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Review

Gold mining in Ecuador: Innovative recommendations for the management and remediation of mercury-contaminated waters

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Abstract: ASGM Mining processes have increased in recent years, becoming one of the main activities re-sponsible for serious impacts on ecosystems, affecting biodiversity and valuable resources such as soil and water. It is necessary to analyze the successful management developed by some countries in gold extraction, through innovative techniques and procedures, and recommend its replication in Ecuador. It is undeniable that mercury is one of the main contaminants in gold mining, it is important to establish the best techniques to protect natural resources. The first section of this paper analyzed the changes in Ecuadorian mining management with a focus on gold mining processes, followed by a description of ASGM mining and mercury use in Ecuador. Finally, the main sources of contamination were analyzed and recommendations were made to improve mining management and reduce contamination of water bodies. The methodology used was based on a bibliographic review of gray and scientific literature. The recommendations establish that mining management in Ecuador should focus its efforts on improving control and monitoring capacity, regularization of mining registries, and strengthening regulations with new policies. Finally, to reduce the impact of Hg on water bodies, it is necessary to educate ASGM miners about the risks of indiscriminate use of mercury and about techniques that can provide better socioeconomic benefits.

Keywords: Amazon, Andes, Coastal, gold; mining management; artisanal and industrial mining; environ-mental impacts; Hg

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1. Introduction

Mining is one of the oldest activities of mankind, since prehistoric times man has used minerals for the manufacture of tools as a means of livelihood. In technical terms, mining is defined as a primary economic activity, which consists of the extraction or exploitation of metallic or non-metallic elements that accumulate in the soil or subsoil in the form of ore deposits [1]. It is one of the oldest economic activities of mankind. It is not in vain that prehistoric times are classified according to the minerals used: Stone Age, Bronze Age and Iron Age. This activity has basically three dimensions worldwide: large-scale mining, medium-scale mining and small-scale or artisanal mining. The latter appears especially in developing countries and has been fundamental in the economic and social progress of mankind, contributing to the production of goods and services. The search for new materials has been a constant throughout the centuries; all civilizations have depended to a greater or lesser extent on this activity [2]. Latin America has historically been linked to the mining industry and the exploitation of raw materials, being one of the economic pillars in colonial and modern times. Today, the region is one of the main mining areas in the world, and countries such as Brazil, Peru, Chile, Colombia, Bolivia and Ecuador depend heavily on this activity for their economies [3].

Gold (Au) is a metallic element that occurs only in its natural state and cannot be manufactured. It is inert, i.e. practically immune to deterioration. This element is ex-tremely rare and is found in low quantities in rocky substrates. Its main use is for the manufacture of jewelry or it is simply stored as monetary reserves in banks around the world. This metal is considered as a sign of royalty, power and wealth; thus, it became a prerogative of high and powerful people in history and nowadays [4]. Today, the ex-traction process is carried out using artisanal and industrial techniques.

Gold Mining is an economic activity that has expanded on all continents in the last four decades. Its production has varied significantly; at the beginning of the last century, annual production reached 400 tons, while today, according to the World Gold Council, production reaches approximately 3,500 tons per year. Historically, an estimated 190,000 tons of gold have been mined. Latin America produces 17% of the world's gold and the countries with the largest reserves in this region are Venezuela, Mexico and Brazil[5]. Thus, since the 1990s, the largest investments in mining prospecting have been made in this region.

Gold mining worldwide has been grouped into two main groups, Artisanal and small-scale mining (ASGM) and large-scale or industrial mining, depending on the level of extraction and the methods used. ASGM mining plays an important role in the economy of developing countries, especially in communities and rural areas, where economic alternatives are extremely limited. [6]. While this activity provides economic benefits and livelihoods to local communities, it is important to recognize that the impacts to ecosystems and human health can be devastating. Proper management and compliance with environmental regulations in gold mining processes are vital to mitigate impacts [7]. Au extraction processes (gold mining) release the largest amount of mercury (Hg) in-tentionally in the world. The management of Hg as a mining waste is a universal challenge that constantly generates a risk of contamination of surface water and its biota. The methods and techniques applied in gold mining generally involve open-pit activities that generate impacts on the natural environment [8].

Hg in all its physical and chemical forms is considered one of the ten most polluting elements. This contamination can be caused by natural sources such as volcanoes, soil erosion and oceans, or by anthropogenic sources such as fossil fuels, metal production and gold mining, among others [7,9]. Toxicologically, there are three forms of Hg: elemental, inorganic (Hg salts and Hg oxide) and organic. Each of these forms has different toxicity spectra, both to the environment and to humans. This element is mainly used in ASGM to separate and extract gold from rocks or stones in its natural state. It has been estimated that the average mercury losses relative to gold production in ASGM is 1.96 [10]. Hg residues have a great impact on ecosystems [11]. This impact is related to sedimentation processes, runoff, erosion, geological faults, alteration of the hydrological cycle and pre-cipitation. Thus, these wastes end up in rivers and by bioaccumulation through the food chain in the human body [12]. The impacts of mining come mainly from tailings and accumulations of residual material as a result of extraction processes [13].

The use of mercury in ASGM has increased in recent decades, governments worldwide have been working on the implementation of new strategies to reduce and eliminate its use, this has not been different in Ecuador. Thus, in this study, in order to learn about the reality in this country, the following objectives have been established i) Analyze the changes in mining management in Ecuador; ii) Describe gold mining in Ecuador with a focus on ASGM; iii) Analyze the sources of Hg contamination from ASGM mining effluents; iv) Establish recommendations for ASGM management and prevent Hg contamination of water bodies. In order to respond to these objectives, a bibliographic review of scientific and grey literature was carried out. In terms of scientific literature, high impact articles were reviewed from the Scopus and Web of Science databases; and regional databases such as Scielo and Redalyc. This information was complemented with gray literature such as laws, reports, regulations and manuals, i.e. documents that have not undergone scientific review. Finally, the authors established recommendations for mining management in Ecuador and the application of strategies aimed at reducing the contamination of water bodies.

2. Mining management in Ecuador

Mining activities in Ecuador until June 30, 2020 were managed by three entities: Mining Regulation and Control Agency (ARCOM), Hydrocarbons Regulation and Control Agency (ARCH) and the Electricity Regulation and Control Agency (ARCONEL). As of July 1, 2020, these three entities are merged by Executive Decree 1036 of May 6, 2020, giving rise to a new institution in charge of mining management, the Agency for Regulation and Control of Energy and Non-Renewable Natural Resources (ARC). This institution is attached to the Ministry of Energy and Non-Renewable Natural Resources. ARC's vision is to be an institution recognized as a highly specialized agency in the regulation and control of the electricity, hydrocarbons and mining sectors, with high standards of quality, effectiveness and transparency, promoting the development of these sectors in a responsible manner and with the use of state-of-the-art technologies, contributing to the economic growth and service of the country. Among its functions is to regulate, control, supervise and audit the activities of Energy and Non-Renewable Natural Resources, as well as to safeguard and guarantee the interests of the consumer or end user, promoting the optimal use of these resources with social and environmental responsibility. The institutional strategic objectives are focused on increasing the regulation, control and auditing of non-renewable energy and natural resources at the service of the country for the benefit of its economic development; reducing the illegal exploitation of minerals and promoting the sustainable use of these resources; and strengthening institutional capacities.

ARC has a technical coordination for mining regulation and control. This coordination is divided into four directorates: i) Directorate of Mining Regulation and Standards; ii) Directorate of Mining Property Administration; iii) Directorate of Control, Monitoring and Technical Inspection and Intervention in Illegal Mining; and iv) Directorate of Auditing and Economic Mining Control. For better management in the territory, territorial deconcentrated levels have been created, called Zonal Deconcentrated Units (UDZ): Imbabura, Orellana, Chimborazo, Guayas, Azuay and El Oro. These UDZs cover all the remaining provinces of the country according to their geographic location. In addition, there are four strategic technical offices in Pichincha, Santo Domingo de los TSachilas, Ponce Enriques and Portoviejo. In order to fulfill its strategic objectives, the ARC has laws, rules, regulations, instructions and board resolutions. The Mining Law was created through Official Registry 517 on January 29, 2009, its objective is to regulate the exercise of the sovereign rights of the Ecuadorian State, to administer, regulate, control and manage the strategic mining sector, in accordance with the principles of sustainability, precaution, prevention and efficiency. Oil and other hydrocarbons are exempted from this Law. There are two regulations, the first one focused on safety and the other one regulating the Mining Law. In addition to the mining law and its two regulations, there are seven regulations that contribute to the control and monitoring of activities.

The former ARCOM through its 9 regional coordinations and 3 technical offices, has executed follow-up and control inspections to the holders of mining rights in order to verify compliance with legal and technical regulations. These inspections have varied over time, thus, for 2016 3817 were carried out, in 2018 it decreased to 3082 and for 2019 it increased again to 3586. On the other hand, it is important to highlight that the institution in the last 4 years has increased the execution of inspections to combat illegal mining nationwide, thus, for 2016 151 inspections were carried out and for 2019 they rose to 492. In these inspections in the years 2015,2016 and 2018 886 machinery, equipment and vehicles used in mining activities have been seized. These operations are carried out with the collaboration of the Armed Forces, National Police, Attorney General's Office, Environmental Authority, among others. With respect to training processes in the territory, the institution strengthened the knowledge of its technicians on issues related to equipment handling, safety at work, user service, illegal mining, expertise, drilling, blasting and mining cadastre.

Mining management covers all competencies (monitoring, control, intervention and auditing) in the phases established at the national level. There are currently two US$9 million macro investment projects under execution, financed by the Ecuadorian government and initially managed by the former Mining Regulation and Control Agency and currently by the Agency for Regulation and Control of Energy and Non-Renewable Natural Resources [14]. The first is for monitoring, control and evaluation of mining operations in the Zaruma-Portovelo district; this project is being developed in the Zaruma, Portovelo and Atahualpa cantons in the province of El Oro, benefiting 26,665 people living in the area. The second project is aimed at monitoring, control and oversight of mining activities at the national level. Its objective is to technify and systematize the processes of monitoring, control and oversight of large-scale mining activities with specialized human talent, state-of-the-art equipment and software; the target population that will benefit indirectly is approximately 545,114 people.

As a fundamental contribution to mining management in the country, it is important to analyze the new National Mining Development Plan 2020-2030. This plan is organized in six axes (Table 3) that contribute to the fulfillment of both national and global objectives and constitutes the strategic vision for the development of the mining sector through the implementation of a harmonious, efficient, transparent and sustainable management; based on research and development.

Table 3. Strategic axes of the National Mining Development Plan.

Axis	Description
Economic Development	Seeks to position the mining sector as a relevant industry in the national economy in order to attract private investment, to contribute to the fulfillment of the national objectives defined in the National Development Plan and the Sustainable Development Goals of the 2030 Agenda.
Environmental and Social Sustainability	Promotes the adoption of good environmental and occupational health practices in the mining industry, also seeks to harmonize relations between the various mining stakeholders, promoting the development of the areas of influence, through mechanisms of participation and dialogue.
Research and Development	Promotes research, innovation, transparency and entrepreneurship for the development of the mining sector, establishing responsibility in the different actors in the use of technology as a means of continuous improvement in the preservation of the environment and the use of resources.
Management and Administration	Promotes an articulated, timely and efficient public administration, recognizing the capabilities of human talent as the basis for the development of the mining industry.
Regulation, Control and Combating Illegal Mining	Seeks to strengthen the administration, regulation and control of the State in mining activities with emphasis on the territories of greatest risk, consolidating co-responsibility with private sector companies as key actors in the fight against illegal mining.
Regulations	Promotes a solid regulatory framework for the development of the mining industry, in order to establish the norm as a framework for the development of sound public policies.

For the implementation of the National Mining Sector Development Plan, a management model is proposed that involves all public and private institutions, academia and other organizations that integrate or participate directly or indirectly in the activities of the mining sector; and for the follow-up and control of the plan, a strategy is proposed that allows the monitoring, follow-up and evaluation of compliance with the Mining Public Policy, in accordance with the planning policies determined by regulations that are applicable to the entire governmental sector.

One of the new fundamental plans for the management and use of Hg in gold mining is the National Action Plan on the use of Hg in Artisanal and Small-scale Gold Mining (ASGM) in Ecuador. This plan is a project that the Ministry of Environment in conjunction with the United Nations Industrial Development Organization and the Artisanal Gold Council (AGC) has launched, whose objective is to carry out a diagnosis of artisanal and small-scale gold mining activities in the country. In addition, it aims to propose measures to improve mining management in order to prevent and gradually eliminate the clandestine use of Hg, as well as to propose measures in the area of health within the communities engaged in this type of activities. In May 2020, the MAE presented the "National Action Plan (NAP) on the Use of Hg in the Artisanal and Small-scale Gold Mining Sector in Ecuador", a final document describing the different strategies and activities aimed at reducing the use of Hg in ASGM.

3. Artisanal and small-scale gold mining (ASGM) in Ecuador

Mining in Ecuador has been known since Inca times, when gold was commercially exploited in Portovelo, Zaruma and Loja. Regarding official information on gold production, gold is mined in Ecuador at the artisanal, small-scale, medium-scale and large-scale levels. Between the years 2005 to 2012 the average gold production reached around 4900 kilos of gold per year, and for the period 2013 to 2016 an annual average of around 7700 kilos of gold per year was reached [15]. However, there is evidence of a decrease in production in 2016 and 2017, which is probably due mainly to the illegality and informality of small-scale and artisanal mining, as well as high levels of smuggling [16]. Small-scale metal mining in Ecuador emerged in the late 1970s as a result of the bankruptcy of the public-private company Industrial Mining Associate - CIMA in the Portovelo-Zaruma area of southern Ecuador [17,18]. The increase in gold prices led to the emergence of informal and precarious small-scale mining activities, developed by former workers of the closed company. At this time, new facilities offering services such as milling and beneficiation plants emerged, due to the inexistence of technologies and the generation of conflicts between miners and the state that arose due to the inability to manage the mining processes [19].

ASGM in Ecuador represents a productive activity that has served as a source of employment and income for thousands of people, either directly or indirectly, especially for rural communities, due to the remote locations where these activities are concentrated. Artisanal mining is characterized by low-tech processes, precarious labor conditions, deficient technical knowledge, low productivity yields, and low formalization. One of the disadvantages of artisanal mining is that this activity is not taxed, which does not generate income for the state, and the government is unable to receive benefits from this sector, in addition to the environmental damage generated by these activities. In 2016, there were a total of 1821 artisanal mining permits for metallic minerals, the concentration was in the southern provinces of the country such as Zamora Chinchipe, Loja, El Oro, Morona Santiago, Azuay, as well as in the northeastern side in the provinces of Napo and Sucumbíos. This implied that the area under concession for artisanal mining is 10,979 hectares, which corresponds to 0.23% of Ecuador's territory, leaving aside protected natural areas. Artisanal mining has the largest number of operating units in the country.

According to data available in the Mining Cadastre Geoportal, at the Agency for Regulation and Control of Energy and Non-Renewable Natural Resources (https://n9.cl/g3zra), as of June 2021, 2237 ASGM mining concession processes have been legally registered in Ecuador. Of this amount, 1806 correspond to artisanal mining and 251 to small mining. On the other hand, in terms of informal mining, 76 artisanal mining processes and 286 small-scale mining processes have been registered. This gives a total of 2,599 ASGM concession regimes (Table 4) between formal and informal.

Table 4. Legal and informal ASGM in Ecuador.

	Artisanal Mining		Small Mining	
	Legal	Informal	Legal	Informal
Esmeraldas	4	6	1	14
Santo Domingo	4	1	0	1
Manabí	2	0	0	0
Los Ríos	0	1	0	0
Guayas	18	2	4	0
Santa Elena	0	0	0	0
El Oro	151	0	42	21
Total Coast Region	*179*	*10*	*47*	*36*
Carchi	1	1	2	4
Imbabura	1	1	5	7
Pichincha	10	1	5	5
Cotopaxi	7	0	13	1
Tungurahua	0	0	0	0
Bolivar	16	3	2	1
Chimborazo	16	0	2	1
Cañar	9	1	0	2
Azuay	131	13	57	50
Loja	381	0	47	12
Total Andean Region	*572*	*20*	*133*	*83*
Morona Santiago	210	37	29	25
Napo	82	3	37	17
Orellana	2	0	2	6
Pastaza	2	0	1	7
Sucumbíos	28	3	18	58
Zamora Chinchipe	731	3	164	54
Total Amazon Region	*1055*	*46*	*251*	*167*

The Amazon Region has the highest number of ASGM mining concessions with a total of 1101 artisanal and 418 small-scale, legal and informal. In this region, the provinces of Zamora Chinchipe and Morona Santiago have the highest number of registered concessions with 952 and 301, respectively. In the Andean region, a total of 592 and 216 artisanal and small-scale ASGM mining concession processes have been registered, between legal and informal, respectively. The Andean provinces with the highest ASGM activity are Loja and Azuay with 440 and 251 respectively, between legal and informal processes. The province of El Oro in the Coast or Littoral region has the highest number of mining concessions with a total of 214, of which 151 are artisanal and 63 are small-scale mining between legal and informal. It is important to note that in the three continental regions of Ecuador there are a significant number of informal ASGM mining processes. Thus, in the

Andean region, the province of Azuay; in the Amazon region, the province of Sucumbíos; and on the coast, the province of El Oro, with 63, 61 and 21, are the provinces with the most informal activity in the country.

4. Mercury use in Ecuador

Until the beginning of 2013 the Ecuadorian Mining Law allowed the use of mercury in ASGM processes. On July 9, 2013, through Official Gazette No. 37, the Organic Reformatory Law to the Mining Law was issued, which among other things in its article 17 requests the addition of a new article to the Ecuadorian Mining Law regarding the prohibition of the use of mercury in mining operations. It is important to consider that for the eradication of the use of mercury in mining activities, natural or legal persons, national or foreign, and holders of mining rights, from the effective date of the law and for a period of two years, had to apply alternative methods that allow the progressive elimination of such substance in the mineral recovery processes. In order to comply with and control the import of mercury, the regulation was created to establish the requirements and procedures to obtain import licenses and authorizations for the transfer and consumption of mercury. Among the main requirements to obtain the import license is to have a technical responsible of chemical or related profession and an environmental license for the storage and transportation of hazardous substances.

Between 1994 and 2018 Ecuador imported 403 tonnes of Hg, the vast majority (90 %) for informal gold mining. This figure places it as the sixth country that imported the most of this chemical within the Amazon Biome, after Peru, Colombia, Brazil, Bolivia and Guyana. The use of Hg in Ecuador is common in artisanal and small-scale gold mining. Especially in the provinces of Esmeraldas, El Oro and Azuay. One of the reasons for continuing to use Hg in mining to extract gold is the speed and ease. It can be used by a single person, unlike mega-mining, which requires more people. And it is cheaper because it can be transported in plastic bottles. Miners who work with Hg admit to having problems such as skin rashes, eye irritation and even lung problems. Many of them confess that it is their only alternative in the absence of work. If given a choice between contamination and access to work to eat, most choose to eat. This is a national reality that is far from changing.

There is evidence of Hg use in gold mining activities in at least 25 cantons corresponding to 12 Ecuadorian provinces (Table 5). Primary, alluvial and processing areas were identified in these provinces. Mining areas such as Nangaritza Alto, located in the upper part of the river of the same name, Zamora province; Mira, located in the Ecuador-Colombia binational watershed bordering the provinces of Imbabura and Carchi; and Santiago, located in the Santiago river basin in Esmeraldas province, develop their activities in watersheds. This is an obligation acquired by the mining owners in order to contribute to the preservation of the environment by applying better processes in the extraction of gold. But this has not prevented the use of Hg in gold mining, so its commercialization can be found at different levels. The first one in stores or minority hardware stores where it is sold in small quantities for local consumption, especially for milling processes "chanchas", at this level it is marketed by ounces, at most 1 pound. Another level is developed by gold traders at district or zone level, their main function is to act as intermediaries in the sale of Hg between wholesale suppliers and retail distributors.

Hg is used to separate and extract Au from the rocks or stones in which it is found. The Hg adheres to the Au, forming an amalgam that facilitates its separation from the rock, sand or other material. The amalgam is then heated so that the Hg evaporates and the Au remains. Several different techniques are used that release different amounts of mercury. The first and most polluting is "Whole ore amalgamation", in this process Hg is added to the whole ore during crushing, grinding and washing, only 10% is combined with the Au, the rest is released into the environment. Another, Gravity concentration is widely used to concentrate gold together with other heavy minerals. The mercury is then added only to the concentrate to capture the free gold particles. This process reduces drastically the use and losses of mercury when compared with the primitive whole ore amalgamation process. The amalgam with 40 to 50% mercury is then burned to evaporate the mercury and this process if frequently conducted without retorts (condensers) exposing miners and neighbors to toxic vapors [9,20].

In 2013, Ecuador, through the Ministry of Environment, signed the Minamata Convention, the first international agreement to reduce the use and trade of Hg to prevent damage to health and the environment. The United Nations Development Programme (UNDP) in Ecuador is developing the "National Programme for the Environmental Sound Management and Life Cycle Management of Chemical Substances", which aims to provide advice and training on Hg management in artisanal and small-scale gold mining (ASGM). UNDP together with the Geological and Energy Research Institute. The use of Hg in mining activities generates negative impacts on the environment and human health. Water contamination, Hg entrainment due to acidification processes and the emission of toxic vapors are the main environmental impacts related to the use of Hg in gold mining in Ecuador.

Table 5. Mining areas and Hg use.

Province	Canton	Mining area
Imbabura	Cotacachi	Intag
	San Miguel de Urcuquí	Buenos Aires
	Ibarra	Carolina
		Lita
Carchi	Mira	Cielito
Esmeraldas	Eloy Alfaro	Río Santiago
	San Lorenzo	Río Bogotá
Napo	Tena	Ahuano
		Misahuallí
		Arosemena Tola
Pichincha	Quito	Pacto
Chimborazo	Cumanda	Cumandá
Bolivar	Chillanes	
Cotopaxi	La Maná	La Maná
		California
Azuay	Ponce Enriquez	Ponce Enriquez
	Chordeleg	Chordeleg
Zamora	Zamora	Chinapintza
	Paquisha	Nambija

	Nangaritza	Anto Nangaritza
	Chinchipe	Chito
Loja	Célica	Célica
	Cariamanga	Cariamanga
El Oro	Portovelo	Zaruma Portovelo
	Atahualpa	
	Zaruma	
	Piñas	
	Santa Rosa	Santa Roja
	Pasaje	Pasaje

5. Source of Hg pollution coming from mining effluents

Most mercury contamination in ASGM mining comes from informal activities [21]. This type of activity corresponds to those that did not obtain the proper authorizations to start activities. In Ecuador, as shown in Table 4, the provinces with the greatest amount of informal activity are in the provinces of Azuay, Sucumbíos, Zamora Chinchipe and El Oro [7,17,22,23]. It is important to note that in a study on the baseline for Artisanal and Small-scale Gold Mining in Ecuador, according to the Minamata Convention on Mercury, the province of Sucumbíos was not considered, but this is not necessarily because there is no concern about the growth of informal ASGM activities, in that study the visit was not carried out for analysis due to security problems and armed conflicts caused by this activity [24]. The situation in the Amazon Region is of concern because in addition to informal mining, cases of illegal mining have been detected, for example, in protected areas such as the Podorcapus National Park in the south of the country (Loja and Zamora Chinchipe) and the Cofán Bermejo Ecological Reserve in the north of the country (Sucumbíos) [25,26].

One of the particular characteristics of ASGM is the application of conventional techniques. These practices cause this activity to generate a negative impact on the environment as a result of the use of Hg. In these processes there is a high loss of Hg for example in the processing centers at the time of grinding all the material with the different techniques and technologies available, these mercury residues end up in the tailings that are mixed with cyanide and generate $Hg(CN)_2$ losses that affect water bodies [22,27,28]. The big problem starts here, because almost all forms of mercury that enter ecosystems can be converted to methylmercury, these bioaccumulate through aquatic biota and can cause serious effects (biomagnification) through the food chain. This is of concern because studies indicate that up to 90% of the methylmercury present in food can be absorbed by the digestive system of animals such as humans.

Due to the increase in the price of gold worldwide, ASGM gold mining activities have increased in recent years [29]. Thus, the number of processing centers has increased considerably in Ecuador. The rudimentary processes carried out at the processing centers are generally not efficient since the mercury is pulverized and lost in the tailings in the milling process. In the processing centers in southern Ecuador, it is estimated that 40 to 50% of the element forms an amalgam and is recovered. The remaining and sometimes up to 80% of the Hg introduced to the process is lost with the tailings. Tailings with residual gold are subjected to cyanidation processes on leaching-precipitation surfaces with zinc chips. This leaching cycle can last several days depending on the type of tailings. At the end of this process, when the miners visually observe that gold is no longer collected in the zinc shavings, i.e., that it does not acquire a black color, they discharge the tailings into the environment which are still rich in cyanide, zinc and mercury. This has caused strong effects on biota in water bodies due to the formation of mercury cyanide $Hg(CN)_2$. Several studies at the national level have demonstrated these impacts. [17,22,30,31].

In the northern Amazon region in the Putumayo and Napo hydrographic systems, specifically in the upper basin of the Aguarico and Napo rivers in the provinces of Sucumbíos and Orellana, respectively, there is evidence of Hg levels outside the permissible limits for the protection of water bodies and their life in continental zones. [7,33]. These impacts are mainly associated with anthropogenic activities such as small-scale gold mining. Of the total water samples taken between 2012 and 2016, 35% showed results outside acceptable thresholds [34]. Results indicate that Hg contamination in Amazonian areas can be evidenced in ichthyofauna communities, and that some fish species are contaminated by Hg. Considering the high consumption of fish and its use as an ecosystem service in indigenous riverbank communities, the exposure of rural communities to Hg is high. All of this, together with high deforestation rates due to changes in land use and constant rainfall in the Amazonian zone, leads to increased runoff and dynamic Hg waste flow due to gold mining [35].

There is evidence of Hg contamination in the southern coastal zone. Subway water samples taken in the Ponce Enriquez mining area, exactly in the Siete, Guanache, Fermin, Fermin Norte and Villa rivers in the Naranjal-Pagua, Jubones, Santa Rosa, Arenillas and Zarumilla hydrographic systems in the provinces of Azuay and El Oro, show elevated concentrations of heavy metals such as Hg [36]. Hg contaminants have been found in the Puyango-Tumbes River, with high concentrations and high mobility of heavy metals in the hydrographic systems, mainly due to gold mining activities in the Portovelo-Zaruma area. These effects have caused transboundary problems, and Peru has repeatedly appealed to international organizations to demand greater care from Ecuadorian authorities regarding the use of Hg in gold mining processes. In terms of health, there have been problems of intoxication among local miners; although the number of reports in recent years has decreased, there is still evidence of the after-effects of Hg use [17,23]. Mining activities in the southern coastal zone and the use of Hg are severely impacting water quality and the functionality of its ecosystems [23]. The mismanagement of Hg and cyanide causes serious and geographically extensive problems, affecting up to 160 km from the point of generation in the course of the water systems in the lower basins [37].

Most people engaged in gold mining activities are aware of the various risks associated with the use of Hg, both to health and the environment. Despite this, the amalgamation method and the use of Hg is still preferred by miners, as it is very accessible, easy to use and relatively cheaper. On the other hand, in recent years the prohibitions by the Ecuadorian government and its control entities on the use of Hg in gold extraction processes have led to a greater use of cyanide [24,38]. It is important to consider that this element is also harmful to the environment and human health. Biota can accumulate cyanide that is transferred to humans, increasing lactate in the blood, causing a decrease in oxygen and mainly affecting the brain and heart [39–41]. This acceptance can also be associated to higher profits in gold recovery processes by cyanidation than Hg amalgamation. Thus, in recent years cyanidation processes have increased and a decrease in the use of Hg for gold extraction has been evidenced [38]. It is necessary to pay more attention to studies that allow the implementation of clean technologies in processing centers that reduce environmental impacts and, at the same time, work on innovative techniques for the remediation of Hg-contaminated water.

There are three aspects that can explain the high consumption of mercury in ASGM. First, its low cost, although this has been changing in recent years due to the total ban on gold mining processes, so that its price in the illegal market has doubled and sometimes tripled [42,43]. On the other hand, the low level of education of the miners can be evidenced by a lack of knowledge of the effects of Hg on the environment and health. In addition to a lack of access to credit, their minimal capacity to save and invest, and their distrust of new technologies have been obstacles to adopting more environmentally friendly practices [42].

Once the literature has been reviewed, there is evidence of a large impact of heavy metals, including Hg, as a result of ASGM mining activities in several areas of Ecuadorian territory. Among them, in four of the five provinces in the Amazon region, these activities are carried out very close to protected areas such as Podocarpus National Park (Zamora Chinchipe) [44], Yasuní National Park (Orellana and Napo) [35] and Cofán Bermejo Ecological Reserve (Sucumbíos) [45] and in some cases within these areas. Similarly, in the Andean region, in the provinces of Loja [46] and Azuay [47], studies have shown that the natural environment has been affected, and recently there has been an increase in activities in the provinces of Imbabura and Pichincha [19]. In the coastal region, the province of El Oro has historically been involved in contamination problems, and recently the province of Esmeraldas has seen an increase in ASGM mining activities, which have also affected the environment [18,31,48]. In view of this, it is important to establish practical, simple recommendations that have been successful in other places where ASGM activities have been carried out, in order to reduce the impact of Hg on ecosystems and human health.

6. Recommendations for ASGM management and prevention of Hg contamination of water bodies

6.1 Mining management in Ecuador

The mining control entity should currently socialize the updates in its functional organization chart to all social actors in mining processes considering that there is a strong misinformation about the mining formalization and regulation processes. This will allow mining processes at different scales to carry out a correct regulation regarding rights and environmental regularization processes. Only then will it be possible to have an updated registry that contributes to a correct management that can prevent social and environmental problems at the national level. It is also necessary that the government entities in charge of regularization, control and surveillance processes carry out a purge of unethical officials, who are easily persuaded with bribes by illegal actors developing mining activities. It is relatively easy to see when there has been a leakage of information after a citizen complaint for illegal activities, and it is at that moment when administrative or legal processes should be applied with bad technical elements belonging to the environmental authority.

In medium and large-scale mining, the State should incorporate a broadly defined environmental prevention objective in a general environmental legal framework or in specific environmental laws for each effect. Develop specific goals, measures and technical guidance to achieve prevention in the context of mining instruments. Improve planning instruments for pollution prevention, especially closure planning requirements. In addition, it is essential to strengthen public participation mechanisms, considering that a key component of an environmental prevention strategy is effective public participation in environmental decision-making and oversight. This participation can increase incentives for developing environmental prevention strategies and for monitoring their effectiveness. Better mechanisms should be established to develop and disseminate information on environmental impacts, as well as on emissions and discharges to the environment that are taking place (especially those that are toxic). Finally, governments can explore as a strategy the use of public participation funding mechanisms, including environmental prevention education programs.

The State should establish and promote special programs for technical assistance, environmental management, mining safety and professional training for ASGM, for which the academy should provide support, this will allow miners to learn about the risk of using prohibited substances such as Hg and opt for new, less harmful techniques. Considering that the greatest Hg contamination occurs in the Amalgamation process, the importance and benefits of using a retort should be explained. In addition, adopt sustainable development policies for artisanal and small-scale mining. Also, establish incentives for environmental protection and generation of more efficient productive units. All of this will allow the adoption of better environmental practices in the gold extraction process in the ASGM sector, which will result in less contamination of the natural environment due to illegal use of Hg, considering that this sector is the one that pollutes the most.

6.2 Prevention of Hg contamination of water bodies

There are sufficient studies which demonstrate that the problem regarding the contamination of water bodies and their biota by ASGM activities originates in the processing centers at the stage of cyanidation of Hg-contaminated tailings [7,22,27,28,49]. This is a source of formation and release of mercury cyanide into the environment. At this point the types of mercury are easily methylated and bioaccumulate, in several studies it has been shown that near the cyanide leaching areas fish contain high levels of mercury [2,35]. This is due to the fact that in the cyanidation stage in the processing centers, mercury dissolves in cyanide more slowly than gold, thus, the tailings dumped in the rivers still contain metallic mercury and mercury cyanide. In view of this situation, this study has managed to establish practical recommendations to prevent contamination of surrounding water bodies and their biotic elements [43,50,51].

One of the main ways to prevent Hg from affecting water bodies in ASGM activities is through education. This will make miners aware of the health and environmental risks of indiscriminate Hg use. On the other hand, learning about new technologies and how efficient they can be will serve to demystify that the only and best option to extract the greatest amount of gold is the use of Hg. These education campaigns will demonstrate that there are more efficient and mercury-free techniques, i.e. cleaner, and that they can also increase gold production. It is necessary and fundamental to share experiences from other countries on successful cases, for example in Colombia [43], this will allow to gain the confidence of the miners and try to replicate this type of practices. It is important to mention that these educational campaigns should go beyond just presenting new techniques as an alternative to solve pollution problems; it is important to pay attention to socioeconomic problems and propose complementary interventions such as strengthening collective miners' associations that fight for their rights [42]. The objective of these ASGM miners' associations should not only focus on improving their economic income, but they should also join efforts to improve their overall quality of life, including health, food and a healthy environment.

A case that can be taken as an example for the whole country is the small mining concession "Mina Corazón" managed by the company "Agroindustrial El Corazón", located in the province of Imbabura, canton Cotacachi. This company maintains a strict community relations plan through which it provides direct employment to the population and assistance in areas such as roads, health, and education. The canton is also known for its agro-ecological development and promotion of ecotourism. Aspects that have led to strong opposition to ASGM development in the area and close social scrutiny regarding compliance with good environmental practices. This has allowed minimizing the use of Hg and applying mostly cyanidation techniques to extract the gold. In addition, there is a closed process that allows water reuse and when it is really necessary to discharge the water, an in-situ treatment is performed prior to discharge with hydrogen peroxide allowing the elimination of cyanide in the tailings water. The effectiveness of the treatment is corroborated by annual analyses of the water quality of the receiving watersheds and their biota. As a result, it is the only mine site in the country where aquatic life has been maintained without Hg affectation "downstream" of an ASGM processing plant [19].

7. Conclusions

Mining management in Ecuador presents serious problems in its organizational processes, and in recent decades it has undergone several changes that make it difficult to understand how it works. Starting with its governing body, the name of this ministry has undergone several changes as new presidents have taken office. The functional organization chart is constantly changing, this has been justified as a consequence of staff optimization due to lack of budget. These problems prevent the development of adequate control and monitoring of mining activities in Ecuadorian territory. This has led to an increase in illegal and informal activities in the ASGM sector.

Promoting training and education processes with artisanal and small-scale miners in Ecuador regarding the risks and impacts that can be caused by the indiscriminate use of Hg on health and the environment is a practical option for the application of new techniques and clean technologies to reduce the use of mercury in ASGM and therefore the impact on water bodies and their biotic elements. In addition, it is important to socialize successful results where the application of new techniques where only cyanide is used allows obtaining higher purity and quantity of gold. In some cases, miners are aware of the risks of Hg, but the lack of trust and communication among them prevents the correct application of techniques. At this point it is necessary to encourage associative grouping that allows them to opt for social capital and socioeconomic benefits.

The Ecuadorian government must establish mechanisms for the promotion, technical assistance, training and financing of sustainable development for artisanal and small-scale mining. Likewise, it should propose incentive systems for environmental protection and the generation of more efficient productive units. Finally, it is essential to carry out new studies that contribute to improving mining management at all levels and environmental protection. One of the main limitations of our study was the scarcity of information available on successful management processes to reduce the impact of ASGM activities on water bodies.

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