PHILIPPINE ENGINEERING JOURNAL
PEJ 2017; Vol. 38, No. 2: 79-98

Process Water Use and Water Quality in Selected Small Scale Gold Processing Sites in the Philippines

Roberto S. Soriano
Institute of Civil Engineering/ Environmental Engineering Program
College of Engineering, University of the Philippines Diliman

Virginia J. Soriano
Department of Industrial Engineering and Operations Research/ Environmental Engineering Program
College of Engineering, University of the Philippines Diliman

***Abstract*— Small-scale gold production contributes significantly to the total value of gold mined in the country. While the economic benefits from small scale gold production are promising, certain concerns such as water management and heavy metal pollution have been raised. This study provides actual documentation at nine observation sites across the Philippines to quantify the use of process water and the changes in water quality indicators in small-scale gold production. The results show a wide variability in the amount of water use due to the choice of method employed in the recovery of gold. Process water was measured to range from 1,424 to 38,512 liters per ton of ore with a mean of 17,723 liters per ton of ore. On the average, the process water usage associated with sluicing, milling, cyanidation, and panning accounted for 79%, 16%, 4% and 1% of the total process water, respectively. The laboratory analysis of the process water also showed that heavy metal content for arsenic, cadmium, mercury and lead above the effluent standards for gold ore mining were detected in some stages during the gold extraction process. The results can be used to identify potential stages in improving the efficiency of water use in the gold extraction stage for small scale facilities and in adopting water saving alternatives. Furthermore, the results can be useful for identifying the potential impacts and proper management of the effluents from the processes. Recommendations to improve management of water resource and water quality are discussed and presented.**

Keywords— Sustainability, Small scale gold production, Water use, Water quality

1. INTRODUCTION

Gold production is a significant economic activity in the Philippines. According to the Mines and Geosciences Bureau (MGB), the estimated value of gold produced by the country's mining industry in 2014 is at PhP 33 Billion [1]. It is further estimated that about 28 tons of gold, or 80 percent of the country's annual gold production, was produced by the artisanal and small-scale mining over the past 10 years which amounts to an annual gold production worth PhP 56 billion at the average price of gold in 2017 [2].

Roughly 300,000 individuals benefit, directly or indirectly, from small-scale mining activities in the country [3]. The Benguet Federation of Small Scale Industries, a group of small-scale miners in Benguet, produces roughly three to four tons of gold annually (personal communication with Engr. Lomino Kaniteng). At the 2017 price of gold, three tons of gold amounts to PhP 6 Billion produced by these miners [2].

While this activity is recognized to have largely contributed to rural development and poverty reduction, the small-scale gold production in the country is perceived to be an informal and unregulated industry with minimal standards. With the increasing number of small-scale miners, sustainability has become a major concern mainly due to the production inefficiencies, the associated wastes from the ore and mineral processing, and their improper disposal.

The continuity and growth of the small-scale gold production industry is hinged to a large extent on the sustainability of small-scale mining activities. It is therefore important to determine the level of sustainability performance of current practices in small-scale gold production. Based on literature, a framework for sustainability indicators as a tool for performance assessment and improvements for mining and minerals industry has been developed but is more applicable to large scale operations [4]. Thus, there is a need to develop a performance assessment tool with sustainability indicators relevant and suitable for the small-scale gold production systems.

In view of the foregoing, a project study was commissioned by the Philippine Department of Science and Technology (DOST) through the Engineering Research and Development for Technology (ERDT) under the Mineral Extraction with Responsibility and Sustainability (MinERS) Program, entitled: Project G - "The Gold and Copper Chase: Life Cycle Analysis of Sustainable Small-Scale Production Systems". The study used life cycle and systems thinking approach to assess the impact of current practices on the economic, environmental, and social aspects on the sustainability of small scale gold production activities.

This MinERS project study was conducted within the period of October 2013 to November 2016. Small-scale mining sites located in the provinces of Abra, Benguet, Camarines Norte and Compostela Valley were chosen for their reputation as regular gold mining areas for many decades. The locations of the observation sites and the relevant political and watershed boundaries are shown in Figure 1.

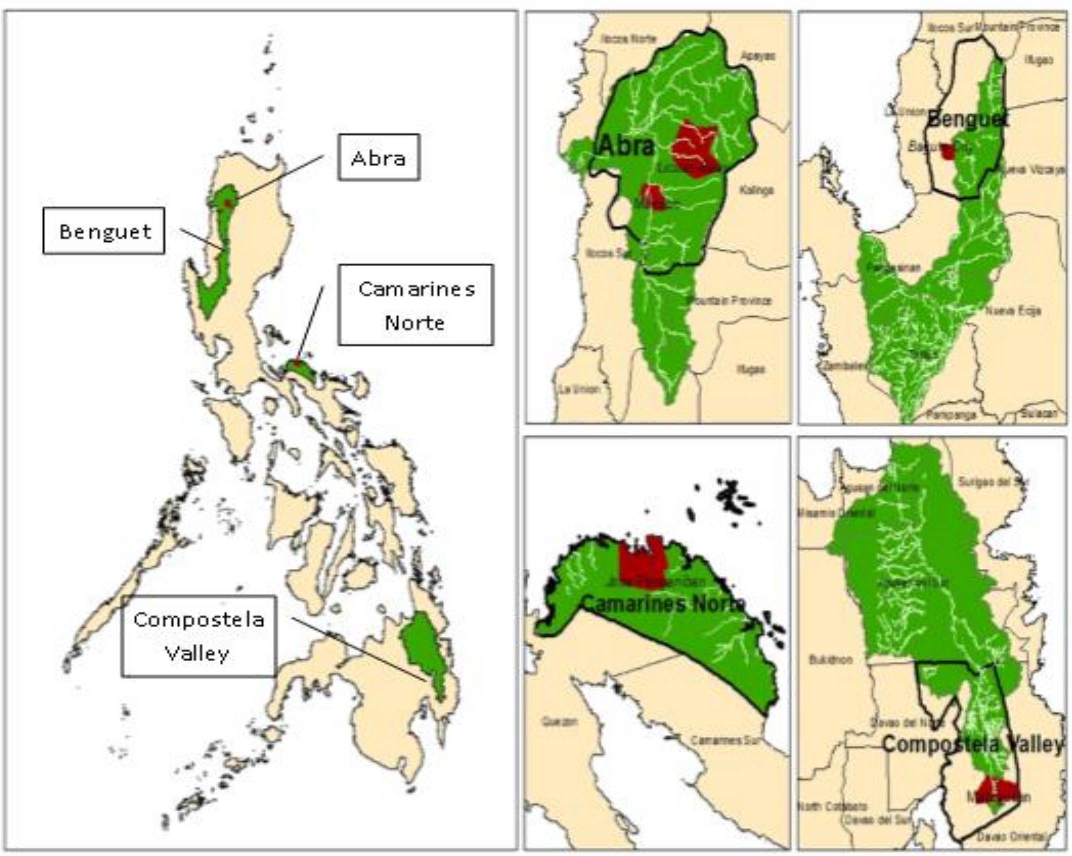

Figure 1. Map showing the location of the municipalities of the observation sites and their respective political (provincial) and hydrological (watershed) boundaries

Small-scale entities involved in gold ore mining and processing were identified. Coordination meetings, workshops, initial site visits and interviews were conducted with relevant government agencies and local government units, owners and staff of the gold mining and processing facilities, and officers of existing small-scale miner associations and cooperatives. These consultations yielded a total of nine (9) observation sites that were amenable for observation and detailed documentation.

The MinERS project study observed and analyzed the life cycle stages of small-scale gold production systems specifically from ores mining, gold extraction to storage and disposal of tailings from extraction processes, as shown in Figure 2. This paper is part of the MinERS project that deals with the water usage and the associated changes in water quality of the process water during the gold extraction stage and tailings storage (enclosed in a dashed box, Figure 2).

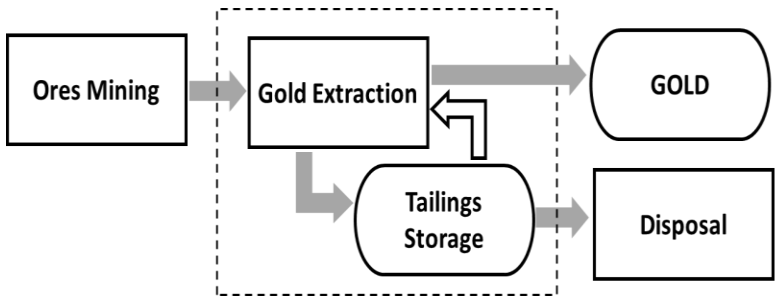

Figure 2. Stages of small-scale gold production system used in the MINERS project study

To provide the basis for assessing the sustainability performance of the small-scale gold production sites, the key factors for small-scale gold production system were identified and documented in order to characterize the various activities and the physical flows of materials and resources for the production of gold. The main project activities included the detailed data collection, research and documentation on life cycle costs, productivity or efficiency, and environmental data for the current processes. Structured interviews with survey tools, direct observations and actual measurements were carried out together with collection of water and wastewater samples for laboratory testing. The input – output material flow based on the diagram in Figure 3 was used for the detailed inventory and measurements of the factors of production including material, energy, water and other inputs, as well as the product output, wastes, emissions and other releases.

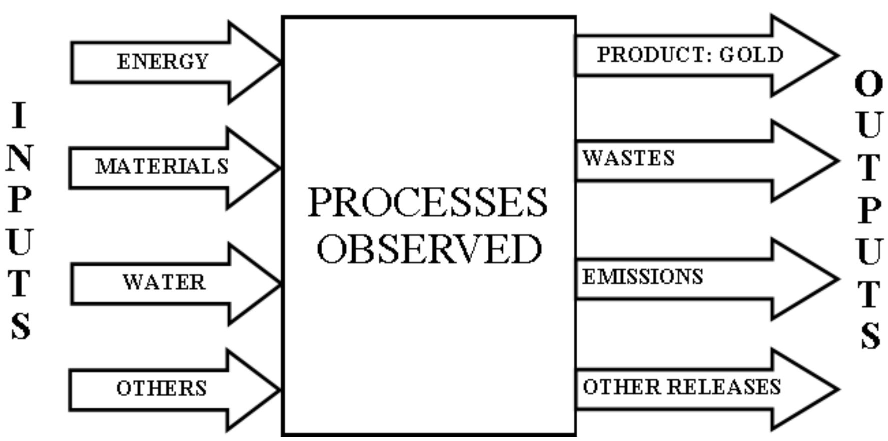

Figure 3. Input - Output Material Flow Diagram

For the economic and environmental aspects of sustainability performance of the observed processes, measurement of the relevant inputs (such as cost of materials, energy, water, labor and processing time) and impacts from the use of input resources, wastes, emissions and other releases from all life cycle phases were determined. Once data is available, the systematic evaluation of environmental burden of the processes of a product or system can be applied [5].

Water is one of the main inputs in the gold production industry. During the ore processing stage, water is utilized in some of the processes or steps used in extracting gold. Information on water use and the quality of the ensuing discharges from the processes involved in small-scale production process in the Philippines are still lacking [6].

As a finite resource, its availability could influence the different activities during the gold ores processing which in turn could also impact the hydrological regime and the environment. Apart from availability, the water quality risks can be traced to the exposed mine voids, the waste rock and tailings dumps or ponds through drainage, seepage or overflow that may result to release of potentially saline, metalliferous or acidic pollutants [7]. Furthermore, long term water quality risks that are linked to the management of waste material and mine voids must be taken into account since the water quality impact from the filling of abandoned mine voids may even continue for many years as a function of the hydrologic retention time and geochemical interactions [8].

This paper focuses on quantification of water as an input to the processes and the indicative effect of these processes to its quality.

2. OBJECTIVE AND SCOPE OF THE STUDY

This paper aimed to quantify the amount of process water associated with the currently practiced gold extraction processes and assess the potential environmental implications in terms of changes in the quality of process water from the processing sites.

This study is limited to the observations and analysis of water use from a total of the nine processing sites. The scope of this study is shown by the dashed box in Figure 2. The ores containing gold are already available at the processing sites, then undergo selected extraction processes until gold is produced while the tailings are stored in ponds or dumpsites.

3. SMALL-SCALE GOLD PRODUCTION IN OBSERVATION SITES

Fundamentally, the mineral ores are broken up and carried to the surface at the mining sites. In small-scale gold processing, the extraction and processing of ore materials are done either on-site or transported to a community processing facility where gold is extracted from the ore materials. Comminution is done first by crushing, the process of breaking the materials containing gold into smaller pieces to facilitate the liberation of the gold particles from unwanted mineral wastes through the use of crushers. Crushing is usually a dry process. Further, fine size reduction is achieved by milling, the process of grinding through the use of mills with steel rods or balls. Milling or grinding is usually a wet process.

Copyright 2017 | Philippine Engineering Journal

Gold bearing concentrates are separated from the host rock material by gravity concentration method or chemical leaching. The ore concentrates then undergo refining to recover the gold from the other minerals.

The observed gold extraction processes varied from one site to another and is summarized in Figure 4. The sequence and combination of processes shown in the figure are based on actual field observations as practiced in the nine observation sites.

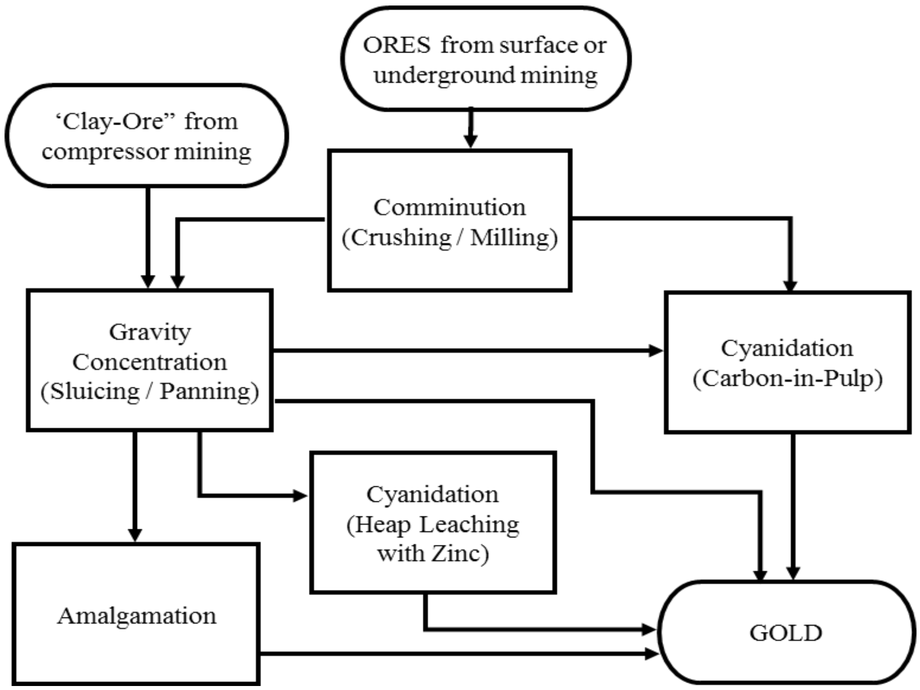

Figure 4. General process flow for gold processing

As observed, there are several combinations of processes to extract the gold from the ores. These include a) gravity concentration through sluicing of clay particles containing the gold that were obtained from "compressor mining" b) amalgamation of the tailings from process (a); c) comminution and gravity concentration through sluicing; d) comminution and gravity concentration then amalgamation; e) comminution and gravity concentration then cyanidation; f) comminution and gravity concentration, amalgamation then cyanidation, and g) comminution and cyanidation.

4. METHODS

This section describes the methodology done to quantify water use in ore processing plants and measurements of water quality.

4.1 Measurement of Water Use in Ore Processing Facilities

The ores are transported to the processing plants where the gold is extracted. These ores are crushed or reduced in particle size. From the documentation of the processes, it was found that water is utilized during milling, gravity concentration (sluicing and panning) and chemical leaching (cyanidation). These water consuming processes monitored at the observation sites are illustrated in Figure 5. During gold extraction stage and tailings storage, water may be classified as 1) Mill water - water used to crush and grind ore, 2) Process water - water used in the physical and chemical extraction of metals, 3) Leachate - water which has trickled through solid mine wastes or tailings storage or dumpsites and may contain dissolved minerals, process chemicals, and/or metals, and 4) Effluent - mining, mill, or process water which is being discharged into surface water, often after being treated [9].

For the milling step, the mill water was used to grind the crushed ores. The water used during unloading from the mill and reloading of slurry for another pass, if practiced, was included in this step as mill water. To enable the light materials to separate from the heavier ones, water was used to flush the milled slurry along the slanted platform or sluice. This step referred to as sluicing accounts for the major portion of water use during ore processing. In leaching, water is required to keep the consistency of the slurry for pumping into the leaching tanks, as well as to unload the slurry from the tank. The amount of water use under this step includes the loading and unloading requirements.

Figure 5. Water consuming steps in ores processing

Measurement of water use during each process was carried out by the volumetric method either by observing the actual amount of water containers, if using a container of known volume or taking note of the time that a tap with a predetermined flow rate was used. Since the processing was carried out by batch, the amount of water used was dependent on: a) the processes implemented, b) the amount of ore being processed, and c) the capacity of the equipment such as the rod mill or cyanidation tanks. Together with the determination of other material inputs, volumetric measurements of all water inputs for one complete production cycle were carried out during the detailed observation in the processing stage.

In the analysis, the water input was converted into the volume of water utilized for each unit weight of ore material. By doing so, the volume of water use can be compared across all observation sites regardless of the capacity of the facility in terms of the unit weight of ore being processed. Table 1 presents the water use for the water consuming processes in the sites in liters of water for each ton of ore material measured.

4.2 Measurements of Water Quality

One of the concerns associated with small-scale gold production has been the pollution from the process water emissions. Gold mine tailings characteristically have elevated concentrations of toxic heavy metals [10]. For this study, the water quality parameters tested were concentrations of cyanide (CN-), arsenic (As), cadmium (Cd), mercury (Hg) and lead (Pb), which are some of the significant water quality parameters included in the Department of Natural Resources (DENR) Administrative Order (DENR DAO) No 2016-08 or the Water Quality Guidelines and General Effluent Standards of 2016 for minimum requirements for effluents from gold ore mining to be released to Class C waters.

To test for the impact of the ore processing stage on the water quality in small scale gold production, water samples from the groundwater source and effluents at different stages and processes were collected in polyethylene bottles and brought to a reputable laboratory within the allowable holding time for analysis using standard laboratory techniques. For each sampling point, two replicates of one-liter samples were collected. Cyanide content was analyzed using ion selective electrode, arsenic by hydride generation atomic absorption spectroscopy (AAS), cadmium and lead by flame AAS and mercury through cold vapor AAS. The laboratory results were compared to the the DENR DAO 2016-08 guidelines

5. RESULTS AND DISCUSSION

This section provides the discussion of findings and analysis of results.

5.1 Quantification of Water Use in Ore Processing

Table 1 shows the process water use during the gold extraction stage at the processing facilities. To compare the relative contribution of each process to the total water use, Figure 6 illustrates the percentage contribution of each process to the total process water.

Table 1. Process water use during gold extraction stage at the processing facilities
Unit: liters of water /ton of ore

Site No.	Location	Comminution	Gravity Concentration		Chemical Leaching	All processes
		Milling	*Sluicing*	*Panning*	*Cyanidation*	
1	Abra A	522	17,560	150		18,232
2	Abra B	10,828	23,764	122		34,714
3	Benguet A	143	3,579		690	4,412
4	Benguet B	438	9,756	4	54	10,252
5	Camarines Norte A		7,145			7,145
6	Camarines Norte B	9,405	28,407	700		38,512
7	Camarines Norte C	1,038	7,707	53	12	8,810
8	Compostela Valley A	148			1,276	1,424
9	Compostela Valley B	18			1,525	1,543
Mean	All Sites	2,818	13,988	206	711	17,723
Std. Dev.		4,532	9,388	282	690	13,879

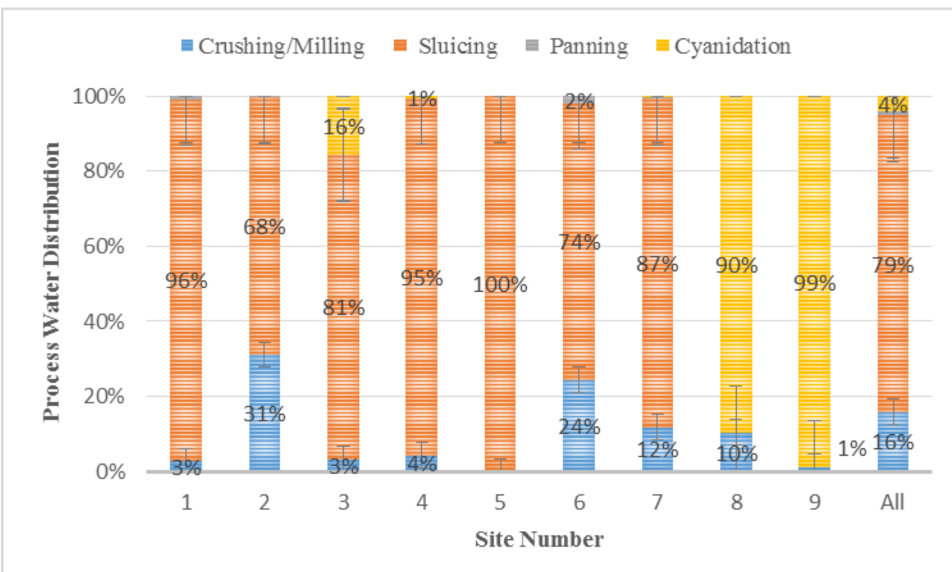

Figure 6. Process water distribution (percentage of process water over total process use) during gold extraction at the observation sites
Standard error limits are indicated by the whiskers

Both sites in Abra use the gravitation method through sluicing and panning to recover free gold. Process water in Site 1 includes water for milling, sluicing and panning. Sluicing accounts for 96% of total process water. In Site 2, the following processes required water as input - milling, unloading, panning and sluicing. While the same processes were applied in both sites, in Site 2 there was higher mill water usage amounting to 31% while sluicing accounted for 68% of the total water use.

In the Benguet sites, a combination of free gold extraction through sluicing and panning and cyanidation were recorded. Site 3 used water during loading and unloading to mills, sluicing, lime preparation, loading of slurry to cyanidation tank and harvesting. Unloading and sluicing accounts for 81% of all the processes in Site 3. Although not measured, it was noted that Site 3 practices water conservation through rainwater harvesting and recycling. In Site 4, water use was noted during loading and unloading to the mill, sluicing, panning, loading of ore into the leaching pond, and harvesting. Sluicing accounts for 95% of total water use in Site 4.

In Camarines Norte, Site 5 used sluicing and amalgamation for gold recovery while Sites 6 and 7 practiced sluicing, amalgamation and cyanidation. In Site 5, the practice of using compressed air as miners dive underwater to collect mud with free gold under submerged condition was observed. Already in fine texture, there is no need for the mud to undergo milling. Locally referred to as "compressor mining", water pumped out from the shallow water table is used for sluicing. While amalgamation is also observed, water use is minimal and sluicing accounted for most of the water use. Sluicing was observed to be done twice i.e., the tailings from the first pass were returned for a second pass. In another site (Site 6), water consuming processes included loading and unloading to mill, sluicing, remilling, unloading after remilling, panning and acidation. Sluicing accounted for 74% of total process water. In another observation site, Site 7, a different set of processes were observed: milling, unloading/sluicing (1st pass), remilling, unloading/sluicing (2nd pass), sluicing, panning and unloading after cyanidation. In Site 7, process water for sluicing accounted for 87% of total process water where the first stage alone consisting of unloading and sluicing already making up for 61% of total process water.

In the Compostela Valley sites, Site 8 used cyanidation through Carbon-in-Pulp (CIP) to extract gold. Processes using water include milling, cyanidation, and harvesting where cyanidation accounted for 90% of total water use. Although water reuse was observed in the facility, no estimate of the amount of water reuse which is collected in a storage tank was carried out. Site 9 uses same processes as in Site 8: milling, cyanidation, and harvesting. Cyanidation process water accounted for 99% of total process water.

The breakdown of water uses in the major steps involved during the ore processing stage reveals that the variation is influenced by the extraction process or steps used to obtain the gold concentrate. In all sites, the most water consuming process is sluicing. Sluicing is a method of collecting the gold using water to convey the loosened, crushed or milled material along a slanted sluice or artificial channel with various configurations such as riffles, corrugations, mats, cloth or the like to trap the heavier particles while allowing the waste material to flow over. Sluicing, where practiced, accounted for the bulk of the total water use during ore processing based on observations ranging from 3,579 to 28,407 li/ton and a mean of 13,988 li/ton from the nine sites. Where other gravitation methods like panning and amalgamation were involved, the water required whenever sluicing was combined would dominate the water use.

The other significant water use can be traced to the milling process and the associated handling of ore slurry while loading and unloading from the mill. Water is added together with the ore before the milling process and afterwards to wash out the milled ore slurry from the milling machine and to allow the slurry to be transferred to the next step. A wide range of water use for the steps associated with the milling process ranges from the least of 18 li/ton (Site 9) to the highest measured value of 10,828 18 li/ton (Site 2), the latter accounting for 31% of water use for the site, largely for unloading the material from the mill. Similarly, the milling water in Sites 6 and 7 accounted for 24% and 12% of the total process water use, respectively, where about half is due to the unloading of slurry during milling and remilling. In the rest of the sites, the mill water accounted for less than 10% of the total water use.

In Sites 8 and 9 in Compostela Valley, the water intensive practice of sluicing was not observed. Gold, however, was recovered through chemical leaching using cyanidation. With this method, water is needed to enable the milled slurry to be pumped into the leaching tanks. About 90-99% of the total water use can be accounted for by this step. The average amount from the two sites was measured at 1,400 li/ton of ore material, which is much less than the water requirement for sluicing. While panning also utilizes water, this manual process accounts for merely 1-2% of the total water use in gold ore processing in the observed sites.

Due to the wide range of process water use among the various ore processing steps across the sites, the total water use varies widely as well. From Table 1, it can be seen that the lowest water use was observed in Compostela Valley with 1,424 li/ton and 1,543 li/ton, for Sites 8 and 9, respectively. The most intensive water use was registered in Camarines Norte B (Site 6) with 38,511 li/ton of ore processed followed by Abra B (Site 2) with 34,714 li/ton. Benguet A (Site 3) used 4,412 li/ton followed by Sites 5 and 7 (Camarines Norte) with 7,145 li/ton and 8,810 li/ton, respectively. Larger amounts were used in Benguet (Site 4) at 10,251 li/ton followed by Abra A (Site 1) with 18,232 li/ton.

To illustrate the relative intensity of the mill and process water use across all sites, the ratio for each process was divided by the total process water use, yielding the relative impact of each process to the total water use during the extraction process. Figure 6 shows that whenever applied, sluicing is the most water intensive process as it dominates the water use profile. Across all sites, the mean total process water use was computed as 17,723 li/ton of ore sluicing process water and mill water accounted for 79% and 16%, respectively while process water during leaching and panning accounted for the balance of 4% and 1%, respectively.

5.2 *Assessment of Water Quality*

Tables 2.1 to 2.4 show the results of the laboratory analysis of water samples taken at various ore processing stages from sites in Abra, Benguet, Camarines Norte and Compostela Valley, respectively. From the observed water quality parameters, the background water quality levels from the groundwater sources used for processing are all within the permissible standards. During the processing, the quality of the process water changes as it interacts with the ore and other chemicals used in the extraction process. The water samples were collected after the process was carried out between steps during the gold extraction stage and tailings storage/disposal stage, respectively. The measured levels were compared with the standards. The highlighted cells indicate values where the limit for the effluent standards were exceeded.

To depict the exceedance values, Figure 7 shows the percent deviation of the measured parameter from the standard value. Plots lower than the reference level “0” indicate measurements below the DENR effluent standards while positive values denote the degree of exceedance from the standards.

Table 2.1 Water quality analysis from Abra sites at various processing stages

Site	Location	Water Sample	Water Quality Parameter (mg/l)				
			Cyanide (CN^-)	***Arsenic (As)***	***Cadmium (Cd)***	***Mercury (Hg)***	***Lead (Pb)***
1	Abra Processing Facility Site A	1. Groundwater	<0.05	<0.001	0.009	<0.0001	<0.01
		2. Sluicing Process Water 1	<0.05	0.842	0.013	0.0025	0.686
		3. Sluicing Process Water 2	<0.05	1.107	0.022	0.0030	0.948
		4. Tailings Process Water 1	<0.05	0.680	0.078	<0.0001	0.290
		5. Tailings Process Water 2	<0.05	0.842	0.084	0.0020	0.618
2	Abra Processing Facility Site B	6. Groundwater	<0.05	<0.001	<0.003	<0.0001	<0.01
		7. Sluicing Process Water	<0.05	0.336	0.036	<0.0001	11.66
DENR Effluent Standards for Gold Ore Mining (2016)			**0.200**	**0.040**	**0.100**	**0.004**	**0.100**

Table 2.2 Water quality analysis of tailings effluent from a Benguet site

Site	Location	Water Sample	Water Quality Parameter (mg/l)				
			Cyanide (CN^-)	***Arsenic (As)***	***Cadmium (Cd)***	***Mercury (Hg)***	***Lead (Pb)***
3	Benguet Processing Facility Site A	8. Tailings Process Water 1	<0.05	0.005	5.661	0.1377	0.54
		9. Tailings Process Water 2	<0.05	0.005	5.217	0.1377	1.36
		10. Tailings Process Water 3	<0.05	0.070	2.171	0.0663	190.69
DENR Effluent Standards for Gold Ore Mining (2016)			**0.200**	**0.040**	**0.100**	**0.004**	**0.100**

Table 2. 3 Water quality analysis from Camarines Norte sites at various processing stages

Site	Location	Water Sample	Water Quality Parameter (mg/l)				
			Cyanide (CN^-)	*Arsenic (As)*	*Cadmium (Cd)*	*Mercury (Hg)*	*Lead (Pb)*
5	Camarines Norte Processing Facility Site A	11. Sluicing Process Water Sample 1	nd	0.026	<0.003	<0.0001	5.720
		12. Sluicing Process Water Sample 2	nd	0.011	<0.003	0.0006	1.830
		13. Sluicing Process Water Sample 3	nd	<0.001	<0.003	0.0014	1.92
		14. Sluicing Process Water Sample 4	nd	<0.001	<0.003	0.0021	2.10
		15. Panning Process Water Sample 1	nd	<0.001	<0.003	0.0065	0.54
		16. Panning Process Water Sample 2	nd	0.054	<0.003	Nd	110.53
6	Camarines Norte Processing Facility Site B	17. Sluicing Process Water	nd	<0.001	0.004	<0.0001	0.46
		18. Remilling Process Water	nd	<0.001	<0.003	0.0099	<0.01
		19. Panning Process Water	nd	<0.001	<0.003	<0.0001	0.78
7	Camarines Norte Processing Facility Site C	20. Pre -Leaching Process Water Sample 1	nd	nd	nd	0.0053	nd
		21. Pre -Leaching Process Water Sample 2	nd	nd	nd	0.0036	nd
DENR Effluent Standards for Gold Ore Mining (2016)			**0.200**	**0.040**	**0.100**	**0.004**	**0.100**

nd – no data

Table 2. 4 Water quality analysis from Compostela Valley sites at various processing stages

Site	Location	Water Sample	Water Quality Parameter (mg/l)				
			Cyanide (CN^-)	*Arsenic (As)*	*Cadmium (Cd)*	*Mercury (Hg)*	*Lead (Pb)*
8	Compostela Valley Processing Facility Site A	22. Groundwater Sample 1	<0.05	0.006	<0.002	<0.0001	<0.005
		23. Groundwater Sample 2	<0.05	0.007	<0.002	<0.0001	<0.005
		24. Tailings Process Water Pre-Leaching	<0.06	0.174	0.031	0.0021	9.53
		25. Tailings Process Water Post-Leaching	<0.05	0.053	0.435	0.0424	8.30
		26. Tailings Pond Sample 1	0.22	0.010	0.030	0.0734	0.251
		27. Tailings Pond Sample 2	0.20	0.010	0.027	0.1406	0.134
9	Compostela Valley Processing Facility Site B	28. Tailings Process Water 1	<0.05	0.124	0.015	<0.0001	2.39
		29. Tailings Process Water 2	<0.05	0.237	0.257	0.0066	5.54
		30. Tailings Pond Sample 1	0.33	1.529	<0.002	0.0158	97.513
		31. Tailings Pond Sample 2	<0.05	1.111	0.088	0.0204	5.427

Site	Location	Water Sample	Water Quality Parameter (mg/l)				
			Cyanide (CN^-)	*Arsenic (As)*	*Cadmium (Cd)*	*Mercury (Hg)*	*Lead (Pb)*
DENR Effluent Standards for Gold Ore Mining (2016)			**0.200**	**0.040**	**0.100**	**0.004**	**0.100**

.

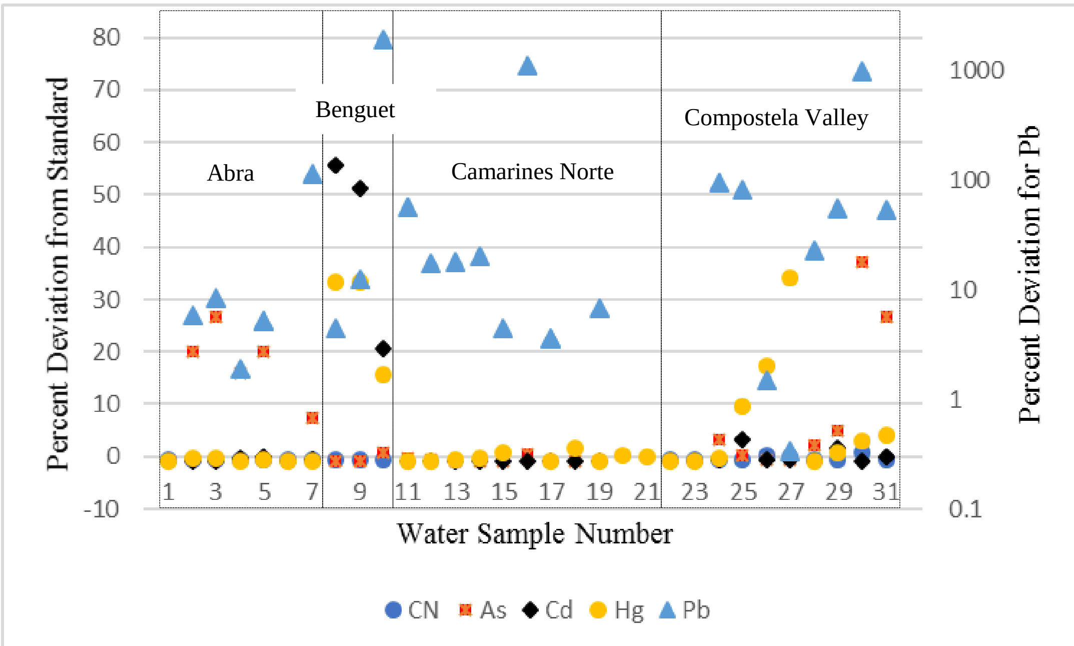

Figure 7. Comparison of levels of cyanide, arsenic, cadmium, mercury and lead in water samples relative to DENR effluent standards (percent deviation from the standard)

From Figure 7, it can be seen that the most prevalent heavy metal in the water samples was lead (Pb) which is shown to be found in all process waters and tailings pond in all sites, the highest being three orders of magnitude more than the standard. Lead is a heavy metal that is toxic at the lowest concentration and naturally non-degradable. It may exist in various oxidation states and its ionic form is the most reactive and most common form that are released into surface water, ground water and soil [10]. Lead may be present in gold ore in the form of galena (PbS) usually when there is high level of sulphide concentration [11].

Elevated levels of arsenic (As) were found in the sluicing and tailings process water in Abra (Sites 1 and 2) and the tailings process water and tailings pond samples in Compostela Valley (Sites 8 and 9). Arsenic does not appear to be significant in Benguet and Camarines Norte. Owing to its high potential toxicity, arsenic is one of the most dangerous heavy metals of environmental concern [12]. Occurring as arsenopyrite [FeSAs], realgar [As_2S_2] and orpiment [As_2S_3] in gold bearing rock, high levels of arsenic have been reported in gold mine tailings at Ghana [13], [14].

Found in gold bearing orebodies as trace element in sphalerite, cadmium is one of the most toxic heavy metals to most organisms and may accumulate in the food chain, drinking water and soil. Cadmium has an exceptionally long biological half-life, highly mobile in soil-plant systems and can greatly impact the ecosystems [15]. For the water samples tested, only a few were slightly elevated in Compostela Valley while all the tailings process water samples in Benguet (Site 3) exhibited high levels.

As a result of its common usage in gold extraction by small scale gold miners, large quantities of Hg are released into the environment. In a study, in 2011, an estimated 1400 metric tons of mercury was used and an annual average of 1000 metric tons of inorganic Hg was discharged. About a third of this amount goes into the air while the rest is lumped up in tailings dump, soil and waterways [16]. For every 1 kg of gold produced about 1.32 kg of Hg is lost as it moves directly into water, soil and rivers as inorganic Hg and may later be converted into organic forms [17]. From the observations, elevated levels of mercury were detected in process water samples in Benguet despite the claim that the use of mercury has been discouraged by the federation members. Increased concentrations were also observed in Compostela Valley even though only cyanidation was observed as the main gold extraction method. It is notable that mercury concentrations in samples from Abra were below permissible levels. Only sluicing and panning is practiced in the Abra sites. For Camarines Norte, mercury levels slightly exceeded the limits, in some cases.

For cyanide concentrations, only the tailings pond samples slightly exceeded the permissible limit. All other observations were below the allowable standards. Cyanide is known not to bioaccumulate and does not appear to pose significant health risks. In its most toxic form as free cyanide, it is short-lived in the environment and degrades rapidly [18].

The groundwater quality presents the background levels prior to usage. Upon mixture with the ore and other chemicals during the extraction process, some notable changes in the heavy metal content of the process water were detected. It is worthwhile to note that the tailings and process water would eventually be discharged to the tailings disposal site or pond. Improper management or disposal of contaminated tailings and effluents poses danger to ecosystem and human health [19]. For the communal processing facilities catering to the small-scale gold mining industry, their tailings storage consists of ponds or open dump sites near the processing plants without treatment and designed provisions for seepage control and stability of embankments as seen in Figure 8.

Figure 7. Tailings ponds in ores processing sites

5. RECOMMENDATIONS AND CONCLUSIONS

From the nine observation sites, process water used to recover the gold concentrate vary widely from the least of 1,424 li/ton to 34,714 li/ton with a mean of 17,723 li/ton and standard deviation of 13,879. The difference across sites can be explained by the gold recovery process being employed which could also be influenced by the availability of raw water in the processing facility. The most water consuming step or process during the recovery of gold is sluicing followed by milling and its associated activities such as unloading of milled ore material. The water intensive process of sluicing accounted for 68% to 98 % of the total water used in gold recovery.

The processing of ores to recover the gold were also shown to liberate from the rock material some elements and metals that would eventually flow with the tailings or effluents during disposal. Increased concentration levels of heavy metals - lead, arsenic, cadmium and mercury were found to exceed the allowable limits in the effluents after the milling process.

The relative location of the processing sites for small scale mining activities are mostly found in the upstream portion or headwaters of the main watershed they belong as seen in Figure 2. For example, the Abra observation sites are located in the municipalities of Manabo and Licuan-Baay which is part of the Abra River Basin that drains to the West Philippine Sea near Vigan City. In Benguet, the sites are located in Itogon, which is located in the upstream part of the Agno River Basin which spans the provinces of Benguet, Tarlac and Pangasinan where it eventually drains to Lingayen Gulf. The sites in Maragusan, Compostela Valley lies at the head waters of Agusan River basin, the 3rd largest river basin in the country. On the other hand, the Camarines Norte sites are close to the Philippine Sea. The potential impact of ores processing activities for small-scale gold industry must be continually assessed due to their potential impact to water resources, health and ecology if the leachates and effluents from mine and processing sites mix with the downstream water bodies or shallow groundwater. Policies on sustainable development should address management of mine wastes through preventive measures such as selective mining and separation of acid forming minerals, collection of seepage and covering of waste piles and diversion of water around them to prevent flushing of pollutants through seepage and excess water runoff and spills to nearby land or water bodies [20] [21].

For future study, some site-specific recommendations related to the integrated management of water resources and their benefit as well as requirements for implementation are listed in Table 3.

Table 3. List of recommendations, implementation requirements and their potential benefits to address water management issues related to small-scale mining and production

RECOMMENDATION	BENEFIT	REQUIREMENTS	SITES APPLICABLE
Water saving practices such as wastewater recycling and rainwater harvesting should be used. Although natural water sources are accessible, the miners should be made aware of the need to conserve water and be efficient in their water usage.	• Minimize water wastage so that some of the water may still be used for other purposes • Lesser competition on water source among the miners and the community near the mining and processing areas	• Design and construction of water saving system	• Abra • Benguet • Camarines Norte Note: This is already being used in some of the observed sites in Benguet and Compostela Valley.
Containment ponds for waste rocks and solid tails and research for possible uses. Most of the processing plants in Benguet use cyanidation through heap leaching which produce more solid tails than liquid tails. The current practice of disposing solid tails to nearby water bodies causes sedimentation downstream.	• Minimize sedimentation and the possibility of acid mine drainage downstream • What is considered as wastes will be put into use and will have additional value, e.g. these wastes can be used as backfills in the tunnels.	• Feasibility analysis, design and construction of the appropriate tailings facility at the right location • Research on identifying other uses for the waste rocks and solid tails	• Benguet
Building of Tailings / Settling Ponds with Wastewater Treatment Because of naturally occurring heavy metals in the ores, it is not safe to just dispose the wastewater of the process directly to the waterways. Wastewater treatment can be focused on the heavy metals Hg, Pb, As, Cd, Cu as they are the significant parameters according to Department Administrative Order 35 (DAO 35) of 2008 of the Department of Environment and Natural Resources which were also found to be prevalent in the wastewater.	• Wastewater treatment facility will ensure that the wastewater has reached the allowable concentration limits of heavy metals and other environmental parameters before they are discharged to the waterways • Sedimentation in the rivers is usually blamed on the small-scale mining activities. Settling ponds will allow the solid part of the tails settle first before release to the waterways	• Feasibility analysis of the appropriate tailings pond with wastewater treatment facility at the right location • Proper coordination on the management of the facility are needed. • Identification for other uses for the sediments that settled at the bottom of the ponds	• Abra • Benguet • Camarines Norte • Compostela Valley

RECOMMENDATION	BENEFIT	REQUIREMENTS	SITES APPLICABLE
Complete elimination of mercury usage while assisting the miners in adopting a new technology during a transition period. Training on the use of mercury-free technology and they must be made aware of, not just the environmental advantage of this technology, but also the economic and social advantages. Other safe and efficient gold extraction technologies suitable for Philippine conditions may be adopted [22].	• The elimination of mercury will facilitate the sites to comply with the law. • Elimination of mercury in the processes will remove the risks it poses to the miners, community and environment.	• Effective information campaign on the harmful effects of using mercury • Highlighting the economic, environmental and social advantages of mercury free technologies. • Design and construction of plants that do not use mercury	• Camarines Norte
Zoning can be a strategy to contain the wastes of the processes and prevent its spread to the communities, residential areas, watersheds and water bodies.	• Effluents of the processes are contained and treated in an area away from the communities • Monitoring visits and access to the mining and processing sites will be efficient. • Regulations will also be implemented easier as everyone can monitor each other.	• Feasibility analysis of the declared mining and processing area • Identification of the location and coordination with the land and claim owners if necessary • Proper coordination on the management and regulation of the facility are needed.	• Abra • Benguet • Camarines Norte Note: Currently, the observed sites in Compostela Valley implement zoning in their municipality.
Sustainable groundwater and surface water resources management • Identification, delineation and adoption of policy regarding the use of watershed such as ground water recharge areas for protection of existing and future sources for community water supply. Mining activity must not be allowed in these areas. • Proper location of centralized processing plants to consider the hydrogeological, ecological and health impacts and their proper design and monitoring to mitigate these associated risks. All emissions must pass the environmental quality standards. • Comprehensive rehabilitation program for exhausted or abandoned mine sites. Proper closure and reclamation procedures must be developed and adopted.	• Protection of watershed areas • Minimize competition on water resource among the mining industry and communities • Wastewater discharge will be within the allowable concentration limits of heavy metals and other environmental parameters	• Consultations with stakeholders regarding new policies that have to be in place • Identification of location where mining and processing activities are allowed • Funds that will be used for the rehabilitation programs	• Abra • Benguet • Camarines Norte • Compostela Valley

6. ACKNOWLEDGEMENTS

The authors acknowledge the support provided by the Engineering Research and Development for Technology (ERDT) program of the Department of Science and Technology and spearheaded by the UP College of Engineering. The data requirements gathered for this study was made possible through the ERDT Mineral Extraction with Responsibility and Sustainability (MINERS) Program, Project G, entitled: "The Gold and Copper Chase (Life Cycle Analysis of Sustainable Small-Scale Production Systems").

7. REFERENCES

[1] Mines and Geosciences Bureau (MGB),"The Philippine Minerals Industry at a Glance," [Online]. Available: http://www.mgb.gov.ph/images/links-images/ThePhilippineMineralsIndustryAtAGlance.pdf

[2] R. Gamboa.. "A reader's view of small-scale mining," The Philippine Star, March 21,2017 [Online]. Available: http://www.philstar.com/business/2017/03/21/1682996/readers-view-small-scale-mining, .

[3] Department of Environment and Natural Resources (DENR), "Situationer on the Status of Small-Scale Mining Operations and Policy Recommendations," Presentation Material, 2009.

[4] A. Azapagic, "Developing a framework for sustainable development indicators for the mining and minerals industry," *Journal of Cleaner Production*, vol.12, pp. 639 – 662, 2004.

[5] M. Curran, Environmental Life Cycle Assessment. New York: McGraw-Hill Companies, Inc.,1996.

[6] V. Soriano, I. Bernaldez, and M. Tamayao, "Development of a Risk Assessment Tool for Small-Scale Gold Mining in the Philippines" In: P. Arezes (Ed.) Advances in Safety Management and Human Factors, AHFE 2017. Advances in Intelligent Systems and Computing, vol. 604. Springer: Cham. 2018. doi 10.1007/978-3-319-60525-8_38.

[7] S. Northey, G. Mudd, E. Saarivuori, H. Wessman-Jaaskelainen and N. Haque, "Water footprinting and mining: What are the limitations and opportunities?", *J. Clean. Prod.*, vol. 135, pp. 1098-116, 2016.

[8] P. Younger, "The longevity of minewater pollution: a basis for decision-making", *Sci. Total Environ.*, vol. 194-195, pp. 457-466, 1997.

[9] B. Lottermoser, B. (2012). Mine Wastes: Characterization, Treatment and Environmental Impacts. New York: Springer, p. 400, 2012.

[10] E. Da Silva, C. Zhang, L. Pinto, C. Patinha, and P. Reis, "Hazard assessment on arsenic and lead in soils of Castromil gold mining area, Portugal," *Appl. Geochem.*, vol. 19, pp. 887–898, 2004.

[11] C. Matocha, E. Elzinga and D. Sparks, "Reactivity of Pb(II) at the Mn (III, IV) (oxyhydr)oxide--water interface," *Environ Sci Technol*., vol. 35(14), pp. 2967-72, 2001.

[12] B. Choudhury, S. Chowdhury and A. Biswas, "Regulation of growth and metabolism in rice (*Oryza sativa L.*) by arsenic and its possible reversal by phosphate," *J. Plant Interact.*, vol. 6, pp.15–24, 2011.

[13] K. Ahmad, D. Carboo,"Speciation of As(III) and As(V) in some Ghanaian gold tailings by a simple distillation method," *Water Air Soil Pollut*., vol. 122, pp. 317–326, 2000.

[14] C. Bempah, A. Ewusi, S. Obiri-Yeboah, S. Asabere, F. Mensah, J. Boatengand H. Voigt, "Distribution of arsenic and heavy metals from mine tailings dams at Obuasi municipality of Ghana," *Am. J. Eng. Res.*, vol. 2, pp. 61–70, 2013.

[15] United States Environmental Protection Agency, List of Contaminants and Their Maximum Contaminant Levels (MCLs), USA: Washington, DC, 2004.

[16] K. Telmer and M. Veiga, “Mercury Fate and Transport in the Global Atmosphere,” World emissions of mercury from artisanal and small-scale gold mining, pp. 131–172, Heidelberg, Germany: Springer, 2009.

[17] K. Matshusa, J. Ogola and K. Maas, “Dispersion of metals at Louis Moore gold tailings dam, Limpopo province, South Africa,” Proceedings of the International Mine Water Association Symposium, Bunbury, Australia,; pp. 334A–334E, 30 September 2012.

[18] T. Zolnikov, “Limitations in small artisanal gold mining addressed by educational components paired with alternative mining methods,” *Science of the Total Environment*, vol. 419, pp. 1–6, 2012.

[19] S. Obiri, P. Yeboah, S. Osae, S. Adu-Kumi, S. Cobbina, F. Armah, B. Ason B, E. Antwiand R. Quansah,”Human Health Risk Assessment of Artisanal Miners Exposed to Toxic Chemicals in Water and Sediments in the Prestea Huni Valley District of Ghana,” *Int J Environ Res Public Health*, vol. 13, 2016. doi: 10.3390/ijerph13010139.

[20] D. Franks, D. Boger, C. Cote, and D. Mulligan, “Sustainable development principles for the disposal of mining and mineral processing wastes”, *Resour. Policy,* vol. 36, pp. 114-122, 2011.

[21] M. Edraki, T. Baumgartl, E. Manlapig, D. Bradshaw, D. Franks and C. Moran, “Designing mine tailings for better environmental, social, and economic outcomes: a review of alternative approaches”, *J. Clean. Prod.*, vol. 84, pp. 411-420, 2014.

[22] L. Hylander, D. Plath, C. Miranda, S. Lucke, J. Ohlander and A. Rivera,” Comparison of Different Gold Recovery Methods with Regard to Pollution Control and Efficiency,” *Clean- Soil, Air, Water,* vol. 35, pp. 52-61, 2007.