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Riverine biota as environmental indicators of artisanal small-scale and large-scale gold mining impacts on riverine ecosystems in Brong Ahafo Region, Ghana

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Abstract. A study on two adjacent small ephemeral river systems in the upper Tano River Basin in Brong Ahafo, Ghana; one impacted by ASGM and the other by a modern large gold mining (LSM), showed that impacts of mining on river sediment and water quality and quantity were reflected in the macroinvertebrate and microbial communities. This study investigated the impacts of ASGM on the ecology of the Surow River and that of a large-scale mining (LSM, the Ahafo mine) on the Subri River between February 2013 and April 2014. Macroinvertebrate communities responded to the shift in river water and sediment qualities, whilst microbial communities tended to respond to water quality only. Bioaccumulation and biomagnification of mercury were evident in fishes in the river system impacted by ASGM, although mercury was barely detected in river water and sediment. The study confirmed that impact assessment of ASGM or the modern LSM on rivers should not be limited to the physical and chemical properties of water and sediment, but also include its riverine biota.

1. Introduction

Regardless of scales of operations and technology used, environmental impacts of gold mining on freshwater ecosystems may come from the mining works, mineral processing and disposal of mine wastes, mine dewatering, post-mining flooding and uncontrolled discharge of polluted waters [1] [2]. Such impacts may manifest at local, regional and global scales throughout the mine life cycle, and then even for millennia after the mine ceases [1] [3].

Most commercial gold mining operations are now modernized to improve their economic and environmental performance, however, millions of people with limited access to capital and modern technology still practice artisanal and small-scale gold mining (ASGM) using rudimentary mining and processing methods [4]. Mining techniques employed in ASGM range from panning and dredging the alluvial material deposited in riverbeds, to the digging of vertical shafts and tunnels, often by hands, to depth of up to 30 m to reach gold-bearing veins. ASGM commonly uses mercury amalgamation techniques, although cyanide processing has been introduced in many countries. ASGM operations can be legal or illegal, but the sector is typically undercapitalized, unorganized, and transient in nature [5]. ASGM is recorded from more than 70 countries but it mostly occurs in developing countries, where governments lack the technical and institutional capacity to provide adequate technical assistance or



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enforce compliance [6] [7]. This, often result in environmental degradation that is not properly assessed, monitored, recorded nor mitigated. Of particular concern is the fact that ASGM is commonly situated near streams or rivers which provide process water and sites for mine water discharge [8]. Ironically, ASGM operates mostly in tropical developing countries including Ghana, Brazil, Indonesia and the Philippines where access to clean water is a key environmental and sustainability issue.

Various standards and protocols are applied to water management in the modern mining industry across the globe. The standards and protocols, however, are largely based on the physical and chemical parameters, partly because these parameters are easily defined [9] and methods of analysis are standardised [10] [11]. The standardised physico-chemistry analysis of environmental water, however, may not always be appropriate in the flowing water environments[12]. Numerous substances in a wide range of concentrations can affect the quality of river water. In a flowing water environment, the types and concentrations of the substances vary continuously and erratically so that chemical survey can only represent stream conditions at the time and location of sampling [13]. Therefore, spills of highly concentrated substances that may occur occasionally, for example, may not be easily detected. Chemical testing can also be particularly difficult when applied to highly treated wastewater commonly seen in larger mining industry. Chemical testing on such samples may not reveal any evidence of pollution, while toxic substances at below detection limit concentrations may still seriously affect the aquatic organisms [9] [13]. Unfortunately, many countries lack of regulatory requirements on mining industry to monitor and assess its biological impacts [14] [15]. Much of the effort in incorporating biological parameters in the assessment and management of mining impacts on riverine ecosystems had been limited to Australia, New Zealand, North America, and Europe where biological parameters are part of their national water quality guidelines [16] [17].

Using results from our study on two river systems impacted by ASGM and a large gold mining in the Brong Ahafo Region of Ghana, this paper shows that biological parameters can be used in the assessment of large and small-scale gold mining impacts on riverine ecosystems as well as in differentiating impacts between the two different scales and methods of mining and processing. Specifically, the study aimed to determine whether and how ASGM and LSM impacted the respective river's water and sediment quality, macroinvertebrate and microbial (Archaea and Bacteria) community structures and resulted in mercury biomagnification in fish.

2. Method

This study investigated the impacts of ASGM on the ecology of the Surow River and that of a large-scale mining (LSM, the Ahafo mine) on the Subri River between February 2013 and April 2014. Potential impacts arising from ASGM and large-scale mining activities on riverine ecosystems is depicted in a model (Figure 1) that guided the study [18]. The model has been developed based on the knowledge that land clearing, pitting and tailings disposal for mining often lead to erosion and in some cases acid mine drainage (AMD). These processes increase transport of sediments, nutrients and metals including Hg in ASGM into the aquatic ecosystems that can turn into key environmental stressors affecting aquatic ecosystems through changes in habitat quantity and quality. Increased suspended solid concentrations which lead to sedimentation and mine water discharge or river water abstraction, can change local hydrology including flow and wetted area affecting habitat availability [19]. Metals, including Hg in the ASGM case, and in some places cyanide, used in processing can escape directly to the aquatic environment or indirectly to the soil and atmosphere which in turn are deposited into the aquatic ecosystems through rainfall and surface and subsurface runoff. Elevated concentrations of metals, nutrients and suspended solids in the water, may also result in poorer sediment and water quality which in turn can decrease (or increase) food for and reduce survival of aquatic biota resulting in changes in macroinvertebrate and microbial (Archaea and Bacteria) community structures and bio-toxicity (Figure 1)

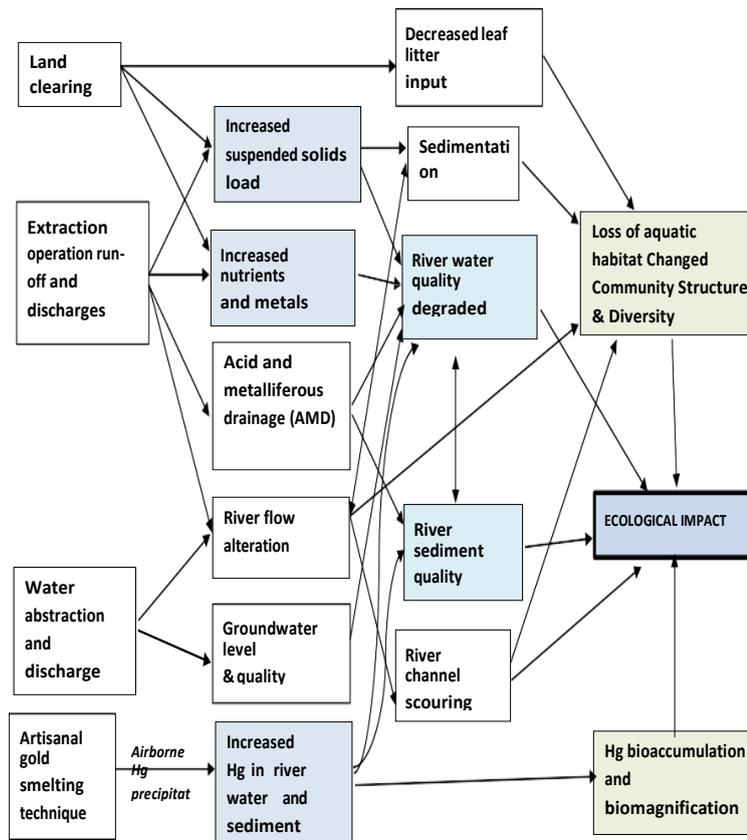


Figure 1. Gold mining impacts on riverine ecology.

Both the Surow and Subri rivers are ephemeral tributaries of the Tano River, in Brong Ahafo, Ghana. The Ahafo mine, currently operated by Newmont Ghana Gold Limited (NGGL), has been operating on the Subri River catchment since December 2006 and monitored environment water quality data since then, whilst ASGM started operations along the Surow River in 2007. Major ASGM operations ceased in May 2013 although smaller operators and processors remained.

We used a reversed BACI (Before/After and Control/Impact pairing) experimental design to determine ASGM impact on river water and sediment quality, and a conventional BACI design for that of LSM. Impacts on macroinvertebrate community structure were determined by comparing multiple control and impact sites sampled multiple times. The sequencing of 16S rRNA of Archaea and Bacteria was based on a one-off sampling and comparison between multiple control and impact sites on both rivers. The biomagnifications of mercury in fish was tested via analysis of correlations between mercury concentrations in fish tissue and fish trophic level, fish length (proxy for age) and fish weight.

Water, sediment, macroinvertebrates, and sediment microorganism were sampled from 11 sampling points on the Surow River and 3 on the Subri River which. The sampling sites were selected based on access, safety, representativeness of catchment land uses and longitudinal position relative to mining activities. Within the framework of BACI design, sites located upstream of known impacts (e.g. discharge from mining) were assigned as control sites, and those downstream as impact sites. Sampling sites selection also considered confluences between tributaries and the main river to allow for not only categorical analysis, but also gradient and multivariate analysis. Water samples were collected monthly, sediment and macroinvertebrate samples were collected four times during the study period, whilst the sediment microbial samples were collected once. Sixty fish samples were collected once from both rivers and downstream of their confluences with the Tano River.

3. Result and Discussion

3.1. *Impacts of ASGM on the Surow River's water and sediment quality*

At ASGM impacted sites on the Surow River, turbidity often exceeded the Ghanaian EPA Guidelines for freshwater ecology, whilst total concentrations of metals including Fe, Hg, and Mn exceeded the water quality guidelines applicable in the region, particularly during the active mining period. At a concentration ranging between 0.14 ppb and 2.6 ppb during the active mining period, the concentrations of total Hg in water in this study were not as high as that of reported from other ASGM studies.

Elevated concentrations of metals including Cr, Fe, Hg, Mn in riverine sediment around ASGM sites also exceeded the threshold levels of sediment quality for the protection of aquatic life. In February 2013, when mining was active, Hg was below detection limit of 0.03 mg/kg at the source of the river but was particularly high at ASGM sites exceeding the recommended maximum concentrations of 0.1 to 0.2 mg/kg for protection of freshwater ecosystems. The longitudinal trend of Hg concentrations and the fact that there was no other industry but ASGM along the river corroborated the inference that ASGM was the main possible source of Hg enrichment in the Surow riverine sediment. Positive correlations between mercury and Al, Ba, Ca, Co, Fe, Mg, Mn, P, K, Sr and S concentrations in sediment were also evident. Most metal and metalloid concentrations in riverine sediment, however, did not correlate with their corresponding total and dissolved concentrations in river water.

Most of the key features of impact on river water and sediment were reversed with the cessation of major ASGM operations along the river. They were also seasonal with increased dissolved metal and metalloid concentrations detected during the heavy rainy season. The differences between mining and non-mining sites also intensified by high precipitations.

3.2. *Impacts of large scale mining on the Subri River's water and sediment quality*

Unlike in the Surow River, despite the spatial and temporal changes due to gold mining operations, water quality of the Subri River complied with the Ghanaian EPA water standards for mine-related discharges and Ghana Water Company Guidelines for raw water.

However, exceedances in the concentrations of sulfate, nitrate, EC and TDS did take place, particularly in the mine site, indicating the potential for the leaching and release of elevated sulfate, nitrate and salt ions from the mine.

Elevated concentrations of salt ions and the temporarily increased concentrations of metals including Fe were recorded during land clearing and mine site preparation time in 2006. Turbidity, TSS, and concentrations of total As, Fe, Cl, Pb, and Mn in downstream Subri were reduced to levels similar to or lower than upstream and before mining since the installment of a series of Environmental Control Dams (ECDs) as sediment control measures. Riverine sediment quality also complied with sediment quality guidelines for aquatic ecology at all sites.

3.3. *Fish total Hg concentrations*

Concentrations of As, Cd and Pb in all fish (60) in this study were below the LOD of 0.05, 0.05 mg kg⁻¹ and 1 mg kg⁻¹ respectively. Mercury, however, was detected in most fish samples, particularly in carnivorous species and larger herbivores (aged). Positive significant correlations between Hg concentrations with fish length across all rivers suggested that the Hg concentrations were affected by potential differences in fish age. In other words, Hg was bioaccumulated with age. Hg concentrations and trophic levels in both Surow and Subri rivers were also positively and significantly correlated, confirming that Hg was not only accumulated in fish tissue but was also biomagnified along the food web in the systems.

3.4. *Macroinvertebrate community structure*

The abundance, taxonomic richness and diversity indices of the macroinvertebrate communities did not significantly differ with rivers nor between control and impact. The interaction between rivers and control and impact was also not significant. However, macroinvertebrate community compositions

differed between rivers, control and impact, and the interaction between the two factors was also significant. The Subri River generally supports more macroinvertebrate taxa with higher diversity and abundance than the Surow. Further pairwise analysis showed that the macroinvertebrate community compositions at impact sites were also significantly different between rivers. More sensitive to pollutant taxa, including Ephemeroptera, were found in downstream Subri than in downstream Surow, whilst more tolerant to pollutant taxa, including Chironomidae, were found in downstream Surow than downstream Subri.

While the study does not have the before and after information to positively demonstrate whether gold mining had impacted macroinvertebrate community in the Surow and Subri rivers, this study shows strong significant relationships between macroinvertebrate community assemblage and some physico-chemical and hydrological features associated with the effects of ASGM and the Ahafo gold mine activities on receiving rivers. Differences in concentrations of metals/metalloids (Fe, Mn), salt ions (Ca, Mg, sulfate), TDS, nutrients (FRP and NO_x) as well as hydrological features (velocity, depth, discharge, rainfall) significantly correlated with differences in macroinvertebrate assemblages between rivers, between control and impact sites, and between the wet (flood) season and drier ones.

3.5. *Microbiology study*

In the one-off study of microbial communities, we found sediment microbial communities in the Surow and Subri rivers to be similar. Spatial variability within each river, however, was greater and unrelated to sediment chemistry, but significantly related to water chemistry. The shifts in microbial communities' composition at sites impacted by mine dewatering were evident. The shift was more significant in sites affected by mine dewatering from ASGM operations on the Surow than in sites affected by the large and modern mining operations on the Subri.

The study demonstrated that gold mining, regardless of size and methods, impacts the river ecosystems studied. The most significant pollutants in the affected riverine ecosystems appeared to be sediment particulates and minerals naturally available in the rock formation but exposed to the environment by mining activities. The study, however, strongly indicated that the types, magnitudes and effects of the impacts of ASGM on the riverine ecosystems were different from that of modern large-scale mining. The use, or the lack of, environmental management systems to mitigate impacts appeared to be the most important differentiating factor. We also witnessed significant improvements in both water and sediment quality in the Surow River with the cessation of major ASGM in the area.

Mercury, which was used in the ASGM in relatively small quantities compared to other countries, was largely undetectable in the waters but detected in the Surow River sediment (despite naturally low concentrations of Hg in the local soils). It also was undetected altogether in both sediment and water after ASGM ceased. Undetected Hg in river water, as experienced in this study, can also be due to the complications inherent with Hg analysis of natural water samples or the generally low concentrations of Hg. Mercury in water is also volatile and instable, changing into various forms, each may need specific method of analysis [20] that can be expensive and not easily accessed in places including Ghana. This highlights the shortcoming of a mere physico-chemical criteria in the assessment of ASGM impacts on river water. The fish tissue analysis of total mercury, however, confirmed that mercury bioaccumulated and biomagnified in fish from both the Surow and Subri rivers as well as in the Tano River, indicating the presence of mercury in the rivers. The source of Hg, however, could not be clearly established but may have been from artisanal amalgamation processes and from smelting.

Changes in the sediment and water qualities due to mining were reflected in the macroinvertebrate communities of both rivers. Increased sediment load and decreased sediment quality in the Surow River were reflected in the domination of sediment-tolerant taxa and lack of pollutant-sensitive taxa including Ephemeroptera and Trichoptera families. Contrarily, the mine-affected area in downstream Subri River had more sensitive taxa including Ephemeroptera families than the Surow River that could be due to the improved water and sediment quality as a result of the sediment control measures applied by the Ahafo gold mine. Although mine discharge in downstream Subri was of good quality water, it appeared to have altered the ecosystem compared to upstream control sections. Cessation of mine discharges at closure could see downstream sections of the river return to conditions more consistent with upstream.

Unlike the macroinvertebrates, the Archaea and Bacteria communities found in the Surow and Subri Rivers sediment did not respond to the shifts in sediment quality, but tended to respond to water quality, particularly turbidity and concentrations of sulfate, Fe and FRP. showed that. This is more evident in the Surow River reaches affected by ASGM dewatering discharges. This is consistent with the fact that in freshwater ecosystems, including flowing rivers, bacteria are sessile in the sediment and films, and are continually exposed to the water column [21]. The ubiquitous presence of bacteria, their roles in controlling water quality and sessile habits in river ecosystems give rise to the potential for bacteria as indicators of water quality and anthropogenic impacts, including mining, on riverine ecosystems. Given the one-off sampling nature of the sediment microbiology study, however, further study with repeated sampling regime is recommended.

4. Conclusion

Thorough investigation of the Surow and Subri rivers, two tributaries of the Tano River in the Brong Ahafo Region in Ghana, has demonstrated that gold mining significantly impacts adjacent river ecosystems. Sediment particulates were the most significant pollutants in the affected riverine ecosystems whilst excess surface water flows from the mining areas that were discharged into the rivers potentially became stressors affecting the biota communities in the riverine ecosystems. The macroinvertebrate communities of both rivers reflected the changes in the sediment and water quality due to mining, whilst the water microbial communities tended to respond to the differences in water quality only. Mercury, which was used by ASGM but barely detected in the Surow River water, was detected in sediment during the peak of ASGM operations and biomagnified in fish from both the Surow and Subri Rivers as well as the Tano River.

The study also showed that the physico-chemical criteria should not be used exclusively when assessing impacts of mining on stream water quality, but rather should be treated as a supplementary data to the more meaningful approach of the evaluating the biological conditions of the stream.

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