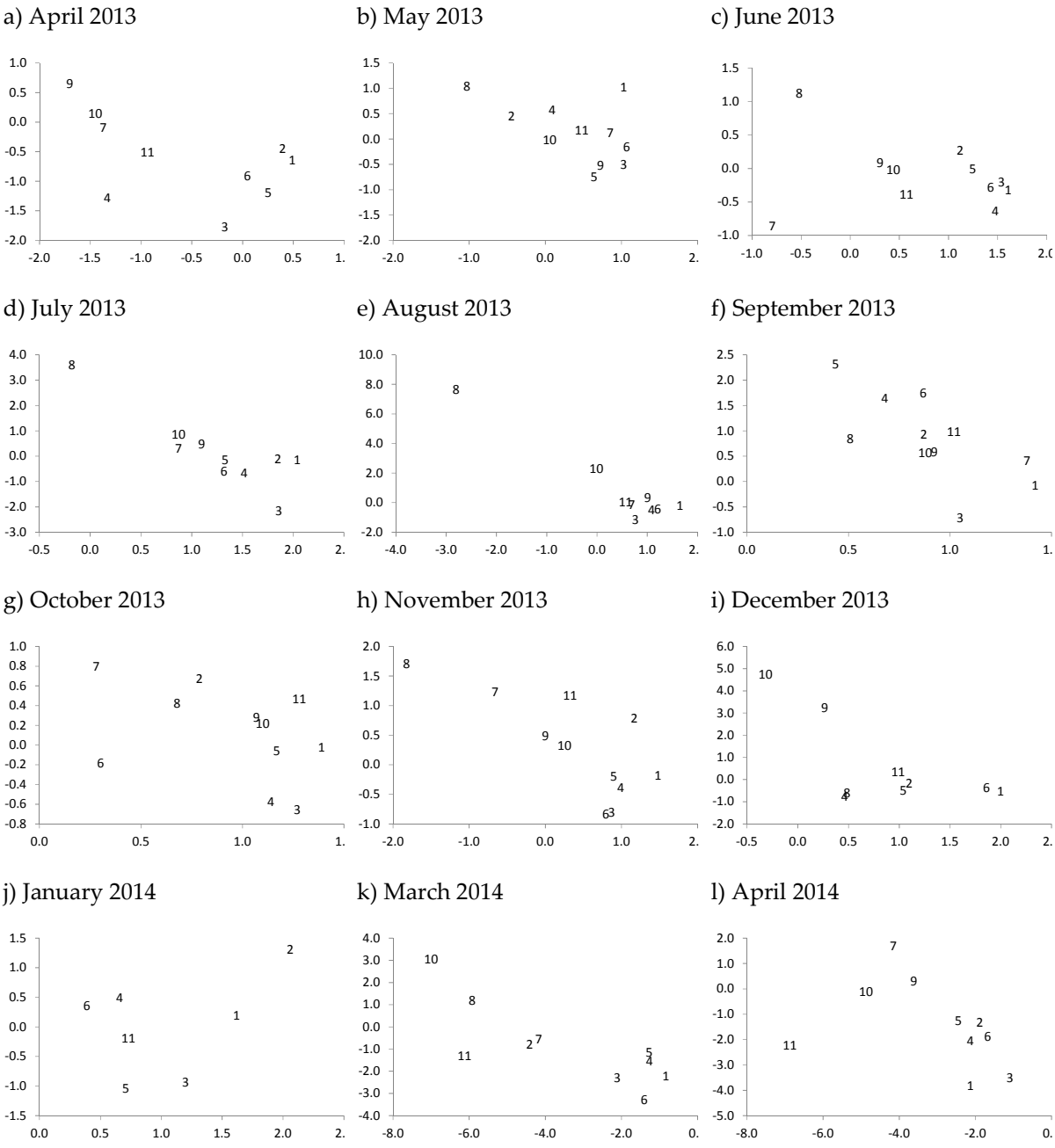


Figure 3 PCA of water quality data per sampling month (a-l) showing each site. Each graph is a subset of a single PCA on all available data. Note different axis scales

Sites 5 and 6 were similar to 1, 2, and 3 on most occasions (Figure 3), even during the period of highest ASGM activity (prior to May 2013) at site 4. At sites 5 and 6, EC ranged between 0.14—0.31

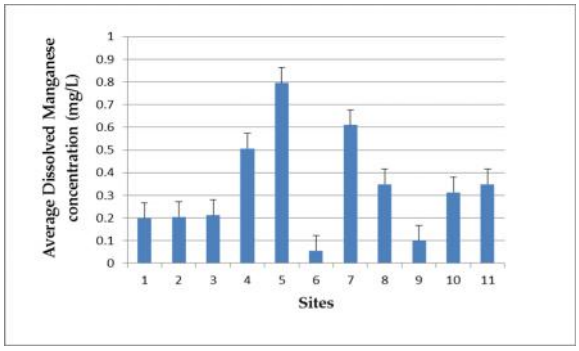
mS cm^{-1}, turbidity was 30—247 NTU and pH was 6.57—7.69, with metal concentrations similar to that of the upstream sites, except for Mn concentrations, which were among the highest of all sites at site 5 ranging between 0.03—3.11 mg L^{-1} (mean 0.8±0.3 mg L^{-1}). The similarity of sites above and below site 4, a site of intense ASGM activity, suggests that the impacts of ASGM, as measured, are highly localized.

Site 4 was separated from headwater sites (1-3) in April 2013 at the height of AGSM operations. Pairwise comparisons between all sites (across all times) show no significant differences between the two main ASGM sites 4 and 7, with 5 similar to 7 but not to 4. The start of the wet season in September 2013 altered the relationship among all sites. Although ASGM activity partially returned to site 4 in April 2014, the impact on overall water quality was not pronounced (as indicated by a lack of separation from other sites; Figure 3), possibly due to the heavy rainfall and high flows at this time. Magnitude and timing of flows appeared to have a variable impact on how different site 4 was from the rest of the data set.

At site 4, accumulation of sediment from processing at Kenyase II turned the defined river channel into a broad swamp. The site had a wider range of water temperatures (23.4-31.6 ^{o}C) than other sites - possibly due to its lack of canopy cover. The site had EC similar to the headwater sites (0.11—0.24 mS cm^{-1}) despite its proximity to an ASGM site, although underground mining activities were not significant during the study period (i.e., highly conductive groundwater was not being discharged into the river) Surface mining and ore processing were the main activities, resulting in high turbidity (peak >2000 NTU; mean 277±141 NTU) and sedimentation at site 4 (Figure 4). The number of exceedances of the Ghanaian EPA standard for turbidity was the same as site 3, although values were lower at site 3. Although the impact of ASGM operations on increasing turbidity are clearly visible before April 2013, after this time turbidity was also being generated at site 3. Higher flows during the wet seasons are naturally high in turbidity, with the sedimentation generated at site 3 washed downstream to site 4, and then carried further downstream to site 7. With the exception of Mn, dissolved metal concentrations were also similar at up- and downstream sites (5 and 6). Mean Mn concentrations at site 4 (0.51±0.24 mg L^{-1}) were higher than at site 3 (0.21±0.03 mg L^{-1}), indicating that ASGM activity was a source of the metal. Further, the only times that Mn concentrations were higher at site 4 than at site 3 was during periods of mining activity (April 2013, 2014, and December 2013). Mn is a hematological toxicant in fish, mammals and human (Crossgrove and Zheng 2004). Over discharge of manganese into aquatic ecosystems may affect the survival of natural fish population (Agrawal and Srivastava 1980).

In addition to site 4, sites 7 and 8 were highly impacted by ASGM activities, and tended to separate from other sites, particularly in June, July August, and November 2013 (Figure 3). Site 7 was highly turbid (up to 2000 NTU), particularly in comparison to headwater sites (Figure 4). At site 7, EC ranged from 0.20-0.95 mS cm^{-1}, pH ranged between 6.7—8.2, and occasionally had very high concentrations (and consequently mean concentrations) of NOx-N, TKN, Ca, and P compared to site 6 (site 6 being directly upstream of site 7, and unimpacted by mining). At site 7, metals were similar in concentration to site 6, with the exception of Mg which between December 2013 and April 2014 has concentrations at least an order of magnitude higher than site 6. There was a marginal increase in Mg seen at site 4 during April 2013.

a) Manganese



b) Turbidity

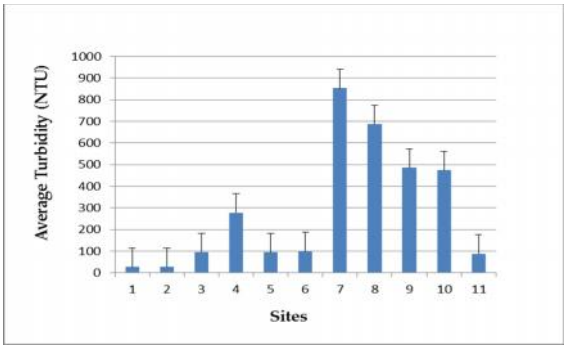


Figure 4 Mean (+SE) of a) manganese and b) turbidity at sites in the Surow River between February 2013 and April 2014. Sites are ordered upstream (1) to downstream (11)

The occasional spikes seen in nutrient concentrations at site 7 might be related to surrounding farming activities (cocoa plantation and cattle). Alternatively, in a forested stream, following a disturbance such as deforestation in the catchment, vegetative nutrient uptake is reduced while mineralization of organic matter is accelerated, which can result in elevated concentrations of NOx-N, Ca, Mg, K and Na (Webster et al. 1992). Site 7 is a swamp resulting from the deposition of sediment that came with the run-off from the exposed land, elutriation boxes, unregulated tailing, and waste material disposal at Kenyase I site. The size of ASGM operations at Kenyase I (site 7, 8) was larger than Kenyase II (4) this was also reflected in the relative size of the two swamps and mean turbidity values (Figure 4). River sediment is a sink of many pollutants and a medium for bio-geological processes including methylation of mercury; the quality of river water and habitats can strongly be influenced by quality of sediment (Chon et al. 2012; Kehrig et al. 2003).

Table 2 Significance of pairwise comparisons between sites from PERMANOVA (ns = P>0.05, t<1.3; s= P<0.05, t>1.3). See Table 1 for site details

	2	3	4	5	6	7	8	9	10	11
1	ns	s	s	s	ns	s	s	s	s	s
2	-	s	s	s	ns	s	s	s	ns	ns
3	-	-	s	s	s	s	s	s	s	s
4	-	-	-	s	s	ns	s	s	s	ns
5	-	-	-	-	s	ns	s	s	s	ns
6	-	-	-	-	-	s	s	s	s	ns
7	-	-	-	-	-	-	s	s	ns	ns
8	-	-	-	-	-	-	-	s	ns	s
9	-	-	-	-	-	-	-	-	s	ns
10	-	-	-	-	-	-	-	-	-	ns

Site 8 was significantly different to all other sites except 10 (Table 2), and was characterized by high EC (0.58±0.08 mS cm^{-1}; peak 1.02 mS cm^{-1} in April 2013) for the duration of the study, particularly during the height of ASGM operations (February-April 2013). Five out of 13 times EC exceeded the

Ghanaian drinking water standard (0.5 mS cm^{-1}) but not the EPA standard of 1.5 mS cm^{-1}. Site 8 received dewatering water from the underground mines at Kenyase I via a drain. Dewatering water at the Kenyase I mine was sampled directly in April 2014 and had an EC of 1.3 mS cm^{-1}, suggesting this as the most likely source of the high EC at site 8. Calcium, Mg and Zn concentrations were generally similar to site 7; and higher than sites 1 to 6, particularly during the dry seasons (although the reason for this pattern was unclear). Site 8 had a pH between 6.7—8.5 (the highest recorded pH at any site during the study); turbidity was high between 19—2000 NTU, with the low turbidities occurring during the wet season when discharge of a large amount of dewatering water occurred.

Sulfate concentrations were substantially higher at site 8 than at all other sites (108.3±46.4 mg L^{-1} compared to <13 mg L^{-1} at sites 1—6), except for in December 2013 when sulfate at site 7 was 281 mg L^{-1}. Sulfate concentrations exceeded the drinking water standard of 250 mg L^{-1} on four occasions. Dewatering water appears to be source of the sulfate obtained from the mineralization of the ores in the area, which mostly contain sulfide composites (NGGL 2005) typical of the Sefwi belt of the Birimian host rocks, the main source of gold and diamonds that extends across Ghana (Akabzaa, et al. 2009). Similarities between sites 7 and 8 were not observed in May, July and August 2013, where site 7 had water quality similar to the headwater sites, possibly reflecting the downturn in ASGM activity at this time.

Site 9 is surrounded by ASGM processors, but no mining activities, and water quality at site 9 was significantly different from all other sites except site 11 (Table 2). Although the high turbidity recorded at sites 7 and 8 also occurred at site 9, values at site 9 were generally lower (Figure 4). The high EC at site 8 did not persist at site 9, and concentration of most metals at site 9 were lower than at sites 7 and 8 –below the Ghanaian drinking water standard with exceptions of Fe (2 occasions) and Mn (8 occasions). Broadly, water quality at sites 9, 10 and 11 tended to be similar (Figure 3, Table 2), with the exception of after December 2013 where 11 separated from 9 and 10 (although water quality overall at site 11 was not significantly different to sites 9 and 10; Table 2). Although overall water quality at sites 9, 10 and 11 tended to be significantly different to upstream sites (Table 2), this distinction was not reflected in the PCA ordinations for May, June, October and November 2013, possibly due to increased hydrological connectivity during the times of highest rainfall.

Water quality at site 11 was only significantly different to sites 1, 3 (headwaters) and 8 (ASGM dewatering), likely because as the most downstream site, site 11 represents the cumulative impacts of land use within the catchment.

CONCLUSIONS

Previously, we identified a range of possible environmental impacts of ASGM on riverine systems. In the Surow River, Ghana, ASGM activities increased sedimentation, altered river morphology, and elevated Mn concentrations. As evidenced by high pH across all sites and times, we did not observe acid mine drainage, although the mineralogy of the area made it unlikely because it contains low levels of pyrite. Mercury was only detected in headwater sites, presumably from natural rock sources. Dewatering water discharges were found to substantially increase EC in the river, although, as with most observed parameters, impacts were local. During the wet seasons, we observed that higher flows in the river tended to reduce the differences between sites. Overall, water quality in the river at many sites did not meet the standards set for the environment by the Ghanaian EPA and for drinking water. Future work will investigate the effect of ASGM activities on river ecology.

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