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**Risks and impacts of mercury use in gold mining in  
Ecuador**

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## **DOCTORAL THESIS**

Risks and impacts of mercury use in gold mining in Ecuador

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## List of publications

The work is constituted by a set of publications that have been accepted and published after the first enrollment of academic tutelage. As a result, seven publications have been obtained (Annexes I, II, III, IV, V) included in the first two quartiles of the Journal Citation Report JCR. In the text the publications will be referred to with the following numbering:

Mestanza et al.	<p>Mestanza–Ramón, C., Jiménez–Oyola, S., Gavilanes Montoya, A. V., Vizúete, D. D. C., D’Orio, G., Cedeño–Laje, J., Urdánigo, D., &amp; Straface, S. (2023). Human health risk assessment due to mercury use in gold mining areas in the Ecuadorian Andean region. <i>Chemosphere</i>, 344, 140351.</p> <p><a href="https://doi.org/https://doi.org/10.1016/j.chemosphere.2023.140351">https://doi.org/https://doi.org/10.1016/j.chemosphere.2023.140351</a></p> <p>Indexación: Journal Citation Report <b>Elsevier Chemosphere</b> WoS – JCR Q1, IF = 8.8 (2023)</p> <p><a href="https://www.sciencedirect.com/science/article/pii/S0045653523026218">https://www.sciencedirect.com/science/article/pii/S0045653523026218</a></p>
Mestanza et al.	<p>Mestanza–Ramón, C., Jiménez–Oyola, S., Montoya, A.V.G. et al. Assessment of Hg pollution in stream waters and human health risk in areas impacted by mining activities in the Ecuadorian Amazon. <i>Environ Geochem Health</i> (2023).</p> <p><a href="https://doi.org/10.1007/s10653-023-01597-6">https://doi.org/10.1007/s10653-023-01597-6</a></p> <p>Indexación: Journal Citation Report <b>Springer–Nature Environmental Geochemistry and Health</b> SJR Q1, (2023)</p> <p><a href="https://link.springer.com/article/10.1007/s10653-023-01597-6">https://link.springer.com/article/10.1007/s10653-023-01597-6</a></p>
Mestanza et al.	<p>Mestanza–Ramón, C.; Cuenca–Cumbicus, J.; D’Orio, G.; Flores–Toala, J.; Segovia–Cáceres, S.; Bonilla–Bonilla, A.; Straface, S. Gold Mining in the Amazon Region of Ecuador: History and a Review of Its Socio–Environmental Impacts. <i>Land</i> 2022, 11, 221. <a href="https://doi.org/10.3390/land11020221">https://doi.org/10.3390/land11020221</a></p> <p>Indexación: Journal Citation Report <b>Land</b> WoS – JCR Q1, IF = 3.905 (2022)</p> <p><a href="https://www.mdpi.com/2073-445X/11/2/221">https://www.mdpi.com/2073-445X/11/2/221</a></p>
Mestanza et al.	<p>Mestanza–Ramón, C.; Ordoñez–Alcivar, R.; Arguello–Guadalupe, C.; Carrera–Silva, K.; D’Orio, G.; Straface, S. History, Socioeconomic Problems and Environmental Impacts of Gold Mining in the Andean Region of Ecuador. <i>Int. J. Environ. Res. Public Health</i> 2022, 19, 1190. <a href="https://doi.org/10.3390/ijerph19031190">https://doi.org/10.3390/ijerph19031190</a></p> <p>Indexación: Journal Citation Report <b>Int. J. Environ. Res. Public Health</b> WoS – JCR Q1, IF = 2.849 (2022)</p> <p><a href="https://www.mdpi.com/1660-4601/19/3/1190">https://www.mdpi.com/1660-4601/19/3/1190</a></p>

Mestanza et al.	<p>Mestanza–Ramón, C.; Mora–Silva, D.; D’Orio, G.; Tapia–Segarra, E.; Gaibor, I.D.; Esparza Parra, J.F.; Chávez Velásquez, C.R.; Straface, S. Artisanal and Small–Scale Gold Mining (ASGM): Management and Socioenvironmental Impacts in the Northern Amazon of Ecuador. <i>Sustainability</i> 2022, 14, 6854.  <a href="https://doi.org/10.3390/su14116854">https://doi.org/10.3390/su14116854</a></p> <p>Indexación: Journal Citation Report <b>Sustainability</b> WoS – JCR Q2, IF = 3.889 (2022)  <a href="https://www.mdpi.com/2071-1050/14/11/6854">https://www.mdpi.com/2071-1050/14/11/6854</a></p>
Mestanza et al.	<p>Mestanza–Ramón, C.; Paz–Mena, S.; López–Paredes, C.; Jimenez–Gutierrez, M.; Herrera–Morales, G.; D’Orio, G.; Straface, S. History, Current Situation and Challenges of Gold Mining in Ecuador’s Litoral Region. <i>Land</i> 2021, 10, 1220.  <a href="https://doi.org/10.3390/land10111220">https://doi.org/10.3390/land10111220</a></p> <p>Indexación: Journal Citation Report <b>Land</b> WoS – JCR Q1, IF = 3.905 (2021)  <a href="https://www.mdpi.com/2073-445X/10/11/1220">https://www.mdpi.com/2073-445X/10/11/1220</a></p>
Mestanza et al.	<p>Mestanza–Ramón, C.; D’Orio, G.; Straface, S. Gold mining in Ecuador: Innovative recommendations for the management and remediation of mercury–contaminated waters. <i>Green World Journal</i> (2021). <a href="https://doi.org/10.53313/gwj42028">https://doi.org/10.53313/gwj42028</a></p> <p>Indexación: <b>Green World Journal</b>, Latindex 2.0  <a href="https://doi.org/10.53313/gwj42028">https://doi.org/10.53313/gwj42028</a></p>

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## Abstract

Gold mining in rivers and aquifers in Ecuador has been a history and evolving activity that has left its mark on the country's environment. However, this mining practice has also generated a series of problems, especially in terms of environmental risks and impacts associated with the release of mercury (Hg) into surface and groundwater bodies. The general objective of this research is to establish a comprehensive baseline on the History situation and evolution of gold mining in continental Ecuador, taking into account the environmental risks and impacts caused by the presence of mercury in water sources. To achieve this, we seek to implement techniques and strategies to improve gold mining processes and, at the same time, promote a harmonious approach to life and well-being.

The methodology used to achieve these objectives initially includes a detailed review of scientific literature and historical data related to gold mining in Ecuador. In addition, chemical analysis and sampling will be conducted in different rivers to determine the mercury concentrations present in the water, and socio-ecological risks will be assessed using probabilistic and deterministic techniques. A double-entry matrix and SWOT will be used to assess environmental impacts and then propose improvement techniques and strategies through a critical diagnosis.

The main results indicate that the lack of community participation in decision-making, insufficient coordination between government institutions, communities and miners, and the lack of control of mining activities are factors that contribute to ineffective compliance with environmental policies in the gold mining sector in the Amazon. The provinces of Loja, Azuay, Imbabura and Pichincha are the most conflictive areas in the region due to the impacts of mining activities. In socioeconomic terms, there are conflicts between the inhabitants for and against these activities and problems associated with human health. In environmental terms, the findings suggest History contamination of water sources by heavy metals, which has altered the surrounding aquatic and terrestrial systems in addition, in the coastal region, specifically the provinces of El Oro and Esmeraldas are essentially the most conflictive areas of the region, as they have sometimes had to establish precautionary measures due to the risks generated by illegal mining. In addition, in both areas there is a great socioeconomic impact ranging from lack of opportunities, oblivion, migration,

emigration and violation of rights, among others. In terms of environmental impacts, the study highlights the contamination of water sources (which generates a lack of drinking water for people), and damage to aquatic and terrestrial ecosystems.

Regarding Hg contamination in river water and risk to human health in the Amazon region, 100% of the samples analyzed exceeded the maximum permissible limit (MPL) according to the water quality criteria for the preservation of aquatic life in Ecuadorian regulations, while 7% of the samples exceeded the MPL for drinking water. The risks assessment revealed that the probability of developing adverse health effects from exposure to Hg is below the recommended limits according to the probabilistic assessment; this in relation to the criterion of residential and recreational use of water resources. However, it was identified that the child population doubles the acceptable systemic risk level according to the results of the deterministic assessment in the residential scenario. In the Andean region, Hg concentrations show out-of-limit values for the total samples in Carchi (73.33%), Imbabura (22.73%), Pichincha (83.33%), Cotopaxi (9.09%), Bolivar (37.50%), Azuay (51.11%) and Loja (21.02%). The high presence of mercury in the provinces, mainly in Azuay and Loja, related to gold mining activity, represents a threat to water quality and aquatic life in the Andean region of Ecuador. Similarly, in the coastal region, high concentrations of Hg were found in the provinces of El Oro and Esmeraldas, located to the southwest and northwest, respectively, of the area analyzed. These values exceeded the Ecuadorian regulatory thresholds designed to safeguard the quality of the drinking water supply. The hypothetical cause of these notorious Hg concentrations could be related to mining activity in the area, particularly gold mining involving the use of mercury as a component in the separation of gold from other substances.

The socio-environmental impacts include contamination of bodies of water, soil and atmosphere due to the use of mercury and the disturbance of flora and fauna due to the use of machinery in the exploration process. Finally, the government should focus efforts on strengthening public policies to socialize the importance of good environmental practices in ASM and the effects of impacts on human health and environmental issues, with the support of social actors such as ministries, universities, NGOs, ASGM associations and private enterprise.

The recommendations state that mining management in Ecuador should focus its efforts on improving control and monitoring capacity, regularizing mining registries and strengthening regulations with new policies. Finally, to reduce the impact of Hg in water bodies, it is necessary to educate ASGM miners on the risks of indiscriminate mercury use and on techniques that can provide better socioeconomic benefits.

1. Introduction

## 1. Introduction

Mining worldwide is currently experiencing an unprecedented growth in production. The world market for minerals and precious metals has skyrocketed and the quantities extracted have multiplied exponentially (Banco Central del Ecuador, 2020; Concha, 2017) Gold (Au), recognized as one of the most sought after and demanded elements in international trade, is also the most exploited precious metal in world mining production (Espinosa, 2022; Rudel, 2018). In the case of South America, member countries such as Colombia, Peru, Bolivia, Chile, Brazil and Argentina stand out for the production and export of Au. The market in which Ecuador has become increasingly competitive in recent years as part of a strategy to diversify its production (Bottaro & Sola Álvarez, 2018; Carvalho, 2017)

Most of the attention in the gold mining industry is focused on large companies; however, in various parts of the world, especially in developing countries, minerals are extracted through artisanal and small-scale mining (ASM), a complex and diversified sector (Katz-Lavigne, 2019; Katz, B.J.; Holmes, F.; Holmes, 2012; Rozo, 2020; Veiga & Marshall, 2019). It encompasses a wide range from informal independent miners seeking a livelihood to formal small-scale commercial mining entities that produce minerals in a responsible manner. For several countries, ASGM is an important source of livelihood and environmental damage (Cossa et al., 2021; Hook, 2019; Wilson et al., 2015).

Artisanal and small-scale gold mining (ASGM) is an important source of income for rural sectors where economic income alternatives are extremely limited (Verbrugge & Geenen, 2019). Generally, in remote sectors, this activity is carried out in a rudimentary manner, without complying with environmental regulations or illegally, for example, using Hg in gold extraction processes (Niane et al., 2019). In the last decade, with the increase in demand for gold, illegal mining activities have gone from being rudimentary to employing mechanized processes, generally financed by criminal groups (Ebus & Martinelli, 2022; Rettberg & Ortiz-Riomalo, 2016) which resulted in an increase

in production and with it an increase in the illegal use of Hg (Bengtsson & Hylander, 2017).

In Ecuador, ASM dates back to colonial and pre-colonial times, reaching greater development and production in the 1990s, a period in which the existence of gold, silver and copper deposits was determined through geological studies sponsored by the Central Bank (Espinosa, 2022). In addition, the increase of mining activities in the Ecuadorian gold sector has placed natural resources under analysis in both academic and social spaces (Miserendino et al., 2013). Exploration and exploitation activities are generally carried out against the will of neighboring communities, which has generated social problems such as eviction of inhabitants from their properties and community discontent due to continuous environmental contamination, among others (Marshall et al., 2020). Artisanal and large-scale gold mining can negatively affect the environment (health risks, changing land use and livelihood options) and cause serious impacts for miners and surrounding communities, leading to conflicts over property and land use (Ebus & Martinelli, 2022; Rettberg & Ortiz-Riomalo, 2016). Despite all this, the miner takes risks and works with the well-being and daily needs of his family in mind (Mestanza-Ramón, Paz-Mena, et al., 2021; Mestanza et al., 2018; Veiga & Gunson, 2020).

Despite the socioeconomic benefits of Au mining development in the country, the environmental impacts generated by this activity are classified disadvantageously as a source of pollution, which depends on the extraction methods, scale of operation, location and characteristics of the receiving environment (Guerra & Peralvo, 2010). In terms of health, the impacts of Au extraction are concentrated in the exposure of workers to toxic substances, such as mercury (Hg) and cyanide (CN), especially in the manual and rudimentary practices of artisanal and illegal mining (O. Betancourt et al., 2005; Calderón Robles, 2020). Similarly, improper disposal of mine tailings and infiltration of toxic substances into the soil and water bodies can result in health problems for people, plants and animals near mining sites, as well as those located downstream of Au extraction sites (E. A. Mora, 2002).

The present research is focused on establishing a baseline on the History situation and evolution of gold mining in continental Ecuador along with environmental risk and impacts considering mercury (Hg) concentrations in surface and groundwater bodies, which will allow implementing techniques and

strategies to improve gold mining processes and promote life in harmony and good living.

### **1.1. Gold mining in Ecuador**

Gold mining has been an activity of great economic and social relevance in Ecuador throughout its history (Vilela–Pincay et al., 2020). Since pre–Columbian times, indigenous communities were already using gold for ornamental and ritual purposes (Fuenzalida & Otárola, 2008). However, over time, the search for this valuable metal has become a more industrialized and controversial process, especially in the exploitation of rivers and aquifers (Massa–Sánchez et al., 2018).

The gold rush in Ecuador began during the 16th century, when the Spanish conquistadors were attracted by the abundance of this precious metal in Ecuadorian territory (Osorio Rivera et al., 2018). Throughout the centuries, gold mining remained an important activity, but with a more artisanal and local approach. However, in the 20th century, with the advance of technology and the increase in demand for gold in the international market, the exploitation of this resource intensified, and more destructive methods began to be used, such as large–scale mining and the use of mercury for extraction (Estupiñan et al., 2021).

During the 1970s, industrial gold mining was boosted in Ecuador with the creation of the National Mining Corporation of Ecuador (ENAMI), which led to a significant increase in extraction (Almeida, 2019a). This mining boom also attracted foreign companies seeking to exploit the country's gold deposits. Although gold mining generated economic income for the country, it also generated environmental problems and social conflicts due to the lack of regulation and control of the activity (Zárate et al., 2020).

Gold mining in rivers and aquifers has had serious environmental consequences in Ecuador. One of the main problems is water pollution from the use of mercury in gold mining (Sarria–Villa et al., 2020). Mercury, a highly toxic metal, is used to separate gold from other minerals, but once released into rivers and aquifers, it is converted into methylmercury, a particularly dangerous form that bioaccumulates in the food chain, affecting aquatic fauna and people who consume contaminated fish (Parra et al., 2018). In addition, deforestation and soil degradation are common in gold mining areas, leading to habitat loss and soil erosion. Sediments and chemicals released during the mining process

can severely affect water quality and local biodiversity, putting endemic plant and animal species at risk (Yauripoma & Alarcon, 2019).

Currently, gold mining in rivers and aquifers remains a controversial activity in Ecuador. Although some regulations have been implemented to control illegal mining and environmental impacts, effective enforcement of these measures is a challenge. Local communities and environmental groups have expressed concern about the lack of control and the negative consequences of mining activity in their territories (Madrigal Garzón, 2019).

The Ecuadorian government has attempted to strike a balance between economic revenue generation and environmental protection. Some proposals include encouraging more sustainable practices, such as responsible mining and the use of clean technologies to reduce pollution. The promotion of economic alternatives for affected communities, such as ecotourism and sustainable agriculture, has also been considered (Meza Aldas & Gallegos, 2000; Vela-Almeida et al., 2021).

Gold mining in rivers and aquifers in Ecuador has been a long-standing activity, with significant History, economic and environmental implications. Over the years, gold mining has evolved from an artisanal practice to an industrialized activity, which has increased environmental impacts and social conflicts in the country (Cisneros, 2011).

While gold mining has generated economic income, it has also left a legacy of pollution and environmental degradation. It is essential that the Ecuadorian government implement effective control and regulation policies to mitigate the negative impacts of this activity on the country's rivers and aquifers. It is also crucial to promote sustainable economic alternatives that respect and value Ecuador's rich biodiversity and natural heritage. Ultimately, gold mining must be carried out in a responsible and sustainable manner, taking into account economic as well as environmental and social aspects. This is the only way to ensure a prosperous and equitable future for Ecuador's local communities and environment.

### **1.1. Classification by processing of gold mining in Ecuador**

The Ecuadorian Mining Law classifies mining activities into four groups: artisanal or subsistence mining, small-scale mining, medium-scale mining and large-scale mining. In addition, it should be noted that artisanal and small-scale mining are usually related by the term ASM (Gonçalves et al., 2017); which

encompasses the requirements and regulations applicable to both classifications (Cossa et al., 2021; Zvarivadza, 2018). The main characteristics of the mining classification with a focus on the gold segment are described below.

#### **1.1.1. Artisanal or subsistence mining**

Artisanal mining, in the global context, is defined as an activity that is carried out intensively in remote and difficult to access sites, where people focused on its development use rudimentary techniques with little or no technical knowledge in extraction and mineral exploitation activities, low levels of environmental education, safety and occupational health (Hilson, 2002). In terms of Ecuadorian legislation, artisanal mining is defined as an activity that is developed through individual, family or association work by those who carry out mining activities in open areas, solely and exclusively for survival purposes. These activities are regulated and may not exceed 4 hectares in subway conditions and 6 hectares in open pit conditions. Similarly, production and processing capacity is restricted for metallic minerals such as gold to 10 tons per day in subway mining activities and 120 cubic meters per day in alluvial mining (Asamblea Nacional, 2018). Something common in this activity is that artisanal miners are based on their survival instinct, to supply the economic needs of their families and to pay for the investments made for the operation; this approach is the central axis or driving force used by them. In addition, they develop their activities from the perception of producing more gold with the least number of extraction processes carried out, which shows the little interest they have in improving the techniques and methods used in gold recovery (Veiga & Gunson, 2020).

The definition of artisanal mining varies according to the legislation in force in each country, so it is important to analyze its variations in order to have a general context. In this context, for example in Colombia, artisanal mining is considered to be an activity that takes place in rural areas, individually or in small groups and is generally carried out in a very rudimentary manner, without technical assistance and only through the use of hand tools and without machinery (Specht & Ros-Tonen, 2017; Veiga & Marshall, 2019). In Peru, it is recognized and defined as a subsistence activity whose product provides for family needs; it is developed by intensive local labor, which makes it a great source of employment generation and, therefore, brings with it the promotion

of productive collateral benefits in areas surrounding the area of influence of the operations (Congreso De La República De Perú, 2002; M. K. Romero et al., 2005). On the other hand, artisanal mining in Bolivia does not have an established legal definition, which is why it is most often associated with small-scale mining (Sajama, 2020; Zamora Echenique et al., 2017).

### **1.1.2. Small-scale mining**

As a first approximation to provide a clearer definition of small-scale mining, the United Nations (UN) in 1972 defined this activity as: "Any mining operation activity developed on an individual basis that has an annual production of gross materials of approximately 50,000 metric tons" (Seccatore et al., 2014). In the context of Ecuador, small-scale mining is defined as an activity that is feasible to rationally exploit directly, without the prior execution of exploration work or in the case of simultaneous work focused on exploration and exploitation of minerals. In terms of production capacity, small-scale mining is allowed to exploit up to 300 tons per day in subway mining; up to 1000 tons per day in open pit mining; and up to 1500 cubic meters per day in alluvial mining (Asamblea Nacional, 2018).

On the contrary, in neighboring countries, such as Colombia, small-scale mining is defined as the activity that is carried out through the use of conventional tools and implements manually, which are managed by means of manual labor using human strength; this activity is characterized by not exceeding 250 tons of material per year under any circumstances (Güiza, 2013). In Peru, this activity is mechanized and therefore incorporates a large amount of labor; current legislation in that country establishes restrictions regarding the volume of mineral extraction, allowing people dedicated to this activity to only have up to 2,000 hectares of land and excavate 350 tons of material per day (Congreso De La República De Perú, 2002). In the Chilean context, the national geology and mining service defines small-scale mining as an activity that develops rudimentary production and processing techniques. It should be noted that Chilean legislation is based on the number of workers hired per year, with 80 being the minimum number of workers to be considered small-scale mining (Castro & Sánchez, 2003).

### **1.1.3. Medium Scale Mining**

Medium mining is considered to be the activity where mineral reserves have been quantified that allow the exploitation of the same over the previously established volume under the small-scale mining regime. This allows interpreting that miners engaged in small-scale mining can be reclassified to medium mining as long as they comply with the pre-established requirements (Asamblea Nacional, 2018). Regarding production volumes, in this modality the exploitation of metallic materials ranges from 301 to 1000 tas per day in subway conditions, 1001 to 2000 tons per day in open pit; and 1501 to 3000 cubic meters in alluvial mining.

In the Latin American context, medium-scale mining is differentiated by the volume of material allowed to be exploited per day, such is the case that in Peru the current legislation allows excavating material of no more than 5000 tons per day (Congreso De La República De Perú, 2002); in Bolivia this activity stands out for considering all operations based on the exploitation of more than 500 tons per day (Bocangel, 2001), while in Chile it is defined as any mining activity whose production is greater than 200 tons of material per day (Sánchez & Enríquez, 1996).

### **1.1.4. Large scale mining**

In Ecuador, large-scale mining is considered to be that activity that exceeds all the maximum volumes described for medium-scale mining. In this context, this activity is associated with large scales in terms of surface exploitation, which is why it is of great interest to investors and large foreign companies (Asamblea Nacional, 2018). Another important aspect, which is important for scale independence, is the high degree of application of specialized technology and techniques in mineral extraction, which allows minimizing environmental impacts and extracting as much gold as possible. Therefore, it is interpreted that this activity requires heavy investment in infrastructure construction, waste management and reduction of environmental impacts (Carvalho, 2017). Large-scale mining differs from other classifications because it considers several stages in its development: prospecting, exploration, planning and exploitation, which demonstrates its high level of organization and technification for the exploitation of minerals such as gold (Calderón Robles, 2020).

Like other types of mining, large-scale mining has definitions and regulations in countries other than Ecuador. In the Peruvian context, it has a similar criterion, indicating that this activity is highly industrialized and has greater investment, which allows extraction levels to be constant; in this way, Peruvian legislation establishes that large-scale mining is that which has the capacity to extract amounts greater than 5,000 tons of gold per day (Congreso De La República De Perú, 2002). Additionally, in Colombia this type of mining is described as an activity that stands out for the application of more technical and specialized methods in gold extraction, which allows it to provide greater industrial security to the skilled labor in charge of these operations, in addition to having a higher level of financing and investment (Betancur-Corredor et al., 2018).

### **1.2. Mercury (Hg) and gold mining**

The amalgamation of raw ore is present throughout the national territory (Vilela-Pincay et al., 2020). This practice goes hand in hand with the burning of the amalgam, which is often done in the homes of the miners themselves without minimum safety conditions, due to the prohibition of mercury use. Among the provinces most noted for the use and release of mercury are: Zamora, Imbabura, Esmeraldas and Azuay (Rea Toapanta, 2017). The province of Imbabura is not by history a mining province as such, but its recent boom has been due to the presence of illegal mining, mainly in the site called Buenos Aires. In 2019, after the intervention of the National Government, through an intelligence operation, it managed to dismantle the gold exploitation and production network in the Buenos Aires site, thus taking control of the area and evicting the people who were carrying out gold ASM activities, considered illegal (Zavala Chumbiauca & Poma Fernandez, n.d.).

Regarding the use of mercury in mining, the mining law in the article listed after article 86 of Chapter II On the preservation of the environment of Title IV On the obligations of mining owners establishes the "prohibition of the use of mercury in mining operations" (Reglamento General a La Ley De Minería, 2021). Like any prohibition, it gives weight to the mining authority in controlling the use of prohibited substances, but it also promotes evasive behavior and attitudes on the part of miners, especially artisanal miners (Morán Lescano, 2022).

Mercury is sold in the different mining sites through local businesses such as stores or hardware stores. In these places, small doses are sold for local consumption, especially in the milling of "chanchas". At this level, from one ounce (28.35 g) to one pound (453.6 g) of mercury is sold at an average price

of \$10 to \$12 dollars per ounce of mercury (Osorio Artunduaga & Devia Ocampo, 2020). Usually, these quantities are related to the use of "chanchas" so it is not uncommon for the owners of the "chancha" plants to be the mercury suppliers at this level of use. It is common in mining sites with access to cyanidation for the hog house owner to provide the mercury without charging money in exchange for ownership of the tailings remaining after milling (Castillo Osorio et al., 2017).

It is common for district and zonal gold traders to also be sellers of mercury. Their role as local intermediaries facilitates distribution logistics as they are located at sites where both wholesale suppliers and retail distributors converge (Bustamante Jaén, 2023). At this level they sell from one pound (453.6 g) to one liter bottles (13 500 g) at a price that varies between \$80 and \$120 dollars per pound of mercury. It is important to note that gold traders, in some cases jewelers as well, have workshops where they melt the "sponge" gold and recover mercury that they then sell again in the local market (Riascos Riascos, 2020).

There are also the zonal and national traders, who handle "a pipe" that can weigh up to 22 kilograms and cost between US\$4000 and US\$6000 (Bustamante Jaén, 2023). his level of traders was not clearly identified in this study. Some testimonies pointed to district and zonal leaders of the mining sector of being involved in mercury trafficking, however, this information could not be contrasted (Morán Lescano, 2022).

From a general perspective, the mercury market follows the same logistics of gold stockpiling and collection for gold distribution. In other words, the mining sector itself ensures that artisanal and small-scale miners are supplied with mercury so that they have a basic input available in their gold extraction and processing model (Kerguelén, 2021). Therefore, it can be inferred that mercury enters the country following the money route that finances these activities. Hence, it is essential to develop a financing strategy from the formal financial sector to the ASM gold mining sector as a measure to control the bad mining practices currently implemented (Romero Zegarra, 2017).

The use of mercury is not restricted to artisanal miners only, but is also used by small-scale miners to take advantage of the "free" gold that settles in Chilean mills. This practice remains widespread, even in mining sites that have implemented technological improvements such as Portovelo and Ponce Enriquez that do not replace the type of milling (Guetio López & Romero Acosta, 2019) . It is this type of milling that "allows" the miner to access the pre-

cyanidation material and extract gold by amalgamation. This practice is gradually being eliminated from these sites due to the implementation of more efficient milling systems such as ball mills or through the installation of gravimetric systems that collect the sediments from the mills and obtain the gold without amalgamation. cyanidation and extract gold by amalgamation (Ruíz Solano, 2016). This practice is gradually being eliminated from these sites due to the implementation of more efficient milling systems such as ball mills or by installing gravimetric systems that collect the sediments from the mills and obtain the gold without amalgamation (Gallos Carrasco et al., 2008).

Unlike mining sites related to primary mining and including beneficiation processes where improvements are being implemented to minimize amalgamation, no improvements or technological alternatives to reduce mercury use are observed in alluvial mining sites (Carrillo et al., 2010). The separating sieve, locally known as "zeta", is the most widespread separation and recovery technology in the country. This equipment classifies the gold in two chambers as "coarse" gold and "fine" gold. In the chamber where the fine gold is collected, bottles of 1 to 2 liters of mercury (between 13.5 and 27.0 kg Hg) are used for each "wash" of material, which lasts between 1 to 5 days, depending on the formation. National authorities have not been able to control this type of mining, especially the use of mercury in mining, so it presents the main management challenges and the greatest opportunities to reduce mercury use in ASM gold mining in the country (Glave & Kuramoto, 2002).

It is worth mentioning the existence of Chordeleg, a picturesque town located just an hour from Cuenca, the third most populated city in the country. This charming place is mainly dedicated to gold and silver goldsmithing, housing numerous smelting workshops and more than 100 stores specializing in the sale of exquisite gold and silver jewelry (G. Romero, 2010). Chordeleg, along with the cities of Cuenca and to a lesser extent Loja, is the preferred destination for gold produced in the country in the gold ASM sector. In this picturesque locality, gold from Nambija is especially valued for its unparalleled quality and purity (Saquicela Prado, 2021). Here, it is possible to trade gold that is not regularized by the mining authorities and transform it into dazzling jewelry that captivates the local market. It is worth mentioning that gold traded in this way is not reported in the national annual production, since official records only consider gold exported through customs (Afanador Gonzalez et al., 2013).

It is also relevant to highlight the estimated gold production for 2018, which amounted to 23.6 tons, of which 10.1 tons were obtained by mercury amalgamation (Cardona Sánchez, 2021). The rest of the precious metal was produced by using other methodologies, such as cyanide or flotation concentration, as gold extraction methods. In addition, an approximate annual loss of 29.6 tons of mercury is estimated in the gold ASM sector in Ecuador (Marrugo Negrete et al., 2022).

The dispersion in the Hg: Au ratio is due to the type of technology or process used at each mining site. For example, there are places like Nambija where the adoption of new technologies has decreased the use of Hg, which in comparison to places like Esmeraldas or Nangaritzá, characterized by alluvial mining and with little technology when processing gold, requires a greater amount of mercury per operation (Cuentas Alvarado & Velarde Ochoa, 2019). Another reason for the dispersion in the Hg: Au ratio is the control of the State to regulate the activity through controls, implementation of best practices and technology (Zapata Jaramillo, 2020). The progress of this work is evident in consolidated and regularized mining sites, especially primary mining, such as Portovelo–Zaruma or Ponce Enriquez. In contrast to non–regularized mining sites such as Chinapintza and Buenos Aires, and all mining sites with alluvial mining, where mercury losses are significantly higher than in primary mining sites (Montoya Salvador, 2018).

Regarding the location of gold ASM in Ecuador, it is grouped into 5 zones based on administrative criteria defined by the National Planning Secretariat (SENPLADES): North Zone (1), North Central Zone (2), Central Zone (3), South Central Zone (6) and South Zone (7). This classification will facilitate the implementation of the National Action Plan (required by the Minamata Convention) as it is in line with the planning structure of the State. The different institutions such as Ministries, Agencies, Institutes will be able to designate resources and personnel without affecting their Annual Organization Plans (Marrugo Negrete et al., 2022).

### **1.3. Human health risks associated with gold extraction**

Gold mining is an important economic activity in many parts of the world due to the high value of this precious metal. However, this practice can also have serious implications for human health (Garrido Peralta, 2021). . Over the years, numerous risks and negative health effects associated with gold mining have

been identified, both for the workers involved in the activity and for the communities living in areas near the mining operations (Arias et al., 2021).

One of the most significant risks to human health in gold mining comes from exposure to toxic substances used in the mining process. For example, cyanide is commonly used to extract gold from ores, but the handling and use of this substance can result in poisoning if not handled properly (López-Jiménez et al., 2023). Workers and nearby communities can be exposed to cyanide through contaminated water or the accidental release of cyanide solutions used in mines (Ore Huashuayllo, 2017).

In addition to cyanide, mercury is another hazardous chemical used in artisanal gold mining. Mercury is used to separate gold from other minerals, but its release into the environment can cause serious harm to human health (Amaya Ladino, 2018). Inhalation of mercury vapors or consumption of food contaminated with methylmercury (a toxic form of mercury) can cause neurological problems, kidney problems and other adverse effects (Rodríguez Heredia, 2017).

Gold mining often takes place in areas close to rural or indigenous communities. These populations may face direct and indirect impacts on their health due to the proximity to mining operations (Cantos Zambrano, 2019). Water and air pollution can affect drinking water supply and air quality, increasing the risk of respiratory, gastrointestinal and dermatological diseases (Nordberg & Nordberg, 2017). In addition, gold mining can cause social conflict and displacement of communities. The loss of traditional lands and sources of livelihood can negatively affect the mental health and social well-being of affected people (L. E. Sandoval et al., 2017).

Workers in gold mines are exposed to a variety of occupational hazards that can have a significant impact on their health. Hazardous working conditions, lack of adequate protective equipment, and exposure to toxic chemicals can lead to occupational accidents and diseases (Briceño Zavaleta & Sandoval Rosales, 2021). Working in subway mines, for example, can increase the risk of respiratory diseases and musculoskeletal injuries due to exposure to dust and repetitive movements. Landslides and explosions also pose serious safety risks to mine workers (Pastor Sierra et al., 2020).

Gold mining can result in the release of toxic substances into the environment, which affects public health in areas near the mines. Water and land contamination can have negative health consequences for people living in

these areas, especially for those who depend on natural resources such as fishing and agriculture for their livelihoods (Sandoval Ebensperger, 2018). Chronic exposure to toxic chemicals in the environment can increase the risk of chronic diseases, such as neurological problems, kidney disorders, and cancer (Pastor Sierra et al., 2020).

It is essential to implement effective measures to protect human health in the context of gold mining. Some of the key measures include (i) Regulations and Oversight, (ii) training and awareness raising, (iii) use of Cleaner Technologies: The adoption of cleaner and sustainable technologies in gold mining can significantly reduce human health risks and negative environmental impacts and (iv) Promotion of Responsible Mining (Vaca Sarango & Gaona Añazco, 2023).

Gold mining can have significant human health implications due to exposure to toxic substances, impacts on local communities and associated occupational risks. It is critical to address these risks by implementing sound regulations, promoting responsible practices and using cleaner technologies in the mining industry. This is the only way to ensure that gold mining is conducted in a safe and sustainable manner, protecting both human health and the environment.

#### **1.4. Ecological risks associated with gold mining**

Gold mining is an activity that has been carried out for centuries due to the high economic value of this precious metal. However, this practice also carries significant ecological risks that severely affect the environment, one of the greatest ecological risks of gold mining is water pollution (Vilela-Pincay et al., 2020). To extract gold from ores, various techniques involving the use of chemicals such as cyanide and mercury are used. These compounds can leach into nearby water bodies, affecting water quality and endangering aquatic life (López-Jiménez et al., 2023).

Cyanide is commonly used to separate gold from rock, forming a gold cyanide solution that is stored in large ponds. If these structures rupture or collapse, a massive release of cyanide into the environment can occur, causing environmental disasters such as contamination of rivers and aquifers, as has happened in some cases in different parts of the world (Cueva Balbin, 2022).

Mercury, on the other hand, is used in artisanal and small-scale gold mining. This highly toxic metal is released into the environment and converted into methylmercury, which is absorbed by aquatic organisms and accumulates along

the food chain. As a result, fish and other marine animals can become dangerously contaminated and pose a risk to human health when consumed (Rioja Nogales, 2022).

Gold mining also involves the clearing of large areas of forest to access the mining sites (Mendoza & SALAZAR, 2014). The resulting deforestation leads to the loss of critical habitats for biodiversity, affecting a wide variety of flora and fauna species. Many animals, including endangered species, are displaced or exposed to altered habitat conditions, which can have devastating consequences for their populations and local ecology (Alonso et al., 2020).

In addition, the alteration of natural ecosystems can result in a loss of ecosystem services, such as crop pollination by insects and water purification through forests and wetlands. Biodiversity loss can also affect the stability and resilience of ecosystems in the face of environmental change and natural disturbances (de Lima Abouhamad et al., 2017).

The removal of large amounts of land during gold mining can result in soil erosion, loss of vegetation and exposure of soil to weathering facilitate its displacement by water and wind action. As a result, sediment accumulation occurs in watercourses, which can adversely affect aquatic life by clogging their habitats and decreasing light penetration into the wáter (Naranjo Aguazaco, 2018).

Sediment contamination can also transport heavy metals and other toxic substances that are released during gold mining. These sediments can be deposited downstream, affecting aquatic ecosystems distant from mining operations and causing damage to local fauna and flora (Loaiza Choque, 2016). It is crucial to address the ecological risks associated with gold mining in an effective and sustainable manner. Some of the solutions that can help mitigate these negative impacts include:

- Encourage responsible mining practices: Mining companies should adopt responsible practices that reduce pollution and environmental degradation. This includes the use of cleaner technologies and the implementation of efficient environmental management systems. (Huerta & García, 2009).
- Enforce regulations and control illegal mining: It is essential that governments establish sound regulations for the mining industry and ensure that they are properly enforced. This includes monitoring and

controlling illegal mining, which is often responsible for the worst environmental impacts. (Ospina–Correa et al., 2021).

- Promote restoration of affected areas: After gold mining, land restoration programs should be carried out to rehabilitate affected habitats and restore biodiversity (P. Carrión et al., 2018).
- Encourage the transition to sustainable mining: It is essential to encourage the adoption of sustainable mining practices that minimize the environmental and social risks associated with gold mining. (Dufey, 2020).

Gold mining is an activity that presents significant ecological risks, ranging from water pollution to biodiversity loss and soil degradation. It is essential that these risks are effectively addressed through the implementation of responsible and sustainable practices, as well as the application of appropriate regulations by governments. Only in this way can we protect the environment and ensure mining that is more respectful of ecosystems and local communities.

### **1.5. Social impacts of gold mining**

Gold mining in rivers and aquifers is an economic activity that has had a major impact on communities around the world. While this activity can generate significant economic income and employment opportunities, it also brings with it a number of negative social impacts that affect local populations (Fernández–Labbé, 2020; Gonzales Villalobos, 2019).

Gold mining often takes place in areas that are home to indigenous and rural communities. The arrival of mining operations can result in forced displacement of these communities, either directly to enable mining or due to the environmental pollution and degradation resulting from mining activity (V. V. García et al., 2023). Forced displacement can have devastating effects on communities, leading to loss of cultural identity and disconnection from their traditional ways of life and subsistence (Cuéllar Ramírez & Pacito Mora, 2021). In addition, the loss of territories and natural resources can generate social tensions and conflicts with other communities or stakeholders (Ramos Suárez et al., 2017).

Gold mining in rivers and aquifers often involves community and social conflicts. Local communities may have divergent interests surrounding mining, as some may benefit from the jobs and economic opportunities generated, while others may be concerned about negative environmental and social

impacts (Lostaunau Ramos, 2020). These conflicts may arise between members of the same community or between neighboring communities. In addition, the presence of mining companies and competition for resources can intensify social tensions and divisions (Jáuregui et al., 2017).

Gold mining in rivers and aquifers can have a significant impact on the health of local communities. Water contamination and the release of toxic chemicals used in gold mining can put the health of people who depend on contaminated water sources for drinking, cooking and bathing at risk (Parra et al., 2018). Exposure to toxic substances such as mercury can lead to serious health problems, such as neurological and renal disorders. In addition, environmental degradation can affect the availability of food and natural resources, which can lead to malnutrition and other related health problems (Latorre & Tovar, 2017).

Gold mining in rivers and aquifers can also result in cultural challenges and loss of traditions. Indigenous and rural communities often have a strong connection to the environment and depend on it for their cultural practices and traditional ways of life. In addition, the arrival of mining can disrupt these practices and disconnect communities from their cultural roots. The loss of territories and natural resources can also affect traditions and ancestral knowledge passed down from generation to generation. (Massa-Sánchez et al., 2018).

Gold mining in rivers and aquifers can have a significant impact on local communities, including forced displacement, community conflicts, health problems and loss of cultural traditions. It is essential to address these negative social impacts by implementing effective measures that protect the rights and well-being of affected communities. Only through a responsible and sustainable approach to gold mining can social risks be minimized and equitable and environmentally sound development promoted.

#### **1.6. Legal framework and mitigation measures**

Gold mining has been a major activity in Ecuador, providing significant economic income and employment in different regions of the country. However, it has also been the subject of controversy due to its negative environmental and social impacts. To address these challenges, Ecuador has established a legal framework that regulates mining and has implemented mitigation measures to reduce the negative impacts of the activity (Avilés, 2023).

In Ecuador, gold mining is mainly regulated by the Mining Law and its General Regulations, which establish the regulations and procedures for the concession, exploration and exploitation of mineral resources, including gold. The Mining Law establishes the rights and obligations of mining concession holders, as well as penalties for non-compliance with regulations (Reglamento General a La Ley De Minería, 2021).

In 2008, the Constitution of Ecuador was enacted, which grants rights to nature and establishes the need to guarantee the preservation of the environment and biodiversity in the development of extractive activities. This has led to the adoption of a more comprehensive view of mining, which seeks to protect the interests of society and the environment (Constitución Política de la República del Ecuador, 2008). In 2013, the Ecuadorian government suspended the granting of new licenses for large-scale metallic mining, including gold mining, as part of a moratorium to review and reform mining legislation. This decision was taken to evaluate the environmental and social impacts of mining and to establish stricter control and regulation mechanisms (Almeida, 2019a).

Despite the economic importance of gold mining, Ecuador has adopted various mitigation measures to protect the environment and affected communities. Some of these measures include (Águila & Urdaneta, 2023; Barragán, 2017):

- **Environmental Assessment:** The Mining Law requires the submission of an Environmental Impact Assessment (EIA) to obtain a mining concession. This study evaluates the potential environmental and social impacts of the mining activity and proposes mitigation measures to minimize risks.
- **Restoration of Affected Areas:** The law also establishes the obligation of mining concession holders to carry out restoration and rehabilitation activities in areas affected by mining. This includes reforestation and revegetation of degraded areas to restore natural ecosystems.
- **Protection of Water Sources:** Ecuador has implemented measures to protect water sources and prevent contamination of water bodies by chemicals used in gold mining. Mining exclusion zones are established near rivers and aquifers to preserve water quality and protect aquatic biodiversity.
- **Community Participation:** The law requires the participation of local communities in the prior consultation process before mining

concessions are granted. This ensures that affected communities have a voice in the decision-making process and can express their concerns and demands.

- Promotion of Responsible Mining: Ecuador has sought to promote responsible and sustainable mining, encouraging cleaner practices and less invasive technologies to reduce the environmental impacts of gold mining.

Despite efforts to mitigate the impacts of gold mining, Ecuador still faces significant challenges in this area. Some of the main challenges include (Cuenca Cumbicus, 2022; Estupiñan et al., 2021):

- Oversight and Compliance: Oversight and compliance with mining regulations remain a challenge in Ecuador. It is essential to ensure effective oversight to ensure that mining companies comply with established environmental and social standards.
- Social Conflicts: Gold mining can generate social conflicts between local communities and mining companies, especially in areas where the interests and values of the parties differ. Community participation and constructive dialogue are essential to resolve these conflicts and promote sustainable development.
- Sustainable Economic Alternatives: To reduce dependence on gold mining, it is important to promote sustainable economic alternatives for affected communities. This could include the development of sectors such as sustainable tourism and organic agriculture.

In terms of future prospects, Ecuador must continue to work on improving its legal framework and effectively implementing mitigation measures to ensure that gold mining is developed in a responsible and sustainable manner. Environmental protection and the well-being of affected communities must remain priorities in the planning and management of mining activity in the country (Morán Lescano, 2022).

Gold mining in Ecuador has had a significant impact on the country's economy, but it has also generated environmental and social challenges. The current legal framework and mitigation measures in place seek to address these impacts and promote more responsible and sustainable mining. It is critical that Ecuador continues to work on strengthening its legal framework and effectively implementing mitigation measures to ensure that gold mining is carried out in a manner that respects the environment and local communities. Only through a

comprehensive and sustainable approach to gold mining will it be possible to minimize the risks and maximize the benefits of this activity for the country's development.

## 2. Hypothesis and objectives

### 2. Hypothesis and objectives

The introduction and analysis of the thematic axes addressed in this doctoral thesis clearly describe the current situation of gold mining in continental Ecuador, considering the concentrations of Hg in surface and subway water bodies. In this sense, few studies have been carried out in continental Ecuador, analyzing the situation, risk and impacts generated by mining activities, considering the concentrations of Hg used in these extractive processes. This has prevented to offer a real and updated vision to decision makers to strengthen the management of these resources. Based on the above, this doctoral thesis proposes the following hypotheses:

- Artisanal and industrial gold mining in continental Ecuador has undergone a history evolution marked by political, socioeconomic and environmental challenges that have influenced its development and regulation over time.
- The mercury (Hg) used in gold mining causes ecological risks and significantly harms the human health of Ecuadorians.
- Mercury (Hg) used in gold mining generates environmental impacts, causing contamination of surface and subway aquifers.
- Promoting awareness and training of artisanal and industrial miners on safer and more sustainable practices in the use of mercury can result in a significant reduction of environmental impact and the adoption of more responsible techniques for the preservation of the natural environment.

Based on the established hypotheses, the study focuses on analyzing the current situation of gold mining, considering mercury (Hg) concentrations in surface and subway water bodies in order to establish strategies for improvement.

### **General Objective**

Establish a baseline on the History situation and evolution of gold mining in continental Ecuador along with environmental risks and impacts considering mercury (Hg) concentrations in surface and subway water bodies, to implement techniques and strategies to improve gold mining processes and promote life in harmony and good living.

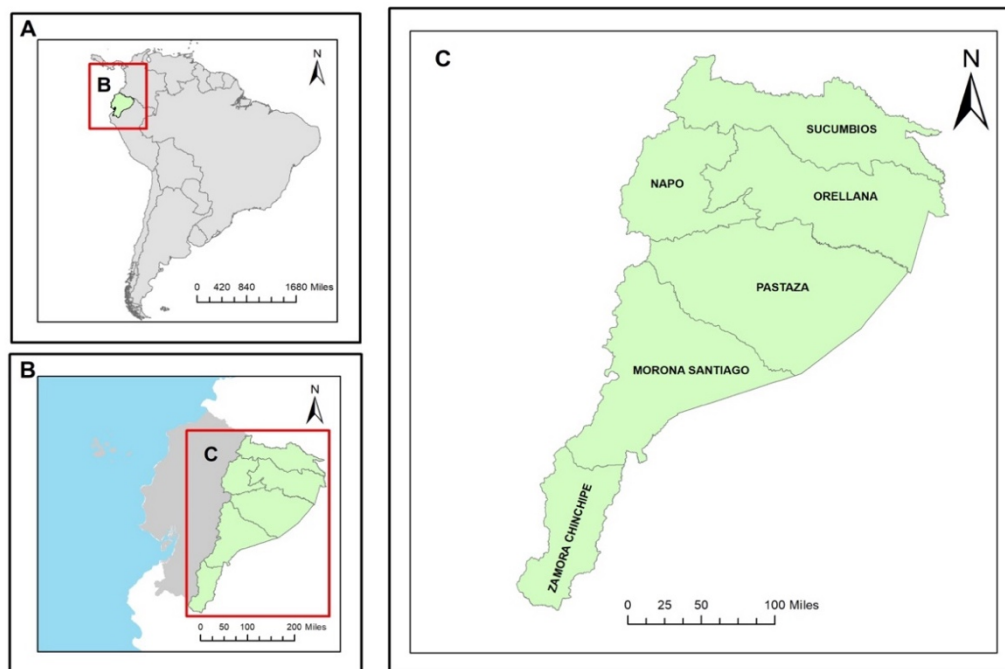
### **Specific objective**

- Analyze the History and current situation and challenges of artisanal and industrial gold mining in continental Ecuador by applying a literature review and field work to understand the evolution in political, socioeconomic and environmental aspects.
- To evaluate the ecological and human health risk in continental Ecuador considering mercury (Hg) concentrations in surface and groundwater bodies.
- Identify the main environmental impacts on rivers and aquifers in Ecuador, generated by the use of mercury (Hg) in artisanal and industrial gold mining, through the use of case studies in the northern Amazon of Ecuador.
- Describe techniques and strategies to improve the management and treatment of mercury in gold extraction processes, applying a bibliographic review to reduce its impact on the natural environment.

### 3. Study area

The Republic of Ecuador is located on the northwestern coast of the South American continent. The territory is crossed by the Equatorial Line, 22 km north of its capital (the city of Quito). Distributed in two components: the continental area of 248,357 km<sup>2</sup> and the insular area of 8010 km<sup>2</sup>. The continental area, crossed from north to south by the Andes Mountains, is divided into three natural regions: the Coast or Littoral Region, the Highlands or Inter-Andean Region, and the Amazon or Eastern Region.

Ecuador, with a territorial extension of 270,670 km<sup>2</sup>, is located in the tropical zone of the northwestern coast of South America. It has 17.5 million inhabitants, 739,754,000 of whom live in the Amazonian provinces (Agencia de Regulación y Control Minero., 2020) This region is made up of six provinces: Sucumbíos, Napo, Orellana, Pastaza, Morona Santiago and Zamora Chinchipe.



**Figure 1.** Study area: ( A ) Geographical location of Ecuador; ( B ) Amazon region of Ecuador; ( C ) provinces belonging to the Amazon region.

Although gold mining in Ecuador is currently expected to represent a maximum of 4%, its socioeconomic and environmental analysis is relevant

because of the impact it has on local communities in economic terms, as they see it as a source of subsistence and pollution problems caused by the use of hazardous chemicals in their extractive processes. The provinces and cantons in which there is most legal and illegal gold mining activity were considered, and the data were obtained from the Geoportal of the Mining Cadastre of the Republic of Ecuador (Table 1) (Agencia de Regulación y Control Minero., 2020).

**Table 1.** Registered gold mining concessions in the Amazon region of Ecuador.

No	Province <sup>1</sup>	Canton <sup>2</sup>	Type of application or regime					total
			General regime	Large-scale mining	Medium mining	Small mining	Artisanal mining	
1	Sucumbíos	Gonzalo Pizarro	--	--	1	4	6	11
		Sucumbíos	--	5	1	9	1	16
		Cáscales	--	--	1	3	18	22
		Lago Agrio	--	--	--	2	3	5
		Subtotal	--	5	3	18	28	54
2	Napo	Tena	--	--	--	16	69	85
		El Chaco	2	--	--	5	--	7
		Carlos Julio Arosemena	3	--	--	16	13	32
		Subtotal	5	--	--	37	82	124
3	Orellana	Orellana	--	--	--	1	2	3
		Loreto	1	--	--	1	--	2
		Subtotal	1	--	--	2	2	5
4	Pastaza	Arajuno	--	--	--	--	2	2
		Pastaza	--	--	--	1	--	1
		Subtotal	--	--	--	1	2	3
5	Morona Santiago	Gualaquiza	3	7	4	6	66	86
		Limón Indanza	--	21	--	3	16	40
		Santiago	--	5	--	5	69	79
		Tiwintza	--	3	--	10	28	41
		Logroño	--	18	--	--	--	18
		Morona	1	16	--	2	1	20
		Palora	--	--	--	1	28	29
		San Juan Bosco	--	3	--	2	2	7
Subtotal	4	73	4	29	210	320		
6	Zamora Chinchipe	Zamora	--	7	--	39	232	278
		Yacuambi	--	10	--	5	80	95
		Paquisha	1	2	--	25	42	70
		El Panguí	--	5	--	9	37	51
		Nangaritzá	1	5	--	23	56	85
		Chinchipe	--	3	4	28	167	202
		Palanda	--	7	--	14	60	81
		Yantzaza	--	11	1	12	36	60
Centinela del Condor	--	4	--	9	21	34		
Subtotal	2	54	5	164	731	956		

**General regime:** Mining permits with old laws, which are currently in the process of being updated according to the new regulations;  
**Small mining:** In terms of production capacity, small mining is allowed to exploit up to 300 tons per day in subway mining; up to 1000

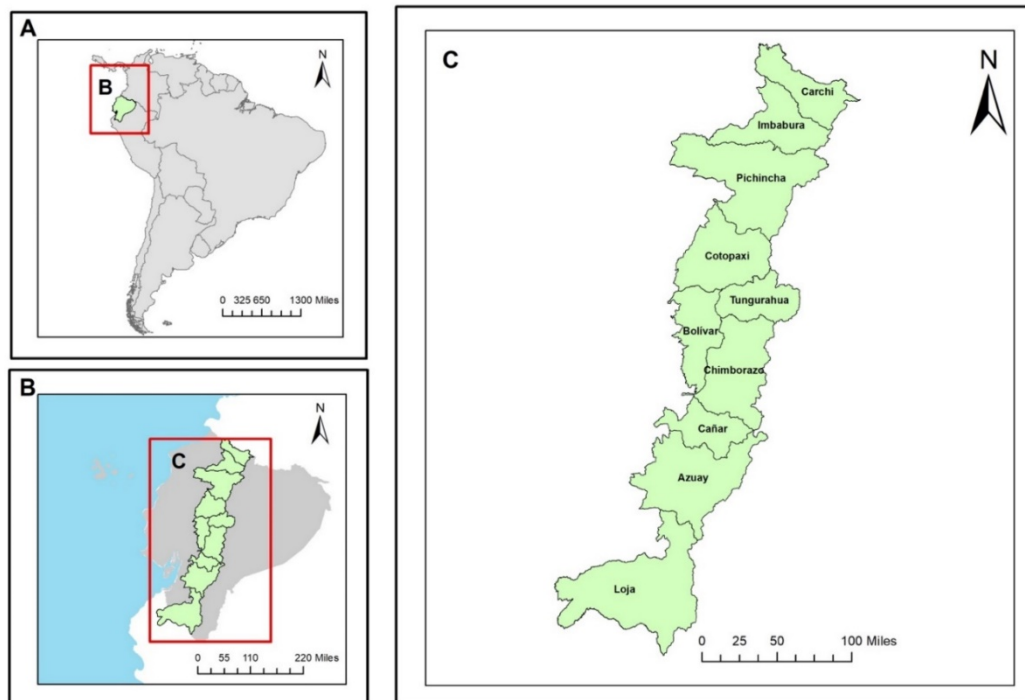
tons per day in open pit mining; and up to 1500 cubic meters per day in alluvial mining; Artisanal mining: Activity carried out in free zones for survival purposes, not exceeding 4 hectares in subway conditions and 6 hectares in open pit conditions. Medium-scale mining: Mining ranging from 301 to 1000 mt per day in subway conditions, 1001 to 2000 mt per day in open pit; and 1501 to 3000 m<sup>3</sup> in alluvial mining; Large-scale mining: activity that exceeds all the maximum volumes described for medium-scale mining.

<sup>1</sup> The political division of Ecuador begins with regions (4: Coast, Highlands, Amazon and Insular) and each region is made up of provinces.

<sup>2</sup> The union of cantons make up a province.

Each of the regions into which the Ecuadorian territory is divided has different climatological and geographic characteristics, which have allowed it to have a great biodiversity per unit área (Markowski et al., 2006). Likewise, the characteristics of each region have allowed Ecuador to benefit from a great geological wealth, finding mineral deposits that represent economic quantities of elements, such as gold, silver, copper, molybdenum, iron, titanium, etc. (Agencia de Regulación y Control Minero., 2020).

For this research, the Andean region was also considered, a region with extensive mountainous areas (Andes Mountains) composed of 10 provinces (Table 2). The mining au in each of these provinces was verified through the Mining Cadastre Web Geoportal (Markowski et al., 2006) provided by the Mining Regulation and Control Agency (ARCOM), from which only those concessions registered in the aforementioned institution were filtered.



**Figure 2.** Study area: ( A ) geographic location of Ecuador; ( B ) Andean Region of Ecuador; ( C ) provinces belonging to the Andean region.

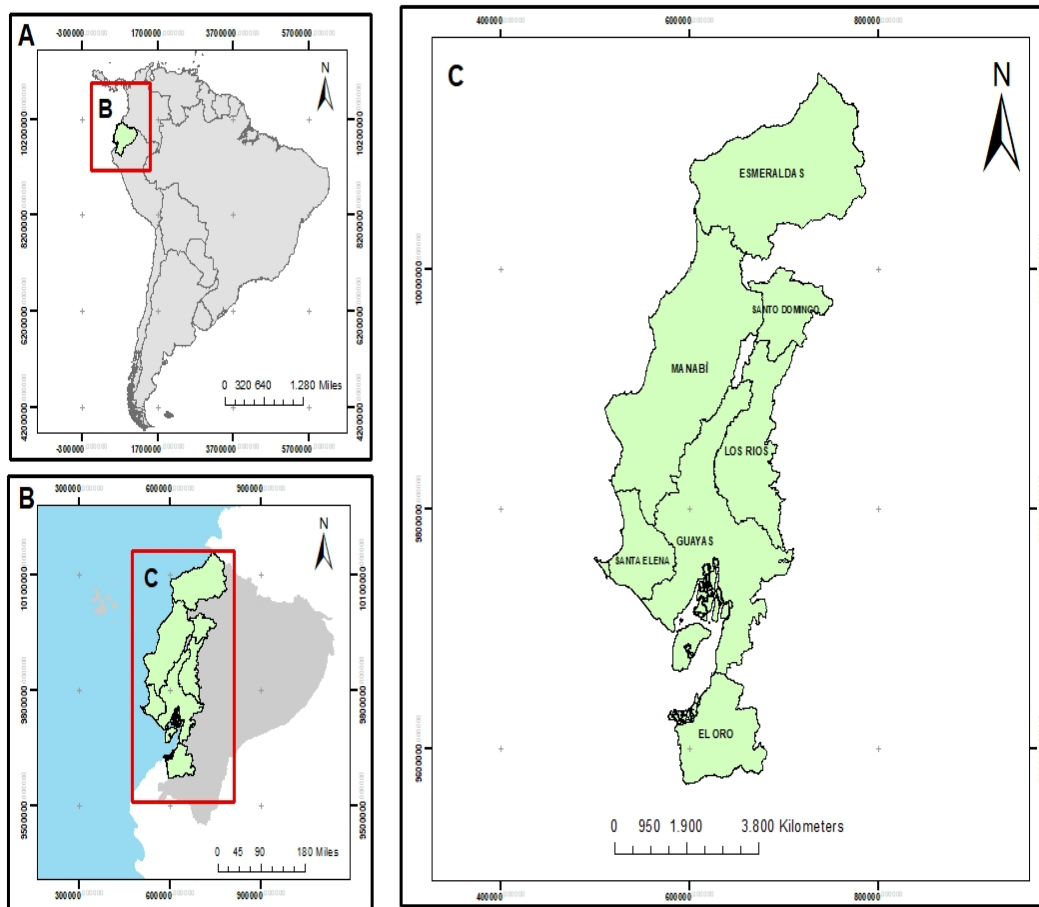
**Table 2.** Registered Au mining concessions in the Andean zone of Ecuador.

No	Province	Canton	Concession Regime					Total
			Artisanal Mining	Small Mining	Medium Mining	Large Mining	General Regime	
1	Carchi	Tulcan	1	2	1	4	--	8
		Mira	--	--	--	6	--	6
		Espejo	--	--	1	4	--	5
	Subtotal		1	2	2	14	--	19
2	Imbabura	Cotacachi	--	3	2	11	--	16
		Ibarra	--	--	1	6	1	8
		San Miguel de Urcuqui	--	--	4	--	--	4
		Otavalo	--	--	--	1	--	1
Subtotal		--	3	7	18	1	29	
3	Pichincha	Quito	10	5	--	--	7	22
		San Miguel De Los Bancos	--	--	--	--	5	5
		Mejia	--	--	--	--	2	2
		Subtotal		10	5	--	--	14
4	Cotopaxi	Sigchos	1	--	--	2	--	3
		La Mana	6	9	--	2	--	17
		Pujili	--	1	--	--	--	1
		Pangua	--	3	--	1	--	4
Subtotal		7	13	--	5	--	25	
5	Tungurahua	----	--	--	--	--	--	0
6	Bolivar	Chillanes	16	2	--	--	5	23
		Guaranda	--	--	7	--	--	7
		Caluma	--	--	--	1	--	1
Subtotal		16	2	7	1	5	31	
7	Chimborazo	Alausi	2	--	--	--	--	2
		Riobamba	4	1	--	--	--	5
		Cumanda	10	1	--	--	--	11
Subtotal		16	2	--	--	--	18	
8	Cañar	Suscal	1	--	--	--	--	1
		Cañar	8	--	--	--	--	8
	Subtotal		9	--	--	--	--	9

9	Azuay	Cuenca	14	4	3	2	1	24
		Pucara	32	5	--	1	--	38
		Ponce Enriquez	57	42	--	3	5	107
		Santa Isabel	10	2	--	1	--	13
		Giron	--	--	--	1	--	1
		Sigsig	12	2	--	1	--	15
		Oña	--	--	1	--	--	1
		Paute	--	1	--	--	--	1
		Gualaceo	1	--	--	--	--	1
		El Pan	5	--	--	--	--	5
		Nabon	--	1	--	--	--	1
Subtotal		131	57	4	9	6	207	
10	Loja	Macara	139	15	--	--	--	154
		Celica	5	6	--	--	--	11
		Paltas	44	14	--	1	--	59
		Saraguro	4	1	--	--	--	5
		Loja	16	3	--	--	--	19
		Catamayo	12	2	--	--	--	14
		Zapotillo	14	1	--	--	--	15
		Olmedo	--	1	--	--	--	1
		Calvas	38	2	--	--	--	40
		Chaguarpamba	1	1	--	--	--	2
		Espindola	11	1	--	1	--	13
		Quilanga	23	--	--	--	--	23
		Sozoranga	57	--	--	--	--	57
		Gonzanama	14	--	--	--	--	14
		Puyango	3	--	--	--	--	3
Subtotal		381	47	--	2	--	430	
<b>Total</b>		571	131	20	49	26	797	

The Litoral or Coastal region is located between the coastal profile and the Andes Mountains (Secretaría Nacional de Planificación y Desarrollo., 2017). The study area corresponds to a total of 70,647 km<sup>2</sup>, covering the provinces of Guayas, Santa Elena, Manabí, El Oro, Los Ríos, Santo Domingo de los Tsáchilas and Esmeraldas (Figure 3).

From a geomorphological point of view, the coastal region is characterized by a variety of reliefs, plains and large types of coasts (high cliffs with small bays; medium and low cliffs with small cliffs and large beaches; low, adeltaic type with an anastomosed network) (Winckfill, 1982). on the other hand, it also has a privileged diversity in soil structure, which can vary according to the province. The soils that can be observed are: vertisols, alfisols, entisols, aridisols, molisols, andisols, inceptisols and inceptisols (Rivera Grunauer, 2019)



**Figure 3.** Study area ( A ) Geographical location of Ecuador; ( B ) Littoral region of Ecuador; ( C ) provinces belonging to the Littoral region.

There are currently a large number of gold mines scattered throughout the coastal region, both legal and illegal. However, Table 3 only shows the gold mining concessions that are registered, according to the Geoportal Web of the Mining Cadastre of the Mining Regulation and Control Agency (ARCOM).



**Table 3.** Gold mining concessions in the Litoral region.

N°	Province	Canton	Concession Regime				Genera l Regim e	Total Concession s by Canton
			Artisanal Mining	Small Mining	Medium Mining	Large Mining		
1		Esmeraldas	---	---	---	1	---	1
	Esmeraldas	Atacames	1	---	---	---	---	1
		Eloy Alfaro	2	1	---	---	---	3
		Muisne	---	---	---	---	1	1
		Quinindé	---	---	4	2	---	6
		San Lorenzo	1	---	---	3	---	4
Total concessions by regime in Esmeraldas			4	1	4	6	1	---
2	Santo Domingo de los Tsáchilas	Santo Domingo	4	---	---	---	---	4
	Total concessions by regime in Santo Domingo			4	---	---	---	---
3	Manabí	Jama	1	---	---	---	---	1
		Pedernales	1	---	---	---	---	1
	Total concessions by regime in Manabí			2	---	---	---	---
4	Los Ríos	Babahoyo	---	---	---	---	2	2
		Montalvo	---	---	---	---	1	1
		Urdaneta	---	---	---	2	---	2
	Total concessions by regime in Los Rio			---	---	---	2	3
5	Guayas	Guayaquil	15	---	---	---	---	15
		Balzar	---	1	---	---	---	1
		General antonio elizalde	---	---	---	---	2	2
		Naranjal	---	3	---	---	---	3
		Balao	3	---	---	---	---	3
	Total concessions by regime in Guayas			18	4	---	---	2
6	Santa elena	---	---	---	---	---	---	---
	Total concessions by regime in Santa Elena			---	---	---	---	---
7	El Oro	Pasaje	29	3	---	---	3	35



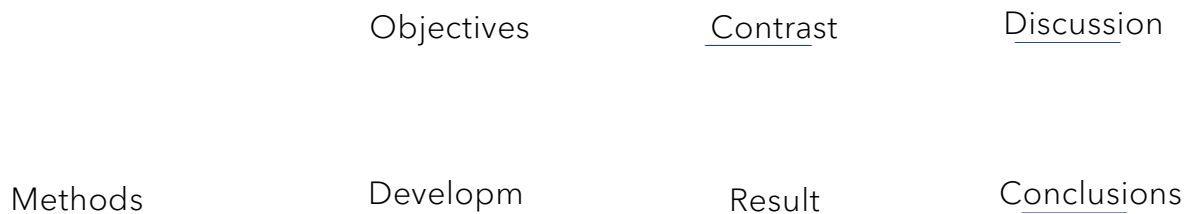
Chilla	3	---	---	---	3	6
El Guabo	4	7	---	---	---	11
Santa Rosa	62	diec iséis	---	---	2	80
Atahualpa	36	2	---	---	4	42
Zaruma	6	10	---	---	5	21
Marcabeli	3	---	---	---	---	3
Portovelo	8	2	---	---	2	12
Piñas	---	2	---	---	1	3
Total concessions by regime in El Oro	151	42	---	---	20	---
<b>Total number of mining concessions in the Litoral región</b>						

## 4. Methodology

## 4. Methodology

The research was explanatory, correlational, descriptive and explanatory (Figure 4). Independent methodologies were used for each specific objective, which included bibliographic analysis, determination of mercury concentrations in surface and groundwater bodies, evaluation of ecological and human health risks, identification of environmental impacts and expert judgment. The study applied quantitative and qualitative techniques such as sampling, literature reviews, surveys, interviews and visits to the study area.

Gold mining



**Figure 4.** Methodological process.

In summary, bibliographic sources were evaluated to analyze the History and current situation and the challenges of artisanal and industrial gold mining in continental Ecuador. On the other hand, to evaluate the ecological and human health risk, the HQ hazard coefficient was considered. The risk assessment

was developed using a double-entry impact matrix and SWOT analysis. The techniques and strategies were carried out by means of critical expert judgment.

Table 4 shows the different sources of information used in the methodological processes that made it possible to respond to the objectives set

**Table 4.** Sources of information, methods related to the objectives of the doctoral thesis.

Objective	Research Method	Source of information	Reference
<b>Analysis of the current situation and challenges of the mining industry</b>	Review of high impact, regional and grey literature sources	Articles, laws, programs, manuals, reports.	(Knopf, 2006)
<b>Assess ecological and health risks from Hg use.</b>	Sample Analysis (Standard Method–Ed. 23. 2017, 3112B.) HQ Hazard Quotient	Concentration analysis of 147 samples	(AIHC, 1994; Israeli & Nelson, 1992; Jiménez–Oyola, Segovia–Escobar, et al., 2021; Spence & Walden, 2001; USEPA, 2011)
<b>Identify environmental impacts on water bodies</b>	Double–entry impact assessment matrix SWOT Matrix	Interviews and surveys	(O. Betancourt et al., 2005; Cuenca et al., 2016)
<b>Describe improvement techniques and strategies</b>	Expert judgment	Interviews	(Rodríguez–Prieto et al., 2017)

#### 4.1. Analysis of the current situation and challenges of the mining industry

For a better understanding, the methodological process was divided into three subsections. In the first section, an exhaustive bibliographic review was applied to respond to the first objective of the study on the History situation of gold mining in aspects such as its policies, laws and relevant socio–environmental impacts. In the second section, a semi–structured interview was applied to social actors related to gold mining activity in the Amazonian provinces to extract information on socioeconomic (population displacement, loss of livelihoods, migration of people, cost of living, water scarcity and health). effects) and environmental (biotic and abiotic) aspects, and as a last step, pointed out the political, socioeconomic and environmental challenges

involved in the development of artisanal and industrial Au mining in the Ecuadorian territory.

In order to respond to the first and second methodological sections, it was necessary to conduct a systematic literature review focused on the search and evaluation of several articles published in high impact journals and databases, such as Science Direct, Springer, Scielo and Google Scholar. During the literature search and evaluation process, filters were applied by title, keywords, abstract and year of publication. Twenty–six documents on the History context of Au mining in Ecuador and fourteen on the current situation of artisanal and industrial Au mining in this same area were obtained from this selection process (Table 5).

**Table 5.** Search process and most relevant results of the literature review.

Subject	Search parameters	Web of Science, Scopus and Regionals
<b>Amazon region</b>		
<b>History situation of gold mining in the Amazonian region of Ecuador</b>	"Gold" and "mining" and "Ecuador" and "Amazon".	(Abrahan et al., 2018; Capparelli et al., 2020; González–Merizalde et al., 2016; Lane, 2009; López–Blanco et al., 2015; Tarras–Wahlberg et al., 2001)
	"Gold" and "mining" and "Hg" and "Ecuador" and "Amazon".	(Almeida, 2019a; Gonçalves et al., 2017; Osorio Rivera et al., 2018; Ospina, 1996)
	"Gold mining" + "Amazon" + "mercury exposure" + "Ecuadorian Amazon".	(Fernández–Llamazares et al., 2020; Mainville et al., 2006; Roy et al., 2018; Webb et al., 2004)
<b>Andean region</b>		
<b>History context of gold mining in the Andean Region</b>	"Gold mining in Ecuador" and "Gold mining in the Ecuadorian Andean region".	(Calderón Robles, 2020; ENAMIEP, 2023; Garzón–Gutiérrez & Rodríguez–Miranda, 2015; Guerra & Peralvo, 2010; Lopez Bravo et al., 2016; E. A. Mora, 2002; Rodrigo Oviedo et al., 2017)
<b>The current situation of gold mining in the Andean Region</b>		(Appleton et al., 2001; Markowski et al., 2006; Murillo Carrión, 2000; Thomas et al., 2019)
<b>Coastal region</b>		
<b>History of gold mining in the Litoral Region</b>	"Gold" and "mining" and "Ecuador".	(M. Betancourt, 2016; Calderón Robles, 2020; Cao et al., 2020; F. Carrión, 2003; Lapierre Robles & Marín, 2018; Massa–Sánchez et al., 2018; OCMAL et al., 2019; Oviedo–Anchundia et al., 2017;

Rea et al., 2017; F. Sandoval, 2001; Tarras-Wahlberg et al., 2001; Vélez, 2017)

**Current situation of gold mining in the Litoral Region**

(Cando Jácome et al., 2020; Marshall et al., 2020; Moreno Parra, 2019; Vásconez, n.d.; Vilela-Pincay et al., 2020)

In addition to the literature review process (Table 5), the methodological process was complemented with an analysis of gray literature (Table 6) and information obtained from semi-structured interviews, field observations, documentaries and web news (common search engines, social networks, networks and video recordings). The gray literature corresponds to a set of documents that have not undergone review, editing or bibliographic control processes (ISBN, ISSN, Impact Indexes) and are available in non-conventional or low coverage channels. The documents selected from this type of literature were laws, national plans, accountability reports, theses and economic and research reports.

**Table 6.** Gray literature for the History state of gold mining.

Gray literature	Date of creation
Constitution of the Republic of Ecuador 2008	Official Gazette No. 449 of October 20, 2008
Foreign investment and mining policy in Ecuador	June 2017
Mining legislation in force in Ecuador, including the Mining Code	1986
Mining Law	Official Gazette Supplement 517 of January 29, 2009
General Regulations to the Mining Law	Official Gazette Supplement 67 of November 16, 2009
Mining Code Reform Law	nineteen eighty-two
National Mining Sector Development Plan	July 2016
Organic Reformatory Law to the Mining Law, Reformatory Law for Tax Equity in Ecuador and Organic Law of the Internal Tax Regime.	Official Gazette 037, 16-VII-201
Integrated environmental management in the Puyango river basin	2013
Intervention in large-scale mining in Ecuador and violation of human rights	2010
Large-scale mining in Ecuador-Analysis and statistical data on industrial mining in Ecuador	2012

To describe the current situation, semi-structured interviews were conducted with the participation of key actors in Ecuador's mining sector. Face-to-face interviews were preferred with a duration of 30 to 60 min, which facilitated the understanding of the reality of gold mining in Ecuador. The strength of the tool

used was its ability to uncover a wide variety of political, socioeconomic and environmental factors potentially related to this economic activity that may not be known beforehand. The majority of interviewees were people affected by mining, with a variety of voices for, against, and neutral in each area. Interviews were conducted with a total of 392 people, including local miners, local authorities, national government representatives in the provinces studied, and inhabitants of the mining towns (Table 7). In addition, field observations were made in the areas visited by the research team. This important information gathered helped to identify the current situation of gold mining in Ecuador, focusing on aspects such as displacement of people, loss of livelihoods, migration of people, cost of living, water scarcity and health impacts.

**Table 7.** Participants and key questions to understand the current situation of gold mining in the Amazon.

Interviewed persons	Questions
<b>Local Miner/Association Representative ( interviewed, mining concession holder)</b> <b>Amazon region: 48</b> <b>Island region: 48</b> <b>Coastal region: 26</b>	¿What type of mining is developed? ¿Do you have a permit for mining activities? ¿What type of technique is used for gold extraction, amalgamation or cyanidation? ¿Is the wastewater in the extraction process subjected to any treatment process prior to environmental discharge? ¿Do you, as a miner, use any procedure to mitigate the impacts of gold extraction? ¿Indicate three elements/components of the environment that are most affected by pollution. ¿Over the years, do you think there have been water shortages?
<b>Local authority (political leaders of the mining area)</b> <b>Amazon region: 48</b> <b>Island region: 48</b> <b>Coastal region: 26</b>	¿In your jurisdiction have ordinances been created for the control and surveillance of mining activities? ¿Do you know if illegal gold mining exists in your canton and/or parishes? ¿Do you know if the inhabitants of your canton and/or parishes have had health problems associated with gold mining?
<b>MAAE (acronym in Spanish): Ministry of Environment, Water and Ecological Transition. (government representatives per province)</b>  <b>Amazon region: 10</b> <b>Island region: 10</b> <b>Coastal region: 6</b>	¿Do you know if gold mining is taking place in your province? ¿Do you know if illegal gold mining is taking place in your province? ¿Have there been any reports of contamination from gold mining? ¿How has the Environmental Authority carried out audits of gold mining concessions (rights)? ¿How has the Environmental Authority carried out water monitoring in the water bodies in the mining area of influence? ¿During the visits and/or audits has the accumulation of mining waste been evidenced? ¿Do you consider that leaching occurs in the residual accumulations?

Mining inhabitants (48 interviewees, community representatives per canton)

Amazon region: 48  
 Island region: 48  
 Coastal region: 26

- ¿Do you consider that gold mining has improved the quality of life in the area?
- ¿Does your monthly income cover all monthly expenses?
- ¿Has gold mining caused population displacement for any reason?
- ¿Has gold mining resulted in loss of livelihoods?
- ¿Has the cost of living changed since the advent of gold mining?
- ¿Do you consider that, with gold mining activity, there is a shortage of water for daily activities?
- ¿Have any family members or acquaintances experienced health problems or death due to gold mining pollution?

Finally, based on the bibliographic analysis of the first two sections and the information gathered from interviews and field observations, a working group was formed. A method called expert judgment was applied, a process that allowed (i) validating the information obtained so far, and (ii) discussing and establishing the main political, socioeconomic and environmental challenges surrounding the development of ASM and large-scale mining in the Andean territory of Ecuador. The experts who participated were specialists in mining, environmental and conservation issues.

## 4.2. Ecological and health risk assessment in gold mining

### 4.2.1. Sampling and laboratory analysis

The field work was carried out during the period between April and June 2022, corresponding to the months in which precipitation varies between 200 and 350 mm, according to (Ilbay-Yupa et al., 2021) In each region, a total of 147 water samples were collected from rivers and streams that cross or are in proximity to mining concessions. The main objective of the study was to detect the concentration of mercury (Hg) in surface water samples obtained from these water bodies. For this purpose, the samples were collected in 250 mL amber bottles and acidified by adding 0.10 mL of nitric acid. Quality, confidentiality and code of ethics policies were strictly followed when transporting the samples, which were guarded until their arrival at the Science Laboratory of the Escuela Superior Politécnica de Chimborazo, Sede Orellana, Ecuador.

The determination of Hg concentration was performed using the atomic absorption and hydride generation method (Atomic Absorption Spectrophotometry). The measurement range used for Hg ranged from 0.0005 to 10 mg/L, using the reference method Standard Methods, Ed. 23. 2017, 3112B – Acid digestion: EPA method 3015, 2007. Prior to analysis, samples were subjected to a preparation process using the nitric acid digestion

procedure described in U.S. Environmental Protection Agency (EPA) method 7473, as detailed by (Mensah et al., 2015).

#### 4.2.2. Exposure assessment and risk characterization

In this study we considered two exposure scenarios; (1) the residential scenario, whereby residents use river water for drinking and basic household needs, and (2) the recreational scenario whereby river users are exposed to contaminants through activities such as swimming in local rivers. The exposure routes evaluated were water ingestion and dermal contact. The risk assessment was performed for adult and child receptors following the models proposed by the US Environmental Protection Agency (USEPA, 2001, 2004).

The input dose of Hg (ADD: mg/kg-day) through water intake was calculated by the following equation:

$$ADD_{\text{ingestion}} = \frac{C_{\text{sw}} \times EF \times IR \times ED}{AT \times BW}$$

donde  $C_{\text{sw}}$  es la concentración de Hg en el agua (mg/L); EF es la frecuencia de exposición anual (días/año); IR es la tasa de ingestión de agua (L/día); ED es la duración de la exposición a lo largo de la vida (años); AT es el tiempo medio (días); y BW es el peso corporal (kg).

Hg input dose (ADD: mg/kg-day) through dermal contact was calculated by the following equation:

$$ADD_{\text{dermal contact}} = \frac{C_{\text{sw}} \times EF \times ET \times ED \times SA \times kp}{AT \times BW}$$

Where  $C_{\text{sw}}$  is the concentration of Hg in water (mg/L); EF is the annual exposure frequency in local rivers (days/year); ET is the exposure time (hours/event); ED is the lifetime exposure duration (years); SA is the exposed skin surface area (cm<sup>2</sup>); kp is the skin permeability constant (cm/hour); AT is the mean time (days); and BW is the body weight (kg). The traditional approach to calculating DAD using the USEPA empirical formulas has been the deterministic approach. (Parveen, 2023), which uses point values (e.g., central tendency values or reasonable maximum exposure) for the input parameters in the risk assessment. However, this approach has a high uncertainty associated with it and, therefore, the results may be uninformative and even unreliable, depending on the input data. On the other hand, probabilistic methods consider the uncertainty and variability of the data through the probability distributions of the input parameters, which makes them more robust in risk assessment

(USEPA, 2001). In recent years, the application of the probabilistic approach has had an important growth due to the development of computer tools that allow quick and simple evaluations by integrating a large amount of information of the input variables in risk assessments (Du & Lu, 2022; Goswami & Kalamdhad, 2022; Moriarity et al., 2022).

In our study, the parameters used for the assessment of DDA by the deterministic and probabilistic methods correspond to: residential exposure frequency (EF<sub>residential</sub>) for adults and children of 350 days/year, with triangular distribution 345 (180 – 365); recreational exposure frequency (EF<sub>recreational</sub>) of 120 days/year, with triangular distribution 120 (26 – 3260) for adults and children (Jiménez-Oyola et al., 2021a); residential exposure time (ET<sub>residential</sub>) of 0.22 hour/event for adult and child receptors (Spence and Walden 2001); recreational exposure time (ET<sub>recreational</sub>) of 2.6 hour/event and triangular distribution 2.6 (0.5 – 6) for adult and child receptors; water intake ratio in residential setting (IR<sub>residential</sub>) for adults (2.04 L/day) and children (1.28 L/day) (Jiménez-Oyola et al., 2021a); recreational intake (IR<sub>recreational</sub>) for adults (0.053 L/day) and children (0.090 L/day) (USEPA 2011); exposure duration (ED) 30 years for adults and 6 years for children (Israeli & Nelson, 1992; Spence & Walden, 2001); exposed skin surface area (ES) of 23000 cm<sup>2</sup> and 7280 cm<sup>2</sup> for adults and children respectively, with normal distribution  $18,400 \pm 2,300$  for adults and normal distribution  $6800 \pm 600$  for children (AIHC, 1994; Anderson et al., 1985; Spence & Walden, 2001); body weight (BW) of 72 kg and 15.6 kg for adults and children, respectively, with normal distribution  $72 \pm 15.9$  for adults and normal distribution  $15.6 \pm 3.7$  for children (AIHC, 1994; Anderson et al., 1985).

The potential risk to human health, with respect to non-carcinogenic effects, was quantified in terms of Hazard Quotients (HQ), by dividing the ADD for the reference dose of Hg (RfD<sub>oral</sub> = 0.0003 mg/kg-day and RfD<sub>dermal</sub> = 0.000021 mg/kg-day) (USDoE, 2022). The Hazard Index (HI) represents the cumulative non-carcinogenic risk, and is estimated by summing the ingestion HQ and dermal contact HQ. The safe exposure threshold for both HQ and HI is equal to 1.

The Hg concentration value at each site was used for deterministic risk estimation and to produce the point risk maps. For concentrations < LoD, LoD/2 was used. The risk calculation was performed using the R programming

language. Spatial analysis of the data and risk maps were performed using ArcMap 10.8.3 software.

### **4.3. Identification of environmental impacts of Hg on water bodies**

The methodology used to achieve this objective employed a double-entry data collection matrix to evaluate the socio-environmental impacts and a technique known as expert judgment was used to establish the challenges.

#### **4.3.1. Impact assessment**

Environmental impact assessment is based on the identification of external pressures on an ecosystem and its components. The proposed method has been widely used in various environmental impact assessments to identify the main pressures resulting from anthropogenic activities. The technique is qualitative and consists of the application of a double-entry matrix, which is a tool that has important advantages over other methods: (i) to carry out the valuation, experts are not required, so it is easily accessible; (ii) the different impacts caused can be evaluated; (iii) criteria can be taken from several people who have knowledge of the subject; (iv) the criterion or valuation issued should be based only on the physical environmental conditions present; (v) it is a very easy matrix to apply, adapts to the different impacts, poses a reliable valuation, is very practical in environmental management processes and therefore serves to propose means of prevention to its deterioration.

In this section, the methodology is divided into 4 steps. The first step consisted of characterizing the anthropic pressures, for which an interview was conducted with artisanal miners in the area to learn about the processes, activities and techniques used in gold extraction. The second step was to determine the evaluation components, and six components were established, two biotic (flora and fauna), two abiotic (water and soil), economic and social. It is important to note that the difficulty in identifying the ecological and anthropogenic components can be complex, depending on the characteristics of the ecosystem in the study area. The third step consisted of identifying and describing the impacts; in this process, a group of people involved in and knowledgeable about gold mining activities, such as government technicians, academics. This group of stakeholders was provided with History evidence of mining activities (photographs and videos), and a field visit was scheduled to the study area in the parish to identify and evaluate the magnitude of the impacts of gold mining activities.

Finally, in the fourth step, to determine the magnitude of the environmental impacts, the technique of expert judgment was used, which consisted of

forming a technical working group (Table 8), made up of academics and professionals with experience in issues related to the identification of environmental impacts.

**Table 8.** People involved in and knowledgeable about ASM activities in the study area.

Name	Age	Gender	Educational Background	years of experience	Relationship with the Area
Hinerth Velázquez	33	Masculine	Environmental Engineer	8	Environmental Comptroller in the Cascales Canton
Álvaro Borja	64	Masculine	Environmental Technician	32	Environmental Technician in Canton Cascales
Juan carlos lopez	56	Masculine	Primary education	25	Local Artisanal Miner
Luis Rivera	45	Masculine	Secondary Education	21	Local Artisanal Miner
María cango	45	Feminine	Primary education	16	Local Artisanal Miner
Andrea chango	34	Feminine	Environmental Engineer	11	Environmental Technology in the Cascales Canton

With the results obtained in the previous steps and the impacts identified, this technical committee, as in the previous step, used History evidence (images and videos) accompanied by a field visit that allowed assigning a magnitude of impact (Table 9). It is important to highlight and clarify that the methodological process to evaluate the environmental impacts of ASM gold mining activity is based on expert knowledge, a technique called "expert judgment" that focuses on establishing the impacts perceived at the time of reviewing videos and images and prior to a tour of the mining areas. In other words, the methodology does not consider the geochemical analysis of biotic or abiotic elements.

**Table 9.** Experts selected to develop the assessment of socio-environmental impacts generated by ASM in El Dorado de Cascales.

Name	Age	Gender	Educational Background	years of experience	Relationship with the Area
<b>billy coronel</b>	41	Masculine	Master in Management Systems	17	Research professor in the area of study
<b>Carlos Mestanza-Ramón</b>	34	Masculine	D. in Conservation and Management of the Natural Environment	15	Researcher in the area of study.
<b>Demmy Mora</b>	24	Femenine	Environmental Engineer	5	Researcher in the area of study.
<b>Álvaro Borja</b>	64	Masculine	Environmental Technician	23	Environmental Technician in Canton Cascales
<b>Yader Moreno</b>	35	Masculine	Environmental Engineer	11	Former Environmental Analyst of the Ministry of Environment and Water of Ecuador in the Province of Sucumbios.

Three levels (low, medium and high) were used to assign the magnitude of the impacts; these levels (Table 10) consider the pressures and fragility of the evaluated components. Thus, the severity of the pressures and the vulnerability of the components are directly related to the magnitude of the impact. On the other hand, the magnitude of the impacts depends on the frequency and extent of the processes. It is important to consider that the fragility of the ecosystem components will influence the degree of vulnerability at the time of the assessment. It is also important to note that, once the three levels of impact magnitude have been established, the technical team establishes one of the three levels considering the type of impact and the components affected based on its experience in the environmental and biodiversity field.

**Table 10.** Description of the magnitude of impacts.

Magnitude	Description
High	Those that are incompatible with conservation. Their presence would lead to the prohibition of use or substantially modify the activities.
Medium	Those that can be compatible with conservation, prior implementation of management measures.
Under	Compatible with conservation and susceptible to natural regeneration in the absence of activities.

To establish the challenges, the results of the situational diagnosis of gold mining in the El Dorado de Cascales parish and the impact assessment were used. Based on this, a SWOT (Strengths, Weaknesses, Opportunities, Threats) matrix was developed. In this process, questions were developed to identify several essential aspects for its structure (Table 11).

**Table 11.** SWOT Matrix (Strengths, Weaknesses, Opportunities and Threats).

Strengths	Weaknesses	Opportunities	Threats
¿What are the advantages? What is done well?	¿What is affecting you? ¿What opportunities can arise from the problems?	¿What is being done wrong? ¿What should not happen?	¿What do other artisanal ASGM areas do better? ¿What obstacles does artisanal mining face?

#### 4.4. Determination of techniques and improvement strategies for the management and treatment of mercury

Finally, the information obtained from the interviews, bibliographic analysis and gray literature was used to establish challenges for the MAAPE to improve strategic aspects of socioeconomic, political and environmental management. This information served as the basis for the researchers to develop a process called expert judgment. This process made it possible to verify the reliability of the information obtained in the Systematic Review process and interviews. The experts who participated were specialists in mining issues, management and environmental authorities. These professionals established recommendations for mining management in Ecuador and the implementation of strategies aimed at reducing contamination of water bodies.

## 5. Results

# 5. Results

### 5.1. History and current situation and challenges of artisanal and industrial gold mining in continental Ecuador

#### 5.1.1. Amazon region

##### 5.1.1.1. A review of the political and legal evolution of gold mining in the Amazon region

Mining in Ecuador dates back to pre-Columbian times, has developed since colonial times and has gained great importance in recent year(Almeida, 2019b). The first mining regulations in Ecuador date back to colonial times when the Mining Ordinance of New Spain was enacted in 1753, which established that the Spanish Crown had the exclusive right to exploit mines. In 1829, the Bolívar Decree (Bolívar: Venezuelan politician, founder of the republics of Gran Colombia and Bolivia) determined that "mines of any species correspond to the Republic, whose government grants them in property and possession to the citizens who request them", opening the possibility that mines could be concessioned (F. Carrión, 2003). Subsequently, the Ecuadorian Mining Code of 1869 and its reform of 1892 ratified the state domain over the subsoil, the payment of an annual patent, reintroduced royalties as a precondition for maintaining the mining concession, and established surface easements to facilitate mining activities and exemption from all taxes for 25 years. These regulations granted free prospecting to private individuals, provided they paid the legal fees, which attracted foreign investors interested in exploring gold deposits (Ospina, 1996; Tarras-Wahlberg et al., 2001).

Metal mining in Ecuador has Historyly been small-scale and artisanal, concentrated mainly in the south of the country. Ecuadorian mining legislation was correspondingly rudimentary and was defined beginning in 1937, when a law was requested to designate subsoil metals as state property. In the 1970s a large mineral deposit was discovered in the southern Ecuadorian Amazon, the Nambija mine in Zamora Chinchipe. Subsequently, in 1974, the Mining Development Law was enacted, which established that the mines belonged to the State and were inalienable and imprescriptible. In the same year, the Mining Development Law was enacted, which ratified the state ownership of the subsoil

and metals and established the necessary characteristics to be considered as entrepreneurial mining, small mining and alluvial mining, but 11 years after the application of this law (Quezada, 2016).

In 1985, the Mining Development Law was repealed and the Mining Law was enacted, which ratified the inalienable and imprescriptible domain of mining deposits; the Ecuadorian Mining Institute (INEMIN) was created to be in charge of mining policy in the country, and royalties ranging from 1% to 3% were established for the State, the system of concessions and mining rights was regulated, a series of tax incentives were established, and the definition of small mining was eliminated, among other changes (Almeida, 2019b).

Mining-specific environmental legislation was absent in Ecuador until new laws came into force in 1991. This legislation limited the granting of concessions on protected lands and required environmental impact assessments for all mining activities. In 1994, the World Bank funded the Mining Development and Environmental Control Project with the objective of developing the Ecuadorian mining sector (Davidov, 2013). . The project collected mineralogical information from 3.6 million hectares of most of western Ecuador, including seven protected regions. The project's regulatory recommendations were codified into law in 2000, identifying mining as a national priority, and significantly deregulated the sector (Vallejo et al., 2017). However, under the renewed regulations, mining development remained prohibited in government-protected areas (Lane, 2009).

In the History context, the legal framework of the Ecuadorian State sought to develop technologies to improve gold extraction and mining development through the Mining Law and other public policies with social and environmental responsibility (Osorio Rivera et al., 2018). In 2008, the Ecuadorian Constitution created a new legal framework with the objective of regulating mining activities (Villavicencio, 1858). It established that those who explore mineral resources must recover and conserve a healthy environment that guarantees the quality of water, air and soil for people. It also established mechanisms for the prevention and control of environmental pollution and the sustainable management of natural resources (Constitución Política de la República del Ecuador, 2008). In this sense, illegal mining activities that affect biodiversity will be sanctioned in accordance with these laws (Delgado, 2015; Schudel et al., 2019).

The Mining Regulation and Control Agency established that it must audit, supervise, intervene, control and sanction in all phases of mining activities, in accordance with the provisions of the Mining Law and the General Regulations to the Mining Law (Delgado, 2015; Reglamento General a La Ley De Minería, 2021) . While, in all phases of mining activities, the obligation of environmental remediation and remediation is implicit in accordance with the Constitution of the Republic of Ecuador, the law and its regulations (Constitución Política de la República del Ecuador, 2008; Delgado, 2015; Villavicencio, 1858) In the case of the Ecuadorian Amazon, it was established that the Municipal and Metropolitan Governments must regularize, authorize and control mining exploitation in aquatic ecosystems (Constitución Política de la República del Ecuador, 2008; Reglamento General a La Ley De Minería, 2021) They must observe and comply with the principles, rights and obligations contemplated in municipal ordinances and not admit conditions and obligations different from those established in the Mining Law and its regulations (Schudel et al., 2019).

When talking about mining, the first legal institution referred to is the 2008 Constitution of the Republic of Ecuador; however, this activity is regulated by specific legal institutions: the Mining Laws of 1991 and 2009; general rules related to the law: General Mining Law of October 1991, General Regulations of the Mining Law of 2001, Mining Rights of April 2008, and General Regulations of the Mining Law of November 2009. These policy (legal) changes allowed institutions such as the Ministry of Mines and Energy and affiliates to work together to design and agree on an industry strategic plan to eliminate the use of Hg in mining (Ministerio de Minas y Energía, 2016) The Mining Law establishes procedures, standards and guidelines for the management of this department in order to minimize the adverse impact of mining exploration on the environment. In addition, it has also formulated norms for the transformation of mineral resources, which generate environmental, economic and social benefit and protect the rights of miners, the country and society (Reglamento General a La Ley De Minería, 2021). Despite the mining law, they are to ensure the sustainable development of activities, but due to the lack of comprehensive legislation and imperfect enforceability of the law, there are shortcomings.

The Ecuadorian Constitution establishes general rules and guidelines for activities (Asamblea Constituyente Ecuador, 2008). In addition, there is the Mining Law (Nacional & Fiscalización, 2018) and its updates, which are special

laws governing the sector. Important changes occurred with the adoption of Ecuador's new constitution in 2008, which included the Mining Mandate that reverted most mining concessions to state ownership. The new law also allows mining in protected areas upon special request by the president and approval by the National Assembly. In 2009, the government of Rafael Correa drafted a new mining law that increased oversight of mining companies. Although the law has raised some environmental standards, indigenous and social movements have held widespread protests, hoping for greater environmental and social protection. In 2015 and 2016, the Correa government made deregulatory changes to the mining law to incentivize foreign investment. These changes included lower corporate tax rates and special income taxes for mining companies. This made it much easier to acquire mining concessions, leading to the bidding and auctioning of state mining concessions that year and an increase in the (Roy et al., 2018).

The Ecuadorian Constitution establishes that, although all non-renewable natural resources are a strategic sector whose management and regulation is the responsibility of the government (art. 313), communities must be consulted prior to the establishment of extractive projects (art. 400) and the right of opposition must be granted (art. 98). However, the Ecuadorian Mining Law stipulates that communities living within mining concessions must only be consulted after the exploration license is granted, and the agreement of the owners and communities is not required to move forward with the development of mineral resources. Generally, there is no contract between the landowner and the miner, so the landowner is forced to illegally exploit his own land or enter into an informal agreement with the concessionaire. The Mining Law and the Special Regulations for Artisanal and Small-scale Mining state that in situations where land is considered to be of "public utility", the government has the authority to allow mineral exploration and development, even if mining may interfere with communal access to quality food and water (Special Regulations art. 14; Mining Law art. 15; 28). Likewise, the Mining Law also establishes that sanctions may be imposed on persons or groups that attempt to disturb or impede the development of mining activities (art. 100). 15; 28). Likewise, the Mining Law also establishes that sanctions may be imposed on persons or groups that attempt to disrupt or impede the development of mining activities (art. 100). 15; 28). Likewise, the Mining Law also establishes that sanctions

may be imposed on persons or groups that attempt to disturb or impede the development of mining activities (art. 100).

The lack of agreement between owners and communities living within mining concessions represents a challenge for mining law in regulating accessibility to mineral resources, community planning, the rights of individuals and communities, and economic development. Lack of monitoring and oversight by regulatory institutions (Table 13) generates environmental contamination (Spiegel, 2012). Effective monitoring and regulatory mechanisms should be implemented to prevent illegal dumping of toxic substances. Implementation of corrective measures for environmental impacts should also be required in a timely manner. The legislation does not make an exception for illegal miners in terms of remediation. However, the authorities have failed to enforce it.

**Table 12.** Responsibilities of regulatory institutions in Ecuador.

Institution	Responsibilities
<b>Government/Constitution</b>	Promote the development of artisanal, small, medium and large-scale mining, and promote their legalization to ensure technically adequate, socially fair and environmentally responsible conditions..
<b>Ministry of Energy and Non-Renewable Natural Resources</b>	Responsible for the management of public policy in mining matters and the issuance of associated administrative agreements and resolutions, including the management of public policy for MAAPE.
	National Strategic Plan for the Sustainable Development of Small and Artisanal Mining.
	National Training and Education Plan in technical, economic, social and environmental areas.
	Technical assistance in production control, available reserves, ore quality, mining techniques, extraction methods, ventilation, drainage, maintenance and industrial safety in the subsoil and on the surface, etc.
<b>Mining Regulation and Control Agency</b>	There is no special department in charge of MAAPE. Technical and administrative entity in charge of exercising the State's power to supervise, oversee, intervene and control the different phases of the mining activity.

	<p>Establish a system for managing socio–environmental conflicts that may arise in the MAAPE sector, adopting clearly defined processes and procedures for their implementation.</p>
	<p>Not having a special department to deal with ASGM</p>
	<p>Technically, economically and financially independent from the Ministry.</p>
	<p>Coordinate the technical assistance program.</p>
<b>Geological and Energy Research Institute</b>	<p>Promote the integrated management of sustainable mining development, mineral processing, tailings exploitation and maintenance, storage systems, closure of mining activities and development of clean technologies.</p>
	<p>Institutional, organizational and technological strengthening of the institutions responsible for the management and control of the artisanal mining, small–scale mining, medium–scale mining and large–scale mining sectors.</p>
	<p>Implement financing plans to promote and train the artisanal, small, medium and large–scale mining sectors.</p>
<b>Central Bank of Ecuador</b>	<p>Define, create and control the implementation of the country's public environmental management system, including the artisanal, small, medium and large–scale mining sectors.</p>
<b>Ministry of the Environment, Water and Ecological Transition</b>	<p>Define, create and control the implementation of the country's public environmental management system, including the artisanal, small, medium and large–scale mining sectors.</p>

The literature review (Red Amazónica de Información Socioambiental Georreferenciada (RAISG), 2020) and field research identified different reports and activities of illegal mining ( Table 14 ). In particular, illegal gold mining has increased exponentially in recent years. In 2016, it was estimated that about 77% of Ecuador's gold production was mined illegally. Of course, these numbers are now increasing ( Table 14 ). Illegal gold mining has also been exponentially exposed in recent years. Uncontrolled illegal gold mining is one of the main threats to biodiversity areas, which are home to unique and endangered species. The Ecuadorian government has not prioritized the needs of its inhabitants. These activities have turned forests into deserts and exposed biodiversity and communities to Hg. In addition, these activities sometimes cause enormous environmental damage and land trafficking (selling or renting land without documents to carry out mining activities) by these people. The case of illegal logging (logging without authorization from the MAAE), water

contamination and illegal hunting of wild animals has been going on for more than six years.

**Table 13.** Illegal ASLGM activities in the Amazon region of Ecuador.

Title	Description	Year
<b>Machinery used for illegal mining activities seized in Sucumbios</b>	The Armed Forces, in support of the Ministry of the Environment and the Mining Regulation and Control Agency, carried out operations to control illegal mining in the Santa Rosa de Sucumbíos sector.	2018
<b>Machinery used in illegal mining activities seized</b>	The Armed Forces apprehended an Ecuadorian and a Colombian involved in illegal mining activity in the San Carlos sector, Sevilla parish, Cascales canton..	2021
<b>Indigenous communities continue to denounce mining activities in Ecuador</b>	The Coordinadora de las Organizaciones Indígenas de la Cuenca Amazónica (COICA) and the Confederación de Nacionalidades Indígenas de la Amazonía Ecuatoriana (Confenaie) expressed their concern and denounced the increase in mining activity in Ecuador.	2018
<b>Operations against illegal mining in Pastaza and Napo</b>	Operations against illegal mining in Pastaza and Napo. MAEA officials with the support of soldiers from the Pastaza Jungle Brigade carried out the controls.	2016
<b>Intense mining control in Alto Nangaritza</b>	The control of illegal mining in the province of Zamora Chinchipe has resulted in the seizure of machinery, equipment and fuel used in the illegal activity.	2018
<b>Illegal mining endangers Yantzaza's drinking water catchment system</b>	The mayor of the Yantzaza canton, Bladimir Armijos, indicated that his drinking water source for more than 12,000 inhabitants is in danger of contamination due to the work carried out by illegal miners	2017
<b>Mining activity without permits in Alto Nangaritza, Zamora Chinchip</b>	Nuevo Paraíso parish in the Alto Nangaritza area. The majority of the population is Shuar and has no sources of employment.	2018
<b>Alto Nangaritza, another virgin forest under siege by mining in Ecuador</b>	Alto Nangaritza is one of the few remaining virgin native forests in Ecuador and serves as a connection to the Podocarpus National Park.	2018
<b>authorities harm villagers and favor miners</b>	The communities denounce that the MAAE and ARCOM favor illegal miners, allowing free access and violating the rights of the commune and its inhabitants. This is in the Orellana–Mushuc Hullacta commune, in the Punino sector.	2021

In the last 10 years, the increase in the price of gold at the international level has intensified mining activity in the Ecuadorian Amazon territory, damaging legal mining activities in the application, exploration and exploitation phases (Red Amazónica de Información Socioambiental Georreferenciada (RAISG), 2020). . Amazonian indigenous territories are the most affected with 85.8%. Before granting mining rights, Ecuador's indigenous peoples have the right to negotiate with them, but the government recognizes that few indigenous people have mineral rights on or under their lands. However, many indigenous peoples in the Amazon region do not want to exploit their lands (Red Amazónica de Información Socioambiental Georreferenciada (RAISG), 2020; Vallejos & Veit, 2020) This constitutes a major socioeconomic and environmental problem for communities near gold mining activities and, at the same time, a challenge to try to promote policies of regulation and respect for nature and Amazonian communities.

Ecuador's Mining Public Policy guarantees the planning of the sector from 2019 to 2030. It seeks to achieve investment and increase production in the sector within a framework of environmental and social sustainability. It also seeks to improve the administration, regulation, oversight and control of mining activities at the national level. Two of the most important axes seek sustainability and the fight against illegal mining (Red Amazónica de Información Socioambiental Georreferenciada (RAISG), 2020) In Article 93 of the Mining Law, 60% of royalties will be for productive and local development projects through municipal governments, parish councils and, where appropriate, 50% of this percentage to the governments of indigenous communities and/or territorial districts (Reglamento General a La Ley De Minería, 2021).

#### 5.1.1.1.1. Socioeconomic impacts

##### a) Displacement of the population and loss of livelihoods

In the late 1970s and early 1980s, the crisis of the first mining and agricultural companies led to an expansion of small-scale gold mining. Although tinged with political, social and environmental conflicts, in the last decade this sector has tended to consolidate itself as the country's most dynamic sector in the extraction and processing of metallic minerals. Two new mining districts emerged in the early 1980s: Nambija in the Amazon region and Ponce Enriquez on the southwestern flank of the Andes. Both were spurred by the increase in international gold prices and the agricultural crisis on the Ecuadorian coast,

generated by the El Niño phenomenon. The group of people (economic associations) of informal miners had little technical–scientific knowledge of gold extraction. However, the cooperatives played a very important role in the concession legalization process, which gave small–scale mining a greater margin of maneuver in its negotiations with the State and mining companies. Small–scale mining was strengthened in the 1990s through the consolidation of its productive processes, new forms of business organization and its legalization. This was reaffirmed in interviews with the elderly inhabitants of the nine cantons of the Zamora Chinchipe province, who stated that in the early 1980s, with the local crisis, they migrated to these lands in the southern Amazon, tempted by rumors that these lands harbored large concentrations of gold, which gave small–scale mining a greater margin for maneuver in their negotiations with the State and mining companies.

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Locals interviewed about the Napo and Santiago Rivers say that artisanal gold mining is considered traditional along the banks of these rivers and their tributaries. It is true that around 1984, after the remarkable importance of gold production in the Nambija mines, in the Amazonian province of Zamora Chinchipe, in southern Ecuador, expeditions and new human settlements expanded northward, more precisely in the center of the Amazon in the provinces of Morona Santiago, Pastaza and Napo. Thus, one of the first records of gold production in 1988, according to official estimates provided by

government authorities, was four metric tons of gold. However, these estimates corresponded to the declared part of the production, since a very important part was traded irregularly.

The results of the interviews indicate that there are currently two types of movements. The first are people who make expeditions that can last weeks or months to reach the metal mining sites located mainly in the eastern and western foothills of the Andes and in the Cordillera del Cóndor mountain range in the south–central Amazon of Ecuador. In the northern zone, in the provinces of Sucumbíos, the cantons with the most mining activity are Cascales and Sucumbíos Alto. Gold mining expeditions take place in the mountains bordering Colombia and in protected areas such as the Cofán Bermejo Ecological Reserve. The main illegal and informal mining activities take place in the provinces of Zamora Chinchipe, Morona Santiago, Napo and Sucumbíos.

During the tour of the gold mining areas, it became evident that ASM gold extraction activities have been accompanied by the formation of precarious settlements built by the miners, generally located in areas of irregular topography, distant from the basic services network, some of them temporary, and with a mostly male population (camp style), which constitute areas with minimal sanitary conditions and high levels of natural risk. In the past, there have been serious disasters that have caused the death of dozens of people (Nambija) and affected the surrounding river systems. Likewise, social conditions are characterized by an increase in social disorder, with a significant absence of social organization and public powers. A similar phenomenon can be observed in ASGM mining, particularly on the banks of the main Amazonian rivers.

History, local communities in the Amazon have depended on agriculture and cattle ranching. On the other hand, tourism has become very important in the last two decades with the emergence of community–based tourism and traditional lodges on the banks of Amazonian rivers. Seventy–three percent of the miners reported having been previously involved in one of these activities, and 85% of the villagers reported that some of their family members who are currently involved in mining were previously involved in agriculture, cattle ranching or tourism. This change and loss of livelihoods has led to the abandonment of potential agricultural and livestock lands, which is reflected in improved productivity.

b) Human migration, economic growth and cost of living

The communities consider that ASLGM does not contribute to the development of the local communities; on the contrary, these activities bring health problems and conflicts among the population. Currently, local communities claim that the pandemic has increased artisanal mining activity throughout the Amazon region. This is due to confinement, suspension of work, economic crisis and lack of employment. If our goal is to solve ASLGM problems, solutions require challenges where collaboration and integrated work of gold mining stakeholders and local communities is paramount.

In relation to health, gold mining affects workers through high exposure to toxic substances such as Hg and cyanide. This occurs due to the lack of occupational health and safety, health and environmental problems. Likewise, localities located in the lower basin of rivers with mining activity are affected by the high concentration of contaminants present in the water tributaries. These contaminants are found in the ichthyofauna that the communities take advantage of in all their fishing activities (Webb et al., 2004). In addition, it was detected that mining increases the presence of mosquitoes and black flies, which act as vectors of viral diseases and generate ailments in miners and families living near gold mining wells. Finally, veteran artisanal miners and inhabitants of nearby communities reported cognitive impairment. Clearly, long-term exposure and ingestion of toxic substances from these mining activities may be the main cause.

In an interview with local authorities, indigenous peoples throughout the Amazon have announced their resistance to mining projects that allegedly threaten the future of the communities that inhabit this region. Indigenous leaders do not want mining companies or the government to consult on large-scale mining projects. In the interviews, they recalled that some of the mining projects were installed without consulting the local population, and that there were false processes of citizen participation (socialization of the project with the inhabitants), as well as anomalies in the delivery of social services. compensation (food and tools for daily activities). The highest representative affirmed that the indigenous struggle against mining projects in the country has caused more than 260 leaders to be persecuted by the State.

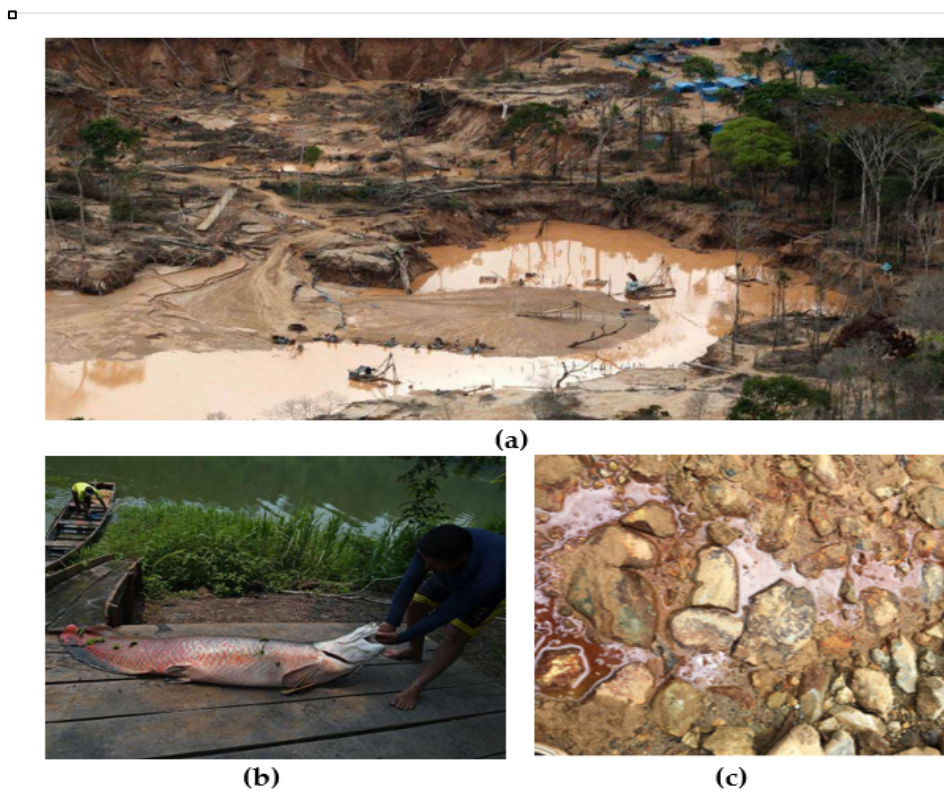
In early May, during a tour with the research team, new illegal artisanal mining activities became evident in places that a decade ago were indigenous territories or protected areas with little disturbance, specifically in Sucumbíos (Cáscales), Orellana (Alto Punino), and Napo (Chontapunta). Families close to the mining activity, lacking economic income, are being affected by deforestation and water contamination. The locals say that before mining, activities such as fishing and bathing in the rivers were very common, but now, for fear of contracting diseases, they prefer not to use the services provided by the rivers. This has affected their livelihoods and daily activities. As a result, the cost of living has increased; what they used to obtain from the ecosystem resources they now have to buy from neighboring towns, and for the vital resource of water, they now have to dig wells for fear of contracting diseases. Several villagers interviewed said that the gold rush attracted people from the provincial capitals and canton capitals, as well as foreigners, Peruvians in the southern zone and Colombians in the northern zone.

c) Water shortage and health effects

At the societal level throughout the Ecuadorian Amazon, indigenous peoples bear an enormous burden of health and livelihood impacts related to industrial development, including agriculture, mining and extractive industries. Greater commitment to environmental stewardship among indigenous peoples is needed to control pollution (Fernández-Llamazares et al., 2020). However, in studies 15 years ago, Hg levels in humans and fish near the Napo River communities were due to significant deforestation and volcanic soils. These had high levels of natural Hg, as gold mining was almost non-existent at that time (Webb et al., 2004). The presence of Hg suggests that deforestation and soil erosion (Hg leaching) contributed to Hg contamination of fish in the Napo River basin (Mainville et al., 2006).

In the field interviews, 67% of the inhabitants of the mining towns stated that one of their family members had presented a condition compatible with cancer. Meanwhile, 87% of the local miners consider that in the last year they have presented health problems or diseases compatible with headaches, hives and red and white spots on the body, mainly on the extremities, and only 12% went for medical consultations at nearby health centers. Another important problem reported by the authorities of the Ministry of the Environment and Local Governments is the fear of contaminant infiltration into groundwater bodies.

They indicate that more research is needed to know the status of the groundwater bodies, as most communities are considering using wells for water (Figure 5).



**Figure 5.** Environmental impacts in the Ecuadorian Amazon ( a ) Deforestation in Amazonian villages due to gold mining, a problem of the last 40 years ( b ) Contamination by leachates from mining areas ( c ) Leaching of toxic pollutants by mercury.

d) Environmental impacts

History, gold mining in the Ecuadorian Amazon has been the main source of Hg contamination (Lessmann et al., 2016; Naranjo et al., 2015) Regarding this activity, there is literature on Hg contamination in the northern Amazon region of Ecuador. However, legal and illegal mining has been present for years in the south of the country (López-Blanco et al., 2015) Anthropogenic activities increase metal concentrations in aquatic ecosystems (Capparelli et al., 2020). The few studies in Sucumbíos and Orellana only evaluate impacts, in general, with respect to gold mining. In addition, studies on Hg contamination in Napo province are still incipient (Naranjo et al., 2015). However, there is ample

evidence of metal contamination in the legal mining areas of Tena, Puerto Napo and Archidona (Capparelli et al., 2020; A. Mora et al., 2019). Results indicate that concentrations of these heavy metals have exceeded their permissible limits by 200 to 700%.

In the northern and southern Amazon (Napo, Aguarico and Santiago river sub-basins), in terms of metallic elements, sedimentation and presence of Hg, it was determined that there are no differences in these three sub-basins. Elements such as Co, Ba, Cd and Hg are the result of oil activity and specifically mark the spills. In the northern Amazon, there are high levels of Hg in the food chain. There is a potential risk when consuming fish due to As and Hg concentrations, as they exceed the limits established by the World Health Organization; results indicate that concentrations of these heavy metals have exceeded their permissible limits by 100 to 400%. Intoxication is likely, especially in children and pregnant and lactating women (Moreno Vallejo, 2017). A study of several rivers in the Nangaritza river basin on exposure in school children residing near gold mining areas shows clear Hg contamination. Children living in high mountain areas have Hg concentrations outside permissible limits. Therefore, this activity causes environmental damage and a risk to human health (Abrahan et al., 2018; González-Merizalde et al., 2016).

In some studies, such as (Abrahan et al., 2018; González-Merizalde et al., 2016; A. Mora et al., 2019; Requelme et al., 2003), there is evidence of high Hg contamination in rivers in Zamora due to gold mining (Capparelli et al., 2020), which exceeds the permissible limits, both for drinking water and for the proper development of wildlife. All miners interviewed stated that the use of mercury in gold extraction processes is still widespread. None of them stated that they use the currently recommended method, such as cyanidation (Schudel et al., 2019).

Recently, artisanal and illegal gold mining has increased in the northern Amazon region of Ecuador, specifically in Sucumbíos (Cáscales), Orellana (Alto Punino) and Napo (Chontapunta) (Figure 6). Families close to the mining activity, lacking economic income, are being affected by deforestation and water contamination with Hg. This disrupts their livelihoods and fishing activities with procedures that affect biodiversity, causing health impacts and water scarcity. The living costs of nearby communities are not affected. This is because there are agreements between communities to keep the costs of goods

and services at a balanced price for all. Economic activities in all sites explored with gold mining activity benefit nearby communities in terms of security and road maintenance; communities without mining do not receive support for forest restoration or protection of protected areas, and agriculture is affected. The activities that most benefit Amazonian communities are agriculture, cattle ranching and fishing. In general, people mentioned fishing and agriculture (palm, banana, yucca, cacao and coffee) as their main livelihood activities and cattle ranching as a secondary source of food and income. Households close to artisanal mining attribute it as their main source of income, while more remote indigenous communities perceive it as detrimental to their rivers and aquatic life. This has had a significant impact on the lives of Amazonian communities.



(a)



(b)



(c)

**Figure 6.** Illegal mining in the northern Amazon region of Ecuador. a ) Operations of the Armed Forces against artisanal gold mining in Sucumbíos (Cáscales). b ) Exploitation and closure of illegal mining in Orellana (Alto Punino). ( c ) Impacts of mining.

The harmful effects of Hg in the southern sector of the Amazon as a consequence of gold mining have intensified since the 1980s, when artisanal gold mining began to develop (Requelme et al., 2003). Although ASLGM generates important economic values in this region, it also causes various types of contamination (López-Blanco et al., 2015). Zamora Chinchipe is the largest economic generator of gold mining. Most of the gold extraction originates from artisanal and small-scale mining (López-Blanco et al., 2015; Requelme et al., 2003). The geology of the site, rich in polysulfides and metamorphic rocks, may be the reason for the presence of Hg. However, Hg concentrations in the soils of the Yacuambi River exceed normal concentrations. This is due to the constant use of Hg as amalgam in gold extraction processes (López-Blanco et al., 2015). Environmental changes caused by artisanal gold mining in the Nambija district due to Hg register high Hg contamination, while soil erosion increases Hg concentrations of sediments in the different aquatic ecosystems of the Nambija stream and river (Abraham et al., 2018; Requelme et al., 2003). This not only represents a serious risk to the health of organisms and plants living in the water, but also poses a threat to the people who use the ecosystem services of the water bodies.

Interviews and field observations identified that environmental impacts on soils and water resources are caused by recurrent inappropriate discharge of sediments from gold mining. In addition, mining activity affects water resources, natural landscapes and fauna, being the aspects that have suffered the greatest impact (Orellana et al., 2019). These forms of contamination are: (1) infiltration of contaminants into the soil from mining extraction; (2) illegal dumping of toxic substances (Hg) into water bodies; (3) infiltration of toxic substances from mining tailings; (4) infiltration of toxic substances into the soil from mining tailings; (5) soil erosion from mining activities; (6) soil erosion from mining tailings; (7) soil erosion due to changes in land use.

Parish authorities, miners, and local residents claim that gold mining activity has been gradually damaging environmental problems. This is related to drastic changes in the landscape (land use modification, soil erosion, relief modification, river patterns, deforestation). Biotic and abiotic components are more affected as a consequence of the use of rudimentary techniques in the extraction processes and the use of Hg as the main element in gold extraction processes (Mora-Silva & Coronel-Espinoza, 2021). Mining activities also affect

the flora, fauna and microbiota present in soils and water bodies. This is due to the inability to adapt to toxic environments in mining areas.

#### 5.1.1.1.2. Challenges of gold mining in the Ecuadorian Amazon

ASLGM represents a great economic contribution to the country; however, it harms the health of communities and generates environmental problem (Vallejos & Veit, 2020; Webb et al., 2004). After analyzing the history and current situation in the Ecuadorian Amazon, it was shown that the environmental and social damages are greater than the economic benefits; however, this activity has increased internationally due to the increase in the price of gold, with greater legal and illegal mining activity in the COVID-19 pandemic. The authorities responsible for mining control should focus their efforts on enforcing mining regulations in a scenario that reduces environmental and socio-economic impacts and is beneficial to the communities near the mine. The pandemic has modified the growth of illegal mining, and although the activities are not adequately controlled and sanctioned, it is possible to analyze and propose essential measures that will improve artisanal and industrial mining activity in the future. In the case of artisanal mining, communities are being affected by amalgams (Hg), i.e. affecting their health and livelihoods (contamination of tailings and rivers, contamination of aquatic biodiversity with Hg), where indigenous peoples are the most dissatisfied. In addition, IWMA affect the amount of natural vegetation and runoff rates. While Ecuador is theoretically more environmentally conscious than other countries, its political, economic and functional challenges limit the effective implementation of these measures in practice.

Due to lack of understanding of the impact of ASLGM, lack of clarity in the policy framework and limited resources, Ecuador's controls and enforcement have failed. This allows for rethinking new alternatives to reduce environmental and socioeconomic impacts. When the usual methods of pollution and hazard control are difficult to implement, knowledge is a viable strategy (Tietenberg & Wheeler, 2001). It is a new opportunity that, by rebuilding it, the sector will be better, more sustainable and inclusive, and the benefits of gold mining will be shared more widely and fairly. It is important that the authorities in the Ecuadorian Amazon take an interest in strengthening dialogue and cooperation with the communities.

Environmental and socioeconomic problems, such as deforestation, river contamination, health, loss of livelihoods, among others, coupled with a history of Hg impacts and the current situation in the Amazonian area of Ecuador, is perhaps one of the greatest challenges for the sector and governments. To address this challenge, strategies based on this study on the history, current situation and expert judgment could be used in combination with existing regulations to strengthen key aspects (Table 15). If communities near gold mining are aware of the unavoidable risks, they are more likely to advocate for improvements in legislation, regulation, toxic waste management and remediation.

**Table 14.** Suggested measures to improve ASLGM in the Ecuadorian Amazon.

(a)	Improve enforcement of existing regulations by strengthening the central authority responsible for oversight of mining activities
(b)	Promote citizen and local government participation in environmental management.
(c)	Facilitate the reorganization of small companies into large companies that are strong enough to maintain reasonable environmental and exploration obligations.

Authorities should concentrate efforts on creating new policies to take advantage of the potential of mineral resources in the Amazon region between Ecuador in a sustainable and balanced manner. The legal classification of gold mining in Ecuador allows for the possibility of an organization of miners. This could facilitate efficient communication between mining representatives, miners, regulators and the community to promote greater awareness of ASLGM impacts. However, rising gold prices and impacts are leading to changes in policies and the way mining activities operate. Artisanal and industrial gold miners around the world are increasingly trying to improve and easily apply new technologies and techniques that regulate excessive environmental pollution (Hinton et al., 2003). Therefore, enabling the mining sector to use more efficient

technologies will likely result in more efficient plants, less pollution, reduced socioeconomic impacts, and the comfort of communities that depend on farming and fishing activities for their livelihood and economy.

### **5.1.2. Andean Region**

#### 5.1.2.1. Evolution of Gold Mining in the Andean Region

Mining in the national territory comprises three scenarios of Ecuadorian history: pre-Columbian, colonial and republican times. The pre-Columbian era was characterized by the mining work of several pre-Hispanic cultures, including those who settled in the current provinces of Azuay and Cañar. The Cañaris worked the Au with perfection, and an example of this is the "El Sol de Oro" mask, found in 1940 in Chunucari, near the Sigsig canton (Rea Toapanta, 2017). Similarly, according to (Rea Toapanta, 2017), Au mining during this period was dominated by the natives of the Inca Empire, with their offerings of Kuri(Gold) to the Sun God. This dominance continued until colonial times, with the arrival of the Spanish in America in 1492. It was during the colonial era that a milestone in the history of national Au mining was reached when the discovery of small Au particles in the effluent sands prompted the establishment of mining areas, such as Zaruma, Portovelo and Nambija (Appleton et al., 2001; Murillo Carrión, 2000; Rea Toapanta, 2017) . In the heat of the gold rush, the cities of Loja (1548, second foundation), Zamora (1549), Jaén (1549), Cuenca (1557), Valladolid (1557) and Sevilla de Oro (1575) were founded (Rea Toapanta, 2017) However, the heyday of mineral extraction by the Spanish lasted until the end of the 16th century, at which time the shortage of labor due to the decrease of aborigines and the reduction of shallow mines gave way to its decline (Oviedo-Anchundia et al., 2017; Thomas et al., 2019).

However, in the Republican era, mining in Ecuador took a new direction with the installation of the Gran Compañía Minera de Oro Zaruma, a former foreign company later sold to SADCO (South American Development Company) Portovelo and Zaruma–El Oro–Ecuador in 1897 (Oviedo–Anchundia et al., 2017; Rea Toapanta, 2017; Thomas et al., 2019) . SADCO undertook industrial Au mining and created Compañía Exploradora Cotopaxi, an entity established to exploit the Macuchi deposit in the Andean zone of the national territory (Cotopaxi province) Oviedo–Anchundia et al., 2017; Rea Toapanta, 2017; Thomas et al., 2019) . Some time after the departure of SADCO, in 1950, the Empresa Industrial Asociada a la Minería (CIMA) was created, which operated until the

1970s, leaving exploitation in the hands of small miners and artisans (Ministerio de minería, 2017; Oviedo–Anchundia et al., 2017; Rea Toapanta, 2017; Thomas et al., 2019; Ulloa Sánchez, 2019) In the 1980s, Nambija was rediscovered (Appleton et al., 2001) and the Ponce Enriquez (Murillo Carrión, 2000) and Cerro Pelado–Los Ingleses deposits were discovered and are currently being exploited (Rea Toapanta, 2017). In the 1990s, with the strengthening of artisanal and small–scale mining, new forms of industrial–type organization and changes in their legal framework were attracted. However, it was not until the government of the Citizen Revolution (2007 onwards) that mining activity, especially large–scale mining, came to be considered as an option for changing national production, with the creation of strategic and second generation projects (Herdoíza et al., 2017; Oviedo–Anchundia et al., 2017; Rea Toapanta, 2017; Rudel, 2018; F. Sandoval, 2001; Ulloa Sánchez, 2019).

Currently, ARCOM, through its Mining Cadastre Web Geoportal, contains about 797 registered Au mining concessions distributed in nine provinces of the Ecuadorian Andean territory. These concessions correspond to artisanal, small, medium and large scale mining, as well as several concessions belonging to the general regime group (Table 2 ). Also, in addition to the concessions registered in ARCOM, there is evidence of illegal mining activity in the Andean zone of the country, which is clearly not registered, but receives income without any type of monitoring or control. Since its beginnings, illegal mining has represented a serious economic and social problem for the country due to the strategic income from which the State and the inhabitants of the mining areas are deprived (Arroyo, 2021).

Given this, according to (Agencia de Regulación y Control Minero (ARCOM), 2019), between January and October 2019, ARCOM, in coordination with the Mining Crime Unit of the National Police and the Armed Forces, conducted 418 operations to combat illegal mining throughout the national territory. As a result, the number of offenders for this crime was reduced by 60% compared to 2018. However, by 2020 and up to the present day, a time when the government's attention has been focused on the health emergency due to COVID–19 and the country's election day. process, illegal mining has not ceased. In fact, several complaints have been registered in the territory in protest of this activity, including those coming from Andean sectors, such as Buenos Aires (Imbabura),

Pacto (Pichincha), La Rama (Loja), Ecuadorian Chocó (between Esmeraldas, Carchi, Imbabura and Pichincha), Sigsig and Ponce Enríquez (Azuay), among others. According to (Gobierno del Ecuador, 1986), thanks to this type of complaints, between 2018 and October 2020, ARCOM has managed to seize 1733.27 tons of mining material in operations carried out nationwide, a figure that, depending on the Au content present in the material, would add up to between USD 15 and 20 million for the State.

#### 5.1.2.2. Political–legal aspects

Mining in its beginnings did not have regulations and a specific legal basis for its development, which generated rejection and misinformation in the population regarding this activity. The first Mining Law dates from 1830, created during the government of Juan José Flores, to promote this activity. Subsequently, in 1937, a new law was issued that determined the State's dominion over the minerals found in the subsoil, later codified by the Mining Law of 1961. Thirty years later, in 1991 and during the administration of Rodrigo Borja, an improved Mining Law was enacted, which for the first time qualified this activity as of national public utility and determined that mines and deposits are inalienable and imprescriptible patrimony of the State. During that same year, the first General Regulations to the Mining Law were also issued, an instrument that designed the procedure for granting concessions and established the tax and economic guidelines applicable to mining investment; this instrument was also modified in 2001 (Rea Toapanta, 2017; F. Sandoval, 2001). In 2008, with the issuance of a new Constitution that recognizes nature as a subject of rights for the first time, the "Mining Mandate" was issued. This controversial document declared the extinction, without any economic compensation, of mining concessions in the exploration stage that had not submitted their environmental impact studies, generating a substantial pause in the development of the mining industry in the country (Aguirre & Atherton, 1987; Rea Toapanta, 2017; F. Sandoval, 2001; Ulloa Sánchez, 2019).

Currently, the Mining Law and the Regulations that have governed the Ecuadorian territory since 2009, both issued with a series of guidelines that promote mining investment in the country and offer the opportunity to promote this industry within globally accepted parameters, require concession holders to adopt mechanisms for environmental protection, employment generation and development in the areas of influence. In addition, it allows the State to receive

important revenues through the payment of taxes, profits, royalties and fees on extraordinary income, the latter being of great relevance for the Ecuadorian economy (Oviedo–Anchundia et al., 2017; Rea Toapanta, 2017; Rudel, 2018; F. Sandoval, 2001). On the other hand, since 2019, the Ecuadorian government has been planning an update of its comprehensive mining policy (Table 16) with the aim of improving mining management in the country and making it a dynamic activity for the economy.

**Table 15.** Mining public policy update.

Axis	Strategic objectives	Public policies
<b>Economic development</b>	Position the mining sector as a relevant industry in the national economy, promoting sustainable competitive investment.	Increase and diversify the production of the mining sector, encouraging national and foreign private investment in the long term.
<b>Environmental and social sustainability</b>	Promote the adoption of good environmental and occupational safety practices. Harmonize good relations between the social actors of the mining activity, promoting the development of the areas of influence through citizen participation.	Promote the responsible use of resources in a manner that protects human and environmental health.
<b>Research and development</b>	Strengthen research by promoting technological development, technology transfer and incentives for innovation.	Promote research, innovation, technology transfer and entrepreneurship for the development of the mining sector..
<b>Management and administration</b>	Articulate the functions and competencies of public institutions in the mining sector through intersectoral coordination.	Promote timely and efficient coordination in public management
<b>Regulation, control and fight against illegal mining</b>	Strengthen regulation and control through auditing, supervision and follow-up processes.	Improve the administration, regulation, supervision and control of mining activities by the State.
<b>Regulation</b>	Promote a solid regulatory framework for the development of the mining industry by reviewing, analyzing and proposing regulations that will lead to the safety of the sector.	Promote the updating and improvement of the mining regulatory framework to orient it towards sustainable development.

In interviews with 48 miners involved in ASM activities in the different cantons of the Andean zone, 75% (36 miners) stated that they develop open-pit mining mainly in the mountains of the provinces of Imbabura, Pichincha and

Chimborazo. In contrast, 25% (12 miners) report that they mainly mine alluvial deposits in riverbeds and riverbanks, mainly in the cantons of the provinces of Azuay and Loja. Of the 48 miners, only 10, or 21%, indicated that they had permits or were in the process of regularization, mostly in the provinces of Imbabura, Azuay and Loja. Of the 48 miners interviewed, only one representative from the Corazón mine in Cantón Intag, Imbabura province, stated that as an internal policy 100% of their processes use cyanidation and their wastewater is managed through a closed system (Ministerio del ambiente del Ecuador, 2013). Finally, in the rest of the provinces, miners stated that they were aware of the government policy that prohibits the use of Hg, but for economic reasons, practicality and tradition they continue with illegal amalgamation processes (Ministerio del Ambiente del Ecuador, 2013).

Regarding the development of policies and laws, interviews were conducted with environmental directors and their technical staff in the Municipal Decentralized Autonomous Governments. In all 48 jurisdictions, they agreed that policies aimed at developing the control and monitoring of ASGM activities had not been discussed or analyzed. Thus, no ordinances were found to be in place for this purpose. The only thing that is evident is the personnel provided for control operations carried out by the control authorities (Ministry of Industry) and public forces (police and military). On the other hand, 100% of the authorities state that they are aware of the informal and illegal ASM activities taking place in their jurisdictions, but it is difficult to carry out controls due to the high risk involved in traveling to these isolated localities, considering that most of the miners are armed and could make an attempt on their lives.

From the point of view of the provincial authorities, in the 10 interviews conducted with directors and technicians, they agree with the cantonal authorities regarding the presence of informal and illegal ASM activities in their provinces; they indicate that control is difficult due to lack of personnel, low technical knowledge, and in the few controls that are carried out, there is evidence of information leakage, since at the time of the operations, only evidence of ASM activities is found, but not those responsible for them. agree with the cantonal authorities regarding the presence of informal and illegal ASM activities in their provinces; they indicate that control is difficult due to lack of personnel, low technical knowledge, and in the few controls that are carried out, there is evidence of information leaks, since at the time of the operations, only evidence of ASM activities is found, but not those responsible for them. The

cantonal authorities agree with the cantonal authorities regarding the presence of informal and illegal ASM activities in their provinces; they indicate that control is difficult due to lack of personnel, low technical knowledge, and in the few controls that are carried out, there is evidence of information leaks, since at the time of the operations, only evidence of ASM activities is found, but not those responsible for them.

#### 5.1.2.3. Socioeconomic impacts.

##### a) Population displacement and loss of livelihoods.

Regarding population displacement issues, the results of the interviews indicate that there are two opposing sides when analyzing ASM and large-scale mining. On the one hand, ASM is the ever-present option for the population of poor communities in the Andean zone. Historically, the vast majority of families in the Andean provinces have been economically dependent on agriculture and livestock. Locals report that the population has been moving in recent years in search of better job opportunities to increase their income. One of the alternatives has been to engage in mining activities or to be part of a new wave of migration to the United States and European countries since the borders were reopened after the COVID-19 confinement period. As a result, the traditional livelihoods on which they have historically depended, such as agriculture and cattle ranching, have been lost. This is reflected in the abandonment of agricultural and livestock lands, resulting in lower production.

Therefore, unemployed or low-income people in the Andean Zone are happy to participate in ASM activities. Of those interviewed in cantons with mining activities, 100% indicated that at least one family member has been involved in mining activities in the last five years. This has led to a decrease in local labor for activities such as agriculture and cattle ranching. In the seven cantons interviewed in the provinces of Carchi and Imbabura, locals are involved in ASM activities in the region of La Merced de Buenos Aires, a small parish in the canton of Urcuquí located high in the Andes Mountains in the province of Imbabura. Large-scale mining has provoked the emergence of new rural settlements, as well as the displacement of indigenous peoples, who are generally evicted from their lands by large mining companies, both legally and illegally.

In Ecuador, most of the illegal mining hotspots are located in the parish of Buenos Aires (Imbabura) and Camilo Ponce Enríquez (Azuay). Although only 0.38% of the national population is concentrated in these areas, 86% of the Au exported by small-scale mining is extracted there, and at least 50% of this comes from illegal and informal activities. However, despite such a wealth of Au, these sites have an average poverty rate of 65% for unsatisfied basic needs, according to data provided by INEC in its 2010 Population and Housing Census. Through informal conversations with some miners and local people, several agreed that they are part of the final piece of a millionaire system and perhaps the most precarious sector. In addition, several of them risk their lives in mines with oxygen scarcity and the possibility of collapse; others tend to break into legal concessions to steal gold material and even apply for jobs in formal companies to physically swallow pieces of Au and silver, thus appropriating the precious metals. Likewise, most miners agreed that they were grateful to have a job that, although sometimes poorly paid, is favorable to not having one due to the health situation and the low economic level in the country. In addition, several miners pointed out that, at the time, they tried to legalize their activities through the corresponding agency, but due to the bureaucracy prevailing in the sector, the formalization process could not be completed.

Regarding large-scale mining, there have been anti-mining resistances in Ecuador, centered on different political positions and ethnic origins and arising in both urban and rural contexts. Despite the heterogeneous and interethnic character of the anti-mining movement, frictions between the government and the indigenous movement have led the latter, through the Confederation of Indigenous Nationalities (CONAIE) or the political party Pachacutik, to assume the mining issue as one of its main axes of protest and to lead the articulation of the opposition to the government. These tensions have been felt in relation to the discourse and rhetoric of the "indigenous philosophy" of Sumak Kawsay, due to the "appropriation" of the concept of Good Living by the Correa government.

#### b) Demographic dynamics, economic growth and cost of living

History, ASM activities have been carried out mostly by men. In recent years, the participation of boys, girls, adolescents and women in this activity has been increasing. Taking into account the different processes developed and their level of difficulty, the different activities are assigned. The cost of living in the Andean

areas has increased in response to a greater demand for products, which over the years are produced in smaller quantities, responding to a decrease in labor due to the displacement of the population. There is also evidence that demand for basic products has increased in mining areas and there is a perception that the presence of miners has caused a rise in the prices of basic foodstuffs.

For decades, in socioeconomic terms, Au mining was the way of life and subsistence for thousands of native and immigrant families (Herdoíza et al., 2017) According to colonial records, in 1897, when SADCO started industrial Au mining in Portovelo, it produced more than 99 million grams until its dismantling in 1950, i.e., approximately 1860 kg/year (Oviedo–Anchundia et al., 2017). In 2000, the estimated small–scale gold ore production by volume of extraction was 416.6 kg/month (F. Sandoval, 2001). Between the years 2005 to 2012, the average Au production reached around 4900 kg/year, and for the period 2013 to 2016, an annual average of around 7700 kg/year was reached. However, a decrease in production was evidenced in 2016 and 2017, an aspect that would probably be explained by the illegality and informality of ASM, as well as the high levels of smuggling, although in 2018 it recovered, reaching a production of 6516 and reaching 8093 kg by 2020 (González–Vicente, 2013).

Mining and the extractive sector, in general, represent a productive activity that has served as a source of employment, income and social investment projects generated by the State for thousands of people, either directly or indirectly, especially for the inhabitants of the communities near where these types of activities are concentrated. However, although part of the population has felt favored, there is another segment that considers itself taxed and deprived of the benefits of the development of this extractive activity in the country. For example, several residents who lived near the Au mines in Macuchi, an area discovered by the Cotopaxi Exploration Company and exploited since 1941, stated that, at that time, this area enjoyed a fairly good economic and social boom: "...it had perhaps the best hospital and theater in the country, sports fields, internationally renowned sportsmen...". However, today this community in the province of Cotopaxi only shows the aftermath of looting, abandonment and contamination of its waters (Pilaló River) by arsenic and cyanide. In fact, there is a documentary made on the site entitled "Macuchi, half a century of contamination and oblivion" (Nabayaogo et al., 2022).

In the interviews with the inhabitants of the populations living near ASM activities, there are two points of view with respect to quality of life. The first corresponds to families in which the heads of household depend directly or indirectly on ASM activities. They indicate that, since their arrival, they have received higher incomes and their quality of life has improved. On the other hand, families that do not depend on mining activities consider that ASM activities have worsened their quality of life, such as environmental quality, water resources and decreased local agricultural production. What both parties agree on is that monthly income is generally not enough to cover basic expenses such as health, food, education and clothing.

In the northern Andean zone of the province of Imbabura, in the La Merced sector of the province of Buenos Aires, giant plastic camps were discovered that attracted attention. These camps contained beds and basic survival products and were used as domestic shelter for illegal miners. Violence was prevalent at these sites, and those who lived there mentioned that it was a daily occurrence, bringing fear and hopelessness. The local population that traditionally lived there clamored for help so that their territory would return to the tranquility that characterized it in the past. Several inhabitants interviewed claim that the Au fever attracted people from southern Ecuador, as well as Peruvians, Venezuelans and Colombians who intimidated the community, and even dissident guerrillas of the Revolutionary Armed Forces of Colombia (FARC) began to charge economic payments in exchange for not attacking them and subjugating the people in their attempt to dominate the illegal mining business.

At the beginning of July 2021, when the research team was conducting fieldwork in La Merced de Buenos Aires, one of the many control processes carried out by government authorities was observed. On this occasion, approximately 1,000 police officers, 1,200 military personnel and 20 public prosecutors raided the area in a lightning operation. In the first days of intervention they managed to get some 3,000 people to vacate the camps and dismantled 30 Au processing plants and a complex system of pulleys for Au transportation. According to officials from the different ministries involved in the control and surveillance processes, it is estimated that some US\$ 500,000 per week were affected in Buenos Aires by this illicit activity.

On the other hand, the arrival of large-scale mining in the Andean zone is causing important changes in terms of territorial control and use of natural

resources, which generate a high level of socio–environmental conflict. In response to this phenomenon, the interethnic dimensions and the indigeneity discourse emerge as very relevant elements in the articulation of local resistance to the Project (Espinosa, 2022). While the indigenous inhabitants of the Andean zones consider themselves legitimate owners of the territory and exercise their property rights through global titles, the mestizo peasants and ranchers are immersed in the process of protest against what they consider the irregular and unfair process of purchase of their property. individual titles, or the threat of being evicted from their lands under the figure of servitude (Rudel, 2018). Faced with this situation, the anti–mining resistance in the area has adopted the strategy of constituting themselves as indigenous communities and circumscribing their properties under a collective title, in addition to claiming the right to Free, Prior and Informed Consultation, which is generally not carried out correctly.

c) Water shortage and health effects

A particular concern for the rural population is the impact of mining activities on water sources and streams that feed local aqueducts. Thus, the inhabitants of Andean mining areas associate water scarcity with four factors: (i) high demand for water from ASGM activities; (ii) increased demand generated by population growth in mining areas; (iii) lack of confidence in the quality of water sources, which renders them unusable; and (iv) poor planning, which prevents dialogued solutions to the problem of water scarcity. In fact, ASGM and large–scale gold mining activities are one of the main causes of water scarcity in addition to the constant social demands due to economic and environmental problems. The use of toxic elements in Au extraction processes and the lack of good environmental practices to reduce their impacts have caused serious damage to ecosystem components, mainly affecting water bodies, soil and atmosphere. As a result, there has been a decrease in the balance of ecosystems, which is reflected in the availability and use of their services. On the social side, water pollution contributes to increased health risks and reduced economic benefits.

Interviews with miners indicate that the most relevant health problems caused by mining activities are related to the nervous system, musculoskeletal system, respiratory and psychological problems. This information was contrasted with data from the Ministry of Public Health showing a 23% increase over the national

average for respiratory ailments, intoxications, headaches, skin conditions, and eye problems. These problems are caused mainly by the release of heavy metals (mercury and zinc, among others) into bodies of water, soil and atmosphere, where they go through a chain of transformation until they reach the human body. These problems are aggravated by the lifestyles inherited from their ancestors, who lacked recreational activities, healthy physiological movements and hours and days of real rest.

On the other hand, it is important to note that gold mining has caused occupational hazards due to the use of Hg and other heavy metals involved in the amalgamation (Patricio C Velásquez-López et al., 2011) and cyanidation (Herrera Herbert & Pla Ortiz de Urbina, 2022), processes, as well as the geographic impacts of this activity (Herrera Herbert & Pla Ortiz de Urbina, 2022), such as telluric movements, landslides and sinkholes, among others. Thus, in Ponce Enriquez, one of the most important Au and Andean mining areas in Ecuador, there have been several deaths due to geological accidents, poor technology (especially in illegal mining) and improper handling of certain materials (Avcı & Fernández-Salvador, 2016; Castillo, 2016; Velástegui, 2010). Furthermore, due to the irresponsibility and negligence present throughout the country's mining history, which has led to serious environmental problems (discussed below in the third aspect of analysis), mining has become a highly controversial issue in Ecuador. For several years, various social movements have criticized the government in its attempt to promote mineral extraction in the country, arguing that mining, especially large-scale mining, is not compatible with the definition of social progress as "good living" (Rudel, 2018; Sánchez-Vázquez et al., 2016).

In Ecuador, the risk of water contamination from large-scale gold mining activity is increasing due to abundant and increasing rainfall in recent years due to global climate change. Most of the current mining projects are located in highly rainy Andean areas (i.e., it rains between 2500 mm and 3000 mm per year). Mining projects in páramo areas could cause an imbalance with serious consequences for water resources and surrounding life. Currently, 12.5% of the surface area of the páramo ecosystem is under mining concesión (Avcı & Fernández-Salvador, 2016). In short, the problem of environmental impacts associated with large-scale mining has its origin in two main sources that can cause pollution in various periods and in different magnitudes. The first consists

of the extraction of large quantities of rock from the subsoil that contain a wide variety of chemical elements: arsenic, lead, chromium, cadmium, sulfur, etc.; and once they reach the surface they are altered by rainwater or air, releasing these elements in dangerous quantities into the water, soil and air. Secondly, when rock is treated with toxic chemicals, these residues remain stored for years and their impact on the natural environment is inevitable.

d) Environmental impacts

As a preamble, it is important to highlight the information provided by the ten provincial Environmental Directorates (director and technical team). According to the records, it was observed that between 2015 and 2019, between three and six complaints were received per month requesting intervention and monitoring of activities potentially causing socio-environmental impacts. As a result, authorities organized a total of 143 inspections per year on average during the same period to respond to these requests in the Andean region.

A teleconference was held with representatives of the Environmental Quality area of the Ministry of Environment, Water and Ecological Transition from the 10 provinces. As the environmental authority, they stated that environmental audits have been carried out on environmental licenses for ASM activities, as indicated in Ministerial Agreement 061. As of 2020, 64% (452 mining concessions/rights) have submitted and approved environmental compliance reports, while 36% (250 mining concessions/rights) have not submitted environmental compliance reports. The provinces with the highest compliance are Imbabura and Loja, while Azuay and Carchi have the lowest percentage of compliance. In the audits in the territory, the environmental authority has not conducted environmental monitoring (biotic/abiotic) to compare with the results presented in the compliance reports due to lack of budget, being tied to rely solely on the monitoring presented by the representatives of the ASM concessions. In addition, in the audits carried out, the technicians claim to have found evidence of accumulation and leaching of mining waste in 237 concession areas and sites adjacent to these activities, mainly in the provinces of Imbabura (2), Pichincha (15), Azuay (99), and Loja (121).

In addition, local miners claim that Hg is used in the ASGM gold extraction processes and some is lost when it is poured into the processing pans or ponds to form amalgam. Another percentage of Hg is released into the atmosphere

when the amalgam is burned. In the provinces of El Oro and Azuay, in the south of the country, workers at the processing centers and miners who rent these centers on a daily basis report having used Hg at some point in the last year. None of them knew about the final disposal of the water or simply indicated that it was stored in pools. In other words, the water is not 100% subject to any treatment prior to discharge. Two very clear arguments emerged from interviews with local miners involved in AGSM. First, artisanal miners engaged in alluvial and surface activities do not carry out procedures to mitigate the impacts generated in the different processes, arguing that they cannot cover the costs of applying procedures such as these. Meanwhile, in the processing centers, workers or people who rent the centers do not know if in the end techniques are applied to mitigate the impacts of Hg and CN use. It is important to highlight that all interviewees agree that ASGM has negative effects on water, soil and air.

In addition to the information gathered in interviews with the main actors involved in ASM activities, there was qualitative evidence of impacts, such as loss of vegetation cover, landslides, subsidence, soil erosion, water resources and a decrease in the scenic beauty of the landscape in general. These impacts were recorded with greater magnitude in the provinces of Imbabura, Pichincha and Azuay, generally generating pressures on biodiversity, affecting its balance and thus causing a decrease in its ecosystem services. The following is a description of specific cases in mining areas where the impact on the natural environment is clearly evident.

In the mining area of La Merced de Buenos Aires, the mining boom generated since 2015 has had serious environmental consequences. The first impacts occur when installing the precarious camps (Figure 7a) that will serve as shelter while mining activities are taking place. At this point, people cut all the vegetation (Figure 7b). There is also evidence of waste (Figure 7c), which is not managed and is mixed with the area's biodiversity. This northern part of the country is characterized by mountains with high concentrations of Au in their rocks, which is why miners extract lumps of material, causing erosion and landslides (Figure 7d). In turn, during fieldwork, we located beneficiation plants that housed generators, fuel, tanks and bags of different chemicals (nitric acid, borax, sodium cyanide) in addition to ball mills, amalgamating cylinders and cyanidation tanks, among others.



(a)



(b)



(c)



(d)

**Figure 7.** Environmental impacts; ( a ) vegetation clearing; ( b ) camp construction; ( c ) garbage contamination; ( d ) erosion, landslides and mudslides.

In the central Andean region, environmental impacts were also observed in the provinces of Pichincha and Cotopaxi. In the first province, located in the northwestern zone, the environmental impact is of great concern to environmental organizations, considering that the area includes legal concessions and illegal mining that directly affects the Chocó Andean Biosphere Reserve. This area is characterized by its high biodiversity and important water reserves for farmers, ranchers, and related communities. Meanwhile, in Cotopaxi, at the Macuchi Au mines, locals say that there is currently contamination in their effluents due to the presence of arsenic and cyanide. A documentary made in the area indicates that during the mining boom that began in 1941 with the installation of the Cotopaxi Exploration Company (Foro Intergubernamental sobre Minería Minerales Metales y Desarrollo Sostenible., 2019). Finally, in the southern part of the Andean region in the province of Azuay in the Camilo Ponce Enríquez canton, environmental impacts continue to affect surface and subway water bodies.

Some environmental and social problems of large-scale mining activities are widely known. The development of this activity involves the generation of huge

amounts of waste. The current trend in metal mining is the exploitation of low concentration deposits because high concentration deposits are mostly depleted. To extract metal from low-concentration deposits, mega-mining is necessary. However, this industrial activity involves the generation of waste in incalculable proportions. As for Au extraction, waste levels are extremely high: the production of 10 g (equivalent to one ring) generates an average of 20 to 60 tons of waste rock, as well as 7000 L of water contaminated with cyanide, a substance known to be highly toxic (O. Betancourt et al., 2005; Oviedo-Anchundia et al., 2017). The equation is simple: the lower the Au content, the more waste. At the end of mine life, millions of tons of tailings accumulate, with multiple risks of soil and water contamination (Murillo Carrión, 2000) The most common cases are acid mine drainage and heavy metals; air pollution is also often caused by dust laden with heavy metals, such as arsenic, cadmium, nickel and even radioactive minerals (Patricio C Velásquez-López et al., 2011).

Modern industrial mining involves the treatment of rock with highly toxic chemicals. Miners must store the large amount of waste rock processed and water contaminated with these chemicals for years. Although the industry claims that these wastes are safely controlled, contamination of the environment is inevitable. On many occasions, this contamination has proved catastrophic. The recent history of industrial mining recounts countless tailings dam ruptures caused by floods, earthquakes or simple human negligence. In seismic regions or regions exposed to heavy rainfall, such as Ecuador, the risks of such dramatic accidents increase.

#### 5.1.2.4. Challenges of Gold Mining in the Ecuadorian Andean Zone

Considering that deforestation, agribusiness, hydroelectricity and mining are the main threats that the biodiverse ecosystems of the Ecuadorian Andes will continue to face, strengthening environmental institutions must be one of Ecuador's greatest challenges. In the midst of the COVID-19 pandemic, mineral and oil extraction activities continued as the main way to generate resources for Ecuador, so in 2020, in the face of a crisis and lack of employment in the population, Au mining increased. The governmental crisis forced to merge ministries in the environmental and control fields, generating doubts about the strength that could be achieved to contain a growing Au mining.

Thus, one of the main challenges is to focus on improving the management and control of mining activity in the country and, above all, to find out whether the government sees in this industry an option for the country's economic reactivation. In the political–legal sphere, it is necessary to establish more rigorous, clear and realistic policies. According to (Foro Intergubernamental sobre Minería Minerales Metales y Desarrollo Sostenible., 2019), the categorical criteria for small and medium mining should be revised as they allow mining activity at much larger scales, with lax environmental management and low tax obligations. It is also important to focus on (i) the insufficient environmental registration in artisanal mining to control its negative impacts, (ii) the lack of coordination in mining–environmental–hydro permits, (iii) the weak sanctioning processes, and (iv) the lack of technical guidelines in environmental management. On the other hand, regarding control processes, the mining companies call attention to reduce bureaucracy and speed up the formalization process of their activities. At the same time, inhabitants of the affected areas request that ARCOM be more aware of this type of situation, as they claim that the agency only responds to complaints after media pressure.

In terms of the socioeconomic aspect, the greatest challenge facing the country is the low level of transparency maintained by local and national authorities in the management of revenues. In view of this, the country must competently manage the revenues obtained from mining extraction and exports and know how to invest them efficiently in the exploited regions, something that is being developed in part with the strategic projects of Loma Larga and Río Blanco in Azuay, and with the royalties established by the national government. Another economic challenge facing the country is the rise or fall of mineral prices. This situation can cause financial instability but can be solved with the establishment of green and complementary economic activities in parallel to the extractive sectors, such as tourism, for example.

In recent years, governments have been betting on compensating for the programmed erosion of oil revenues with revenues from another extractive activity of the same type: mega–mining. Indeed, like oil exploitation, mega–mining extracts non–renewable resources on a large scale and causes socio–environmental impacts of great spatial and temporal extension, perhaps even more important than those associated with oil extraction. The history of oil in the country shows a set of very high costs in social, cultural, environmental,

political and economic terms. It is from these that we must learn and not repeat the problems, considering that large-scale gold mining activity can cause catastrophic events if not properly managed.

Finally, with regard to the environmental aspect, the Evaluation of Ecuador's Mining Policy Framework (ARO, 2020) notes that, in terms of environmental management, the country lacks technical regulations, adequate control and awareness of the environmental impacts of mining, specifically for the proper management of (i) large volumes of solid and liquid waste, (ii) biodiversity in the exploration phase, (iii) water resources, and (iv) emergency preparedness programs and their socialization with communities and authorities. In addition to the above, residents located in mining areas denounced the lack of continuous monitoring and follow-up by environmental authorities to verify their activities, draw attention to them, and prevent future incidents before they become inevitable; for example, the collapse of a tailings dam in Ponce Enríquez that resulted in the contamination of the Tenguel Rive (Mestanza-Ramón, Paz-Mena, et al., 2021).

### **5.1.3. Coastal region**

#### 5.1.3.1. History

Pre-Hispanic cultures were the ones that developed the most mining activities in the Republic of Ecuador. For example, people belonging to the Tolita Culture worked gold and platinum between 500 B.C. and 500 A.D.; while the Cañaris worked gold and silver (Calderón Robles, 2020; Cao et al., 2020; F. Carrión, 2003; Massa-Sánchez et al., 2018; Rea et al., 2017; Vélez, 2017). There is no certainty about the tools used in pre-Columbian times to exploit gold in shallow mines and in the arid material of the Pindo-Puyango rivers. However, it is known that tools such as the wedge, the combo, the pick, the barrette, the shovel and the wheelbarrow were used in colonial times, causing a low yield in the exploitation of gold-bearing quartz (Oviedo-Anchundia et al., 2017).

Later, in the mid-sixteenth century, the discovery of gold particles motivated prospectors to go through rivers and mountains until they finally found the "gold nuggets", which belonged to the areas of Zaruma and Portovelo. The South American Development Company (SADCO) was in charge of the exploitation of the Portovelo mining area at the end of the 19th century until the middle of the 20th century. Once SADCO's activities ended, the Empresa Asociada Industrial

Minera (CIMA) was formed, which operated until the 1970s, giving way to exploitation by small-scale miners and artisans (Rea et al., 2017).

#### 5.1.3.1.1. Mining policy.

In its beginnings, mining did not have regulations or legal bases to control the activities it carried out, which caused repudiation and misinformation among the population due to the lack of mining policies (M. Betancourt, 2016; Cando Jácome et al., 2020; Lapierre Robles & Marín, 2018; Marshall et al., 2020; Moreno Parra, 2019; OCMAL et al., 2019; F. Sandoval, 2001; Tarras-Wahlberg et al., 2001; Vásconez, n.d.). Over the years, the mining industry expanded, and was contemporary to the formation of the Ecuadorian state. Around 1830, great interest was generated by the consecration of property rights and the attraction of foreign investment, which led to the development of the Mining Development Law. The purpose of this law was to reactivate the country's productive sector with the help of alternative mining activity in the southern zone of Ecuador (F. Carrión, 2003). In 1886, the Mining Code of Ecuador was enacted; this law was intended to awaken the interest of foreign investors in the discovery, prospecting and exploitation of mines, in addition to providing legal security to mining concessionaires. This legislation revolved around the forms and conditions of appropriation and exploitation of deposits; it also influenced the transformation of the norms that regulated the subsoil domain (F. Carrión, 2003). It is important to note that this legislation recognized precious stones (such as gold, silver, etc.) as subject matter and, through a reform in 1982 (Ley Reformatoria del Código de Minería), petroleum was added to the list. This reform also allowed property owners to dispose of minerals as property owners (Paz, 1886).

In 1937, the Mining Law was enacted; this law was in charge of determining that the minerals found in the subsoil belonged to the State's domain. One year later, the Codification of the Mining Law was issued (Vásconez, n.d.). By 1991 a new Mining Law, also known as Law 126, was presented. This law incorporated the principles of state ownership of both mines and deposits and categorically involved the rights of miners. It also incorporated the perception that the Ecuadorian State should legalize mining activities that had complied with the requirements established in the law (F. Sandoval, 2001). In 2001, some reforms were incorporated into the Mining Law, which took care of qualifying mining management as of national interest, priority and fundamental for

development, including norms on environmental protection (Vásconez, n.d.). In 2008, the Constitution of the Republic established a series of environmental principles that grant rights to native and indigenous peoples as new values of the State (Foro Intergubernamental sobre Minería Minerales Metales y Desarrollo Sostenible., 2019). A year later, in January 2009, the Mining Law and its Regulations were approved in order to generate an effective model of economic progress focused on responsible and organized mining. This law was charged with administering, regulating, controlling and managing the strategic mining sector, in accordance with the principles of sustainability, precaution, prevention and efficiency (Ministerio de Minería, 2016). Finally, in 2013, a reform to the Mining Law was carried out, called Organic Reformatory Law to the Mining Law, Reformatory Law for Equity in Ecuador and Organic Law of the Internal Tax Regime (Asamblea Nacional de la República del Ecuador, 2013).

It is essential to highlight that there are unique legislative measures that are applied in some areas of the country depending on the mining situation in order to avoid catastrophes. A clear example of this, applied in the province of Esmeraldas on March 24, 2011, is a precautionary measure issued by a judge prohibiting mining exploitation, licit or illicit, in the San Lorenzo and Eloy Alfaro cantons. This mandate was ratified in 2018; however, in consecutive years the established measure was ignored. Formerly, ancestral mining was carried out in the province (without consequences for the environment due to the use of nets and pans), but in recent years it has been practiced in the form of small and medium mining (with machinery and mercury in the open air), which is harmful to the ecosystem (El comercio, 2020; Ponce, 2018). A similar situation occurred in the city of Zaruma, where the Government of the Republic declared a state of exception for sixty days on September 14, 2017 due to the fact that excavations were being carried out on land declared cultural heritage of the homeland. According to investigations carried out, there were areas exploited for gold mining that represented a risk for the inhabitants, so the State took the decision to intervene by taking preventive measures (Vilela-Pincay et al., 2020).

#### 5.1.3.1.2. Socioeconomic sector

At the end of the 1990s, Ecuador was going through a financial crisis. To remedy the situation, the government (during the period 2000–2006) developed processes to offer the country's mining resources to foreign investors interested in this activity. Thus, with the intention of achieving the country's development,

and together with pro-extractivist reforms, the Ecuadorian territory moved towards an authoritarian political system known as "political domination". As a consequence, a social resentment of the people towards political institutions originated, which has been increasing over the years due to several factors (Vélez, 2017).

On several occasions there have been social, political, economic and environmental confrontations in the communities over mining projects. In some cases, the inhabitants of the mining areas say that they are not convinced by the land negotiation agreements and that they are often pressured to sell. In addition, there have been reports of destruction of inhabitants' buildings by the companies in charge of the megaprojects (Massa-Sánchez et al., 2018). Likewise, there have been evictions of families without any relocation agreement to make way for the mining companies. In addition, indigenous movements have been unleashed against mining companies, provoking confrontations with the military that have left leaders injured and even dead (M. Betancourt, 2016; OCMAL et al., 2019).

Esmeraldas is one of the most conflictive areas, and is also considered one of the most excluded and poorest regions of Ecuador, due to the lack of opportunities in the area for 22 years. At that time there was a labor shortage, so gold mining emerged as a labor option for the people, since timber and oil palm activities did not require more labor. Social conflicts caused by gold mining include lack of access to water, mistrust between families and the breakdown of social relations. Armed conflicts have also occurred in the province in the last 50 years, mainly over the illegal appropriation of gold material, resulting in the death of people due to clashes (Lapierre Robles & Marín, 2018). Economic consequences include chronic poverty, as well as illicit activities such as tax evasion, smuggling of mining inputs, capital flight and money laundering, importing unregistered machinery, etc (Ponce, 2018).

#### 5.1.3.1.3. Environmental impacts

In general, the most significant impact caused by gold mining is the contamination of soil and water resources. This can occur due to improper dumping or infiltration of toxic substances used in mining (Calderón Robles, 2020). Sometimes, remediation measures are not applied after the mineral extraction process, leaving pools of contaminated water exposed to the open

air (Figure 8a). As a result, huge expanses of brick-colored soil, fish and macroinvertebrates affected by the accumulation of heavy metals such as mercury, cyanide and arsenic are evident (El comercio, 2020). These contaminants can also cause respiratory, skin and carcinogenic diseases that affect people's well-being. Debris generated by mining waste (Figure 8b) is also a problem, because it can cause the death of aquatic species and even humans (Cao et al., 2020). Another impact related to gold mining is the change in the geographic landscape, as it involves changes in land use such as degradation and erosion, relief modifications and large-scale deforestation to make way for the machinery used in mining activities (Calderón Robles, 2020).



**Figure 8.** Impacts of gold mining: ( a ) Pools of contaminated water exposed in the open pit; (b) debris generated by the extraction of material for gold.

The Puyango–Tumbes watershed serves as the border between northern Peru and the provinces of Loja and El Oro in southeastern Ecuador, covering a total area of 5494.57 km<sup>2</sup> (Humberto, C.; Cáceres, M.; Lorenz, 2013). According to studies carried out since the beginning of the 20th century in the upper Puyango River, high concentrations of contaminants from mining have been found in Portovelo–Zaruma, which has had an impact on Peruvian territory. In 2001, a study was conducted in the area; the results showed that gold mining activity was affecting the ecosystem through tailings in the rivers, which subsequently released cyanide, mercury and other metals that exceeded established quality criteria. The effects consisted of: reduced aquatic diversity, elevated levels of metals in larvae, large amounts of metals attached to suspended sediments at ambient pH conditions, and low levels of metals in carnivorous fish, with the exception of mercury (Tarras–Wahlberg et al., 2001). In 2010, another was conducted that evidenced the presence of about 1.5 tons of mercury released

per year in the city, of which 70% evaporated and 30% was released with tailings (Patricio C Velásquez–López et al., 2010). Subsequently, in 2017, another investigation was conducted to analyze heavy metal contamination; the results indicated that Pb and As concentrations exceeded the permissible limits for metals in soils. In addition, biological samples (blood, urine and hair) were collected and the results determined that inhabitants residing near the Puyango River contained small amounts of Hg and Pb within their organism (Rodrigo Oviedo et al., 2017). As a consequence of all the contamination that the river receives, aquatic life forms do not develop; in addition, water consumption was disabled, and the use of water for agriculture and livestock. For all these effects, in 2018, the Federation of Peasants of Tumbes filed a lawsuit against the government of Ecuador for the alleged contamination of the Tumbes River.

In 2010, an analysis was conducted in bodies of water in Esmeraldas, in the Mario Unión and Sabaleta estuaries, and in the Santiago and Sabaleta rivers. Anomalies were identified in the fish, such as deformities, as well as the presence of heavy metals inside the fish due to illegal gold mining. Subsequently, in 2013, the Catholic University of Ecuador conducted a study that showed that the Maria estuary contained exaggerated amounts of aluminum, exceeding the limits established in the regulations by 580 times, as well as exceeding the copper standard by 2.4 times, the iron standard by 33 times, and the manganese standard by 1.3 times. All these substances were found to be the product of illegal mining in these areas (Ponce, 2018).

#### 5.1.3.2. Current Situation

A There are currently a total of 264 legally registered gold mines in the Litoral region, including artisanal mining, small-scale mining, medium-scale mining, large-scale mining and general regime (Table 3). The province with the highest number of concessions is El Oro, with a total of 213 gold mines, followed by Guayas, with 24 mines, Esmeraldas, with 16 mines, Los Ríos, with 5 mines, Santo Domingo de los Tsáchilas, with 4 mines, and Manabí, with 2 mines. Unlike the other provinces mentioned, Santa Elena has no registered gold mines, so there are no problems related to gold mining in the area.

##### 5.1.3.2.1. Mining policies

In recent months, the Ministry of Energy and the National Police have registered an alarming increase in illegal mining throughout Ecuadorian territory

due to the lack of regularization of the extractive activity of gold mining during the COVID-19 pandemic. Among the provinces with clear signs of illegal mining is El Oro, specifically in the San Lorenzo canton; this indicates that the measures established in the canton in 2011, which prohibit any type of extraction in the area, are being disregarded. As a consequence of the activities carried out in the sector, on November 18, 2020 there was a cave-in in an illegal mine that resulted in the death of several people (El comercio, 2020).

With respect to political issues, the Organization of American States (OAS) in 2020 admitted the petition filed by the Federation of Peasants of Tumbes (Peru) against the government of the Republic of Ecuador for the alleged contamination of the Tumbes River by mining activity in Portovelo-Zaruma district. Likewise, peasants and environmentalists from the neighboring country held a peaceful protest on January 25, 2021 in order to demand a pronouncement from the Inter-American Court of Human Rights, since the presence of heavy metals in the river continues despite the lawsuit filed, and there is a risk to the flora, fauna and health of approximately 200,000 people (Torres, 2021).

#### 5.1.3.2.2. Socioeconomic sector

In Ecuador, cantons such as Zaruma, Portovelo and Camilo Ponce Enríquez extract 86% of the country's gold exports through small-scale mining; however, only 0.38% of the territory's population resides in these areas. Despite the large exports generated by the cantons, they have average poverty rates for unsatisfied basic needs, 62% in Zaruma and 58% in Portovelo, according to the 2010 Population and Housing Census (Manchado, n.d.) In addition, 84.6% of the inhabitants of San Lorenzo canton live in poverty, a percentage that exceeds 60% nationally and 51% in the province of Esmeraldas; only 23% of households have basic services in the cantón (Logroño Vivanco, 2014; Moreno Parra, 2019).

In the interviews conducted, some miners stated that, due to the Mining Agreement decreed in 2009, many people were displaced to make way for large mining concessions. As a result, many opted to engage in illegal mining (inside and outside the canton), and with all this came violence and poverty in the exclusion zones. Faced with the various problems and conflicts generated by illegal activity, they preferred to sell their land and move away from the

concentration zones in search of a better way of life, leaving behind the place that had been their home for a long time. On the other hand, interviewees also stated that people from other regions of Ecuador and Peru are constantly joining the mining areas and are willing to work for lower wages due to the lack of job opportunities and offers.

In the country, informal miners are known as "sableros". They are generally caught between poverty and violence, so they risk their lives performing dangerous activities to obtain gold and thus earn an income to sustain themselves. In Zaruma and Portovelo, sableros often enter subway mines that have no oxygen, so they use long hoses to breathe while searching for gold veins. Some say that they only know how to "sabre" because they have worked in the mines since they were teenagers and that they have often broken into legal and illegal concessions to steal gold material. They also say that sometimes they apply for jobs in formal companies, and once inside, they ingest small pieces of gold and then process them in their bodies and keep the material to make money selling it.

Regarding the cost of living, some residents living near the mining concessions said that they have benefited from job opportunities in the gold mines, but that salaries are minimal. Meanwhile, residents who own commercial establishments (stores) said that mining activities do not influence their economy, because sales have not increased in their establishments and, in addition, government entities are very strict in the price regulation implemented in sales.

One of the main reasons why people resort to informal and illegal gold mining is related to poverty and lack of job opportunities. According to a report by the National Institute of Statistics and Census of Ecuador (INEC), the province of Esmeraldas is one of the poorest and most excluded provinces in the country. Thus, three of its cantons have the highest poverty rate, Rio Verde (63%), Eloy Alfaro (64%) and Muisne (65%) of the coastal region. Meanwhile, in the province of Manabí, two cantons, Pichincha and Olmedo have a poverty rate of 63 and 61 percent. It is important to note that these two provinces have the highest poverty rates in terms of multidimensional aspects, unsatisfied basic needs and access to basic services. These are incentives for the population of these cantons to migrate and go to develop gold mining activities in a precarious and unsafe manner in areas with high gold content, such as Alto Tambo in the

province of Esmeraldas, and in the neighboring province of Imbabura in the area of Buenos Aires. Thus, after the province of El Oro in terms of mining history, the province of Esmeraldas in the last 10 years has shown an exponential increase in gold mining activities in the coastal region.

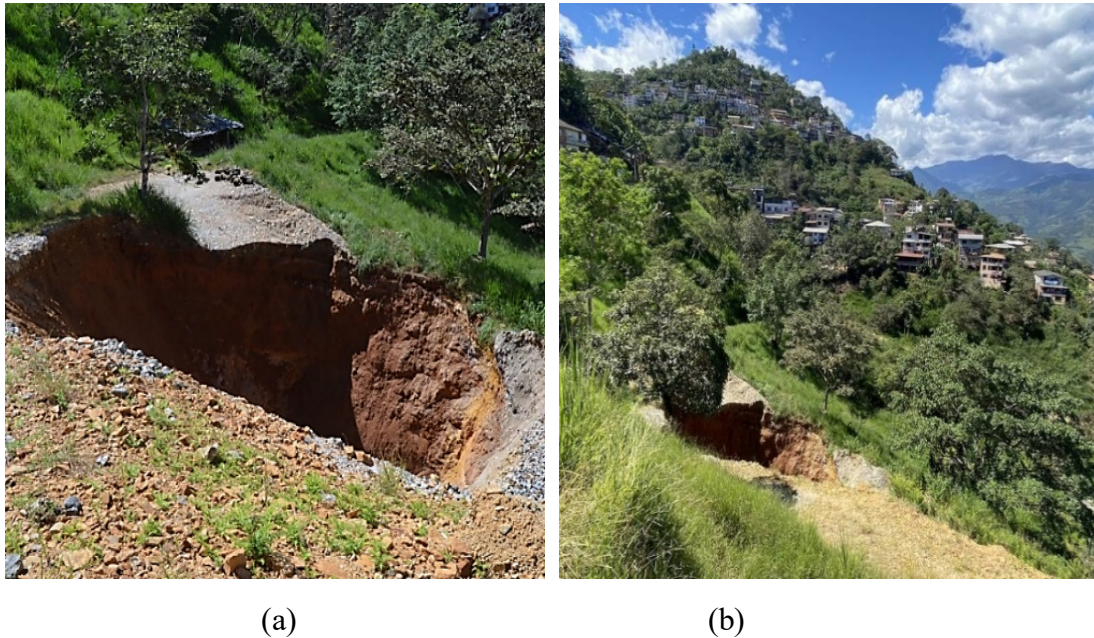
#### 5.1.3.2.3. Environmental impacts

In Ecuador, the use of mercury for gold amalgamation is prohibited; however, its use is still very frequent in the country, so that the substance is spread by rivers and streams. In this regard, activist Nathalia Bonilla stated in 2020 that, due to the increase in illegal mining during the pandemic, the water sources of San Lorenzo and Eloy Alfaro have been contaminated. She also added that 80% of the rivers are contaminated, but people do not have good water, so they have to continue using water resources with toxic substances (La hora, 2020). On the other hand, 19.45% of the water in the province of El Oro is contaminated by the activities carried out in Zaruma and Portovelo (Vilela-Pincay et al., 2020). All these data are of great concern, as they show that most of the populations settled on the banks of rivers in gold mining areas do not have adequate drinking water systems, which represents a serious risk to people's health.

Exposure of people to water contaminated with toxic substances such as mercury can cause illnesses, according to gold mining workers in the province of Esmeraldas. Some of the diseases they reported having contracted included: skin diseases, intestinal disorders, infections, vaginal problems (in the case of women), stomach diseases, and respiratory problems, among others. In addition, they mentioned knowing people who acquired long-term diseases such as Alzheimer's and cancer.

A study was conducted in 2020 in the Portovelo–Zaruma area, specifically in the Puyango–Tumbes river. The results showed that there was cyanide contamination at concentrations 9088 times higher than the established CCME standard of 5 g/L, and 1136 times higher than the 24 h LC 50 concentration of 40 g/L CN-free for some species. The levels of affectation arose from poor mining and environmental management practices in 87 gold beneficiation centers, which used mercury tailings to obtain the ore in the river (Marshall et al., 2020). Another effect that could be observed in the city of Zaruma was the large deformations due to land subsidence generated mainly by the illegal gold mines in the subway (Cando Jácome et al., 2020). The impact of these mining

activities was so great that on July 2, 2021 a sinkhole was created (Figure 9a), which reached a diameter of 20 m and a depth of 30 m, putting 50 houses located near the affected area at risk (Figure 9b).



**Figure 9.** Sinkhole in the province of El Oro, city of Zaruma. (a) Sinkhole formation; (b) houses at risk due to sinkhole formation.

In the Los Ajos sector of the San Lorenzo canton, illegal mining activities were registered in January 2021, despite the fact that the measures imposed prohibit it. As a result, the Ecuadorian Chocó (one of the areas with the highest species endemism in the country) is being affected by indiscriminate deforestation to make way for roads for illegal mining machinery (Bogoni et al., 2020; Lara-Rodríguez, 2018; Tubb, 2020) Inhabitants of the area claim that not even the COVID-19 situation has stopped the *sableros*, as there are 52 active mining camps in the area that are causing great damage to the area, in addition to generating insecurity, so they demand that the authorities control the permits granted for these activities. The Alto Tambo sector was also affected because after inspections carried out by the authorities in May, illegal miners invaded the area and destroyed a large part of the zone, putting the surrounding Awá Nationality at high risk (Figure 10a).



(a)



(b)

**Figure 10.** Invasion by illegal miners. (a) machinery used for gold extraction; (b) deforestation of the affected area.

#### 5.1.3.3. Challenges

The findings suggest that Ecuador faces many challenges, both politically, socioeconomically and environmentally. On the one hand, it is evident that the country lacks policies to guide the mining sector towards more responsible and environmentally friendly activities. There is also a need for greater control of illegal mining due to its exponential increase as a result of the COVID-19 pandemic and the lack of job offers, causing various forms of damage to the ecosystem. The provinces belonging to the Litoral region with the greatest conflict are Esmeraldas and El Oro, which, according to a systematization developed by the Ombudsman's Office and the Colectivo de Geografía Crítica, occupy the first place in terms of violation of human rights and nature at the national level (Moreno Parra, 2019). Considering the problems that have arisen in the two provinces, it should be considered a priority to establish laws to improve the situation in the two zones and avoid conflicts with neighboring countries due to the contamination generated by the zones.

Since gold mineral exploration and extraction began in the country, there have been socioeconomic conflicts that have harmed the workers and inhabitants of

gold mining areas. The Ecuadorian State must give priority to the people involved in gold mining activities in the country, implementing controls on the remuneration of mining workers, since as has been pointed out, they do not receive a fair salary despite the risk they run in carrying out the extraction activities. Strict plans should also be implemented to prevent mining concessions from using mercury to extract gold, as the contamination of water sources means that the local population has no water for drinking or other activities. It would also be advisable to offer jobs and invest in education, given the lack of opportunities in conflict zones such as Esmeraldas and El Oro.

Mining sector regulators should socialize with all social actors involved in mining processes about the lack of knowledge of mining formalization and regulation processes. This will help ensure that these processes are carried out in accordance with the law and comply with environmental regularization processes. In addition, the Ecuadorian government should promote specialized technical assistance programs on issues related to environmental management, mining safety and professional training for ASM; to achieve this, the academy should provide support in the education and training of miners, making them aware of the risk of using banned substances such as Hg, as well as instructing them in the implementation of more environmentally friendly extraction strategies. On the other hand, it is essential to establish incentives focused on environmental protection and the generation of entrepreneurship. These alternatives could be an option that would allow the adoption of better environmental practices in the gold extraction process and improve the local economy of the miners.

Perhaps the most serious challenge facing gold mining concentration zones is the lack of awareness and knowledge about exposure to heavy metals such as mercury, as people are often unaware of the effects they can cause to the environment. This process, together with the lack of control and surveillance in the mining areas, as well as the lack of management of mining waste generated in the extraction areas and the lack of legal regulations for the management of mercury, have a significant influence on the environmental aspect. An effective measure to minimize environmental impacts could be government oversight to ensure that gold mining concessions mitigate the damage caused by their extractions, thus ensuring that they remediate (or at least minimize) the damage caused to the ecosystem.

## 5.2. Ecological and health risks associated with Hg concentrations in water bodies

### 5.2.1. Amazon region

#### 5.2.1.1. Mercury content

The analytical results of Hg concentration in the water samples are summarized in Table 17. Fifty percent of the samples reported values below the detection limit of the measurement equipment (LoD < 0.0005 mg/L). The spatial distribution patterns of Hg concentration are shown in comparison with the quality guidelines established by Ecuadorian legislation for drinking water and according to the admissible quality criteria for the preservation of aquatic and wildlife life in freshwater (INEN, 2020)

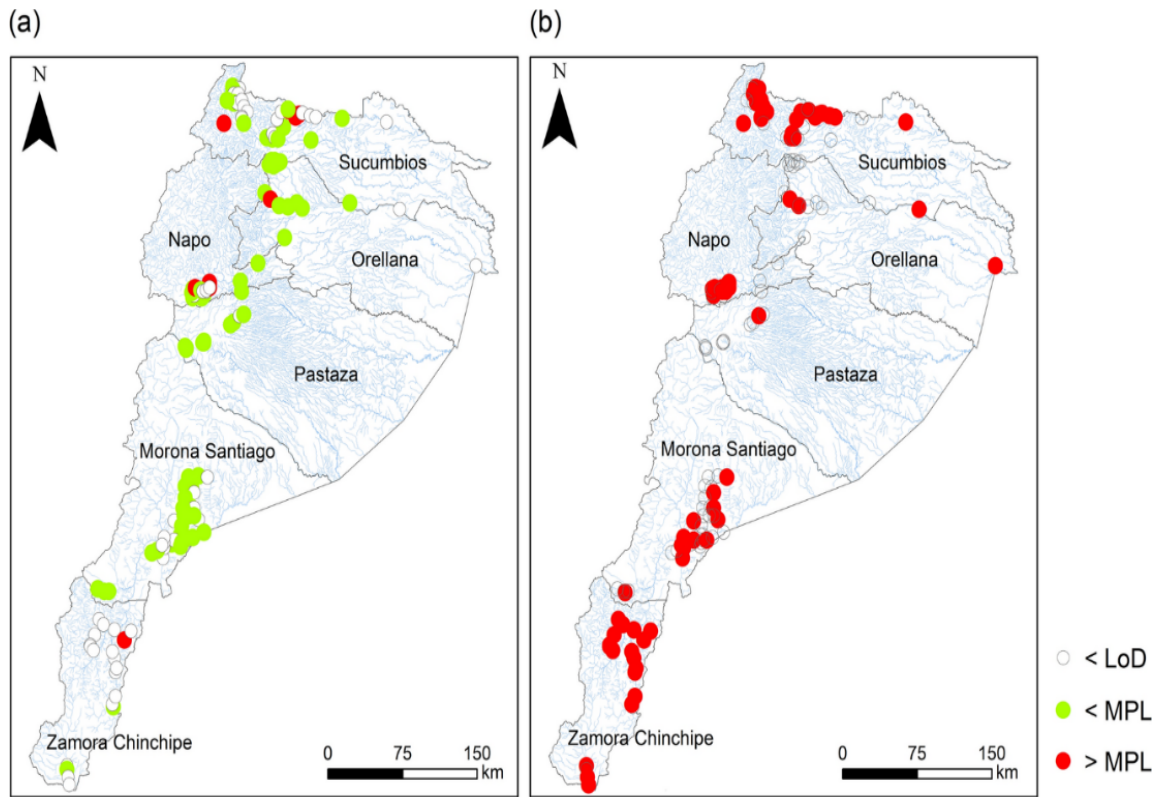
In Figure 11 of the samples quantified, 100% exceeded the maximum permissible limit (MPL) for water quality for the preservation of aquatic life, while 7% of the samples exceeded the MPL for drinking water quality. The high concentration of Hg measured in Amazonian rivers may be related to the amalgamation process that is carried out illegally in the area, and to the intensive and prolonged discharge of mining waste into rivers (Capparelli et al., 2020; López-Blanco et al., 2015; A. Mora et al., 2019). In this sense, it is essential to evaluate the concentration of methylmercury in water, local fish and other food grown in the study area, where river water may be used in agricultural fields.

**Table 16.** Hg concentration (mg/L) in water samples from the Ecuadorian Amazon

Province	North	Nínimo	p50	Meaning	p95	máx.	South Dakota
Sucumbíos	36	0.0006	0.0011	0.0023	0.0078	0.0099	0.0025
Orellana	dieciséis	0.0005	0.0005	0.0011	0.0038	0.0088	0.0020
Napo	23	0.0006	0.0007	0.0025	0.0096	0.0099	0.0032
Pastaza	13	0.0005	0.0005	0.0005	0.0007	0.0011	0.0001
Morona santiago	39	0.0005	0.0005	0.0010	0.0029	0.0041	0.0009
Zamora Chinchipe	20	0.0006	0.0013	0.0021	0.0054	0.0065	0.0018

0.006 mg/L = Hg limit for the protection of human health in drinking water (INEN, 1108) 0.0002 mg/L = admissible quality criterion for the conservation of aquatic life and wildlife in fresh, marine and estuarine waters (TULSMA, 2015).

**Figure 11.** Mercury concentrations in water samples.



The results were compared with the maximum permissible limit (MPL) according to the Ecuadorian Water Quality Guidelines for drinking water and for the preservation of aquatic life.

The Hg concentration detected in this study was in the range of the values reported by (Capparelli et al., 2020) in the Napo River basin. However, the concentration (p50) of Hg measured in our study was up to six times lower than that reported in the study cited above. Furthermore, the results of our study were compared with studies conducted in the Brazilian Amazon, where gold mining is one of the main anthropogenic activities; (Lino et al., 2019) reported Hg values between 0.0006 mg/L and 0.023 mg/L in the Tapajós river basin; (Provedo et al., 2018) reported mean Hg values of 0.0024 mg/L in the Madeira river basin; (Viana et al., 2021) reported mean Hg concentrations of 0.008 mg/L and (da Silva Costa et al., 2022) reported Hg values between 0.005 and 0.0085 mg/L in the Araguaico river. While in the work developed by (Meili et al., 1991) on Hg concentrations in Poznań surface waters, values of  $20 \pm 8$  ng/L (range 8–40) were observed, which showed statistically significant differences between the average Hg concentrations in the river water under

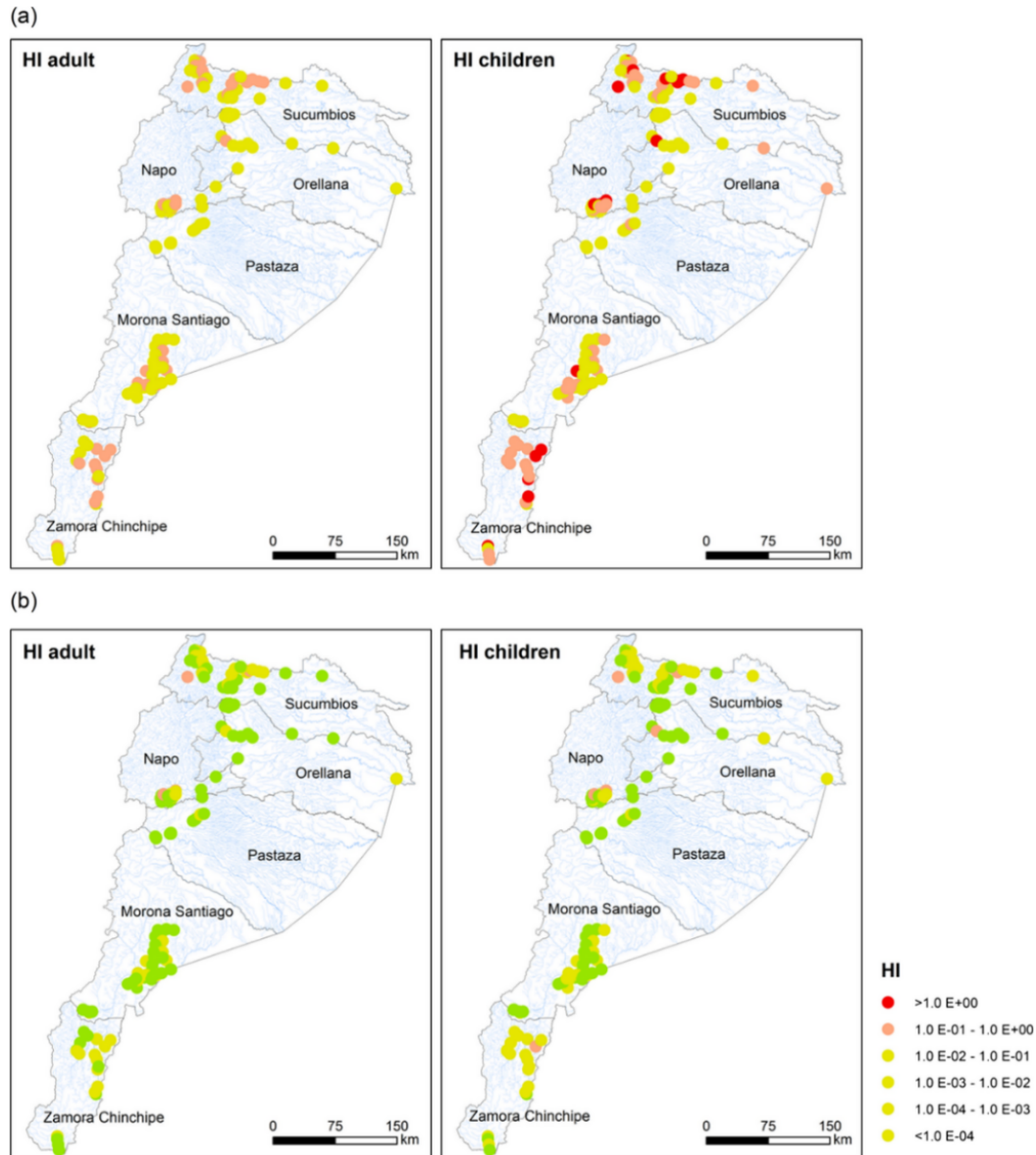
study. For his part, (Enamorado et al., 2022) highlighted that the average presence of Hg was 83 µg/L, a value higher than that allowed by the World Health Organization (WHO). An important consideration is that the variation in Hg concentration in surface water depends on the time and magnitude of flow, with higher contents in drier months and with lower flows (Loza Del Carpio & Ccancapa Salcedo, 2020).

#### 5.2.1.2. Human health risk assessment

The presence of Hg can cause serious health implications for residents who are exposed to this contaminant (Harada et al., 2001; Kobal et al., 2017) For this reason, the risk to human health due to Hg exposure was assessed for both adults and children living in the Amazon using deterministic and probabilistic methods. Table 18 summarizes the deterministic HI values resulting from Hg exposure by province for both age groups. In addition, the results of the deterministic assessment are presented in Figure 12 as point risk maps

**Table 17.** Deterministic HI (p95) for Hg exposure in water for adult and child receptors by province

	Residential scenario		Recreational stage	
	Children	Adultos	Adultos	Children
<b>Adults</b>				
<b>Sucumbíos</b>	8.80E-01	2.51E + 00	1.10E-01	1.50E-01
<b>Orellana</b>	8.20E-01	2.34E + 00	9.60E-02	1.40E-01
<b>Napo</b>	9.00E-01	2.56E + 00	1.00E-01	1.50E-01
<b>Pastaza</b>	1.03E-01	2.90E-01	1.20E-02	1.80E-02
<b>morona santiago</b>	3.10E-01	8.80E-01	3.60E-02	5.40E-02
<b>Zamora Chinchipe</b>	5.50E-01	1.58E + 00	6.50E-02	9.80E-02



**Figure 12.** Map of Threat Index (HI) risk points for receptors exposed to contaminated surface water in the Ecuadorian Amazon for both residential and recreational scenarios.

The point risk maps allow us to identify the sites of greatest concern to the population with respect to systemic risk scores for both residential and recreational scenarios. As shown in Fig. 18, 100% of the sites are below the acceptable risk threshold for both receptors in the recreational scenario. In contrast, there are 20 locations where the risk assessed for the residential scenario exceeds the safe exposure threshold ( $HI = 1$ ) for children, who are the most vulnerable receptors, primarily from water ingestion. Water ingestion has

been identified by several authors as one of the main routes of entry of contaminants into the human body in contaminated areas (Emmanuel et al., 2022; Navoni et al., 2014). On the other hand, the dermal contact pathway presented HQ values in the range of  $1.0E-5$ – $1.0E-2$  for both receptors, being its contribution insignificant in the HI assessment.

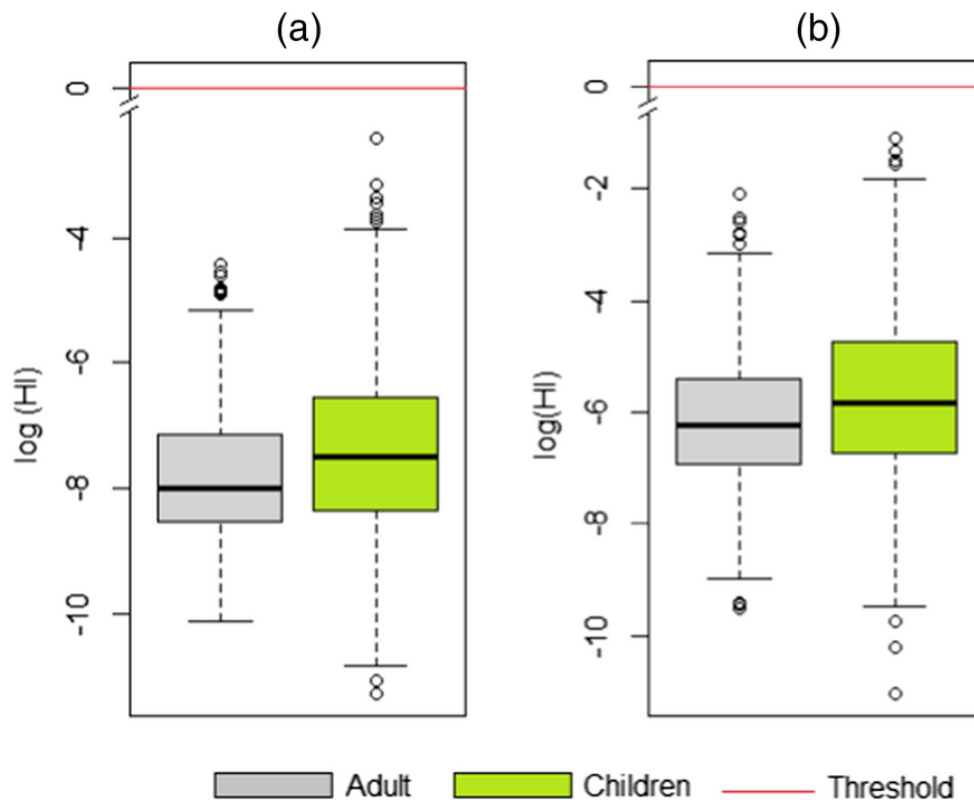
In our study, HI values that exceeded the safe exposure threshold for children were reported (in decreasing order) in the provinces of Napo > Sucumbíos > Orellana > Zamora Chinchipe. The HI results in our study were approximately half the values presented by (Jiménez–Oyola, Segovia–Escobar, et al., 2021) in Napo province, who reported  $HI = 1.85 E + 00$  for adults and  $HI = 4.84 E + 00$  for children, with surface water ingestion being the main route contributing to systemic risk. The main threats to human health caused by heavy metals such as Hg and potentially toxic substances have been widely documented (Marrugo–Madrid et al., 2022; Osorio Artunduaga & Devia Ocampo, 2020; Ralph et al., 2018).

These studies highlight the spatial distribution of the contamination, in addition to the identification of the hazard to which the human populations and ecosystems involved are exposed (UNEP/WHO, 2008). The study by (Feng et al., 2022) shows that Hg is a persistent and bioaccumulative metallic pollutant that represents a serious threat to the ecological system and human health, even at minimal concentrations. More so when the risk of suffering the adverse health effects of Hg is mainly high where fish is the basis of the diet. Our results add information on the assessment of human health risks in gold mining areas in the Amazon region. Therefore, this evidence could support the formulation of public policies to control and mitigate environmental pollution and the risks associated with the presence of potentially toxic elements in areas where gold mining is developed without complying with environmental regulation.

To obtain a probability distribution of risk, in this study, we performed a probabilistic risk assessment. The results estimated by the probabilistic method yielded acceptable non–oncological risk values for adult and child receptors (Fig. 13), with the maximum value of adult  $HI = 1.21 E-02$  and child  $HI = 8.94 E-02$  in the residential scenario, and adult  $HI = 1.23 E-01$  and child  $HI = 3.32 E-01$  in the recreational scenario. In this sense, the probability of Amazon River users developing systemic effects from Hg exposure through the evaluated routes is within the acceptability threshold recommended by (USEPA, 2001).

Similar to the results obtained by the deterministic method, the probabilistic assessment for the ingestion route presented significantly higher values; up to four orders of magnitude higher than those obtained by the dermal contact route.

**Figure 13.** Probabilistic index (PI) related to Hg in contaminated surface water for adult and child receptors for residential and recreational settings



The deterministic risk results were higher than the probabilistic ones. The HI p95 estimated by the deterministic method was  $6.6 \text{ E-}01$  for adults and  $1.9 \text{ E-}01$  for children for the residential scenario. For the recreational scenario, the HI p95 was  $7.7 \text{ E-}02$  and  $1.2 \text{ E-}01$  for adults and children, respectively. In contrast, HI p95 by the probabilistic method was  $3.0 \text{ E-}03$  for adults and  $5.9 \text{ E-}03$  for children for residential scenario, and  $1.8 \text{ E-}02$  for adults and  $3.7 \text{ E-}02$  for children for recreational scenario. A study by (Teixeira et al., 2021) evaluates the risk of Hg to human health and reveals that the highest HQ values were mainly associated with the dermal route (HQ dermal contact) for both children and adults, which is due to direct contact of the contaminant with the skin surface.

Given that the results of the deterministic and probabilistic analysis differ in the risk results for the population evaluated, it is recommended that a more detailed control of the Hg content in the local rivers be carried out to reduce uncertainty in the evaluation process. It is also recommended to obtain specific data on the exposure of potential receptors, in order to have more conclusive results on the risk to which the Amazonian population is exposed. This is in correspondence with current national environmental regulations that promote the management of water resources through public, private and community intervention (Asamblea Nacional Constituyente del Ecuador., 2014).

Despite the results obtained by the probabilistic method, it is important to consider that there are other potential routes of risk to the population, such as ingestion of local fish, as these may have significant amounts of methylmercury in their tissues (Webb et al., 2004) consumption of locally grown food (irrigated with water from rivers with high Hg content). It is now known that even at relatively low concentrations, Hg in the environment can generate elevated levels of methylmercury in food, posing a potential risk to consumers (Fuentes–Gandara et al., 2018) In addition, exposure to Hg–contaminated sediments has also been reported to be an important exposure pathway for residents of the Ecuadorian Amazon (Jiménez–Oyola, Chavez, et al., 2021; A. Mora et al., 2019; Requeme et al., 2003). Therefore, further studies are needed to understand the mechanisms governing Hg mobility in Amazonian rivers contaminated by mining activity and the associated risks to adults and children. In addition to mining activity, other potential sources of anthropogenic contamination in the area are; urban pollution, fish farming, non–functional landfills and oil activities (Capparelli et al., 2020; Maurice et al., 2019; Vargas et al., 2020). Therefore, a comprehensive risk assessment should be performed, analyzing exposure to multiple potentially toxic elements (e.g., As, Cd and Cr) generated by the aforementioned activities.

## 5.2.2. Andina región

### 5.2.2.1. Concentration of Hg in water

Table 19 presents the summary statistics of Hg concentration in the water samples by province. The Hg concentration for the 50th percentile (p50) decreased in the following order: Azuay> Imbabura> Cañar> Carchi> Pichincha> Cotopaxi> Bolivar>Loja> Chimborazo. The Hg concentration was compared with the maximum permissible limit (MPL) established in Ecuadorian regulations,

both for the protection of human health in drinking water (0.006 mg/L) (INEN 1108) and with the admissible quality criteria for the preservation of aquatic life and wildlife in fresh, marine and estuarine waters (0.0002 mg/L (TULSMA, 2015)).

**Table 18.** Hg concentration (mg/L) in water samples

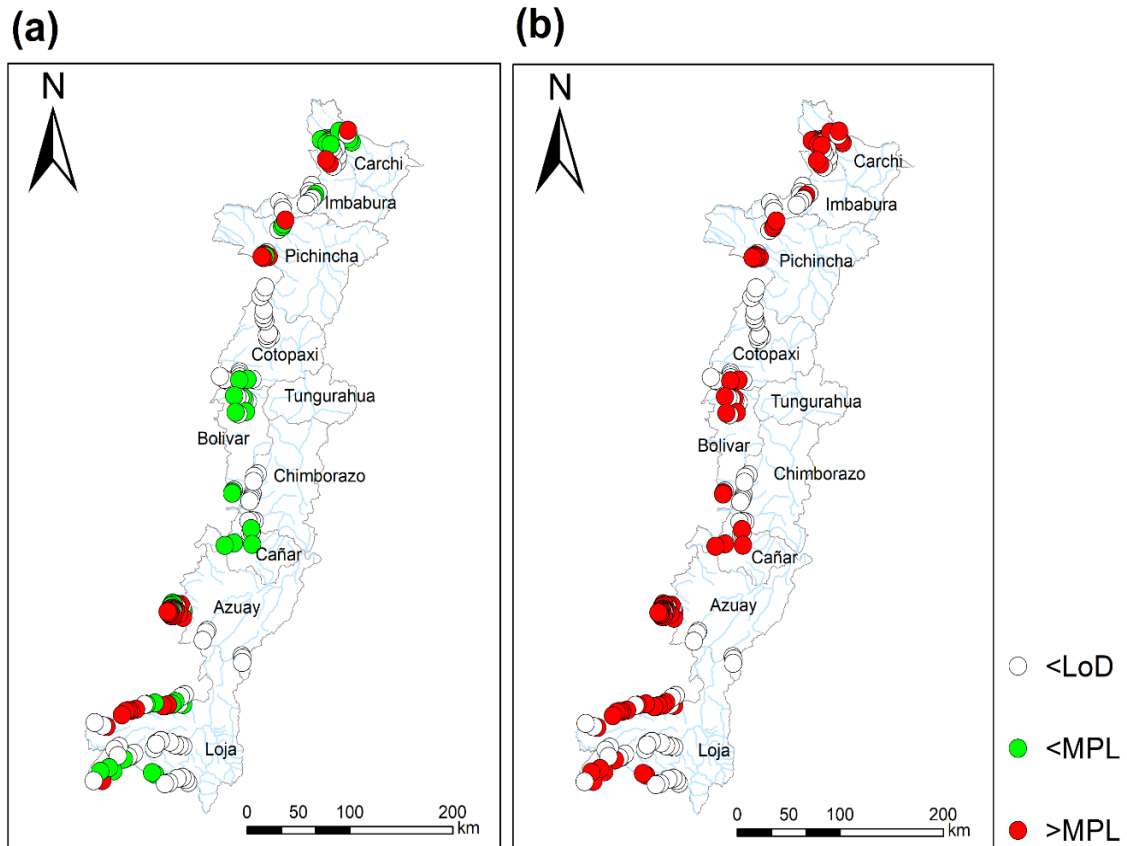
Province	<i>n</i>	Min	p50	Mean	p95	Max	S.D.
Carchi	15	0.0007	0.0013	0.0022	0.0061	0.0099	0.0025
Imbabura	22	0.0008	0.0015	0.0015	0.0084	0.0098	0.0026
Pichincha	12	0.0011	0.0011	0.0033	0.0093	0.0099	0.0036
Cotopaxi	22	0.0011	0.0027	0.0022	0.0041	0.0043	0.0016
Bolivar	16	0.0007	0.0005	0.0019	0.0038	0.0041	0.0012
Chimborazo	5	*	*	*	*	*	*
Cañar	5	0.0008	0.0014	0.0021	0.0049	0.0054	0.0020
Azuay	45	0.0024	0.0064	0.0188	0.0852	0.0913	0.0276
Loja	57	0.0006	0.0054	0.0045	0.0265	0.0387	0.0079

\* values below the detection limit of the measuring equipment (LoD = 0.0005 mg/L)

0.006 mg/L = limit of Hg for human health protection in drinking water (INEN 1108)

0.0002 mg/L = admissible quality criteria for the preservation of aquatic life and wildlife in fresh, marine, and estuarine waters (TULSMA, 2015).

Figure 14 shows the spatial pattern of Hg concentration compared to the MPL established in the Ecuadorian regulations. In the province of Carchi, the concentration of Hg was in the range of 0.0007 mg/L and 0.0099 mg/L. Of the samples, 93.33% were below the MPL for drinking water quality, while 73.33% of the sites sampled exceeded the MPL for freshwater quality. In Imbabura, Hg concentration ranged from 0.0008 mg/L to 0.0098 mg/L, with 90.91% of the samples below the MPL for drinking water quality, while 22.73% of the sites sampled exceeded the MPL for freshwater quality. In Pichincha, the Hg concentration ranged from 0.0011 mg/L to 0.0099 mg/L. Seventy-five percent of the samples were below the MPL for drinking water quality, while 83.33% of the sites sampled exceeded the MPL for freshwater quality. In Cotopaxi, the Hg concentration was in the range of 0.0011 mg/L and 0.00430 mg/L; with respect to drinking water, all samples were within the MPL, but with respect to freshwater quality criteria for the preservation of aquatic life, 9.09% exceeded the MPL. In the province of Bolivar, the Hg concentration was in the range of 0.0007 mg/L and 0.00410 mg/L; all water samples were within the MPL for consumption; on the contrary, 37.50% of the samples exceeded the MPL for freshwater quality. In Chimborazo, the Hg concentration at all sampled points was below the LoD. In the province of Cañar, the Hg content varied between 0.0008 mg/L and 0.0054 mg/L; with respect to drinking water, all samples were within the MPL, but with respect to the freshwater quality criterion for the preservation of aquatic life, 66.67% exceeded the MPL. In the province of Azuay, the Hg concentration was in the range of 0.0024 mg/L and 0.0913 mg/L; 51.11% of the points sampled exceeded the MPL of the regulation for drinking water quality and 62.22% exceeded the MPL of the regulation for freshwater quality. Finally, in the province of Loja, the Hg concentration was in the range of 0.0006 mg/L and 0.03870 mg/L, with 21.05% of the points sampled exceeding the MPL of the drinking water quality standard and 43.86% exceeding the MPL of the freshwater quality standard. In this context, it is identified that the ecosystem is highly vulnerable due to the presence of Hg in the rivers of the studied area.



**Figure 14.** Hg concentration in water samples. The results were compared with the maximum permitted limit (MPL) according to the Water Ecuadorian Quality Guidelines for (a) drinking water and (b) for the preservation of aquatic life.

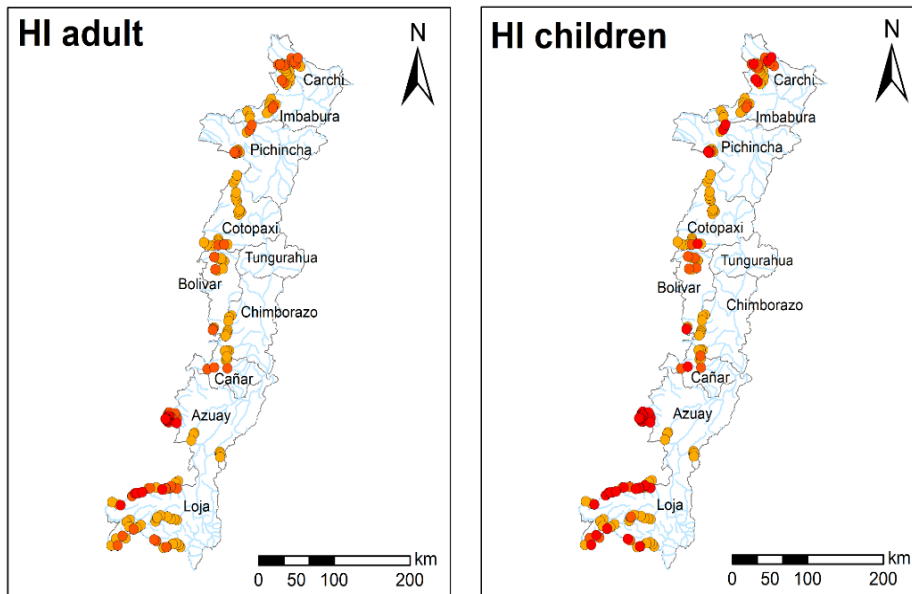
#### 5.2.2.2. Human health risk assessment

#### 5.2.2.3. Deterministic approach

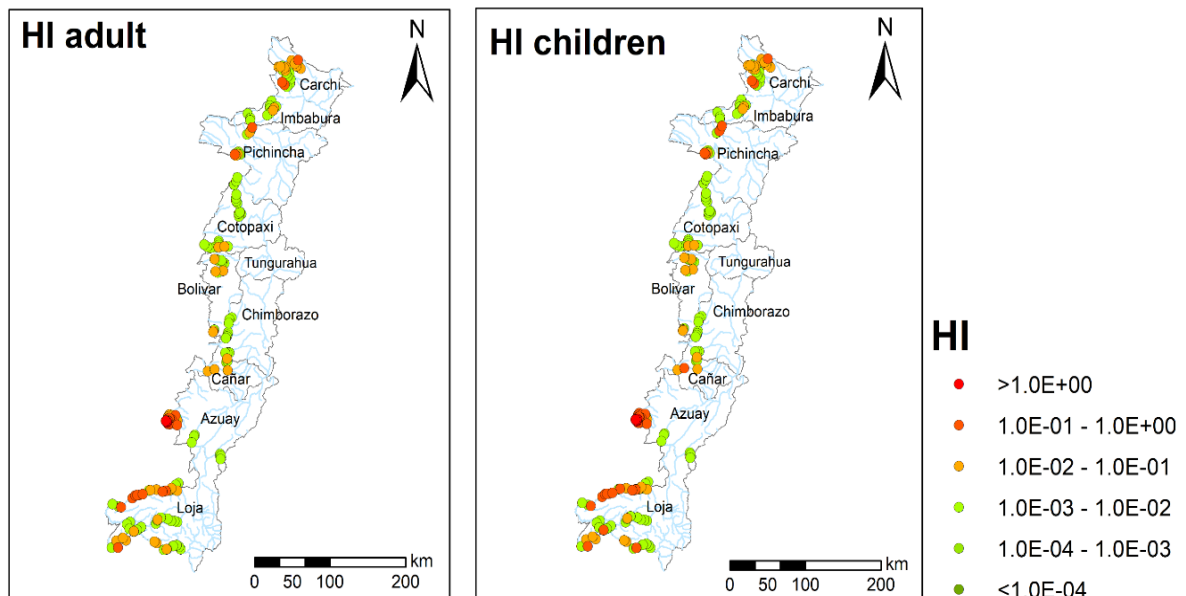
The results of the deterministic risk assessment are presented in Figure 15 as point risk maps. The HI values by province, for the 95th percentile (p95) of the data (Table 20), followed the following decreasing order: Azuay > Loja > Pichincha > Imbabura > Carchi > Cañar > Bolivar > Cotopaxi > Chimborazo. HI values > 1 were reported in the provinces of Azuay, Loja, Pichincha, Imbabura, Carchi, Cañar, Bolivar and Cotopaxi. As shown in Figure 15, in the recreational scenario seven of the sampled sites are above the acceptable risk threshold (HI > 1) for adult and child receptors; these sites are located in the province of Azuay. With respect to the residential scenario, 57 sampling sites exceed the safe exposure threshold for receptors, mainly for children. Sites with HI > 1 are

located in Azuay, Loja, Pichincha, Imbabura, Carchi, Cañar, Bolivar and Cotopaxi.

(a)



(b)



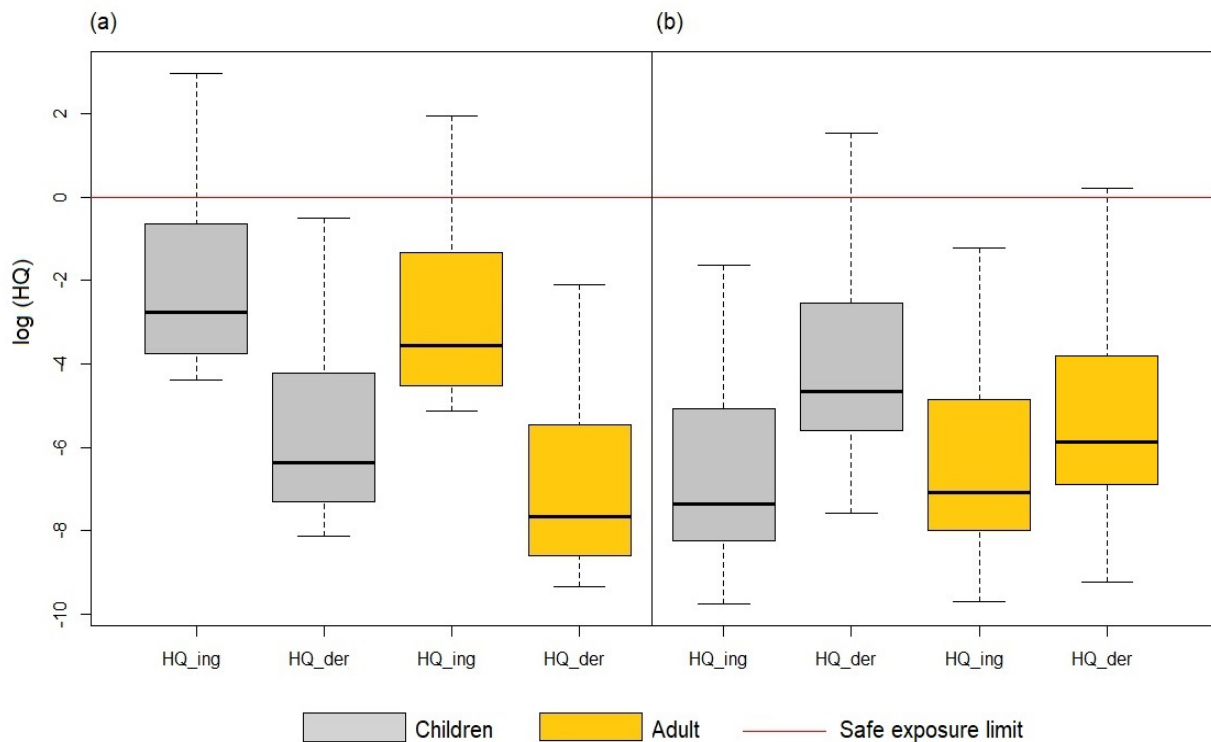
**Figure 15.** Point risk map of Hazard Index (HI) for receptors exposed to polluted surface waters in the Ecuadorian Amazon for both (a) residential and (b) recreational scenarios.

**Table 19.** Deterministic HQ and HI (p95) from exposure to Hg in waters for both receptors by province. Values in bold exceed the safe exposure threshold.

Province	Risk	Residential scenario		Recreative scenario	
		Adults	Children	Adults	Children
Azuay	HQingestion	7.71E+00	2.23E+01	7.44E-03	5.83E-02
	HQdermal	2.73E-01	3.99E-01	1.11E+00	1.62E+00
	HI	7.99E+00	2.27E+01	1.11E+00	1.68E+00
Bolívar	HQingestion	3.10E-01	8.98E-01	2.99E-04	2.35E-03
	HQdermal	1.10E-02	1.61E-02	4.45E-02	6.51E-02
	HI	3.21E-01	9.14E-01	4.48E-02	6.74E-02
Cañar	HQingestion	4.48E-01	1.30E+00	4.33E-04	3.39E-03
	HQdermal	1.59E-02	2.32E-02	6.44E-02	9.40E-02
	HI	4.64E-01	1.32E+00	6.48E-02	9.74E-02
Carchi	HQingestion	5.54E-01	1.61E+00	5.35E-04	4.19E-03
	HQdermal	1.96E-02	2.87E-02	7.96E-02	1.16E-01
	HI	5.74E-01	1.63E+00	8.01E-02	1.20E-01
Chimborazo	HQingestion	2.26E-02	6.56E-02	2.18E-05	1.71E-04
	HQdermal	8.02E-04	1.17E-03	3.25E-03	4.75E-03
	HI	2.34E-02	6.67E-02	3.27E-03	4.92E-03
Cotopaxi	HQingestion	9.19E-02	2.66E-01	8.87E-05	6.95E-04
	HQdermal	3.26E-03	4.76E-03	1.32E-02	1.93E-02
	HI	9.52E-02	2.71E-01	1.33E-02	2.00E-02
Imbabura	HQingestion	7.63E-01	2.21E+00	7.36E-04	5.77E-03
	HQdermal	2.70E-02	3.95E-02	1.09E-01	1.60E-01
	HI	7.90E-01	2.25E+00	1.10E-01	1.66E-01
Loja	HQingestion	2.40E+00	6.94E+00	2.31E-03	1.81E-02
	HQdermal	8.49E-02	1.24E-01	3.44E-01	5.03E-01
	HI	2.48E+00	7.06E+00	3.46E-01	5.21E-01
Pichincha	HQingestion	8.42E-01	2.44E+00	8.12E-04	6.37E-03
	HQdermal	2.98E-02	4.36E-02	1.21E-01	1.77E-01
	HI	8.72E-01	2.48E+00	1.22E-01	1.83E-01

### 5.2.2.3.1. Probabilistic approach

The results of the probabilistic risk analysis yielded values that exceed the safe exposure limit for adults and children in the residential scenario, due to water intake and dermal contact in the recreational scenario (Figure 16 and Table 21). Hazard Quotient (HQ) values for children ranged between  $1.2E-02$  and  $1.9E+01$  for water intake, and between  $2.9E-04$  and  $6.0E-01$  for dermal contact. For adults, the risk was lower, in the range of  $5.8E-03$  and  $7.0E+00$  for ingestion, and  $8.8E-05$  and  $1.2E-01$  for dermal contact. In this sense, it is evident that the risk of ingestion of water with high Hg content in children is twice as high as in adults. On the other hand, with respect to the recreational scenario, the exposure route of greatest risk is dermal contact in both receptors, with  $HQ_{dermal}$  values in ranges of  $9.8E-05$  and  $1.2E+00$  for adults and  $5.0E-04$  and  $4.6E+00$  for children. In contrast,  $HQ_{ingestion}$  was low, in the range of  $6.2E-05$  and  $2.9E-01$  for adults and  $5.7E-05$  and  $1.9E-01$  for children.



**Figure 16.** Boxplot del Hazard Quotient para ingesta ( $HQ_{ing}$ ) y contacto dérmico ( $HQ_{der}$ ) para adultos y niños receptores en escenario (a) residencial y (b) recreativo. Los valores de HQ están dados en logaritmo.

**Table 20.** Probabilistic HQ and HI (p95) from exposure to Hg in waters for both receptors. Values in bold exceed the safe exposure threshold.

Risk	Residential scenario		Recreative scenario	
	Adults	Children	Adults	Children
HQ <sub>ingestion</sub>	2.1E+00	4.4E+00	7.0E-02	5.8E-02
HQ <sub>dermal</sub>	3.6E-02	1.2E-01	2.0E-01	8.3E-01
HI	2.1E+00	4.5E+00	2.7E-01	8.9E-01

The Hazard Index (HI) value indicates that the safe exposure threshold for children in the residential scenario was exceeded at the 85th percentile, i.e., 15% of the receptors are exposed to developing adverse health effects as a consequence of Hg exposure. For adults, the safe exposure threshold was exceeded at the 90th percentile, i.e., for 10% of exposed receptors. In the recreational scenario, the safe exposure threshold was exceeded at the 96th and 99th percentile for children and adults, respectively, indicating that a percentage less than or equal to 4% of the receptors exceed the acceptable risk values. In this sense, it was identified that the scenario of greatest concern is the residential scenario, with water intake as the main contributor to the risk.

Based on these results, it is necessary to work on risk management by implementing strategies that minimize the exposure of people to water resources with signs of contamination, since exposure to Hg puts the health of river users at risk. Furthermore, it should be taken into account that, if contamination levels are not controlled in the areas studied, risk levels may be higher, as they could include new exposure pathways, such as the ingestion of food contaminated with Hg or the inhalation of Hg vapors, which is why continuous monitoring of the quality of water resources is recommended. In addition, there is a need to control illegal mining activities that use Hg in the mineral recovery process, since its use can constitute a public health risk, not only in the areas surrounding the mineral exploitation areas, but in a larger region due to the persistence, mobility and bioaccumulation capacity of Hg.

### 5.2.3. Coastal region

#### 5.2.3.1. Hg concentration in water

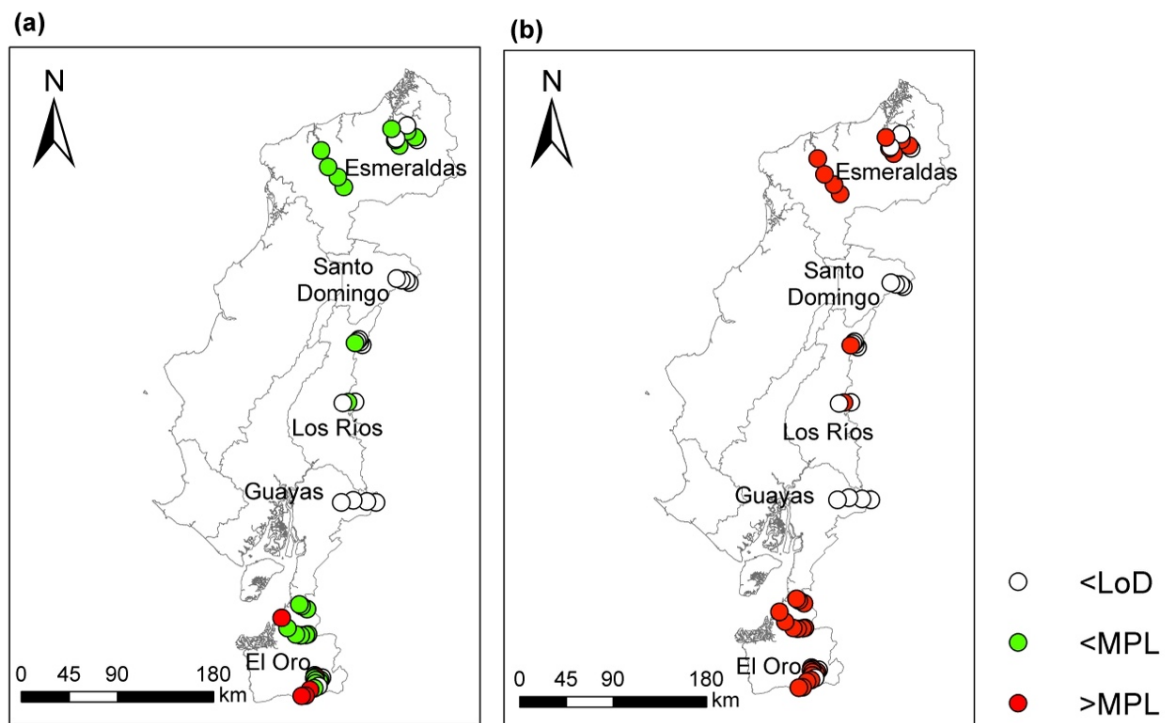
Hg contamination is considered a major ecological threat and significant scientific efforts have been devoted to the remediation of systems contaminated by this element (Pinto et al., 2022). This chemical element has bioaccumulation potential (Castellon et al., 2018) and is considered a high environmental and human health risk element (Bjørklund et al., 2017) The concentration of Hg was compared with the maximum permissible limit (MPL) established in Ecuadorian regulations (Figure 17); Hg limit for the protection of human health in drinking water (0.006 mg/L) (INEN 1108) and with the admissible quality criterion for the preservation of aquatic life and wildlife in fresh, marine and estuarine waters (0.0002 mg/L) (TULSMA, 2015). Additionally, Hg values were compared to the Canadian drinking water quality regulation (0.001 mg/L) and to the Hg limit for the preservation of aquatic life in water bodies (0.0001 mg/L) (TULSMA, 2015).

Hg concentration decreased in the following order: El Oro>Esmeraldas>Los Rios>Santo Domingo de los Tsáchilas>Guayas. In the province of El Oro, the Hg concentration was in the range of 0.0007 mg/L and 0.0965 mg/L. Twenty-eight percent of the sampled points exceeded the MPL for drinking water quality, and 100% exceeded the MPL for freshwater quality. These results agree with those reported by (Cordy et al., 2011), who reported that the province of El Oro has been severely affected by illegal mining practices, inadequate management of mining waste, and indiscriminate use of Hg in mineral beneficiation activities, mainly in the Zaruma–Portovelo Mining District (Appleton et al., 2001; Carling et al., 2013; Salgado–Almeida et al., 2022).

In Esmeraldas, the concentration of Hg ranged from 0.0005 mg/L to 0.045 mg/L. 100% of the samples were below the MPL for drinking water quality; however, 100% of the sites sampled exceeded the MPL for freshwater quality. Esmeraldas, like the province of El Oro, has been severely affected by illegal mining mainly in the riverbeds (Riofrio, 2017), which has caused a high concentration of potentially toxic elements (Rebolledo–Monsalve et al., 2022), constituyendo un riesgo para el ecosistema y la población. constituting a risk for the ecosystem and the population. In contrast, (Capparelli et al., 2020) reported low Hg values in drinking water, suggesting that contamination is localized in mining areas.

In the province of Los Ríos, the Hg content varied between 0.0005 mg/L and 0.0023 mg/L. With respect to drinking water, all samples were within the established limit, but with respect to freshwater quality criteria for the preservation of aquatic life, 100% exceeded the MPL. To our knowledge, there are no studies that report on the degree of affectation of surface water resources due to mining practices in the Los Ríos area, so our study constitutes a baseline for future research in the area, given that the high concentrations of Hg represent a potential risk to the environment.

In Santo Domingo de los Tsáchilas and Guayas, the concentration of Hg at all points sampled was less than the detection limit of the measuring equipment (LoD = 0.0005 mg/L). This may be due to the fact that in Santo Domingo de los Tsáchilas metallic mining activity, mainly gold mining, has not had a great development, as in Guayas, where the predominant mining activity is non-metallic mining and the exploitation of aggregates and stone.



**Figure 17.** Hg concentration in water samples. The results were compared with the maximum permitted limit (MPL) according to the Water Ecuadorian Quality Guidelines for (a) drinking water and (b) for the preservation of aquatic life.

It is difficult to detect mercury at the water surface, because it easily binds to organic matter and is deposited at the bottom of the water, so its concentration in the sediment is possibly higher. In agreement with this statement, (Núñez et al., 2013) also found that the concentration of heavy metals in sediment is higher than that in water as it accumulates from sedimentation, while the low concentration of heavy metals in water is due to the dilution process and the effect of the current pattern (Núñez et al., 2013). On the other hand a study in Phichit province, Thailand, developed in the surface waters of Klong Dai Nam Khun and Klong Sa Luang canals, connected with a mining area (Pataranawat et al., 2007) evaluated Hg contaminated sites related to the concentration level and their distances from ASGM sites, showing Hg concentrations in the range of 0.6–5.4 µg/L. This study showed that there is a higher concentration of Hg than areas at greater distances upstream and downstream, because the amalgamation processes were performed close to the sampling sites. A study developed by Garcia et al. highlights high Hg concentrations of up to 4.60 µg/L in surface water samples (rivers, streams, mining ponds, springs) (García-Sánchez et al., 2008). Thus, Hg can be transferred to the food chain in aquatic environments (Adams et al., 2008; Casso-Hartmann et al., 2022). Therefore, it is possible for mercury to continuously accumulate in water and increase its concentration, in addition to impacts on human health and aquatic and terrestrial ecosystems.

#### 5.2.3.2. Human health risk assessment

##### 5.2.3.2.1. Deterministic approach

The results of the deterministic risk assessment are presented in Figure 18 as point risk maps. In addition, Table 22 summarizes the deterministic HQ and HI values for the 95th percentile of Hg exposure for each province assessed and for each receptor. When Hg concentrations were below the detection limit (LoD) of the measurement equipment, the LoD/2 value was used for risk calculation.

The HI values by province followed the following decreasing order: El Oro>Esmeraldas>Los Ríos> Santo Domingo de los Tsáchilas>Guayas. IH values > 1 were reported only in the provinces of El Oro and Esmeraldas. As shown in Figure 18, in the recreational scenario three of the sampled sites are above the acceptable risk threshold (HI >1) for adult and child receptors; these sites are located in the province of El Oro. With respect to the residential

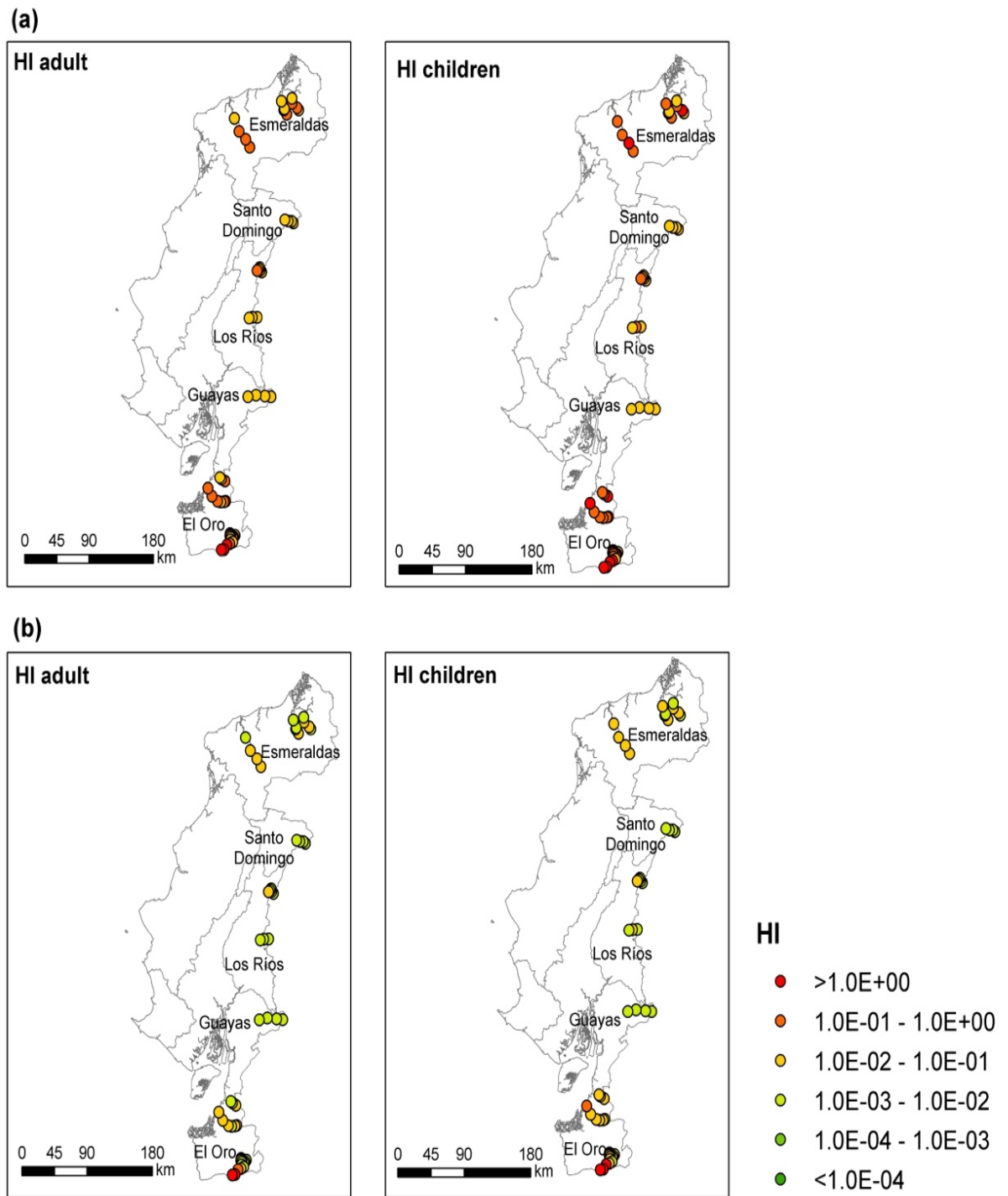
scenario, 15 sampling sites exceed the safe exposure threshold for receptors, mainly for children. Sites with HI > 1 are located in Esmeraldas and El Oro.

Adults and children receive the greatest amount of Hg from food, air and water intake, with most of the Hg in the environment coming from waste from mining activities (Rahayu et al., 2022). In particular, water ingestion has been identified as the main route of exposure in the residential scenario for El Oro and Esmeraldas provinces. Ingestion HQ values ranged between  $2.26E-2$  and  $8.74E+00$  for adult receptors and between  $6.56E-2$  and  $2.53E+01$  for children, with children being the most exposed receptors, as the risk values for children are three times the risk values determined for adults. These findings are consistent with studies by (Emmanuel et al., 2022) and (Custodio et al., 2020), quienes definen a la ingesta de agua como una de las principales vías de entrada de elementos potencialmente tóxicos al cuerpo humano en zonas mineras contaminadas. who define water ingestion as one of the main routes of entry of potentially toxic elements into the human body in contaminated mining areas. On the other hand, the dermal contact route presented very low HQ values in the residential scenario, varying between  $8.02E-4$  and  $3.10E-1$  for adult receptors and between  $1.17E-3$  and  $4.52E-1$  for children, so it is considered that this route of exposure is not significant and does not contribute to the risk. In contrast, in the recreational scenario, intake did not pose a risk to receptors in any of the provinces evaluated; values ranged from  $1.38E-5$  to  $7.07E-3$  in adults and  $1.44E-4$  to  $5.54E-2$  in children. However, in the recreational scenario, dermal contact did exceed the safe exposure threshold for both receptors in El Oro province; HQ<sub>dermal</sub> values in the study area were in the range of  $2.73E-3$  and  $1.05E+0$  for adults and  $3.98E-3$  and  $1.54E+0$  for children. These results were to be expected since the water intake ratio during recreational activities (swimming or playing in rivers) is very low, with intake values (IR) of 0.053 and 0.090 m/L for adults and children, respectively (USEPA, 2011). On the other hand, the skin is highly exposed to contaminants during recreational activities, even more so in places with warm climates as is the case in the coastal region of Ecuador, where the use of rivers is quite common, mainly in rural communities.

The trend of the risk results from the recreational setting agree with the findings reported by (Jiménez-Oyola, Chavez, et al., 2021) in the Ecuadorian Amazon, where Hg through dermal contact in the recreational setting

represented an elevated risk to recipients, with values of  $HI = 1.85$  for adults and  $HI = 4.83$  for children. However, the non-cancer risk results in our study were approximately half of the values reported in the aforementioned study.

Most small-scale gold miners are unaware of Hg toxicity and use Hg to amalgamate Au because it has been effective and affordable (Sherman et al., 2015; Styles et al., 2010; Telmer & Veiga, 2009). Additionally, (Taylor et al., 2005) points out that the gold mining process is a simple, potentially hazardous and polluting technology due to the use of Hg. For example, the health of miners and population in the affected area can be adversely affected by inhalation of Hg vapor (Yard et al., 2012), direct contact with Hg (Calao-Ramos et al., 2021; Gibb & O'Leary, 2014); and consumption of food affected by contamination (Junaidi et al., 2019; Niane et al., 2015), since acute or chronic exposure to Hg can cause adverse effects during any developmental period (Bharti & Sharma, 2022; Bose-O'Reilly et al., 2008). Therefore, further research and assessment of human health risks and their evolution in ASGM communities should be developed.



**Figure 18.** Point risk map of Hazard Index (HI) for receptors exposed to polluted surface waters in the Ecuadorian Amazon for both (a) residential and (b) recreational scenarios.

**Table 21.** Deterministic HQ and HI (p95) from exposure to Hg in waters for both receptors by province. Values in bold exceed the safe exposure threshold.

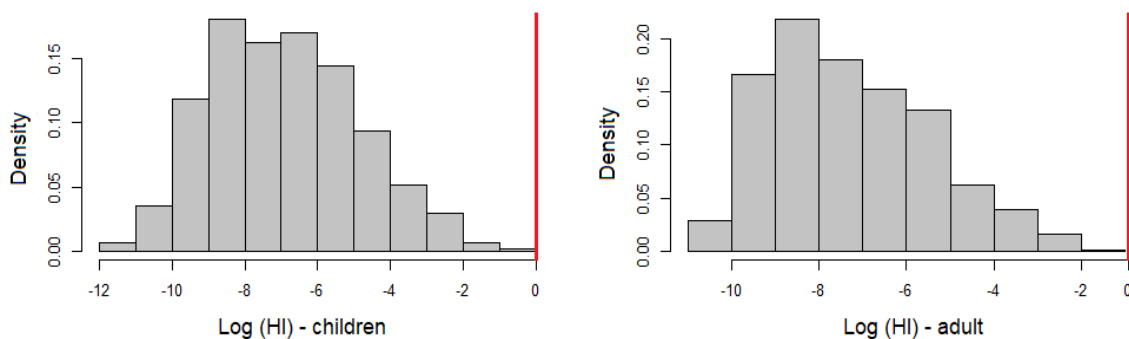
Province	Risk	Residential scenario		Recreative scenario	
		Adults	Children	Adults	Children
El Oro	HQ <sub>ingestion</sub>	<b>8.52E+00</b>	<b>2.47E+01</b>	6.90E-03	5.40E-02
	HQ <sub>dermal</sub>	3.02E-01	4.41E-01	<b>1.03E+00</b>	<b>1.50E+00</b>
	HI	<b>8.82E+00</b>	<b>2.51E+01</b>	<b>1.04E+00</b>	<b>1.55E+00</b>
Esmeraldas	HQ <sub>ingestion</sub>	3.94E-01	<b>1.14E+00</b>	3.18E-04	2.49E-03
	HQ <sub>dermal</sub>	1.40E-02	2.04E-02	4.73E-02	6.90E-02
	HI	4.08E-01	<b>1.16E+00</b>	4.76E-02	7.15E-02
Los Ríos	HQ <sub>ingestion</sub>	1.54E-01	4.46E-01	1.25E-04	9.76E-04
	HQ <sub>dermal</sub>	5.46E-03	7.97E-03	1.85E-02	2.71E-02
	HI	1.59E-01	4.54E-01	1.86E-02	2.81E-02
Santo Domingo de los Tsáchilas	HQ <sub>ingestion</sub>	2.26E-02	6.56E-02	1.83E-05	1.44E-04
	HQ <sub>dermal</sub>	8.02E-04	1.17E-03	2.73E-03	3.98E-03
	HI	2.34E-02	6.68E-02	2.75E-03	4.12E-03
Guayas	HQ <sub>ingestion</sub>	2.26E-02	6.56E-02	1.83E-05	1.44E-04
	HQ <sub>dermal</sub>	8.02E-04	1.17E-03	2.73E-03	3.98E-03
	HI	2.34E-02	6.68E-02	2.75E-03	4.12E-03

#### 5.2.3.2.2. Probabilistic approach

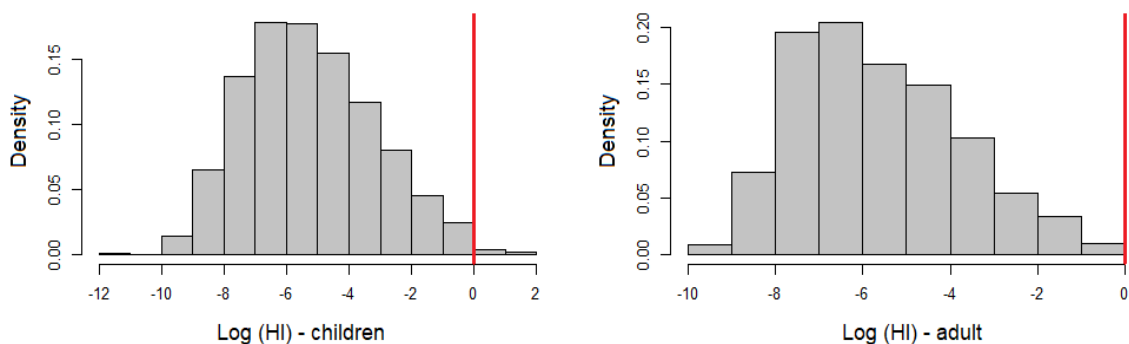
The results of the risk estimated by the probabilistic method yielded acceptable risk values for adult and child receptors in the residential scenario (Figure 19a), with a maximum value of  $H_{I_{adults}} = 1.74E-01$  and  $H_{I_{children}} = 8.71E-01$ . Children are the most vulnerable receptors with HI values up to five times higher than in adults. In the recreational scenario (Figure 19b), the maximum estimated HI value for child receptors was  $4.13E+00$ , exceeding four times the safe exposure threshold, while for adults the risk value remained below the acceptable limit (maximum HI for adults =  $8.69E-01$ ). In the residential scenario water ingestion was the main route of exposure, while in the recreational scenario dermal contact had the highest contribution to the non-

cancer risk. In this sense, there is a possibility that users of rivers in the Costa region, where high concentrations of Hg have been detected, may develop adverse health effects. The safe exposure threshold for children in the recreational setting was exceeded at the 99th percentile, meaning that 1% of child receptors are exposed to developing adverse health effects as a consequence of Hg exposure. Therefore, a risk communication strategy should be implemented to limit the exposure of river users and keep risk levels within acceptable limits.

(a) Residential



(b) Recreational



— Safe exposure limit

**Figure 19.** Histogram of HI related to Hg in contaminated surface water for adult and child receptors in (a) residential and (b) recreational settings. HI values are given in logarithm.

The results of the deterministic analysis differ from the results of the probabilistic analysis; however, the information obtained with both methods can complement each other and improve the interpretation of the results obtained,

as well as provide greater inputs for the analysis of decision makers. The main difference detected is that, according to the probabilistic methodology, the residential scenario does not generate risk for the receptors, while, according to the deterministic methodology, both the residential and recreational scenarios generate risk in localized sites in the study area. In this context, based on a conservative criterion, the use of rivers located in contaminated mining environments is not recommended, since long-term exposure to contaminants such as Hg could affect the health of its users. Furthermore, it is important to consider that in areas of illegal gold mining there are, in addition to Hg, other potentially toxic elements that could generate adverse effects on the ecosystem and the population, so a detailed study of other pollutants such as Arsenic, Cadmium, Chromium, Lead, etc. is recommended.

Deterministic and probabilistic analysis approaches are considered appropriate to adequately account for data uncertainty (Amoushahi et al., 2018). A study reported by (Basu et al., 2015) notes that, in most ASGM settings, women and children are actively involved in ASGM activities and therefore often face health- or life-threatening exposures. These exposures are especially difficult to identify without active surveillance and monitoring with an emphasis on adults and children (Yakovleva, 2007). Another study by (Olujimi et al., 2015) reported that the risk of cancer ranged from  $6.17E-13$  to  $7.77E-05$  and from  $2.73E-12$  to  $4.64E-04$  for adults and children, respectively. The data presented in our study, together with these response options, could provide information to implement lasting solutions to the myriad challenges posed by ASGM on the Ecuadorian Coast. Consequently, improved Hg remediation systems and environmental education programs will be needed to reduce the risk to human health associated with these operations.

### **5.3. Environmental impacts generated by the use of mercury in gold mining**

#### **5.3.1. Impact assessment**

The study made it possible to evaluate the main impacts and conflicts generated by gold mining activities in the El Dorado de Cascales parish. Four main activities were identified in the area (Table 23) in the mining process: classification of gold-bearing gravels and separation of heavy sediments; concentration and separation of gold from heavy sediments; gold recovery

through amalgamation processes with mercury; and amalgamation distillation for the separation of gold from mercury.

**Table 22.** Description of mining activities in the El Dorado de Cascales parish.

Activities	Description
<b>Initial exploration</b>	This stage refers to the initial process in which artisanal miners travel long distances in search of an area with indications of gold-bearing materials. In the process, miners invade previously untouched areas, build roads and highways, cut down trees, build houses and camps, use (and spill) fuel, hunt animals, etc.
<b>Gravel classification</b>	This is the first step of mining is the extraction or excavation of the auriferous gravel. This can be done by hand (shovel) or with small suction dredges. Sorting means the separation of coarse stones from small sand and gravel. This is usually done by sieving.
<b>Preconcentration</b>	This means the separation of light material (sand and gravel) from a mixed concentrate of heavy minerals. This is done by "dumping" into a wooden or metal chute that usually has a rough mat at the bottom, where the heavy minerals and gold are retained and the light material overflows with water. The mat is washed from time to time and the preconcentrate is collected.
<b>Amalgamation</b>	The preconcentrate (also called black sand due to its high content of black iron minerals) is then amalgamated in a pot, where mercury and water are added and the pot is stirred. The fine gold and mercury combine to form coarse amalgam flakes, which are then separated from the heavy minerals by washing. The amalgam is collected for subsequent combustion.
<b>Amalgam burning</b>	Finally, the collected amalgam is burned. This means that the mercury is evaporated by heat (e.g., using a charcoal fire) and enters the atmosphere. It can be inhaled by operators and leads to their metallic mercury poisoning. Usually, most of the mercury vapor, due to its high weight, is deposited around the combustion site and contaminates the soil. Some of it may travel a little farther by wind. Through rain and erosion, this metallic mercury enters watercourses.

Sixteen socio-environmental impacts were identified in the three components (biotic, abiotic and socioeconomic) caused by the five main activities involved in the gold mining process (Table 24). Of the five activities analyzed, the socioeconomic component was the only activity that did not generate substantial impacts on the biotic component. However, the remaining four

activities generated negative impacts on the biotic and abiotic components of the ecosystem in the artisanal gold mining areas of the El Dorado de Cascales parish. Of the three components studied, it was found that water, in terms of the abiotic component, has the highest number of detrimental impacts from gold mining activities, due to the use of mercury to obtain gold.

**Table 23.** Real impacts identified, associated with the components identified during gold mining in the parish.

Activities	Components						
	Biotic		Abiotic			Socio-economic	
	Fauna	Flora	Soil	Water	Atmosphere	Economic	Social
<b>Initial exploration</b>	Disturbance Alteration	Disturbance Alteration Lost	Compaction Contamination	Disturbance Alteration	---	---	---
<b>Gravel classification</b>	Disturbance Alteration Lost	Disturbance Alteration Lost	Alteration	Disturbance Alteration	---	---	---
<b>Concentration and separation</b>	Contamination	Disturbance	Compaction	Contamination	---	---	---
<b>Amalgamation</b>	Alteration	Alteration	Contamination	Contamination	Contamination	---	Diseases
<b>Distillation</b>	Contamination	Disturbance	Contamination	Contamination	Contamination	Income	Diseases

Contamination: Action when elements or substances that should not normally be in an environment enter it and affect the balance of the ecosystem. Perturbation: Interruption or environmental disturbance of the elements of an ecosystem that over time can regenerate. Alteration: Change in the characteristics, essence or form of the elements of an ecosystem that cannot regenerate over time due to their disappearance. Loss: Elimination of species or part of its individuals. Income: Increase in its economy. Diseases: Any type of affectation to human health and quality of life.

The impacts identified in El Dorado de Cascales Parish generated by artisanal gold mining were shown to be highly detrimental during and after mining activities (Table 25). Sixteen different socio-environmental impacts were identified in the study area, seven of high impact, all related to abiotic components (habitat alteration, vegetation disturbance, vegetation disturbance, chemical contamination, disturbance, contamination and contamination by

suspended particles). Followed by eight impacts of medium magnitude, four are related to the biotic component (disturbance by initial exploration, loss of species, contamination by waste, and loss by damage or removal), three to the abiotic component (compaction, disturbance, and soil quality alteration), and one to the socioeconomic component (compaction, disturbance, and soil quality alteration) and one to the socioeconomic component (health). Overall, considering all the activities carried out for gold mining, 54.54% of the activities had a medium impact, 36.36% had a high impact and 9.09% had a low impact on the three components studied.

**Table 24.** Main results of the magnitude of impacts and conflicts in El Dorado de Cascales parish.

Component	Impact	Magnitude
<b>Fauna</b>	Initial scanning disturbance	Medium
	habitat alteration	High
	Loss of species	Medium
	Contamination by waste	Medium
<b>Flora</b>	Alteration of vegetation	High
	Alteration of vegetation	High
	Loss due to damage or removal	Medium
<b>Soil</b>	Compaction	Medium
	Contamination by chemicals	High
	Alteration of soil quality	Medium
<b>Water</b>	Disturbance	Medium
	Modification	High
	Contamination	High
<b>Atmosphere</b>	Contamination by suspended particulate matter	High
<b>Economic</b>	Employment	Low
<b>Social</b>	Health	Medium
<b>Results</b>	Low impact	6,25%
	Medium impact	50%
	High impact	43,75%

The results of this evaluation of the socio–environmental impacts generated by gold mining in the El Dorado de Cascales Parish show that artisanal miners did not have the pertinent environmental registration; in addition, they did not extract in a manner that was friendly to the natural environment (Figure 19). The

magnitude of the impacts was mostly medium, without discarding the concern of the biotic component. The Cascales and Loroyaku rivers, which were used by the local inhabitants as sources of daily use for different household activities and also as tourist centers, are now affected by mining activities.



(a)



(b)



(c)



(d)

**Figure 20.** Gold mining: ( a ) Impact on water bodies; ( b ) use of machinery and equipment; ( c ) anthropic impact; ( d ) earth movement and impact on vegetation.

It is important to highlight that during the field visit, 31 artisanal miners and 12 small-scale miners were interviewed, of which 100% stated that they had used mercury at some time in the last few months in gold extraction activities in ASM. Furthermore, none of them take measures to reduce the impact and risk of mercury use. On the other hand, 100% of artisanal miners finish

processing amalgam at home. While 41% of the small-scale group does it in the mining area with the use of torches that generate fire, i.e. high temperatures that separate the mercury from the gold, and 59% do this process in family homes in rural areas. Finally, they state that mercury is easily obtained from intermediaries in local hardware stores or from medium-sized mining companies, but it is known that mercury comes from Bolivia and Peru.

### 5.3.2. Challenges

Gold mining plays a crucial role in employment production, foreign exchange generation and overall economic activity. Although mining activities came to a standstill following the COVID-19 pandemic, gold mining is still evident today. This can be justified by observing the coloration of the main rivers in the El Dorado de Cascales parish, and these rivers are: Cascales and Loroyaku. The authorities of the study area should focus their efforts on creating ordinances that regulate these activities in the parish. It is essential to analyze the situation of gold mining in general in Cascales in order to take advantage of the potential of the resources in a sustainable manner.

Environmental contamination and health problems due to the use of mercury are perhaps some of the biggest challenges for the sector and the authorities. According to several interviews with local miners, they claim that they use mercury to recover the gold they extract from the rivers. Meeting this challenge requires not only strict measures to prevent and control environmental pollution and environmental quality in general, but also strategies to manage and ensure a balance between mining activities and the health of workers and inhabitants of the sector. New ways of working and understanding the needs and requirements of the workers and citizens of the study area are required.

The incorporation of sustainable methods is essential to ensure that the extraction of this element does not have a negative impact on the environment. To this end, it is necessary to strengthen professional training and establish a mentality of change that will allow this sector to adapt to methods that are less harmful to the environment. The state must enact regulatory frameworks to manage and promote mining activities to prevent them from being carried out with low technology and precarious working conditions, since the greatest advantage of the artisanal sector is that it is a great source of employment and income for the population. community.

The challenges of governance and policies for mining resources should focus their efforts on: (i) exercising effective and democratic governance for the sustainable management of natural resources; (ii) mitigating macroeconomic vulnerability to commodity price fluctuations and terms of trade with intertemporal logic; (iii) increasing the progressivity of fiscal revenues, financing public investment and improving the quality and progressivity of public spending at the national and local levels; (iv) adding value, deepening local production chains and diversifying production and exports; (v) sharing benefits with communities and guaranteeing economic, social, cultural and collective rights; (vi) protecting the environment.

Given the complexity of the issues surrounding ASM, a coordinated and participatory approach is needed to improve its contribution to sustainable development, involving all spheres of government, industry and civil society. The approach considered should be adapted to the particular social, cultural and economic circumstances of Ecuador and the study area. The state should maintain a recognition of the importance of ASM and focus on improving the livelihoods of those involved in ASM and reducing its impacts as part of integrated rural development. ASM activities should also be incorporated into relevant regional and local development programs. The national government has an important role to play in developing appropriate, coherent and transparent policies through a regulatory framework that focuses on the facilitation and management of ASM.

#### **5.4. Improvement techniques and strategies for gold mining**

##### **5.4.1. 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 (Agencia de Regulación y Control Minero (ARCOM), 2019). 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 26) 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 25.** 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 coresponsibility 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.

#### 5.4.2. 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 (Banco Central del Ecuador, 2016). 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 (Rea Toapanta, 2017). 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 (Schutzmeier et al., 2017; Zarroca et al., 2015). 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 (Guamarrigra & Virginia, 2022)

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 27) between formal and informal.

**Table 26.** Legal and informal ASGM in Ecuador.

	Artisanal Mining		Small Mining	
	Legal	Informal	Legal	Informal
<b>Esmeralda</b>	4	6	1	14
<b>Santo Domingo</b>	4			1
<b>Manabí</b>	2	0	0	0
<b>Los ríos</b>	0	0	0	0
<b>Guayas</b>	18	2	4	0
<b>Santa Elena</b>	0	0	0	0

El oro	151	0	42	21
<b>Total Coast Region</b>	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
Boliva	16	3	2	1
Chimborazo	16	0	2	1
Cañar	9	1	0	2
Azuay	131	13	57	50
Loja	381	0	47	12
<b>Total Andean Región</b>	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
Sucumbios	28	3	18	58
Zamora Chimchipe	731	3	164	54
<b>Total Amazon Region</b>	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.

#### 5.4.3. 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 28). 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 is frequently conducted without retorts (condensers) exposing miners and neighbors to toxic vapors (Pearson et al., 2019; Telmer & Veiga, 2009).

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 27.** 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
Napó	Tena	Ahuano
		Misahuallí
		Arosemena Tola
Pichincha	Quito	Pacto
Chimborazo	Cumanda	Cumandá
Bolívar	Chillanes	
Cotopaxi	La Maná	La Maná
		California
Azuay	Ponce Enriquez	Ponce Enriquez
	Chordeleg	Chordeleg
Zamora	Zamora	Chinapintza
	Paquisha	Nambija
	Nangaritza	Anto Nangaritza
	Chinchi	Chito
Loja	Célica	Célica
	Cariamanga	Cariamanga
El Oro	Portovelo	Zaruma Portovelo
	Atahualpa	
	Zaruma	
	Piñas	
	Santa Rosa	Santa Roja
	Pasaje	Pasaje

#### 5.4.4. Source of Hg pollution coming from mining effluents

Most mercury contamination in ASGM mining comes from informal activities (Futsaeter & Wilson, 2013). This type of activity corresponds to those that did not obtain the proper authorizations to start activities. In Ecuador, as shown in Table 30, the provinces with the greatest amount of informal activity are in the provinces of Azuay, Sucumbíos, Zamora Chinchipe and El Oro (O. Betancourt et al., 2005; González–Merizalde et al., 2016; Requelme et al., 2003; Schutzmeier et al., 2017). 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 (Paz–Barzola et al., 2022)P. 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) (Agencia de Regulación y Control Minero (ARCOM), 2019). 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)<sub>2</sub> losses that affect water bodies (González–Merizalde et al., 2016; López–Blanco et al., 2015; Mantey et al., 2020).

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 (Vallejos & Veit, 2020). 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  $\text{Hg}(\text{CN})_2$ . Several studies at the national level have demonstrated these impacts. (González–Merizalde et al., 2016; Schutzmeier et al., 2017; Patricio C Velásquez–López et al., 2010). 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 (Abraham et al., 2018; Requelme et al., 2003).

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 (Capparelli et al., 2020). 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 (Webb et al., 2004). 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 (Pesantes et al., 2019).

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 (O. Betancourt et al., 2005; Schutzmeier et al., 2017). Mining activities in the southern coastal zone and the use of Hg are severely impacting water quality and the functionality of its ecosystems (O. Betancourt et al., 2005). 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 (Tarras–Wahlberg et al., 2001). 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 (Gonçalves et al., 2017). 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 (Jaszczak et al., 2017; Knoblauch et al., 2020). 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 (Gonçalves et al., 2017). 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 (O. García et al., 2015; Saldarriaga–Isaza et al., 2013). 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 (Saldarriaga–Isaza et al., 2013).

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) (González, 2017), Yasuní National Park (Orellana and Napo) (Webb et al., 2004) and Cofán Bermejo Ecological Reserve (Sucumbíos) (Orellana et al., 2019) and in some cases within these areas. Similarly, in the Andean region, in the provinces of Loja (Chiaradia et al., 2009) and Azuay (Atariguana Monserrate, 2020), 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. 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 (Ammirati et al., 2020; Patricio C Velásquez–López et al., 2010; Zarroca et al., 2015). 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.

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

##### 5.4.5.1. 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.

#### 5.4.5.2. 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 (González-Merizalde et al., 2016; López-Blanco et al., 2015; Mantey et al., 2020; A. Mora et al., 2019; Schutzmeier et al., 2017). 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 (Langeland et al., 2017; Webb et al., 2004). 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 (O. García et al., 2015; Henriques et al., 2015; Wang et al., 2020). 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 (O. García et al., 2015), 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 (Saldarriaga-Isaza et al., 2013). 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 (Guamarriga & Virginia, 2022).

## 6. Discussion

# 6. Discussion

### 6.1. History and current situation.

#### 6.1.1. Amazon region.

In this study, the literature review and field work have shown evidence of possible future implications on environmental and socioeconomic impacts as a result of gold mining activities (Klubi et al., 2018; Obiri et al., 2016). The Peruvian, Colombian, Ecuadorian and Brazilian Amazon share similar impacts of Hg emissions from ASLGM activities. The extraction processes and the large extent of gold mining areas detected generate contaminants such as Hg to freshwater, concern for its environmental impacts and socioeconomic problems in local communities in the Ecuadorian Amazon (Kahhat et al., 2019; Lobo et al., 2018; Rozo, 2020). Studies show that the Ecuadorian Amazon is more prone to serious irreversible damage to the environment, which has serious effects on aquatic ecosystems and biodiversity. New mining technologies and techniques should be the priority to reduce these impacts in the Ecuadorian Amazon region.

The recent impacts of ASLGM and the large extension of gold mining areas are damaging Amazonian ecosystems (Kahhat et al., 2019) and are of concern to local communities (Lobo et al., 2018). It is necessary to know the expansion of ASLGM over time in order to take measures that benefit stakeholders. On the other hand, ASLGM must improve the coexistence, agreements of the communities near this activity, as a key policy to change in the future. This will allow ASLGM to prosper at the level of environmental, economic and social care, linked to the country's development. It is necessary to increase knowledge about gold mining in terms of the impacts generated by this activity in order to improve political and environmental management.

The results show the lack of control and enforcement of the law against illegal artisanal gold mining activities, and this highlights the little evidence that exists in the literature on good law enforcement practices or affected by corruption. If the mining activity is illegal, local authorities should enforce the law and close the mines. However, illegal gold mining activity still persists. Measures should be taken to avoid river pollution and health risks when consuming fish (Kambey

et al., 2001). It is important to take advantage of the information to help communities affected by illegal activities. In addition, future decisions should be made on the effectiveness and proper enforcement of the law to reduce illegal environmental activities and address voluntary compliance problems with stricter regulations or policies. Finally, it is important to highlight that the conditions and perception of artisanal, small-scale and industrial mining by the communities in the area of influence is similar to that reflected in studies conducted in other countries such as Brazil (Ueno et al., 2021), Colombia (Rettberg & Ortiz-Riomalo, 2016; Vélez-Torres & Méndez, 2022), Perú (Wyatt et al., 2019), Ghana (Long et al., 2015) and Zambia, where it has caused health problems, conflicts and environmental impacts.

#### 6.1.2. Andean Region

Historically and in recent times, the Andean Region in Ecuador has been characterized by increasing mining activity, especially in the southern zone, but this is no different from other regions such as the Litoral and the Amazon (O. García et al., 2015; Mestanza-Ramón, Cuenca-Cumbicus, et al., 2022). As for social impacts, in the Andean Region they are mainly concentrated in the human movement from the poorest towns to the mining areas, since this activity will always represent an opportunity to generate new income. These results are similar to those found in other countries, such as Colombia (Salem et al., 2021), Perú (Kahhat et al., 2019; Langeland et al., 2017; Rosales, 2019b), Venezuela (Miller & Villarroel, 2019; Rosales, 2021) and Bolivia (Nguyen et al., 2018), where migration problems present similar dynamics. In addition, it became evident that mining areas generally create new settlements and a greater demand for resources, increasing the cost of living in these places. Socially, the natives are affected, and if they are not interested in joining the mining activity, they are forced to look for new places that involve less hostility. Similar situations have occurred in African and Asian countries (Barenblitt et al., 2021; Haundi et al., 2021; Klubi et al., 2018; Valladares & Boelens, 2019).

Today, although the legal framework for mining has improved in recent years, the reality is that the country is still experiencing illegal mining and socio-environmental demonstrations against the government and its extractivist policies (several concessions have been granted in sites with high biodiversity, such as Quimsacocha, for example (Ministerio de minería, 2017; Ministerio del ambiente del Ecuador, 2013)), which makes mining today a very controversial

issue. Illegal mining, as well as artisanal and small-scale mining, in many Latin American countries (such as Colombia, Peru, Bolivia, Chile, Brazil and Argentina) is considered an activity of marginal impact on the economy, depriving the State and the population of several investment and development benefits (Banco Central del Ecuador, 2020; Markowski et al., 2006; Thomas et al., 2019; Patricio C Velásquez-López et al., 2011). Likewise, this type of mining, characterized by the use of Hg and CN in its gold extraction processes (a technique widely applied in countries such as Brazil, Colombia, Indonesia, Venezuela and Zimbabwe), has caused tailings contaminated with cyanide and heavy metals to end up being discharged into water currents and the atmosphere (E. A. Mora, 2002; Patricio Colón Velásquez-López et al., 2020), a fact that, due to poor management and technification, has generated various international problems for the country. Such is the case of the Puyango-Tumbes river, shared with Peru, which was contaminated by traces of Hg from Portovelo-Zaruma (Rivera-Parra et al., 2021; Schudel et al., 2018). The presence of illegal mining in the country, according to several informal workers, is due to the fact that it represents their only source of income because, in recent years, the country's poor economic conditions and climatic phenomena have encouraged them to carry out this activity. They also point out that on several occasions they have tried to legalize their activities but the bureaucratic system has prevented them from doing so (Markowski et al., 2006; Rivera-Parra et al., 2021).

### 6.1.3. Coastal Region

In recent decades, Ecuador has made great efforts to implement legislation to regulate the activities carried out by the mining sector. However, it is evident that in recent years there has been a loss of interest in the political aspect of mining, since the same law has been in force in the country since 2009, without taking into account the effects that have been generated over the years. It is also clear that there is a lack of rigorous control in the application of the laws; this was evidenced by informal conversations with gold mine workers (outside of the interview questions), since on several occasions they mentioned that visits from the authorities were scarce, indicating a lack of follow-up to verify whether or not the mines comply with the established regulations and, most importantly, to verify that they do not use mercury to extract the mineral. According to (Bogoni et al., 2020), Ecuadorian legislation has its own dynamics in situ, and

it is naïve to believe that the laws of the country can control the sector (Bogoni et al., 2020). Other authors, such as (Tubb, 2020), mention that legislation often involves two factors that generate negotiations in the legal framework of the mining sector: national laws and socio–normative agreements, which in this case are the ones that apply in the country, although not in a recognized manner (Lara–Rodríguez, 2018).

At this point, it is important to note that legislation should require the implementation of mitigation measures. However, this could mean a loss, as there is great controversy in the control and regulation of gold mining practices, since, if mitigation measures are implemented, the potential to appease marginalized groups will be reduced, while if restoration measures are not used, environmental contamination impacts. will also be present, as mentioned in (Vangsnes, 2018). o maintain greater control over gold mining in Ecuador, mining activity must be formalized. However, ref. (Bavinck et al., 2014) state that attempts to formalize the mining sector are generally unsuccessful and, as a consequence, pollution levels increase. According to the authors, in order to carry out an effective formalization process, education must first be implemented to avoid the continuation of incorrect extraction methods, thus reducing environmental damage (Bavinck et al., 2014).

The perspective has not changed much in the History and current situation in terms of environmental impacts in the gold mining areas of the coastal region of Ecuador, since the same aspects are present: river contamination, water scarcity for people, reduction or lack of aquatic diversity and people. with the presence of mercury in their bodies. What is most worrisome is that, according to the analyses carried out, all of these impacts have been occurring in the Puyango River since 2000, which is indicative of the lack of control in the Portovelo–Zaruma areas and the lack of awareness on the part of illegal miners. However, ref (Wingfield et al., 2021) mentions that studies conducted in ASM show that mining has not caused water contamination. Furthermore, he adds that in cities such as Portovelo, Zaruma, Nabija, Ponce Enriquez and Santa Rosa, metallic substances and metalloids have been detected well below the limits established in the regulations (Wingfield et al., 2021). Although the studies conducted show low levels of mercury, it should be taken into account that in general the laboratories in charge of the analyses only have the capacity to measure 0.005 ppm, while the maximum permissible parameters in the

country are set at 0.0002 ppm. There is a large difference between these two levels, so the probability of detecting high levels of mercury is very low, not because it is not present, but because of the lack of specialized equipment that can provide concrete results.

Although Ecuador has major shortcomings in the mining sector due to poor extractive practices or illegality, it is not the only country where this occurs. In other countries of the world, these situations are also present. Such is the case of Colombia, where there have also been cases of mercury contamination of rivers due to amalgamation processes used to extract gold, the introduction of solid loads, metals and wastes used in mining, and the use of mercury in the mining industry (Bavinck et al., 2014). On the other hand, in Ghana, there are cases of soil contamination with averages of  $0.024 \text{ mg kg}^{-1}$ , which is a very low concentration, well below the criteria established for human health (Corredor et al., 2021; Gonçalves et al., 2017; Yevugah et al., 2021)

## **6.2. Ecological and health risks associated with Hg concentrations in water bodies**

### **6.2.1. Amazon region**

The results of this study present an alarming panorama regarding the presence of Hg in the Ecuadorian Amazon. The highest concentrations of Hg were reported in the provinces of Sucumbíos, Napo and Orellana, located to the north of the study area, where concentrations exceeded by up to 1.7 times what is established in Ecuadorian regulations for drinking water quality. In terms of water quality for the preservation of aquatic life, the situation is more serious, as Hg exceeded the Ecuadorian regulations by up to 50 times in the provinces analyzed. Considering these results, wildlife would be exposed to a greater impact, putting sensitive ecosystems and species in the Ecuadorian Amazon at risk. On the other hand, regarding the risk to human health, although there is no evidence of a high risk to the population of the provinces analyzed, it was determined that children are the most exposed to risk, especially in the populations of Sucumbíos, Orellana, Napo, Morona Santiago and Zamora Chinchipe. Therefore, the exposure of the infant population must be controlled to maintain risk levels within acceptable limits. As a result, 100% of the samples analyzed exceeded the maximum permissible limit (MPL) according to the water quality criteria for the preservation of aquatic life in Ecuadorian regulations, while 7% of the samples exceeded the MPL for drinking water. On the other hand,

considering the European Environmental Quality Standard (EQS) for surface water bodies ((Jirka et al., 2004), especially in the populations of Sucumbíos, Orellana, Napo, Morona Santiago and Zamora Chinchipe. Therefore, exposure of the child population should be controlled to keep risk levels within acceptable limits.

As a result, 100% of the samples analyzed exceeded the maximum permissible limit (MPL) according to the water quality criteria for the preservation of aquatic life in Ecuadorian regulations, while 7% of the samples exceeded the MPL for drinking water. On the other hand, considering the European Environmental Quality Standard (EQS) for surface water bodies (Jirka et al., 2004), especially in the populations of Sucumbíos, Orellana, Napo, Morona Santiago and Zamora Chinchipe. Therefore, the exposure of the child population should be controlled to keep risk levels within acceptable limits. As a result, 100% of the samples analyzed exceeded the maximum permissible limit (MPL) according to the water quality criteria for the preservation of aquatic life in Ecuadorian regulations, while 7% of the samples exceeded the MPL for drinking water. On the other hand, considering the European Environmental Quality Standard (EQS). In our study, 100% of the samples exceeded the maximum permissible limit (0.07 µg/L), and with respect to the Canadian water quality guideline (Spry & Branch, 2015) 35% of the samples exceeded the permissible limit (0.001 mg/L) for drinking water, and 100% of the samples exceeded the limit for life in water bodies (0.0001 mg/L).

The Hg content in the analyzed samples could be directly related to the presence of illegal gold mining activity, mainly in the northern part of the study area, whose effects on the environment are as follows (Capparelli et al., 2020; Mestanza-Ramón, D'ORIO, et al., 2021; Mora-Silva & Coronel-Espinoza, 2021), whose effects of this activity on the environment are deforestation and water contamination. One of the main factors that has allowed the increase of illegal mining, intrinsically linked to environmental contamination, has been the State's inability to control and monitor mining. Despite the existence of legal sanctioning instruments (administrative and criminal), these have not been effectively applied to eradicate the problem of Hg use and control the environmental impact caused by illegal miners.

In the criminal sphere, in 2014, illegal activity of mineral resources, financing or supplying machinery for illegal resource extraction and environmental

damage were criminalized (Asamblea Nacional Constituyente del Ecuador., 2014). However, there has been no evidence of a significant impact of the applicability of this legal instrument on the reduction of illegal mining activities in Ecuador.

The lack of personnel and technical–operational capacity of those in charge of mining control, the lack of security in the face of threats from the mafias that control illegal mining and internal corruption in state entities are some of the factors that have contributed to this problem, a problem that has persisted over the years. In Ecuador there are areas where illegal mining activities are public knowledge; however, there is no decision on the part of the control entities to implement definitive actions to eradicate this practice that is so harmful to both the population and the environment. This type of situation is recurrent and has been widely commented on in developing countries. In Latin America, similar cases have been reported in Venezuela (Santos–Francés et al., 2011), Brasil (Lino et al., 2019), Colombia (Baena et al., 2021; Cordy et al., 2011) and Perú (Cruzado–Tafur et al., 2021) where illegal mining activities and the indiscriminate use of Hg have caused serious environmental and health impacts on the population.

In this context, it is necessary for the Ecuadorian State to focus its efforts on the control and monitoring of gold mining activities at all levels, considering that it is possible to combine economic benefits for the State and sustainable use of natural resources, in an environmentally friendly and responsible manner with local communities.

#### 6.2.2. Island region

The investigation reveals a worrisome situation regarding the presence of Hg in the Ecuadorian Andean region. Elevated Hg levels were detected in the provinces of Azuay and Loja, which lie to the south of the investigated area, exceeding the standards established by Ecuadorian regulations to guarantee drinking water quality. The reason for these elevated Hg concentrations may be related to mining activity in the area, especially gold mining that uses mercury in the extraction process. Regarding water quality for the preservation of aquatic life, the situation is even more critical, as it was found that in the provinces analyzed, Hg concentrations mostly exceeded the limits established by Ecuadorian regulations. In this context, wildlife in the Andean region would be

exposed to a significant impact, which could endanger both the ecosystems and the most vulnerable species in the region. A study developed by (Rahman et al., 2022), points out that Hg is highly toxic to living organisms and can accumulate in the tissues of animals along the food chain, which can have negative effects on their health, with negative consequences in the food chain. Regarding the risk to human health, the results represent a high risk to the population of the provinces analyzed, children were found to be the most vulnerable, especially in the residential populations of Azuay, Cañar, Carchi, Imbabura, Loja and Pichincha, with water intake as the main contributor to the risk. Therefore, regulation of exposure of children is required to keep risk levels within acceptable limits. The analysis revealed that all samples tested exceeded the maximum permissible limit (MPL) established by the Ecuadorian normative water quality standards for freshwater quality. In addition, in two provinces the samples exceeded the MPL for drinking water: Azuay (51.11%) and Loja (21.05%) of the sampled points. In relation to the European Environmental Quality Standard (EQS) for surface water bodies (BENÍTEZ-DÍAZ & MIRANDA-CONTRERAS, 2013) , all of the samples analyzed in our study exceeded the MPL of 0.07 µg/L. Consequently, according to the Canadian water quality guidelines (Del Pozo Panata & López Panchi, 2022), 100% of the samples exceeded the allowable limit of 0.001 mg/L for drinking water.

According to the findings of the study, there seems to be a direct connection between the presence of Hg in the samples and illegal gold mining activity, especially in the southern part of the investigated area. Studies such as those of (Estupiñan et al., 2021; Veiga et al., 2006; Vélez, 2017) point out the negative effects of this activity on the environment, including deforestation, destruction of natural habitats, generation of toxic waste, water pollution, and contribution to climate change. It is important to take measures to reduce these impacts and promote more sustainable and responsible practices in the mining industry. The lack of state capacity to supervise and regulate mining activity has been a major factor in the growth of illegal mining, which is closely related to environmental contamination. Although there are laws and regulations that allow for both administrative and criminal penalties for the use of Hg and control the environmental effects of illegal mining, they have not been effectively enforced to eliminate the problem.

In Ecuador, there is a law that criminalizes the illegal exploitation of mineral resources, the financing or provision of machinery for the illegal extraction of resources and environmental damage. This law is known as the Organic Mining Law and establishes criminal and administrative sanctions for those who fail to comply with mining and environmental regulations. This law is important to promote the regulation and control of mining activity in the country, and to encourage more sustainable and responsible practices in the mining industry. Despite the existence of this legal instrument, there has been no significant reduction in illegal mining in the country. Enforcement of the law has been limited, and in many cases, it has been difficult to enforce sanctions and control mechanisms.

Over time, the persistence of the illegal mining problem has been influenced by several factors, such as the State's inability to adequately regulate and supervise mining activity, the presence of armed groups and mafias, the lack of sustainable economic alternatives for local communities, the lack of community participation in decision making, and the high international demand for minerals. It is important to address these problems in a comprehensive manner to promote sustainable and equitable development in the mining industry in the country. Although illegal mining is a public and known problem in some provinces of Ecuador's Sierra, the authorities in charge of control have not taken decisive action to eradicate this activity, which is harmful to both the population and the environment. The indiscriminate use of mercury in mining has had serious environmental and health consequences for the population in several Latin American countries, including Peru (Smith, 2019), Colombia (Betancur–Corredor et al., 2018), Brasil (da Costa & Rios, 2022), Venezuela (Rosales, 2019a) where it has led to water contamination and deforestation. Also, local communities have suffered serious health consequences, including neurological and reproductive problems.

In this context, it is essential that the State of Ecuador invest resources in supervising and monitoring all dimensions of gold mining activity, as it is possible to combine economic benefit with sustainable use of natural resources and responsibility towards the environment and local communities. In addition, it is important that the State works to promote responsible and sustainable mining practices. This may include the promotion of cleaner and safer technologies for mineral extraction, the implementation of environmental

restoration practices after the closure of mining operations, and the promotion of the participation of local communities in decision-making on the use of natural resources.

### 6.2.3. Coastal region

The study shows a worrying situation regarding the existence of Hg in the coastal region of Ecuador because mercury contamination can have significant ecological and health implications. Elevated Hg concentrations were found in the provinces of El Oro and Esmeraldas, located in the southwest and northwest of the region analyzed, exceeding the limits established by Ecuadorian regulations to ensure drinking water quality. The possible cause of these high Hg concentrations may be associated with mining activity in the region, specifically gold mining that uses mercury as part of its process to separate gold from other materials. Regarding the preservation of aquatic life, the situation is especially worrisome in relation to water quality. It was found that, in the provinces analyzed, mercury concentrations mostly exceeded the limits established by Ecuadorian regulations. In this sense, the wildlife of the Costa region would face a considerable impact, which could represent a threat to both the ecosystems and the most susceptible species in the area. A study conducted by (Kumar Das et al., 2023) indicates that mercury is a heavy metal that tends to accumulate in the fatty portions of fish tissues and, through the food chain, can enter the liver, representing a significant risk to human health. Therefore, effective monitoring, regulation and mitigation strategies are needed to address this worrying situation and protect both the environment and human well-being. In terms of risk to human health, the findings indicate a high risk to the population of the provinces examined, with children being the most vulnerable. Especially in the residential areas of El Oro and Esmeraldas, water consumption was found to be the main factor contributing to this risk. Therefore, it is necessary to establish regulations that limit the exposure of children in order to keep risk levels within acceptable limits. With this, studies by (Hilson & Murck, 2000); (Esdaile & Chalker, 2018) indicate that it is important to implement water protection and treatment measures by applying actions such as: water treatment, water monitoring, exploring alternative water sources, and promoting education and awareness among local communities about the risks. The analysis showed that all samples analyzed exceeded the maximum permissible limit (MPL) established by Ecuador's water quality standards for freshwater. In

addition, in two provinces samples were found to exceed the maximum permissible limit (MPL) for drinking water: El Oro (28%) and Esmeraldas (100%) of the sampling points. It is therefore essential to address mercury contamination and take measures to protect the health of the exposed population. Regarding the European Environmental Quality Standard (EQS) for surface water bodies (Jirka et al., 2004) , in our study, all samples analyzed were found to exceed the maximum allowable limit of 0.07 µg/L. Furthermore, according to the Canadian water quality guidelines (Spry & Branch, 2015), all samples exceeded the allowable limit of 0.001 mg/L for drinking water.

According to the results of the study, there seems to be a direct correlation between the presence of Hg in the samples and the illegal gold mining activity, mainly in the northern and southern part of the investigated area. A first study developed by (Ahmad et al., 2014) shows that the environmental impacts caused by mining activity is presented through air, water, acoustic pollution and its consequent effect on the health of people who were exposed to pollutants such as Hg. Therefore, it is necessary to have a comprehensive strategy and appropriate regulations to mitigate the negative effects of mining on the environment and make this activity sustainable. A second study by (Dou et al., 2023) indicates that increased environmental regulation has limited the ecological impacts of mining. However, we believe that these impacts of environmental regulation are regionally heterogeneous. A third study by (Maise et al., 2023) notes that mining activities often involve extensive land excavation, deforestation, and displacement of natural ecosystems. This results in the degradation of flora and fauna habitat, which translates into a decrease in biological diversity in the area. It is therefore essential to implement actions to reduce these effects and encourage more responsible and sustainable practices in the mining industry. One of the main factors in the increase of illegal mining, which is closely linked to environmental contamination, has been the inadequacy of the state to supervise and regulate mining activity (Salgado-Almeida et al., 2022) notes that environmental mining regulations in Ecuador are relatively new and still have shortcomings. Although there are regulations and laws that allow both administrative and criminal penalties for the use of Hg and control the environmental effects of illegal mining, they have not been effectively applied to solve the problem.

In Ecuador, there is a law that establishes as a crime the unauthorized exploitation of mineral resources, the financing or supply of machinery for the illegal extraction of resources and the negative environmental impact. The Organic Mining Law establishes both criminal and administrative measures for those who do not comply with mining and environmental regulations. The importance of this law lies in its ability to promote the regulation and supervision of mining activity in the country, as well as to encourage more responsible and sustainable practices in the mining industry. Despite the existence of this legal tool, there has been no significant decrease in illegal mining in the country. Enforcement of the law has been restricted and, in many cases, it has been complicated to enforce sanctions and control mechanisms. With this, (Monteiro et al., 2021) mentions it is fundamental to consider norms and laws that guide activities to be developed in an environmentally, economically and socially sustainable manner. Therefore, we believe that it is necessary to establish regulations for the management of environmental impacts left by mining activities in order to protect the environment and the inhabitants of mining communities.

Over time, it has been observed that the persistence of illegal mining has been influenced by several factors, such as the inapplicability of state regulations to effectively regulate and supervise mining activity, the presence of armed groups, the lack of sustainable economic alternatives for local communities, the lack of community participation in decision making, and the high international demand for minerals. It is crucial to address these issues in a comprehensive manner in order to foster equitable and sustainable development in the country's mining industry. Despite the fact that illegal mining is a public and recognized problem in some provinces of coastal Ecuador, the authorities responsible for control have not taken firm measures to eliminate this activity that is harmful to both the population and the environment. The uncontrolled use of mercury in mining has generated serious consequences for both the environment and the health of the population in several Latin American countries. In Colombia, for example, illegal mining in the departments of Chocó and Nariño has led to water contamination and deforestation, as well as security problems and violence in the región (Le Billon et al., 2020). In Peru, illegal mining in the Madre de Dios region has caused contamination of the Amazon River and deforestation of large areas of forest (Aranoglu et al., 2022).

Furthermore, in Venezuela, illegal mining in the state of Bolivar has caused contamination of the Orinoco River and deforestation (Serrano & Sánchez, 2023). In addition, local communities have suffered serious health effects, including neurological and reproductive problems. Therefore, to effectively address global and local mercury contamination and its health impacts, research and policy need to be integrated. Research must be rapidly translated into appropriate preventive measures and human exposure monitoring programs through biomonitoring.

Given the above, it becomes crucial that the State of Ecuador implement adequate sustainable mining practices and environmental regulations to minimize mercury releases and mitigate its impact on human health and the environment. In addition, monitoring and evaluation of mercury levels in the coastal region are essential to understand the extent of contamination and develop effective remediation and risk management strategies. Responsible mining practices could include the use of clean and efficient technologies for mineral extraction, the implementation of restoration practices for degraded areas after the closure of mining operations, the implementation of practices to minimize waste generation, such as the reduction of Hg use, and increased community participation that may include consultation and prior informed consent of the population to initiate any mining activity. It should be noted that each situation is unique and requires specific solutions adapted to the circumstances of each case.

### **6.3. Environmental impacts generated by the use of mercury in gold mining**

The El Dorado de Cascales parish is one of the areas with the most mining activity in the northern Amazon region of Ecuador and, like other regions of the country such as the Andean (Mestanza–Ramón, Ordoñez–Alcivar, et al., 2022) and Littoral (Mestanza–Ramón, Paz–Mena, et al., 2021; Salgado–Almeida et al., 2022) and other countries in the región (Langeland et al., 2017; Martín et al., 2020; Patricio C Velásquez–López et al., 2011), one of the main problems is the lack of control of mining activities by local, regional and national government authorities. The lack of employment and entrepreneurial opportunities makes people from these areas characterized by high concentrations of gold to engage in this activity, so much so that there are even people from other regions and neighboring Colombia who are tempted by this activity. These social problems of migration and lack of job opportunities are

very similar to what happens in Africa (Ros-Tonen et al., 2021; Yoshimura et al., 2021) or other Latin American countries (Abraham et al., 2018; Feingold et al., 2020; O. García et al., 2015; Webb et al., 2004). The aspects that lead to the generation of conflicts that have been evidenced in the study area are increasing, maintaining the trend of countries in the region with significant gold mining production. To try to change this reality, it is necessary to implement public policies that involve planning, management and handling of socio-environmental, regulatory, institutional, fiscal and strategic conflicts. All of this requires a long-term vision that allows for institutional innovation to maximize social benefits in the present and in the future. It is necessary to consider extra-regional experiences that have created public savings and investment funds for specific purposes (education and innovation) or counter-cyclical macro-fiscal stabilization funds.

It is clear that gold ASM activity in the northern Amazonian area of Ecuador has been a History reality (O. Betancourt et al., 2005; Jiménez-Oyola, Segovia-Escobar, et al., 2021; Tarras-Wahlberg et al., 2001) present and in continuous expansion in the future (Mestanza-Ramón, Cuenca-Cumbicus, et al., 2022; Mestanza-Ramón, D'ORIO, et al., 2021; Mestanza-Ramón, Ordoñez-Alcivar, et al., 2022) due to its high demand and the continuous rise in its market value, all in response to the war between Russia and Ukraine and the growing distrust towards the hegemony of the main world currencies such as the dollar and the euro (Adekoya et al., 2022; Liadze et al., 2023). In view of this, the national government and all institutions linked to this activity should propose political measures, norms and actions to regulate this activity in the economic system, within a framework of sustainable development, focusing efforts on the environmental component and its conservation (Doering et al., 2016; Tarras-Wahlberg et al., 2001), since the polluting elements used affect the balance of ecosystems, as evidenced by the results of this study. Therefore, proposing solutions to the social and environmental problems of small-scale gold mining in Ecuador is an arduous task that requires the active and coordinated commitment of the government, communities, NGOs, private associations, universities and research institutions. Therefore, the institutions and communities involved in ASM gold mining should form an alliance in favor of sustainable and responsible artisanal and small-scale mining, based on the objectives of sustainable development.

As in other countries around the world in ASGM, mercury is the main pollutant used in the gold extraction process (Basri et al., 2017; Rettberg & Ortiz-Riomalo, 2016). This element is initially used to clump gold particles to form a gold–mercury amalgam. Contamination occurs when the amalgam is poured into bodies of water and when the amalgam is allowed to release the mercury, which dissipates into the atmosphere. This is no different in the study area, where 90 % of ASM miners claim to use mercury clandestinely, causing great harm to both the person performing the procedure and those living in nearby areas (Seccatore et al., 2014; Yoshimura et al., 2021). Regarding the origin of the mercury, this element used by illegal miners would have a clandestine origin from Bolivia and Peru through the southern Ecuadorian border. In alluvial mining (river gold), the Hg:Au ratio is usually 1:1. The loss of mercury is usually caused by burning the amalgam. River gold amalgam usually consists of 50 % gold and 50 % mercury, depending on the particle size of the gold (Saim, 2021; Telmer & Veiga, 2009). On the other hand, there is evidence of higher proportions of mercury use when the ore is ground (hard rock mining) and the mercury is ground into small particles and lost in the tailings. In hard rock mining, the Hg:Au ratio can be as high as 10:1 (Esdaile & Chalker, 2018; Kristensen et al., 2014; Seccatore et al., 2014).

## 7. Conclusions

Over the last four decades, mining activity in the Ecuadorian Amazon has experienced a marked increase from artisanal and subsistence mining to include illegal small-scale mining (ASM) and large-scale gold mining. During Rafael Correa's administration, large-scale mining was consolidated and strengthened, although policies and laws have been implemented to mitigate socio-environmental impacts, the capacity to monitor and control these activities remains insufficient. Both ASM and large-scale mining have given rise to socio-environmental problems, such as heavy metal contamination in water, air and soil, affecting the livelihoods and daily lives of communities. To address this issue, it is essential to improve education and counseling on ASM, as well as to promote the use of alternative technologies to reduce the use of mercury. Despite research difficulties due to the pandemic and conflicts with miners and local people, the results obtained provide valuable information for future research, including the evaluation of the concentration of heavy metals in water and the analysis of the conflicts generated by these activities.

The growth of mining as an economic engine in Ecuador, driven by its natural resources and policies of openness to foreign capital, has led to significant socio-environmental problems, including impacts on the environment and territory, lack of prior consultation, violation of human rights and lack of corporate social responsibility. The reactive reaction of governments to these problems has increased the economic, environmental and social costs. Although mining has generated employment and economic reactivation, the benefits are insignificant compared to the serious environmental impacts, such as the contamination of effluents with toxic substances. Large-scale mining has generated conflict and marginalization in certain sectors, such as women and peasants. To address this situation, it is imperative to implement new policies and increase transparency to mitigate impacts and promote local economic development in a sustainable manner.

This study evaluated the concentration of mercury (Hg) in surface water in five provinces of the Amazon region of Ecuador and its impact on the health of

local inhabitants. All samples analyzed did not meet water quality criteria for the preservation of aquatic life according to Ecuadorian regulations. The risk assessment revealed that mercury exposure does not exceed allowable limits for adults and children in residential and recreational settings, but the child population shows a doubled risk in residential settings. The study also identified sites of high systemic risk, especially for children, due to consumption of contaminated surface water. These findings highlight the need to consider the spatial distribution of social and ecological affectation in the study area, and underscore the importance of further research on anthropogenic contamination in the Ecuadorian Amazon, including the assessment of other toxic elements in various matrices. The results can support a participatory approach in the design of strategies and policies for water use and pollution control.

On the other hand, mercury levels in surface water in the Sierran region of Ecuador and found a potential health risk for the inhabitants of the area. The samples did not meet water quality criteria according to Ecuadorian regulations. Although the risk of adverse human health effects was low in residential and recreational settings, the child population exceeded the acceptable risk level in residential settings. The importance of considering a spatial distribution model in the assessment of social and ecological impacts is highlighted. Further research on anthropogenic pollution in the region is required for effective natural resource management and health protection of the exposed population. The results can support the development of participatory policies for water use and pollution control, but the conscious participation of the population in these protective measures is essential.

Regarding mercury levels in surface waters in five provinces of the Coastal region of Ecuador and discovered a potential health risk for people living in the area. According to Ecuadorian regulations, none of the samples tested met water quality standards for the protection of aquatic life. The probabilistic risk analysis showed that the possibility of experiencing negative human health effects due to mercury exposure was below the allowable limits for both adults and children in residential and recreational settings. However, the number of children was found to exceed the acceptable risk threshold in the deterministic risk assessment in residential homes. Additionally, this study noted areas that exhibit potential systemic risk, especially for children, due to ingestion of water from surface water sources. Therefore, these findings highlight the importance

of incorporating a spatial distribution approach when assessing social and ecological effects in the research area. This would enable more efficient management of natural resources and increased safeguarding and medical care for people exposed to Hg contamination.

Gold mining activity in the study area in the canton of El Dorado de Cascales has increased in recent years, generating a socio–environmental impact. It has affected the biotic and abiotic components with high and medium magnitude and the socioeconomic component with medium and low magnitude. The main impacts correspond to habitat alteration, disturbance and alteration of vegetation at the time of land exploration. On the other hand, contamination and chemical alteration of soil and water, when miners use mercury to form the amalgam of gold and mercury, is another important impact. Another strong impact is the atmospheric alteration caused by mercury particles released in the process of burning the amalgam to obtain gold.

The use of mercury in gold extraction processes may initially be an efficient option due to its effectiveness. However, the results show that there are medium and high socio–environmental impacts as a direct result of ASM activities in the El Dorado de Cascales parish. Upon analyzing the current situation in the parish, it became evident that gold extraction is carried out using rudimentary techniques. In addition, there are insufficient controls by the competent authorities to verify compliance with the different requirements for its operation, without harming the environment and the nearby population. Finally, one of the main difficulties in the development of this study was the access to legal and illegal mining areas. The risk is always present due to the social secrecy of this activity. It is recommended to concentrate efforts in new studies focused on the analysis of heavy metal concentrations in water, sediments and biotic elements. This will allow us to generate a contrast with the results observed in situ by researchers.

Mining management in Ecuador presents serious problems in its organizational processes, and in recent decades 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 ASM sector.

Promoting training and education processes with artisanal and small-scale miners in Ecuador on 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 technologies and clean technologies. 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 the techniques. At this point it is necessary to encourage associative grouping that allows them to opt for social capital and, therefore, socioeconomic benefits.

The Ecuadorian government should establish mechanisms for the promotion, technical assistance, training and financing of sustainable development for artisanal and small-scale mining. It should also 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 available information on successful management processes to reduce the impact of ASM activities on water bodies.

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

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9. Annexes  
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**FULL PUBLISHED ARTICLES**

Mestanza et al.	<p>Mestanza–Ramón, C., Jiménez–Oyola, S., Gavilanes Montoya, A. V., Vizuete, D. D. C., D’Orio, G., Cedeño–Laje, J., Urdánigo, D., &amp; Straface, S. (2023). Human health risk assessment due to mercury use in gold mining areas in the Ecuadorian Andean region. <i>Chemosphere</i>, 344, 140351. <a href="https://doi.org/https://doi.org/10.1016/j.chemosphere.2023.140351">https://doi.org/https://doi.org/10.1016/j.chemosphere.2023.140351</a></p> <p>Indexación: Journal Citation Report <b>Elsevier Chemosphere</b> WoS – JCR Q1, IF = 8.8 (2023) <a href="https://www.sciencedirect.com/science/article/pii/S0045653523026218">https://www.sciencedirect.com/science/article/pii/S0045653523026218</a></p>
Mestanza et al.	<p>Mestanza–Ramón, C., Jiménez–Oyola, S., Montoya, A.V.G. et al. Assessment of Hg pollution in stream waters and human health risk in areas impacted by mining activities in the Ecuadorian Amazon. <i>Environ Geochem Health</i> (2023). <a href="https://doi.org/10.1007/s10653-023-01597-6">https://doi.org/10.1007/s10653-023-01597-6</a></p> <p>Indexación: Journal Citation Report <b>Springer–Nature Environmental Geochemistry and Health</b> SJR Q1, (2023) <a href="https://link.springer.com/article/10.1007/s10653-023-01597-6">https://link.springer.com/article/10.1007/s10653-023-01597-6</a></p>
Mestanza et al.	<p>Mestanza–Ramón, C.; Cuenca–Cumbicus, J.; D’Orio, G.; Flores–Toala, J.; Segovia–Cáceres, S.; Bonilla–Bonilla, A.; Straface, S. Gold Mining in the Amazon Region of Ecuador: History and a Review of Its Socio–Environmental Impacts. <i>Land</i> 2022, 11, 221. <a href="https://doi.org/10.3390/land11020221">https://doi.org/10.3390/land11020221</a></p> <p>Indexación: Journal Citation Report <b>Land</b> WoS – JCR Q1, IF = 3.905 (2022) <a href="https://www.mdpi.com/2073-445X/11/2/221">https://www.mdpi.com/2073-445X/11/2/221</a></p>
Mestanza et al.	<p>Mestanza–Ramón, C.; Ordoñez–Alcivar, R.; Arguello–Guadalupe, C.; Carrera–Silva, K.; D’Orio, G.; Straface, S. History, Socioeconomic Problems and Environmental Impacts of Gold Mining in the Andean Region of Ecuador. <i>Int. J. Environ. Res. Public Health</i> 2022, 19, 1190. <a href="https://doi.org/10.3390/ijerph19031190">https://doi.org/10.3390/ijerph19031190</a></p> <p>Indexación: Journal Citation Report <b>Int. J. Environ. Res. Public Health</b> WoS – JCR Q1, IF = 2.849 (2022) <a href="https://www.mdpi.com/1660-4601/19/3/1190">https://www.mdpi.com/1660-4601/19/3/1190</a></p>
Mestanza et al.	<p>Mestanza–Ramón, C.; Mora–Silva, D.; D’Orio, G.; Tapia–Segarra, E.; Gaibor, I.D.; Esparza Parra, J.F.; Chávez Velásquez, C.R.; Straface, S. Artisanal and Small–Scale Gold Mining (ASGM): Management and Socioenvironmental Impacts in the Northern Amazon of Ecuador. <i>Sustainability</i> 2022, 14, 6854. <a href="https://doi.org/10.3390/su14116854">https://doi.org/10.3390/su14116854</a></p> <p>Indexación: Journal Citation Report <b>Sustainability</b> WoS – JCR Q2, IF = 3.889 (2022) <a href="https://www.mdpi.com/2071-1050/14/11/6854">https://www.mdpi.com/2071-1050/14/11/6854</a></p>
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## Human health risk assessment due to mercury use in gold mining areas in the Ecuadorian Andean region

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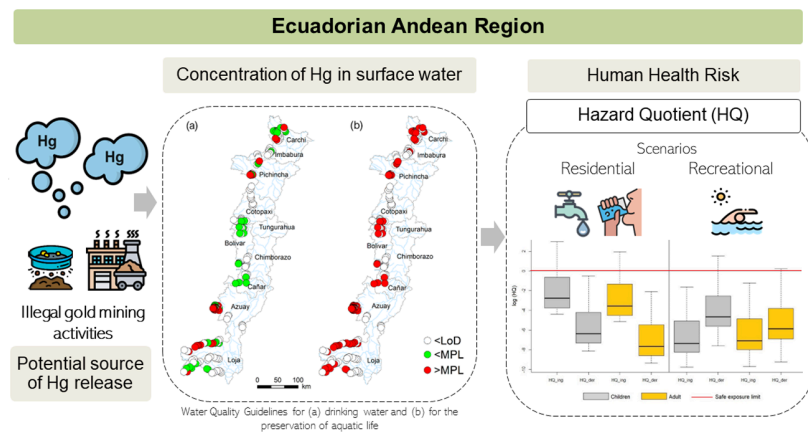
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### HIGHLIGHTS

- A total of 147 water samples were collected in the Andean region of Ecuador to evaluate the presence of Hg.
- The results revealed worrying levels of Hg, especially in the provinces of Azuay and Loja.
- The probabilistic risk analysis yielded values that exceeded the acceptable exposure limit in residential settings.
- 45% of the water samples analyzed did not meet water quality criteria for the preservation of aquatic life.
- The elevated presence of Hg represents a threat to water quality and aquatic life in the Andean region of Ecuador.

### GRAPHICAL ABSTRACT



### ARTICLE INFO

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### ABSTRACT

Mining activity drives economic development and has established itself as one of the main industrial spheres globally. However, illegal, and artisanal gold mining, which uses mercury (Hg), is a major source of global pollution. Hg is highly toxic and persistent in the environment, affecting human health and the ecosystem. The

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# Assessment of Hg pollution in stream waters and human health risk in areas impacted by mining activities in the Ecuadorian Amazon

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**Abstract** Illegal gold mining activities have contributed to the release and mobilization of Hg and environmental degradation in many parts of the world. This study aims to determine the concentration of Hg in five provinces of the Amazon Region of Ecuador, in addition to assessing the risk to human health of exposed populations, applying deterministic and probabilistic methods. For this purpose, 147 water samples were collected in rivers and streams crossing and/or located near mining areas. As a result, 100% of the samples analyzed exceeded the maximum permissible limit (MPL) according to the water quality criteria for the preservation of aquatic

life of the Ecuadorian regulations, while 7% of the samples exceeded the MPL for drinking water. On the other hand, considering the European Environmental Quality Standard (EQS) for surface water bodies, in our study, 100% of the samples exceed the maximum permissible limit (0.07 µg/L), and with respect to the Canadian water quality guidelines, 35% of the samples exceed the permissible limit (0.001 mg/l) for drinking water, and 100% of the samples exceed the limit for life in water bodies (0.0001 mg/l). The risk assessment revealed that the probability of developing adverse health effects from exposure to Hg is below the recommended limits according to the probabilistic

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## Article

# Gold Mining in the Amazon Region of Ecuador: History and a Review of Its Socio-Environmental Impacts

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**Abstract:** Artisanal and small-scale gold mining (ASGM) and large-scale mining in the Ecuadorian Amazon region is potentially harmful to nature, and its impacts are associated with environmental degradation and deterioration of people's health. So far, limited efforts have been directed at exploring the current situation and challenges facing the implementation of environmental policies in the country. The objective of this study focused on analyzing the historical and current situation and challenges of ASGM in the Amazon region of Ecuador in relation to a political perspective (laws), socioeconomic impacts (population displacement, loss of livelihoods, migration of people, cost of living, water scarcity, and health impacts), and environmental impacts (biotic and abiotic). The methodology used was based on a literature review and interviews, and information that was discussed through an expert judgment allowed for establishing challenges to improve ASGM management. The main results indicate that lack of community participation in decision-making, insufficient coordination between government institutions, communities, and miners, and lack of control of mining activities are factors that contribute to ineffective compliance with environmental policies in the gold mining sector in the Amazon. Finally, the study concludes by considering the socioeconomic and environmental scopes within its findings for implementing effective environmental and social policies in the Amazon region of Ecuador.

**Keywords:** mercury; gold; socio-environmental impacts; environmental management; political management; environmental management

## 1. Introduction

Mining is the most important primary source of metals and minerals in the world [1,2]. Millions of people in developing countries depend on artisanal and small-scale gold mining (ASGM) for their livelihoods. However, this activity comes at a price [3,4]. These activities are quite diverse, sometimes illegal or informal, often virtually tolerated by the authorities, and can be seasonal or year-round, long-term, or follow a boom-and-bust cycle. Gold mining has a significant impact on the local climate, the natural environment, and the socioeconomic conditions of local residents. Mining activities and their methods of disposal of toxic by-products are considered one of the main reasons for the deterioration of environmental health [5–7]. ASGM is associated with many occupational and environmental health problems, especially when practiced informally or with limited material



Article

# History, Socioeconomic Problems and Environmental Impacts of Gold Mining in the Andean Region of Ecuador

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**Abstract:** Mining in Ecuadorian territory comprises three stages of Ecuadorian history: pre-Columbian, colonial, and republican times. In its beginnings, this activity did not have regulations or a legal foundation. The first Mining Law dates back to 1830, and it has been modified until the most recent update in 2009. The Andean region consists of 10 provinces, 9 of which have registered gold concessions, the most important of which are Loja, Azuay, and in recent years, Imbabura and Pichincha, which are the provinces with the highest number of reported concessions. The objective of this study focused on analyzing the historical and current situation of Artisanal and Small-scale Mining (ASGM) and the emergence of large-scale (industrial) mining. For the elaboration of this study, different methodological techniques were used, such as literature review, field interviews, and expert judgment validation. The main findings show that the provinces of Loja, Azuay, Imbabura, and Pichincha are the most conflictive areas in the region due to the impacts caused by mining activities. In socio-economic terms, there are conflicts between inhabitants in favor and against these activities and problems associated with human health. In environmental terms, the findings suggest historical contamination of water sources by heavy metals, which has altered the surrounding aquatic and terrestrial systems. Finally, the study concludes that implementing public policies should be promoted to balance socio-economic and environmental aspects in gold mining activities in the Andean region of Ecuador, strengthening the use of new technologies and education to raise awareness of the serious effects of mining activities.

**Keywords:** gold; heavy metals; socio-environmental impacts; political management; environmental management

## 1. Introduction

Mining worldwide is currently experiencing a production growth that has never been seen before. The global market for minerals and precious metals has soared, and the quantities extracted have multiplied exponentially [1,2]. Gold (Au), recognized as one of the most sought-after and demanded elements in international trade, is also the most exploited precious metal in world mining production [3–5]. In the case of South America, member countries, such as Colombia, Peru, Bolivia, Chile, Brazil, and Argentina, are notable for Au production and exports, a market in which Ecuador has become increasingly competitive during the last few years as part of a strategy to diversify its productive output [6,7].

## Article

# Artisanal and Small-Scale Gold Mining (ASGM): Management and Socioenvironmental Impacts in the Northern Amazon of Ecuador

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**Abstract:** Mining is one of the oldest economic activities of mankind. Within this activity, artisanal and small-scale gold mining (ASGM) is one of the most studied sectors due to its high level of environmental contamination and the social problems it causes. In recent years, ASGM in the northern Amazon of Ecuador has increased significantly, and studies that describe its current situation and impact are scarce. In this sense, the present study aimed to analyze the current status and socioenvironmental impacts caused by ASGM gold mining activities in the Cascales canton in the province of Sucumbíos in northeastern Ecuador. The methodological tools used in the present study were a literature review of scientific and gray literature, field visits to assess perceived impacts and an expert judgment to discuss the results and establish challenges. The main results indicate that illegal and informal activities continue to be carried out in the upper zone of the Cascales and Duvino rivers; 90% of local miners still use mercury in this activity, although it is legally prohibited. Among the main impacts evidenced are the contamination of water bodies, soil and atmosphere due to the use of mercury and disturbance to flora and fauna due to the use of machinery in the exploration process. Finally, the government should focus efforts on strengthening public policies to socialize the importance of good environmental practices in ASGM and the effects of the impacts on human health and environmental issues, all this with the support of social actors, such as ministries, universities, NGOs, ASGM associations and private enterprise.




**Keywords:** sustainability; biotic; abiotic; mining; economy; management; geographic information system (GIS); challenges; Sucumbíos; Cascales

## 1. Introduction

Globally, most of the attention in the gold mining industry is focused on large companies; however, in many parts of the world, especially in developing countries, minerals are extracted by artisanal and small-scale mining (ASGM), a complex and diversified sector [1–4]. It encompasses a wide range of informal independent miners seeking a livelihood to formal small-scale commercial mining entities that produce minerals in a responsible

Article

# History, Current Situation and Challenges of Gold Mining in Ecuador's Litoral Region

Carlos Mestanza-Ramón <sup>1,2,\*</sup>, Selene Paz-Mena <sup>3</sup>, Carlos López-Paredes <sup>4</sup>, Mirian Jimenez-Gutierrez <sup>4</sup>, Greys Herrera-Morales <sup>4</sup>, Giovanni D'Orio <sup>5</sup> and Salvatore Straface <sup>1</sup>

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**Abstract:** Gold mining in Ecuador has been present in the country since Inca times; over the years interest in the mineral has increased, leading to the creation of legislation to control the mining sector in a safe manner. The Litoral region consists of seven provinces, six of which have registered gold concessions; the most affected provinces are El Oro and Esmeraldas. The objective of this study was to analyze the historical and current situation of artisanal and industrial gold mining in the Litoral region of Ecuador. Different methodologies were used for the elaboration of this study, including bibliographic review, grey literature, field interviews and a validation of expert judgment. The main results indicate that El Oro and Esmeraldas are essentially the most conflictive areas in the region, as they have sometimes had to establish precautionary measures due to the risks caused by illegal mining. In addition, in both areas there is a great socioeconomic impact ranging from lack of opportunities, forgetfulness, migration, emigration, and violation of rights, among others. With respect to environmental impacts, the study highlights the contamination of water sources (which leads to a lack of drinking water for people), and damage to aquatic and terrestrial ecosystems. Finally, the study concludes that the authorities should control the mining sector more by implementing more laws and carrying out inspections to put an end to illegal gold mining, in order to improve the situation in the areas.

**Keywords:** mercury; gold; socioeconomic impacts; political management; environmental management

## 1. Introduction

Gold mining and extraction dates back to ancient times, during the primitive era approximately 4000 years ago [1]. This economic activity has been transformed globally over the last two decades to such an extent that investment in developing countries has increased [2]. This event is of great significance, as millions of people depend on industrial, artisanal and small-scale gold mining for their survival [3]. In the context of world gold production, it is estimated that there will be a 5% reduction to a five-year low of 3359 t; an event related to the interruption of mining activities during the COVID-19 pandemic. On the other hand, the countries that have positioned themselves as the largest gold producers in recent years are China, Russia, Australia, United States, Canada, Peru, Ghana, South Africa, Mexico, and Brazil, among others [4].

In Ecuador, gold mining makes a great contribution to the country's economy, and in recent years laws and policies have been implemented to maintain a lower impact

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

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DOI/URL: <https://doi.org/10.53313/gwj42028>

**Abstract:** ASGM Mining processes have increased in recent years, becoming one of the main activities responsible 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; environment-mental impacts; Hg



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**Scienze e Ingegneria dell'Ambiente, delle Costruzioni e**  
**dell'Energia**  
-  
**XXXVI\_CICLO**

**VALUTAZIONE DELLA TESI DI DOTTORATO/EVALUATION OF THE PhD THESIS**

*Risks and impacts of mercury use in gold mining in Ecuador*

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Cognome/Last Name: Mestanza

**Tutor:**

Nome/First Name: Salvatore

Cognome/Last Name: Straface

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*Sufficiente / Sufficient*

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*Eccellente / Excellent*

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**Metodologia -Analisi dei dati (i metodi sono appropriati, l'analisi dei dati è adeguata ed esaustiva -se pertinente)**

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*Insufficiente / Insufficient*

*Sufficiente / Sufficient*

*Buono / Good*

*Molto buono / Very good*

*Eccellente / Excellent*

**Descrizione del lavoro di ricerca**

***Research work description***

*Insufficiente / Insufficient*

*Sufficiente / Sufficient*

*Buono / Good*

*Molto buono/Very good*

*Eccellente / Excellent*

**Risultati (i risultati sono presentati in modo chiaro e convincente, il numero e la qualità dei grafici e delle immagini sono adeguati)**

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***Discussion and Conclusions: correct interpretation of the results / advance of the results in the research field***

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***Overall evaluation***

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*Il candidato può essere ammesso all'esame finale ma la tesi richiede minime correzioni/integrazioni; non è necessaria un'ulteriore valutazione da parte del valutatore/The candidate can be admitted to the final examination but the thesis requires minor revisions; no addition review is required by the evaluator*

*Per essere ammessa all'esame finale, la tesi richiede significative integrazioni o correzioni; la versione rivista deve essere caricata dal dottorando entro 6 mesi e deve essere rivalutata dal valutatore/To be admitted to the final examination the thesis requires major revisions (additions and corrections); the revised version must be submitted within 6 months and must be newly reviewed by the evaluator*

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Buono e di grande importanza per l'ambiente e la salute umana. I risultati presentati sono risaldati da sette pubblicazioni in riviste internazionali.

**Relazione della ricerca con la letteratura: completezza e livello di organizzazione dello stato dell'arte**

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Ben organizzata

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l'aspetto applicativo della presente ricerca ha una grande rilevanza per l'ambiente e le imprese che lavorano nel campo dell'estrazione di oro, non solo in Ecuador ma anche in paesi vicini e/o dove si usino le stesse tecniche.

Puerto Real (Cádiz, Spagna), Date 06/02/2024

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Prof. Dr. Giorgio Anfuso

**Università della Calabria**  
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-  
**XXXVI\_CICLO**

**VALUTAZIONE DELLA TESI DI DOTTORATO/EVALUATION OF THE PhD THESIS**

*“Titolo tesi/PhD thesis title”*

**Candidato/Candidate:**

Nome/First Name **Carlos**

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- Insufficiente / Insufficient*
- Sufficiente / Sufficient*
- Buono / Good*
- Molto buono / Very good*
- Eccellente / Excellent*

**Descrizione del lavoro di ricerca**

***Research work description***

- Insufficiente / Insufficient*
- Sufficiente / Sufficient*
- Buono / Good*
- Molto buono/Very good*
- Eccellente / Excellent*

**Risultati (i risultati sono presentati in modo chiaro e convincente, il numero e la qualità dei grafici e delle immagini sono adeguati)**

***Results: convincing and clearly presented results / suitable number and quality of tables and figures***

- Insufficiente / Insufficient*
- Sufficiente / Sufficient*

- Buono / Good
- Molto buono / Very good
- Eccellente / Excellent

**Discussione e conclusioni (interpretazione corretta dei risultati, contributo all'avanzamento nel campo della ricerca)**

***Discussion and Conclusions: correct interpretation of the results / advance of the results in the research field***

- Insufficiente / Insufficient
- Sufficiente / Sufficient
- Buono / Good
- Molto buono / Very good
- Eccellente / Excellent

**Valutazione finale**  
***Overall evaluation***

- Il candidato può essere ammesso all'esame finale/The candidate can be admitted to the final examination*
- Il candidato può essere ammesso all'esame finale ma la tesi richiede minime correzioni/integrazioni; non è necessaria un'ulteriore valutazione da parte del valutatore/The candidate can be admitted to the final examination but the thesis requires minor revisions; no addition review is required by the evaluator*
- Per essere ammessa all'esame finale, la tesi richiede significative integrazioni o correzioni; la versione rivista deve essere caricata dal dottorando entro 6 mesi e deve essere rivalutata dal valutatore/To be admitted to the final examination the thesis requires major revisions (additions and corrections); the revised version must be submitted within 6 months and must be newly reviewed by the evaluator*

**Commenti e suggerimenti - Esplicitare con chiarezza le modifiche/integrazioni richieste**  
***Specific comments and suggestions - Clarify the corrections/additions requested***

*General/formal aspects:* The thesis is well presented and structured and the text is well written, although there are some errors in formatting and spelling. Additionally, there are acronyms that are not explained the first time they appear, making the reading a bit challenging. It is recommended that subheadings in the table of contents appear indented in relation to the main headings to enhance the readability of the index. There are some sentences that have been written in Spanish (see index, methodology, tables,...). It would be necessary to review the text to avoid this type of errors and grammatical errors.

*Quality of the doctoral thesis:* The number of scientific publications (7), the position of the doctoral student in them (all signed as first author) and their quality (5 out of the 7 publications in Q1 journals), show the quality of this doctoral thesis.

**Obiettivi di ricerca/Rilevanza delle domande di ricerca*****Research objectives / Relevance of research***

The objectives of this doctoral thesis are clear and relevant. They are well explained and presented. The significance of this doctoral thesis is undeniable. Gold mining in rivers and aquifers has held considerable economic and social importance in Ecuador throughout its history. However, this activity entails significant environmental impact and risks to human health. Therefore, assessing the effects that this activity may have on the environment and human health, as well as proposing strategies and new techniques to minimize the impact of gold mining, is a topic of great relevance. I consider that this thesis meets the requirements of novelty and high scientific quality that are necessary.

**Relazione della ricerca con la letteratura: completezza e livello di organizzazione dello stato dell'arte*****Report with literature: completeness and level of organization of the state of art***

The introduction is comprehensive and addresses all relevant topics for the thesis. It explains the state of the art regarding the use of mercury in gold extraction. It is well-structured, easy to read, interesting, and appropriate. In addition, it includes a good number of up-to-date references.

**Struttura della ricerca/ Metodologia/Struttura della tesi di dottorato: completezza e livello di organizzazione dell'analisi effettuata*****Structure of the research / Methodology / Structure of the PhD thesis: completeness and level of organization of the carried out analysis***

The research is comprehensive and well-structured. The methodology is sufficiently explained and the techniques used are appropriate for the stated objectives. The diagrams and tables that facilitate understanding of the work carried out are appreciated. It is explained in detail how the bibliographic search and the surveys were carried out. More information could have been included on how mining experts were selected to form the working group. The methodology relating to the analysis of mercury concentration, the exposure assessment and risk characterization, the identification of environmental impacts of Hg on water bodies, and the determination of techniques and improvement strategies for the management and treatment of mercury are also sufficiently detailed. The experts chosen to conduct the analysis of improvement techniques and strategies are all associated with the development of the doctoral thesis, either as supervisors or co-authors. I believe that including Table 12 in the doctoral thesis report is unnecessary, as it may suggest a specific expert selection for a particular objective. In reality, the work has been collaboratively undertaken by the doctoral student and the supervisors, which is a standard practice in a doctoral project.

**Risultati della ricerca/ Implicazioni per future ricerche/grado di innovatività e grado di trasferibilità al settore industriale*****Research results / Implications for future research / degree of innovation and degree of transferability to the industrial sector***

The results are thoroughly developed and explained, accompanied by tables and figures that enhance comprehension. They directly align with the stated objectives, and the level of transferability is high. The outcomes of this doctoral thesis, coupled with those of similar studies, have the potential for significant socioeconomic impact in Ecuador. It is advisable to enhance the quality of some images.

City of Seville, 05 February 2024

Paula Mapelli Brahm

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