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# Risk Assessment of Mining Environmental Liabilities for Their Categorization and Prioritization in Gold-Mining Areas of Ecuador

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**Abstract:** Mining environmental liabilities (MEL) are of great concern because of potential risks to ecosystems and human health. In this research, the environmental risk ($R_I$) related to MEL existing in three artisanal and small-scale gold-mining areas of Ecuador was evaluated. For this purpose, data of 167 MEL including landfills, mining galleries, tailing deposits, and mineral processing plants from Macuchi, Tenguel–Ponce Enriquez, and Puyango mining areas, were analyzed. The risk assessment related to the presence of waste deposits was carried out based on the methodology proposed by the Spanish Geological Survey. Moreover, the procedure outlined in the Environmental Risk Assessment Guide of the Ministry of Environment of Peru for nonwaste deposits was applied. The highest $R_I$ values were identified in Puyango and Tenguel–Ponce Enriquez. Thus, they were both categorized as priority control areas requiring intervention and rehabilitation plans. The MEL that require a high level of intervention include waste deposits and mine entrances associated with potentially toxic elements. Moreover, the point risk maps showed that rivers in the studied areas have a potential pollution risk. This study provides risk levels associated with MEL in mining areas from Ecuador. This information could be used for environmental management and pollution mitigation.

**Keywords:** mining pollution; potentially toxic elements; risk management; abandoned mining areas; mining waste deposits

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**Citation:** Salgado-Almeida, B.; Falquez-Torres, D.A.; Romero-Crespo, P.L.; Valverde-Armas, P.E.; Guzmán-Martínez, F.; Jiménez-Oyola, S. Risk Assessment of Mining Environmental Liabilities for Their Categorization and Prioritization in Gold-Mining Areas of Ecuador. *Sustainability* **2022**, *14*, 6089. https://doi.org/10.3390/su14106089

Academic Editors: Longjun Dong, Yanlin Zhao and Wenxue Chen

Received: 11 April 2022
Accepted: 13 May 2022
Published: 17 May 2022



## 1. Introduction

Mining environmental liabilities (MEL) are elements such as facilities, infrastructures, surfaces affected by spills, disturbed watercourses, machine shops, tool storages, ore storages, mining waste deposits or stockpiles currently located in abandoned mines that pose a permanent potential risk for human health and the environment [1–3].

The absence of clear regulations has led the accumulation of MEL in mining zones worldwide. There are polluted areas due to the mining activities that have been carried out for centuries in different countries such as Peru [1–4], Mexico [5], Chile [6], South Africa [7], Ghana [8], Slovakia [9], Korea [10], Spain [11], and Ecuador [12–16]. Moreover, numerous MEL have been reported in Latin American countries such as Bolivia, Chile, Colombia, and Peru [17].

In most cases, tailings dams are MEL that represent significant ecological risk because it is feasible that they release potentially toxic elements (PTE) such as As, Cd, Cu, Zn, and Mn into the nearby water sources. These contaminated water resources are often used for crop irrigation or for human consumption, creating a serious pollution issue.

Tailing dams pose a potential risk to the environment and the safety of people due to the characteristics of the wastes and the intensive storage [18]. The poor management of mining waste has triggered the failure of dams with catastrophic consequences for the environment, as reported in Minas Gerais—Brazil [19,20], Aznalcóllar—Spain [21], and Karamken—Russia [22].

Several papers have been written about tailings management and mining disposal in recent years, describing the soil contamination, groundwater, and sediment problems [23,24]. These studies provide information about the evaluation of the possible side effects of the contamination of a mining site and its potential influence on the quality of the environment and people's health [7,25,26]. However, despite the associated problems of MEL, there is scarce research in Latin America that aims to provide the risk levels derived from the vicinity of abandoned mining facilities.

A timely risk assessment may help to identify problematic MEL by estimating the probability and severity of the consequences in several scenarios [25], helping to prioritize the MEL intervention and the strategies for environmental management [27]. Accordingly, the environmental risk evaluation is a process that comprises the measurement of the possible negative impacts resulting from the exposition of one or several factors of environmental stress. These stress factors correspond to physical, chemical, and biological entities that may cause damage to the ecosystem [28].

According to Alberruche del Campo et al. [29], the methods of the environmental risk analysis that use evaluation matrices are the ones that best adapt to the objectives of establishing action priorities in territories with a large number of MEL. Nevertheless, for the vast majority of MEL information is scarce, preventing detailed assessments. As an alternative to this problem, the Spanish Geological Survey has developed a methodology called Simplified Risk Assessment. This method is based on an MEL inventory and is supported by available technical and scientific information, i.e., topographic maps, aerial images, geological maps, unit maps, hydrogeological, geochemical maps, land use, distance to population centers and the state of conservation of the ecosystem among others that rank MEL. Once the MEL that requires further attention have been identified, fieldwork should be conducted to collect detailed information so that the remediation or rehabilitation project is realistic and appropriate for the site of interest.

There is a considerable quantity of MEL in Ecuador in three well-known mining districts where the MEL were inventoried, such as the Macuchi, Tenguel–Ponce Enriquez and Puyango. These areas are considered as mining zones of special relevance in terms of artisanal and small-scale gold-mining activity in Ecuador. Nevertheless, there is no available data about the risk level these waste facilities cause to the environment and the exposed population's health. In this context, this research aims: (a) to estimate the associated risk of MEL in each mining district and (b) to categorize and prioritize MEL that require immediate attention based on the contamination they can pose and their effects on the environment and the population. This information could be utilized in future management strategies to mitigate the environmental contamination related to the mining sites' abandonment and contribute to the sustainable development of the population and the environment.

## 2. Materials and Methods

### *2.1. Study Area*

The research focuses on three significant artisanal and small-scale gold-mining (ASGM) districts in Ecuador, which belong to Macuchi, Tenguel–Ponce Enriquez and the Puyango River basin (Figure 1). Macuchi is in the Cotopaxi province and comprises an area of 16 $km^2$ (Figure 1a). Tenguel–Ponce Enriquez is situated between the Guayas and Azuay provinces; it has an area of 192 $km^2$ (Figure 1b). The Puyango River basin is located in the El Oro and Loja provinces and has a surface of 1924 $km^2$ (Figure 1c). The Puyango-Tumbes basin is one of the most critical watersheds in South America [30].

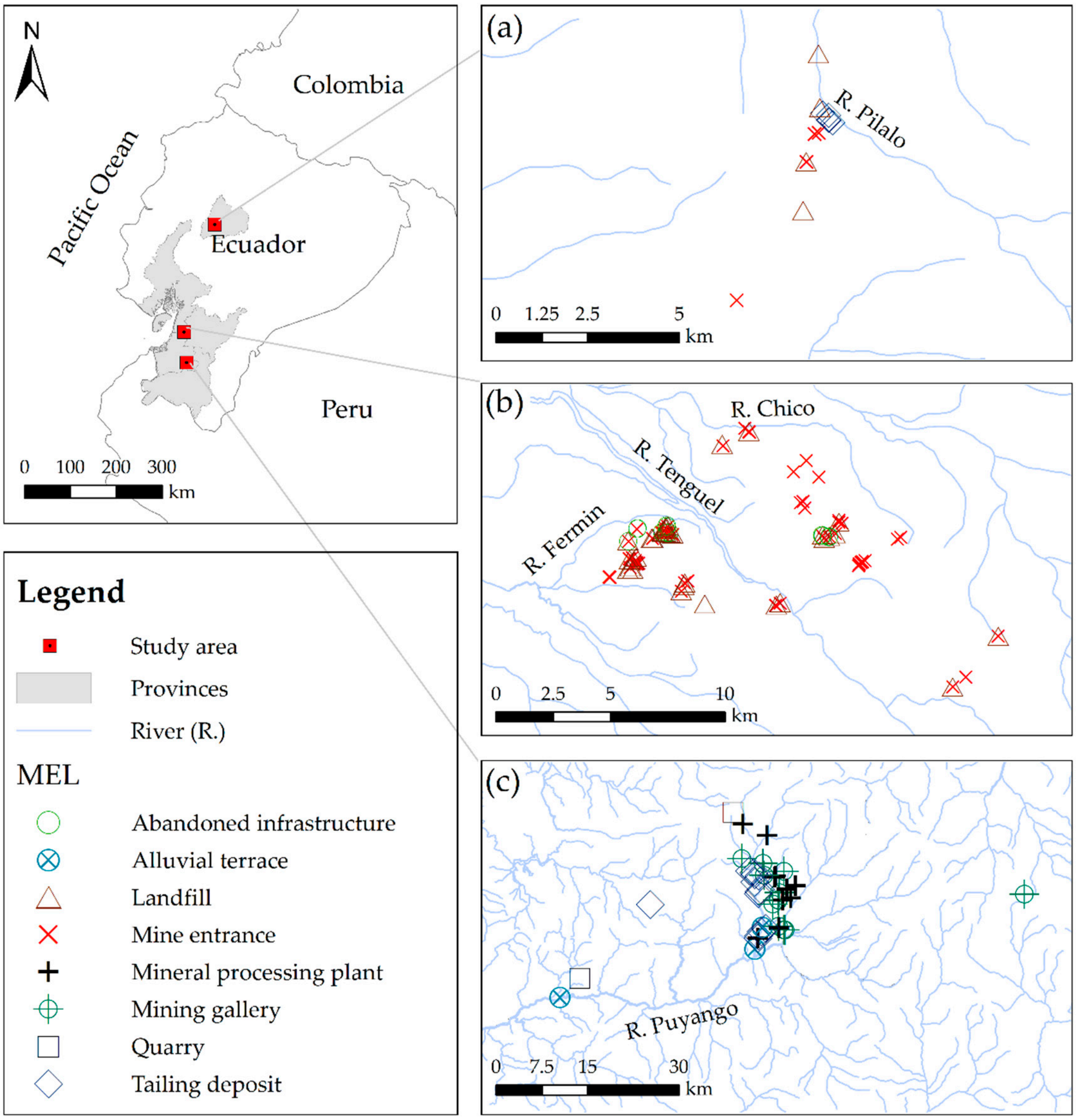


**Figure 1.** Location map of the study area and position of mining environmental liabilities (MEL). The MEL were in the mining districts of: (**a**) Macuchi; (**b**) Tenguel–Ponce Enriquez; (**c**) Puyango.

Intense mining and mineral processing activities (mainly located near rivers) have been reported in the three study areas [31], in addition to the agriculture and livestock activities [13,32]. The improper management of mining disposal, mainly from illegal mining, has derived from the accumulation of MEL and has significantly environmentally affected the ecosystem [13,33,34].

Previous research performed in the areas of interest reported the presence of PTE in several environmental facilities (Table S1, Supplementary Materials) as well as the potential risk of damage to the ecosystem and the population [35]. For example, in Macuchi, concentrations of PTE that exceed the maximum allowable limit (MAL) established in the Ecuadorian standard for water and soil have been reported [36]. At the same time, high levels of PTE, mainly As, in shallow water and river sediments have been reported in Tenguel–Ponce Enriquez and Puyango [12,15,34,37]. The PTE present in the contaminated areas, besides degrading the ecosystem, can enter the human body through different routes of exposure [38,39], affecting the area's residents' health [40,41].

*2.2. Data Collection*

A total of 167 MEL reported by the Ministry of Environment of Ecuador [30,36,42] were used in this study. The MEL included mine dumps, tailing dams, treatment plants, mining works, and abandoned facilities (Figure 1). Table 1 shows the number of MEL identified in each studied area. One of the most important MEL located in Macuchi and Tengel—Ponce Enriquez correspond to abandoned landfills and mine entrances. On the other hand, galleries and abandoned tailings deposits predominate within the Puyango area.

**Table 1.** Mining environmental liabilities reported in the studied areas.

| MEL | Macuchi (*n* = 14) | Tenguel–Ponce Enriquez (*n* = 111) | Puyango (*n* = 42) |
|---|---|---|---|
| Landfills | 4 | 34 | - |
| Mining galleries (Mines) | - | - | 14 |
| Mine entrances | 5 | 64 | - |
| Tailings deposits | 5 | - | 12 |
| Abandoned infrastructure | - | 13 | - |
| Mineral processing plants | - | - | 11 |
| Alluvial terrace | - | - | 3 |
| Quarries | - | - | 2 |
| Landfills | 4 | 34 | - |
| Mining galleries (Mines) | - | - | 14 |

*n* = number of MEL reported in the study area [30,36,42].

*2.3. Risk Assessment*

A simplified risk assessment was performed for the MEL following the procedure shown in Figure 2. For this purpose, the probability ($I_P$) and severity indices ($I_S$) associated with each MEL were calculated. In the case of mining waste deposits, the risk assessment was carried out using the methodology proposed by the Spanish Geological Survey [29]. For the rest of the MEL (nonwaste deposits), the procedure outlined in the Environmental Risk Assessment Guide of the Ministry of the Environment of Peru was followed [43]. The cartographic information was processed using Geographic Information Systems (GIS) through ArcMap 10.8.1 to identify the areas that represent a greater risk of affecting the population and ecosystem. This information allows proposing management actions for the MEL identified as significant concerns in each evaluated area.

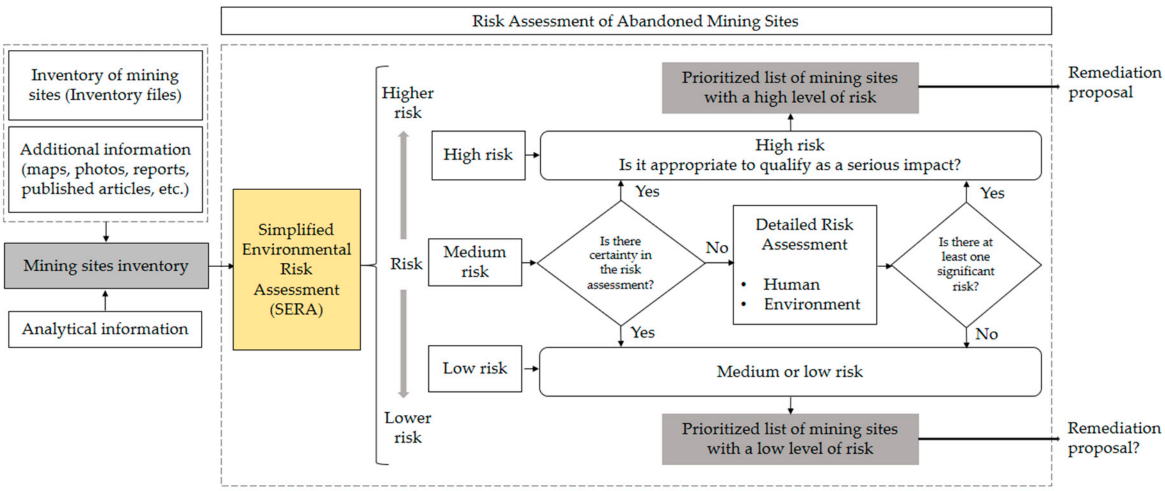


**Figure 2.** General scheme for simplified risk assessment of abandoned mining sites proposed by the Spanish Geological Survey [29].

2.3.1. Risk Scenarios

The risk characterization was conducted for four scenarios (S1–S4) identified as a priority in the present study (Figure 3). Two scenarios were considered for the risk assessment associated with the mining waste deposits: (i) S1—shallow waters are affected by the possible generation of acid mine drainage; and (ii) S2—population health is affected due to direct contact with MEL. In addition, two additional scenarios were considered for the MEL, such as galleries, mine entrances, infrastructure, processing plants, alluvial terraces, and abandoned quarries. Both scenarios potentially impact water bodies, urban areas, and agricultural areas: (iii) S3—contaminated water transportation or acid mine drainage; and (iv) S4—the drag of contaminated sediments.

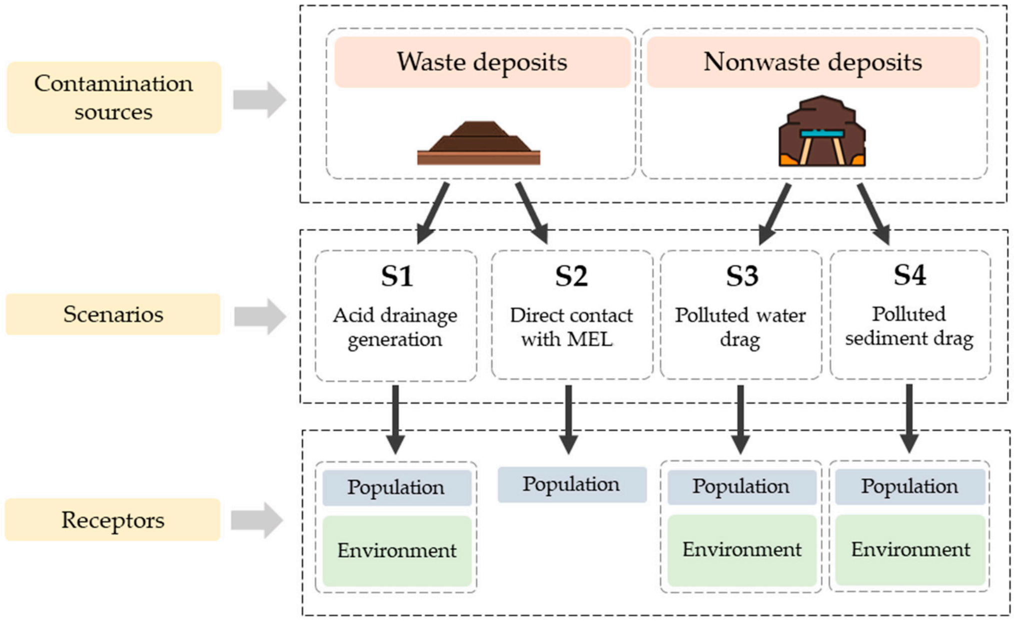


**Figure 3.** Scheme of risk assessment scenarios.

The probability ($I_P$) and severity ($I_S$) indices were rated on a scale from zero to five, being: very low (≥0 and <1), low (≥1 and < 2), medium (≥2 and <3), high (≥3 and <4), and very high (≥4 and ≤5). The environmental risk estimation was obtained by multiplying the probability of occurrence ($I_P$) by the severity of the consequences ($I_S$). The last one included studying the types of receptors: the population effects and the natural environment [27]. Therefore, based on the $I_P \times I_S$ products, three grades of qualification for the risk ($R_I$) were distinguished: low risk ($0 \leq R_I \leq 5$), medium risk ($6 \leq R_I \leq 15$), and significant risk ($16 \leq R_I \leq 25$) [27,43].

2.3.2. The Probability Index ($I_P$)

The probability index for S1 was calculated considering the proximity factor to water bodies ($P_R$), the toxicity factor of the generated waste ($F_{TOX}$), and the factor of unprotected surface ($F_{SD}$), according to Equation (1) [29].

$$I_P\ (S1) = P_R \times F_{TOX} \times F_{SD} \quad (1)$$

The valuation criteria of $P_R$ are shown in Table S2. $F_{TOX}$ = 5 was established for the deposits with pH < 6.5 and the presence of acid mine drainage or heavy metal(loid)s. For the waste deposits with pH between 6.5 and 8.5 in its leachate, an $F_{TOX}$ = 0.5 was rated. Moreover, $F_{SD}$ was calculated by multiplying the exposed area of the waste structure (in ha) by a 0.5 factor, according to the methodology used. The exposed area considered for each deposit was 1 ha.

For the S2 scenario, $I_P$ was quantified using Equation (2), which includes the pollutants direct contact concentration factor ($F_{CCD}$), waste deposits accessibility factor ($F_{ACC}$), and residential area proximity factor ($P_{RR}$).

$$I_P\ (S2) = F_{CCD} \times F_{ACC} \times P_{RR} \tag{2}$$

For the S2 evaluation, the total concentration values of heavy metal(loid)s (As, Cd, Cr, Hg, Ni, and Pb) reported in previous studies in soils and sediments (Table S1) were considered. For the MEL where the heavy metal(loid) concentration in soils was below the MAL of the Ecuadorian legislation [44], a concentration factor $F_{CCD} = 0$ was assigned, and for those which exceeded the MAL, $F_{CCD} = 5$ was allotted. Additionally, the valuation of $P_{RR}$ and $F_{ACC}$ is presented in Table S2. The criteria from Table 2 were used for the probability estimation ($I_P$) of S3 and S4. Both scenarios measure the effects of MEL presence in the population and natural environment.

**Table 2.** Assessment criteria for probability index ($I_P$) determination of scenario S3 and S4.

| Criteria | $I_P$ Value |
|---|---|
| Occurrence of the scenario continuously or daily | 5 |
| Scenario can happen within a week to a month | 4 |
| Scenario can happen within a month to a year | 3 |
| Scenario can happen within one to five years | 2 |
| Scenario can happen within a period greater than five years | 1 |

2.3.3. The Severity Index ($I_S$)

The severity index (Is) for the S1 scenario evaluated the effects on the population $I_S$(S1PO) (Equation (3)) and in the natural environment $I_S$(S1NA) (Equation (4)).

$$I_S\ (S1PO) = 0.5P_{EX} + 0.5(F_{SUP-PO} \times V_P) \tag{3}$$

$$I_S(S1NA) = F_{SUP-NA} \times V_E \tag{4}$$

A population (*n* > 50) exposed to toxic elements by water consumption was considered ($P_{EX} = 5$). The exposition factor ($F_{SUP}$) was established by considering the receivers' distance to the mine waste deposit using the criteria in Table S3 ($F_{SUP-PO}$ for the population and $F_{SUP-NA}$ for the natural surroundings). Finally, the used criteria for evaluating population vulnerability ($V_P$) to the ingestion and/or direct contact with contaminated surface water and the natural environment to contamination with effluent from reservoirs ($V_E$) are presented in Table S3 with the $F_{SUP}$ valuation criteria. On the other hand, in the S2 scenario, the impact on the population $I_S$(S2) was estimated according to the criteria shown in Table 3.

**Table 3.** Assessment criteria for severity index ($I_S$) determination of scenario S2.

| Criteria | $I_S$ Value |
|---|---|
| Uses with very high associated severity: marginal villages, children's parks | 5 |
| Uses with high associated severity: intensive recreational use (sports activities), isolated single-family homes | 4 |
| Uses with moderate associated severity: urbanized residential areas, nonintensive recreational use (trails, viewpoints) | 3 |
| Uses with low associated severity: agricultural and forestry activities | 2 |
| Uses with very low associated severity: other uses (commercial, industrial) with very low exposure | 1 |

For the S3 and S4 scenarios, the severity index ($I_S$) for the population ($I_S$(S3PO) and $I_S$(S4PO)) and natural environment ($I_S$(S3NA) and $I_S$(S4NA)) was estimated according to the impact classification for the population and environment ($G_{PO/NA}$) (Equation (5)).

$$G_{PO/NA} = C + 2P + E + V_{PO/NA} \tag{5}$$

where C is the number of pollutants emitted to the environment, P is the dangerousness of the residue, E is the extension of the environmental impact, $V_{PO}$ is the vulnerability to the affected population, and $V_{NA}$ is the conservation state of the assessed environment. The values of the factors used in the $I_S$ calculation for scenarios S3 and S4 are shown in Table S4.

## 3. Results

### *3.1. Risk Characterization*

Calculated risk values results for S1–S2 and S3–S4 are presented in Tables S5 and S6, respectively.

#### 3.1.1. Macuchi

Figure 4 shows the point risk map for the presence of MEL in the Macuchi area. In total, 93% of the MEL were identified in this region, representing a medium risk for the population and the natural environment. The risk values ranged from $6 \leq R_I \leq 15$. Figure 4a shows the abandoned landfills located at distances of >500 m from waterways, residential areas, and territories of environmental interest with a low probability of affectation. Nevertheless, in the surroundings of the Pilalo river, where the tailings are found, the affectation risk to the population from direct contact and contaminant effluents increases. This rise is because there exists a higher probability of affectation to the water bodies and the health of the people who receive that water. The highest risk valuation of affectation was obtained for the population in scenario S1 ($10 \leq R_I \leq 15$), however, these values only reach a medium-risk classification and not a high-risk one. This risk is caused by the mentioned tailings dams with acid drainage and heavy metal(loid)s, which exceed the MAL of Ecuadorian legislation. On the other hand, in scenario S2, 11% of the MEL presented a low risk, while 89% reported a medium risk for the population ($6 \leq R_I \leq 9$), see Figure 4b. Finally, the S3 and S4 scenarios resulted in a medium affectation risk for the people ($9 \leq R_I \leq 15$) and for the natural environment ($6 \leq R_I \leq 15$), as shown in Figure 4c,d.

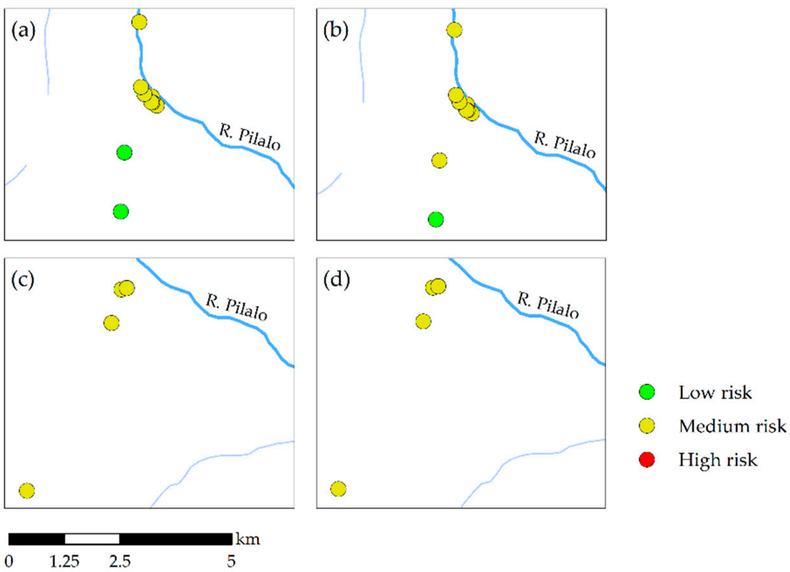


**Figure 4.** Point risk map for scenarios: (**a**) S1 for population and environment; (**b**) S2 for population; (**c**) S3 for population and environment; (**d**) S4 for population and environment in Macuchi area.

According to the MEL inventory [36], 60% of mine entrances studied in the sector do not present water and sediment accumulation. In this area, tailings deposits are the MEL of major concern for the population and ecosystem due to the potential risk of contamination with heavy metal(loid)s to the Pilalo river, which is used as a water supply by the residents of the nearby communities.

### 3.1.2. Tenguel–Ponce Enriquez

In the zone of Tenguel–Ponce Enriquez, no tailings deposits were reported. Approximately 31% of the MEL correspond to landfills, from which 79% represented a medium risk of affectation for the population and the environment in scenario S1 (Figure 5a). The risk ranges of this scenario were medium for the residents of the sector ($8 \leq R_I \leq 12$) and for the natural environment ($6 \leq R_I \leq 9$). The sites that presented a low risk corresponded to landfills located between 250–800 m from the waterways.

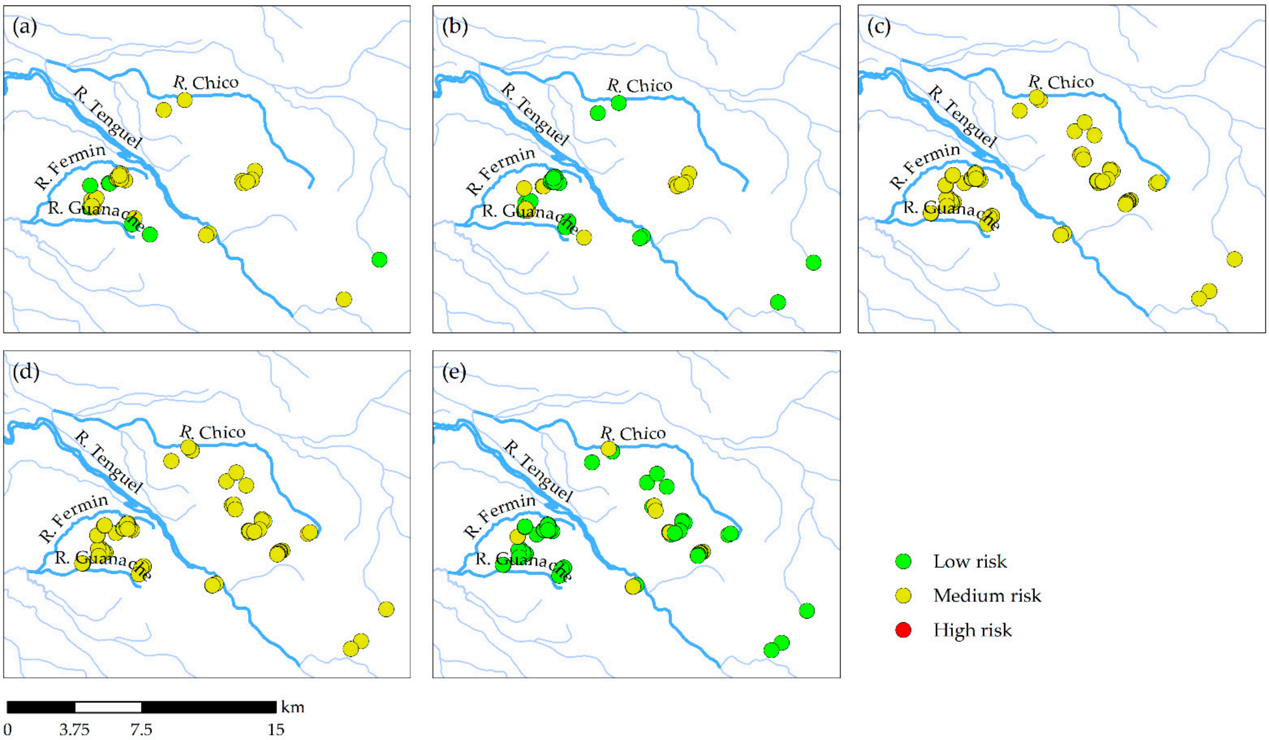


**Figure 5.** Point risk map for scenarios: (**a**) S1 for population and environment; (**b**) S2 for population; (**c**) S3 for population and environment; (**d**) S4 for population; (**e**) S4 for environment in Tenguel–Ponce Enriquez area.

In the S2 scenario (Figure 5b), approximately one-third (35%) of the landfills represented a medium affectation risk for the population with an $R_I = 6$ index. The MEL with a low-risk index were found at distances greater than 2 km from the communities of the sector. On the contrary, in the S3 scenario, the affectation risk was medium for both the population and the environment (Figure 5c). The values were $R_I \geq 9$ and $R_I \leq 15$ for the population and $R_I \geq 6$ and $R_I \leq 15$ for the natural environment. Similar results were obtained in the S4 scenario, in which all evaluated MEL presented a medium affectation risk for the population (Figure 5d). The risk for the natural environment (Figure 5e) was also medium ($R_I = 12$) in 18% of the analyzed sites, while 82% of the MEL showed a low affectation risk ($R_I = 3$). Moreover, the risk analysis allowed the identification of a significant quantity of MEL that are in the proximities of the Chico, Tenguel, Fermin, and Guanache rivers, a fact that represents a persistent threat of contamination by heavy metal(loid)s to the water sources, besides being a potential risk for the people and ecosystem.

3.1.3. Puyango

In Puyango, a significant quantity of abandoned tailings was reported (72% of the identified tailings in the three studied mining districts). As a result, 77% of the tailing deposits of the S1 scenario showed a medium affectation risk for the people and ecosystem (Figure 6a), with values of $8 \leq R_I \leq 12$ for the population and with a range of $6 \leq R_I \leq 9$ for the natural environment. A total of 33% of the tailings resulted in low-risk affectation values for the population and the environment with $R_I \leq 4$ due to the distances between these MEL and the river channels of the area being greater than 300 m. In the S2 scenario (Figure 6b), 100% of the tailings resulted in a medium affectation risk to the population's health, with a value of $R_I = 6$. The evaluation of S3 and S4 scenarios showed a medium risk for the people and the environment, as presented in Figure 6c,d. The risk index values of the S3 scenario were $R_I = 15$, while for the S4 scenario they were $R_I = 12$. For the assessment of each proposed scenario, all the MEL of the area that contained heavy metal(loid)s in concentrations that exceeded the Ecuadorian environmental standard were considered. The point risk maps indicated that approximately 98% of the MEL are located near water bodies such as the Amarillo, El Salado, and Puyango rivers and the Arcapamba creek.

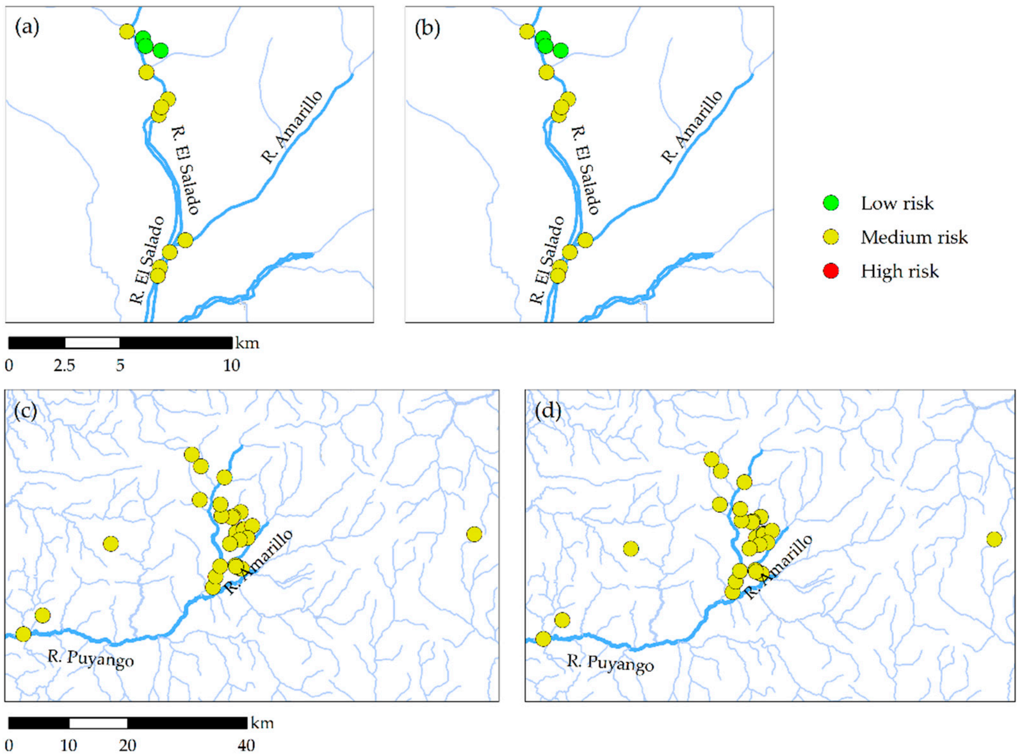


**Figure 6.** Point risk map for the scenario: (**a**) S1 for population and environment; (**b**) S2 for population; (**c**) S3 for population and environment; (**d**) S4 for population and environment in the Puyango area.

The results show that the pollution sources of major concern for the population and the environment are the mine entrances, landfills, and tailings deposits associated with the presence of acid drainage with a high content of heavy metal(loid)s. Moreover, the population near the tailings deposits and mine entrances may have health problems due to exposure to pollutants, released and mobilized from MEL, in the supply water.

## 4. Discussion

In the present study, the areas with the presence of deposits of abandoned waste (tailings and landfills) are Macuchi and Puyango, which reported a medium affectation risk in most of the analyzed sites in the S1 and S2 scenarios, which points out a potential risk that exposes the ecosystem and population. The presence of toxic elements such as heavy metal(loid)s in the MEL (that are released through different mechanisms to the environmental compartments) is causing the risk in the evaluated districts (Figure 7). Consequently, the ecosystem is highly affected by the presence of heavy metal(loid)s in shallow waters, soils, and sediments [15,45,46].

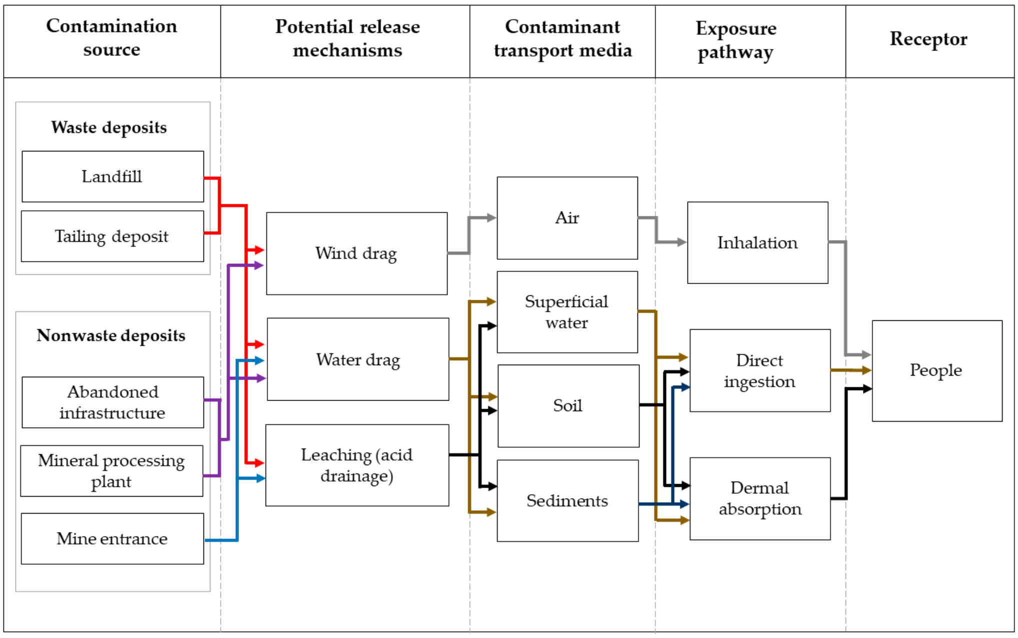


**Figure 7.** Conceptual site model for human health risk.

It is widely known that in the areas where tailing deposits exist, the concentration of heavy metal(loid)s in the soil is high due to the dispersion of the material particles and the drag of contaminants by the erosion processes [47]. The concentration of heavy metal(loid)s in the water in the three mining districts exceeds the MAL established by the Ecuadorian legislation. Additionally, the pH of the soils in the studied areas present acidity characteristics [30,42]. For example, effluents in tailing deposits with pH values of 2 and with concentrations of As (1.1 mg/L), Cd (4.9 mg/L), Cu (1103 mg/L), Fe (8422 mg/L), Pb (1.1 mg/L), and Zn (364 mg/L) are located in Macuchi [36]. Additionally, according to different studies, the detection of heavy metal(loid)s in shallow water and sediments is considered alarming in the zones of Tenguel–Ponce Enriquez and Puyango; a product of the direct or indirect discharges coming from the gold mining activities to the rivers [15,37,48,49]. This fact, therefore, increases the risk in the population and natural environment. The Puyango area may be particularly impacted since most of its MEL (98%) were found near water bodies, which may increase the presence of heavy metal(loid)s in surface waters, and therefore affect nearby populations and river users.

In Macuchi, the Pilalo river presents As, Pb, Cd, Cu, and Zn that exceed the MAL established in the Ecuadorian legislation of water and soils. In the area of Tenguel–Ponce Enriquez, the Tenguel river has Cu as its main pollutant and slight increases in As, Cd, Sb, Pb and Zn derived from gold-mining activities [50]. Moreover, the Fermin River has high concentrations of As, possibly due to the discharges made by the mineral processing plants of the area [37]. Jiménez-Oyola et al. [51] reported a severe ecological risk from As in the river sediments of Ponce Enriquez. On the other hand, Quishpe [46] identified that the Chico River presents average values of As higher than the MAL established in the environmental regulations for conserving aquatic wildlife in freshwater. In Puyango, the water bodies with greater affectation are the Calera and Amarillo rivers, where mineral processing has been carried out [45].

On an international level, a diverse study that evaluated the risk associated with the presence of MEL reported similar results to the ones obtained in the present research work. In San Luis Potosí, Mexico, the principal sources of toxic elements in the contaminated sites by MEL correspond to tailings deposits, dams, and slag deposits from which the pollutants can mobilize or be transported through the wind or runoff water and affect great soil extensions [5,52,53]. Moreover, in Zlata Idka–Slovenian, a study reported a high carcinogenic risk for the residents due to the high concentrations of As in soils, water, and vegetables [9]. Another case is Hualgayoc of Cajamarca, a mining district in Peru widely affected by the presence of MEL, which caused the contamination of agricultural soils with high contents of Pb (4683 mg/kg), Zn (724.2 mg/kg), Cu (511.6 mg/kg), As (3611 mg/kg), and Ag (33.4 mg/kg), exceeding the MAL established in the Peruvian legislation for agricultural soils [4]. In addition, around an abandoned mine of Hg in Asturias–Spain, exorbitant values of Hg were detected in the air, with concentrations up to 203.7 $\mu g/Nm^3$ [54]. Another example of MEL consequences is in South Korea, where most metallic mines have been abandoned, causing severe contamination cases [10]. Similarly, Ngole-Jeme and Fantke [7] reported high levels of heavy metal(loid)s such as As, Cd, Co, and Ni in soils in areas with the presence of abandoned tailing deposits in the mining city of Krugersdorp.

### *4.1. Potential Impacts of MEL on Human Health*

The present study identified that the major affectation related to MEL presence is produced on the population by the direct or indirect exposition to toxic elements contained in waste deposits. In general, in the evaluated sites, the MEL contaminants are released through several mechanisms: leaching and air and water drag and transportation through air, shallow water, soil, and sediments, which finally come into contact with receptors through different routes of exposure such as inhalation, accidental ingestion or dermal absorption (Figure 7). The primary means of exposure is generally contaminated water because it is used for consumption or recreational use. The approximate number of people exposed to the contamination in the evaluated mining areas is between 2400 and 7000 inhabitants. In Macuchi, 59% of families (approximately 2470 people) consume water from the rivers and springs [55]. In Tenguel–Ponce Enriquez, around 25% of the homes (approximately 5500 people) take water from the rivers and springs from the Gala, Tenguel, and Siete basins [10]. In Puyango, nearly 46% of the population (approximately 7135 people) does not have water from a public network [56]. This situation forces the inhabitants to obtain water from wells, rivers, channels, and rainwater. Moreover, the identified MEL in the study zone are without surveillance or protection. People can easily have direct contact with the contaminated waste, especially children, during recreative activities. Figure 7 shows a site conceptual model pointing to the sources of contamination, the transport mechanism of pollutants, and the routes of exposure of significant concern.

Various kinds of human effects caused by exposure to MEL have been reported by several authors worldwide [1,5,8]. Heavy metal(loid)s such as As and Pb, contained in MEL, are potentially toxic for human health and can cause carcinogenic effects in the population at long exposures [57]. Diverse adverse effects for health, such as bladder, kidney, lung, liver, and colon cancer, cardiovascular and neurological diseases, and diabetes, are attributed to As exposure in humans [58]. On the other side, intoxication by Pb has centered on children because they are more susceptible to the present adverse effects during growth and neurobehavioral development [57–59]. Therefore, the risk for human health is strongly related to human behavior, which depends on the activities carried out in the contaminated site. Thus, the risk for human health depends on the pollutants of the environmental system, the heavy metal(loid) toxicity or metalloid, the routes of exposure, and the risk receptors [60]. In this sense, limiting exposure is a key factor in diminishing the risk.

### *4.2. Mining—Environmental Regulation*

The environmentally responsible development of mineral resources is vital for the mining industry [61]. It is essential to consider the regulations and laws that guide the activities to be developed in an environmentally, economically, and socially sustainable way to promote sustainable development in favor of protecting the soil and land [62].

Adler Miserendino et al. [63] mention that the impacts, principally in the degradation of water quality and aquatic ecosystems caused by illegal mining and ASGM, result from deficiencies of the national regulatory framework. Moreover, factors such as the lack of capacity of local actors and internal political struggles contribute to the lack of integrated planning that ensures a postmining economy [64].

Furthermore, the lack of information and knowledge has had a significantly adverse effect on ASGM practices [65]. At the same time, the lack of technological investment in mining processes has potentiated significant impacts on hydric, soil, and air resource [66]. On an international level, the interventions to address the impacts of ASGM have commonly focused on the technological changes in mineral processing through eliminating the use of toxic elements [63]. For example, since 2010, the use of Hg in Ecuador has been forbidden in the gold recovery process. Nevertheless, informal miners still use amalgamation with Hg, and some of them even burn the amalgams inside their homes, exposing all of the members of the family to noxious fumes [67].

In so far as the environmental mining regulations in Ecuador, these are relatively new and still present deficiencies. For example, concerning MEL, unlike other countries such as Brazil, Peru, or Chile, Ecuador does not count with a legal instrument that allows the integral management of them. Additionally, regulation with a preventive and corrective approach is necessary. Moreover,, so is resource assignation permitting control on time and minimizing the generation of MEL in the mining areas [17].

The Mining Law of Ecuador [68] establishes that the mining concession holders and beneficiation plants should incorporate environmental management plans until closure and definitive abandonment of the mining project. In addition, it is found that the closing of operations and rehabilitation of affected areas should be a progressive process in the different stages of the project life cycle [69]. Therefore, the objective of rehabilitating mining zones is to make them safe, stable, nonpolluting, and self-sustainable for soil use after the activities [70,71]. Furthermore, closure and rehabilitation of the mines is an obligation for all the mining holders to prevent future contamination sites. Nevertheless, the subject of the environmental management plan is relatively new for the ASGM sector [72] and in practice still presents certain limitations. Finally, to limit the presence of illegal mining (closely related to environmental degradation), in 2014, illegal mining activities and environmental pollution were categorized as a felony according to the Integral Organic Criminal Code of Ecuador [73].

Despite the different legal instruments of the Ecuadorian environmental standard, there is a notorious deficiency in the associated regulations to recover degraded areas and manage environmental liabilities. Moreover, the ineffective application of the law is evident in many cases. This leads to thinking that an essential factor in the aspect of preservation of the environmental rights of nature and environment is apart from the legislation and regulations of the system, the ethical and moral quality of the system itself, and the people involved to correctly apply and obey the law so that the environmentally, socially, and economically sustainable development of the mining activity is not compromised. It is also important to consider that the main problem of artisanal miners is that there is no guide, such as a simplified rehabilitation plan, nor guidelines with simple techniques that avoid the costly requirements of rehabilitation [72].

### *4.3. Management and Public Policy: Suggested Actions*

The identified impacts in the present study are a legacy from the past. They are associated mainly to ASGM and the illegal mining carried out in the study areas since the end of the XIXth century [31]. The evident lack of regulation in mining activities and the lack of recovery actions (on time) of degraded areas have caused MEL accumulation. The same accumulation has propitiated pollutants' transport in the different environmental compartments, resulting in severe anthropogenic contamination [66].

Table 4 shows the strategies and proposed actions for the management of MEL that represent a high risk for the population and the environment. Puyango and Tenguel–Ponce

Enriquez were identified as priority control areas, that is, they require urgent intervention as well as restoration and rehabilitation plans. MEL that require a high level of intervention include waste deposits, mine entrances, and abandoned processing plants. To achieve ecological restoration of the sites, some actions can be adopted, such as those presented in some research that propose phytoremediation [46,74–76] or the creation of geoparks in areas that do not represent a significant risk for the population [77].

**Table 4.** Categorization of priority areas and proposed strategies for pollution control.

| MEL | Intervention Level | | | Proposed Actions |
|---|---|---|---|---|
| | High | Medium | Low | |
| Landfills | + | | × | Covering, sealing, and revegetation of deposits<br>Chemical and physical stability control and monitoring plan<br>Water, soil, sediment, biotic component and stability control, and monitoring plan |
| Mining galleries | | + | | Chemical and physical stability control and monitoring plan<br>Implementation of geotourism (museums and geoparks) in rehabilitated areas with low impact<br>Plugging of higher risk mine entrances or galleries |
| Mine entrances | + | × | | |
| Tailings Deposits | ×<br>* | | | Reuse/reuse/valorization of mining tailings<br>Covering, sealing, and revegetation of tailings deposits<br>Restoration plan and revegetation near the riverbanks<br>Water, soil, sediment, biotic component and stability control, and monitoring plan |
| Abandoned infrastructure | | | + | Construction of a community meeting place<br>Water, soil, sediment, biotic component and stability control, and monitoring plan |
| Mineral processing plants | * | | | Dismantling infrastructures<br>Chemical stabilization of soils<br>Control and monitoring of chemical stability of soils |
| Alluvial terrace | | * | | Treatment of the waters of affected rivers.<br>Restitution of flora and fauna<br>Physical and chemical stabilization of riverbanks |
| Quarries | | * | | Physical and chemical stabilization of soils<br>Revegetation of the areas<br>Restitution of fauna<br>Water, soil, sediment, biotic component and stability control, and monitoring plan |

(×) Macuchi MEL; (+) Tenguel–Ponce Enriquez MEL; (*) Puyango MEL.

Besides the restoration and rehabilitation plans, it is necessary to have continuous control and monitoring plans for the areas to ensure the correct recovery and restitution of the land. It is important to know that the restoration processes of the degraded mining areas are complex and require joint work between different institutions: mining companies, planners, investors, institutions, and local communities [78], with a common vision focused on sustainability. A lack of common vision can produce inefficacy in management plans [64]. Moreover, it is necessary to point out the importance of having clear public policies that encourage those involved to put social and environmental responsibility into practice during the execution of mining projects.

Regarding abandoned tailings, a sustainable alternative to manage these MEL is their reutilization and reuse in the construction industry [79,80]; tailings have been reused to fabricate bricks, ceramic materials, and cement [81–83]. Therefore, efforts should be focused on searching for the sustainable utilization of mining waste, promoting a circular economy. Finally, a risk communication plan must be in place to minimize the population's exposure to the potentially dangerous areas identified in this assessment.

## 5. Conclusions

This work provides a preliminary assessment of the risk associated with the presence of mining environmental liabilities in three artisanal and small-scale gold-mining areas of Ecuador. According to the results, Puyango and Tenguel–Ponce Enriquez appears to be the most affected mining areas by the presence of MEL, mainly waste deposits and mine entrances. Landfills, tailing, and mine entrances present a medium risk for the people and the environment due to the content of potentially toxic elements. Around 2% of MEL are far away from the population and water bodies, therefore, the result of the risk was low ($R_I < 3$) for the people and the ecosystem. The point risk maps showed that the rivers with major risk of contamination are: Pilalo in Macuchi; Chico, Tenguel, Fermin, and Guanache in

Tenguel–Ponce Enriquez and Amarillo, El Salado, and Puyango in the Puyango River basin. To our knowledge, the impacts caused in the studied areas are a product of the inherent contamination due to illegal mining activities since the end of the XIXth century. In this sense, it is necessary to remediate the polluted sites and practice continuous monitoring to restore the ecosystems properly. In addition, the population's exposure must be restricted from high-risk areas through a communication plan of the risks. Additionally, it is urgently necessary to investigate the bioavailability of heavy metal(loid)s in the environmental compartments, as well as their impact on the environment and people's health. This study highlights the need to implement regulations for the management of mining environmental liabilities in Ecuador to protect the environment and residents of mining communities, ensuring sustainability for the ecosystem, populations, and the mining industry.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14106089/s1, Table S1: Maximum and minimum concentrations of heavy metals in water, soil, and sediment samples from each study area, Table S2: Assessment criteria of parameters for probability index determination of scenario S1 and S2, Table S3: Assessment criteria of the severity index (Is) of scenario S1, Table S4: Assessment criteria of parameters for the severity index determination of scenarios S3 and S4, Table S5: Risk assessment results: scenarios S1 and S2, Table S6: Risk assessment results: scenarios S3 and S4.

**Author Contributions:** Conceptualization, B.S.-A. and S.J.-O.; data curation, B.S.-A.; formal analysis, B.S.-A. and S.J.-O.; investigation, P.L.R.-C., P.E.V.-A. and D.A.F.-T.; methodology, B.S.-A., S.J.-O. and F.G.-M.; supervision, P.L.R.-C., S.J.-O. and F.G.-M.; writing—original draft, B.S.-A., D.A.F.-T., P.E.V.-A. and S.J.-O.; writing—review and editing, P.L.R.-C. and F.G.-M.; project administration, P.L.R.-C. and S.J.-O. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

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