# Analysis of Environmental Sensitivity in Gold Mining through the AHP Methodology: Case Study of the Mina Walter Area of the Montecristo - Bolívar Municipality

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## Abstracts

The ecosystem of the mining area of Mina Walter, located in the village of the Municipality of Montecristo, Bolívar, exhibits notable environmental complexity given its historical and geographical context. To measure this complexity, combinations of methodologies focused on assessing the degree of environmental sensitivity were employed, using the Analytic Hierarchy Process (AHP), the Individual Aggregates Method, and the Environmental Sensitivity Index (ESI). This choice is based on the need to integrate multiple opinions to minimize subjectivity in the assessment and ultimately identify the ecosystem's susceptibility accurately. This approach allows for more informed decision-making to facilitate the implementation of efficient actions to mitigate or control negative impacts. The interactions between biotic, abiotic, and socioeconomic factors were analyzed, as well as how they are affected by gold extraction and other associated local activities. The results revealed an ESI on a scale of 0.28 to 0.48, classified as high, medium, and low for the evaluation of 10 criteria, determining that the loss of fauna and water resource quality present a high level. This is justified by the connection of the study area with the protected zone of high environmental interest adjacent to the area of influence. This combination of three methodologies can be replicated and adjusted in other areas to achieve a comprehensive analysis of zones with little geographical and environmental information.

**Keywords:** Environmental sensitivity, gold mining, environmental impact, ecosystems, gold, Analytic Hierarchy Process.

## 1. INTRODUCTION

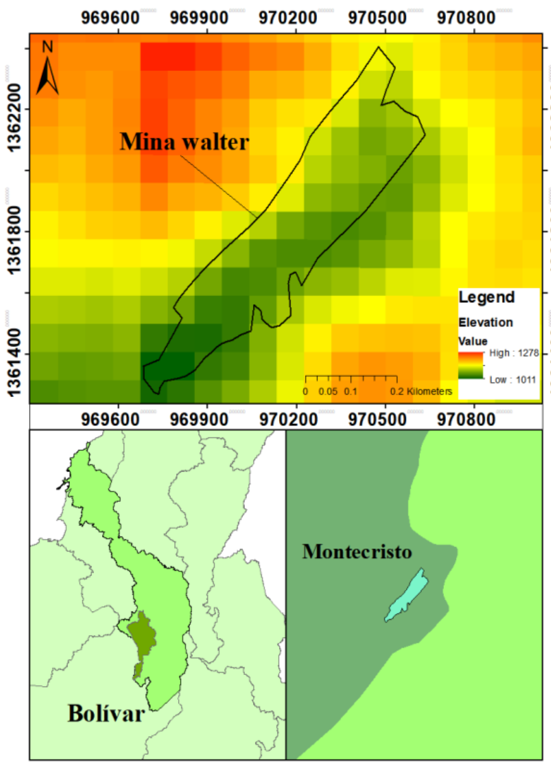
Mina Walter is a gold mining area located in the Montecristo municipality, department of Bolívar. Throughout history, this region has been recognized for its mining potential. According to data provided by the National Mining Agency [1]for the year 2023, the gold mining sector represented 0.37% of Colombia's Gross Domestic Product (GDP). Gold mining in this area has generated employment and contributed to the economic development of the local community. However, this mining activity poses significant environmental challenges that underscore the sensitivity of the ecosystem, such as the lack of open and updated data that hinders the effective regulation of mining activity, which impacts the surrounding natural environment [2]. In addition, difficult access to the area, the presence of illegal groups, land use and other variables hinder efforts to efficiently manage the use of resources.

In recent years, environmental sensitivity has gained relevance because it encompasses the capacity of ecosystems and geographic areas to react and adapt to changes in their environment [3]. Nevertheless, each corner of the planet shows a unique sensitivity, influenced by a variety of elements ranging from local biodiversity to soil and water quality, as well as the fragility of ecosystems and the presence of endangered species. [4].The expression of such sensitivity is manifested through environmental zoning, which plays a crucial role in environmental planning [5].

In the environmental context, countries such as China, Russia and Brazil have adopted the AHP methodology to calculate the level of impact of ecosystems highly affected by anthropogenic activities by combining it with the use of Geographic Information Systems [4]. The purpose is to determine which environmental variables should be prioritized and which areas require greater attention for their conservation, by calculating the Environmental Sensitivity Index (ESI), and to be able to visualize them through a map. Since the environmental impact affects multiple variables, such as slope, population, soil type, deforestation, water quality, climate, land use and conflict, AHP offers a more complete representation by considering all these criteria simultaneously [6]. In addition, by requiring the participation of a panel of experts who act as judges, accurate and objective results are ensured, guaranteeing a consistent evaluation in the area of interest [7].

The AHP methodology was chosen due to its ability to identify the sub-criteria that contribute to the sensitivity of an area to environmental disturbances [8]. This approach is essential for making informed decisions regarding the management and conservation of natural resources. The application of this methodology will have a significant impact on Mina Walter (Image 1). The objective of the research was to determine the level of environmental sensitivity of the gold mining area of Mina Walter in the Alto Caribona region, in the municipality of Monte Cristo, Bolívar, applying the AHP methodology.

Image 1. Study area




## 2. MATERIALS AND METHODS

### 2.1.Area of study

*Characterization of the study area*

The Mina Walter village is located in the Alto Caribona district, located in the municipality of Monte Cristo, in the Department of Bolívar, Colombia. This area belongs to the hydrographic sub-basin of Directos Bajo Cauca- Cga - La Raya, which flows directly into the Cauca River. According to the population projection by area and ethnic-racial affiliation carried out by the National Administrative Department of Statistics [9], it is estimated that in the municipality of Monte Cristo there is a population of close to 18 thousand inhabitants. However, it is important to note that the specific population of the sector known as Mina Walter has not been officially censused, so the estimates of the local population vary with respect to reality.

Regarding economic activities in Monte Cristo, mining, agriculture and livestock farming stand out as the main sources [10]. According to statistics provided by the Mining-Energy Planning Unit, zonal gold mining activity, combined with regional gold mining, represents 6% of total gold production at the national level [11]. Gold mining in the region has been the subject of dispute due to socio-environmental conflicts. On the one hand, the presence of illegal groups that exert influence in the mines has been reported [12]. On the other hand, questions have been raised about the legality and environmental sustainability of mining activity in this region [13].

In response to these challenges, various actions have been undertaken to find a solution to the mining problem in Monte Cristo. For example, a process of formalization of traditional miners was carried out through Decree 933 of 2013. In addition, dialogue has been promoted between the different actors involved with the aim of reaching an agreement that allows the development of responsible and sustainable mining [14]. To date, all mining fronts have the capacity to carry out their operations under the global mining title, as a result of this process of dialogue and agreements [12].

## 2.2.Data (Baseline)

According to the AHP methodology, it is crucial to carry out the collection of primary and/or secondary information for a comprehensive analysis. For this purpose, information was collected from the following databases:

- Institute of Hydrology, Meteorology and Environmental Studies (IDEAM): Areas susceptible to flooding, total water demand, Hydrographic zoning, among other layers.
- Environmental Information System ofColombia (SIAC): Land Cover and Protected Areas.
- Agustín Codazzi Geographic Institute (IGAC): Conflict over land use, vocation of land use, geology, base cartography of Colombia, among other layers.
- Regional Autonomous Corporation of Southern Bolívar (CSB): Mining reports, development plans, among other information.

In addition, other environmental studies were collected from private entities, covering analysis periods of more than ten years. The information collected was classified into three main categories of analysis, corresponding to 1) biotic data, 2) abiotic data, and 3) socioeconomic data.

## 2.3.AHP Application

*Assessment guidelines and influencing factors*

It is essential to know the problem thoroughly, that is, the options that are present and the variables that will affect the final decision that is desired to be reached. It is important that the participation of juries (panel of experts) includes people who are knowledgeable about the problem because the diversity of opinions will enrich the study [15]. Because the application of the AHP methodology is used for the analysis of natural resources in an area of mining interest in Colombia, it is relevant to mention that the guidelines for the selection of the most relevant environmental subcriteria are extracted according to the variables of greatest significance in the area of influence as established by the National Agency for Environmental Licensing (ANLA).

*Definition of criteria and subcriteria*

As a first step in the process of environmental zoning using the AHP methodology modified by the present authors, the evaluation criteria were selected, which correspond to the elements that define the objective and scope of the problem. Based on Arango [16], the biotic, abiotic and socioeconomic media were selected as criteria. The inclusion of these three is essential, since it allows environmental planners to evaluate the potential impact of human activities on the environment in a comprehensive manner and establish different levels of protection based on the characteristics of the territory.

In a subsequent stage, the most crucial variables of each environment that characterized the study area were selected. These variables, in turn, constructed the environmental subcriteria that the AHP methodology used in the evaluation process. The choice of these variables was based on information and data obtained from official sources, which identified the physical, biological and socioeconomic characteristics of the territory over the years, in accordance with the suggestions of Hou et al. [6]. Once this information was collected, the most pertinent variables were selected based on the objective of the zoning, which is to reveal the significant impact that gold mining has had on the environment of the study area.

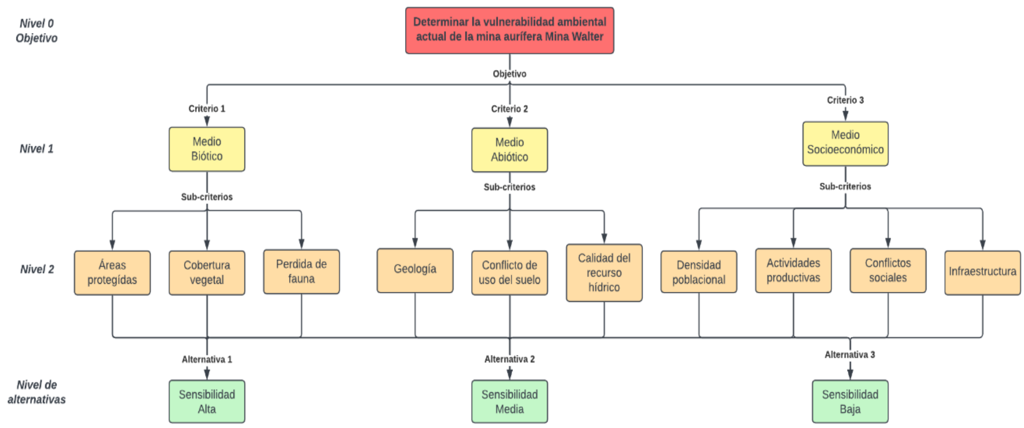
The most relevant environmental subcriteria in the study area were:

- Biotic: Protected areas, vegetation cover and loss of fauna.
- Abiotic: Geology, land use conflict, water resource quality.
- Socioeconomic: Population density, productive activities, social conflicts and infrastructure.

*Determination of priorities*

After representing the problem through the hierarchy, the priorities of the criteria, sub-criteria and alternatives were determined. The AHP approach involves organizing the elements in a hierarchical structure, which unfolds from top to bottom (Figure 2).

Figure 2. System hierarchy




Preferences for the elements (criteria, sub-criteria and alternatives) were determined based on the relevance of one element compared to another. This was achieved through the judgment of experts, who contributed their knowledge based on experience in the area of gold mining and/or environmental consulting. These experts evaluated the relationships of the sub-criteria for each specific criterion. To process their opinions, a survey was conducted where participants evaluated the criteria based on Saaty 's verbal scale.

In matrices, the verbal scale is repeated from the highest to the lowest value. This is because if the rating is done on the left side, criterion A predominates, while if it is done on the right side, criterion B predominates. For example, if criterion A is “absolutely more important” than criterion B, then voting is done on the left side. Conversely, if criterion B is considered “absolutely more important” than criterion A, voting is done on the right side (Table 1).

As previously mentioned, opinions were collected individually and processed using the individual aggregate methodology. This method is distinguished by its ability to collect the perceptions of experts without the need for them to physically meet in a specific location.

This feature is particularly valuable in situations where maintaining constant communication with experts is not feasible or practical [17]. Instead, each expert is asked to provide their opinion and evaluation based on their experience and knowledge, using the Saaty´s scale (Table 2) to convert these preferences into numerical values, which simplified the process. These opinions were then subjected to statistical analysis to calculate the relative weights of the sub-criteria and thus be able to integrate them into the AHP methodology evaluation process.

Table 1. Example of a voting matrix for judges.

| **Subcriterion** | **ME** | **MFM** | **IMF** | **MMI** | **Yo** | **MMI** | **IMF** | **MFM** | **ME** | **Subcriterion** |
|---|---|---|---|---|---|---|---|---|---|---|
| A | X | | | | | | | | | B |
| Subcriterion | ME | MFM | IMF | MMI | Yo | MMI | IMF | MFM | ME | Subcriterion |
| A | | | | | | | | | X | B |

Saaty scale: AMI (Absolutely more important), MFM (Very strongly more important), SMI (Strongly more important) and E (Equal).

Table 2. Saaty Scale.

| **EN** | **EV** | **Description** |
|---|---|---|
| 1 | Equal | Two sub-criteria are equally important |
| 3 | Moderately more important | One subcriterion is slightly more important than another |
| 5 | Strongly more important | One subcriterion is much more important than the other. |
| 7 | Very strongly more important | One subcriterion is significantly more masterable than another |
| 9 | Absolutely most important | One subcriterion is extremely more controllable than another |
| 2,4,6, 8 | Intermediate values between two underlying judgments (VI) | |

Note. EN: Numeric scale, EV: Verbal scale. Table adapted from Mendoza et al.,[17]

*Pairwise comparison matrix*

Using this matrix, the results of the experts' judgments are translated from a verbal scale to a numerical one, reflecting in a simple and quantitative way which elements are dominant. To carry out the comparison between two or more elements, the value was assigned in the corresponding cell of the matrix according to the experts' assessment. This value reflects the extent to which the element in the row is considered important compared to the element in the column, which allowed a more precise and systematic evaluation of the elements involved in the decision process [18]. It should be noted that this matrix is reciprocal, that is, the values should be entered symmetrically with respect to the main diagonal. For example, if a value of 7 is assigned to indicate that criterion A is more important than criterion B, then the reciprocal of the value (1/7) should be assigned to indicate the relationship of criterion B to A.(Table 3).

Table 3. Example of pairwise comparison matrix.

| Comparison | TO | B |
|---|---|---|
| A | 1 | 7 |
| B | 1/7 | 1 |

After collecting the individual evaluations of the 25 experts and converting them into matrices, the next step was to calculate the relative weights of each criterion. This process was done through normalizing the paired comparison matrices, adjusting them to the contribution of each expert. Normalization was essential to ensure that the experts' preferences were given equal weight in decision making. The normalization procedure was carried out by dividing the values of each column in the paired comparison matrix by the total sum of that column [17]. In this way, an adjusted version of the matrices was obtained that reflected the relative importance of each criterion according to the experts' perspective.

Subsequently, the priority vector (average matrix) of each matrix was determined. This was done by calculating the average of each row in the normalized matrix, which involved adding the values of each row and dividing them by the total number of criteria. The result corresponded to the vector representing the relative priorities of the criteria.[17].

*Determining consistency*

Since it was required to be certain that the results obtained in the matrices were valid, the consistency analysis was carried out, which corresponds to evaluating the expert's judgment under equation (1) Saaty [20]:

$$CR = \frac{CI}{RI}(1)$$

Where:

*CR is the consistency radius, CI is the consistency index and RI is the random consistency index that is represented in an order from 1 to 15, where its evaluation will depend on the number of criteria in the comparison matrix (Table 4).*

Table 4. Random index according to the amount of data.

| **Random Index (RI)** | |
|---|---|
| **n** | **RI** |
| 1 | 0 |
| 2 | 0 |
| 3 | 0.58 |
| 4 | 0.9 |
| 5 | 1.12 |
| 6 | 1.24 |
| 7 | 1.32 |
| 8 | 1.41 |
| 9 | 1.45 |
| 10 | 1.49 |
| 11 | 1.51 |
| 12 | 1.48 |
| 13 | 1.56 |
| 14 | 1.57 |
| 15 | 1.58 |

Note. Numerical table for n=15. Taken from Yap, J., Ho, C., &Ting, C., [20].

The consistency index should be CR $\leq$0.10. This indicates that when the consistency ratio is greater than 0.10, the experts' judgment is inconsistent, evaluated by equation (2).

$$CI = \frac{\lambda_{max} - n}{n-1} (2)$$

*Where CI is the consistency index,* $\lambda_{max}$*is the largest value in the matrix and N is the total number of elements compared.*

In the event of inconsistency, it is recommended not to take into account the assessment of one or more matrices that comply with the above, in order to avoid distorting the validity of the comparisons made [17]. However, if CR is equal to or less than 0.10, the consistency of the method is acceptable, so the judgment is valid for decision making.

*Consensus assessment*

The AHP methodology prevents multiple assessments from being made, so it is necessary to generate a single matrix called consensus assessment. The consensus assessment matrix reflects a more refined synthesis of the experts' preferences and seeks to mitigate possible individual biases. This process also involves calculating the geometric mean for each entry in the initial consensus matrix, taking into account the opinions of the different experts [21]. The geometric mean highlights the relative preference relationships between the criteria or alternatives, balancing the contributions of all the experts reciprocally. According to Mendoza et al. [18], Saaty and Aczél highlight that the geometric mean satisfies the reciprocal property, which favors the methodology. In contrast, if the arithmetic mean is used, this property does not comply with reciprocity, affecting the analysis.

The construction of the consensus assessment matrix for each of the criteria was [17]initiated (Table 5). This process excludes the results of expert assessments that were previously identified as inconsistent, i.e., those with a consistency ratio greater than 0.1 (unacceptable value). In this way, the matrices were generated, using the geometric mean of the consistent assessments as the comparison value.

After presenting the agreed matrices, it was necessary to normalize the matrices. This was achieved by dividing each element of the matrix by the total value of its column and to calculate the priority vectors (average matrix), it was necessary to average each row of the normalized matrix to obtain a matrix that shows the relative importance of each element evaluated in the process (Table 6).

Finally, to further strengthen the validity of the results, the consistency of the agreed matrices was assessed (Table 7). The purpose of this assessment is to verify the integrity of the procedures used to be accurate and consistent. If not, this step provides the opportunity to review and adjust the procedure to ensure the quality of the analysis to be performed.

Table 5. Consensus assessment matrices

| CONVENTIONS | |
|---|---|
| **BI** | Biotic |
| **AB** | Abiotic |
| **SE** | Socioeconomic |
| **AP** | Protected areas |
| **CV** | Vegetation cover |
| **PF** | Loss of wildlife |
| **GE** | Geology |
| **CU** | Land use conflict |
| **CRH** | Water resource quality |
| **DP** | Population density |
| **AP** | Productive activities |
| **CS** | Social conflicts |
| **IN** | Infrastructure |

| **Criteria** | **BI** | **AB** | **SE** |
|---|---|---|---|
| **BI** | 1 | 1.1539 | 1.2564 |
| **AB** | 0.8666 | 1 | 1.3315 |
| **SE** | 0.7959 | 0.7511 | 1 |

| **Subcriteria (BI)** | **AP** | **CV** | **PF** |
|---|---|---|---|
| **AP** | 1 | 2.2533 | 0.3330 |
| **CV** | 0.4438 | 1 | 0.1426 |
| **PF** | 3.0000 | 7.0000 | 1 |

| **Subcriteria (AB)** | **GE** | **CU** | **CRH** |
|---|---|---|---|
| **GE** | 1 | 1.1460 | 0.2391 |
| **CU** | 0.8726 | 1 | 0.3945 |
| **CRH** | 4.1817 | 2.5351 | 1 |

| **Subcriteria (SE)** | **DP** | **AP** | **CS** | **IN** |
|---|---|---|---|---|
| **DP** | 1 | 0.7230 | 0.6020 | 1.3636 |
| **AP** | 1.3831 | 1 | 0.8683 | 1.1029 |
| **CS** | 1.6610 | 1.1517 | 1 | 1.3077 |
| **IN** | 0.7334 | 0.9067 | 0.7647 | 1 |

Table 6. Standardized consensus assessment matrices.

| CONVENTIONS | |
|---|---|
| **BI** | Biotic |
| **AB** | Abiotic |
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| **CRH** | Water resource quality |
| **DP** | Population density |
| **AP** | Productive activities |
| **CS** | Social conflicts |
| **IN** | Infrastructure |

| Criteria | BI | AB | SE | Eigenvector |
|---|---|---|---|---|
| **BI** | 0.3756 | 0.3972 | 0.3502 | 0.374327 |
| **AB** | 0.3255 | 0.3442 | 0.3711 | 0.346943 |
| **SE** | 0.2989 | 0.2585 | 0.2787 | 0.278729 |

| Subcriteria (BI) | AP | CV | PF | Eigenvector |
|---|---|---|---|---|
| **AP** | 0.2250 | 0.2198 | 0.2257 | 0.223492 |
| **CV** | 0.0999 | 0.0975 | 0.0966 | 0.098005 |
| **PF** | 0.6751 | 0.6827 | 0.6777 | 0.678503 |

| Subcriteria (AB) | GE | CU | CRH | Eigenvector |
|---|---|---|---|---|
| **GE** | 0.1652 | 0.2448 | 0.1464 | 0.185457 |
| **CU** | 0.1441 | 0.2136 | 0.2415 | 0.199741 |
| **CRH** | 0.6907 | 0.5416 | 0.6121 | 0.614802 |

| Subcriteria (SE) | DP | AP | CS | IN | Eigenvector |
|---|---|---|---|---|---|
| **DP** | 0.2093 | 0.7230 | 0.1861 | 0.2856 | 0.21806 |
| **AP** | 0.2895 | 1 | 0.2684 | 0.2310 | 0.263345 |
| **CS** | 0.3477 | 1.1517 | 0.3091 | 0.2739 | 0.308814 |
| **IN** | 0.1535 | 0.9067 | 0.2364 | 0.2095 | 0.209781 |

*ESI Index*

It is a method used in Geographic Information Systems (GIS) and data analysis to classify data into different categories or classes where biotic, abiotic and socioeconomic variables interact, based on homogeneous natural groupings present in the distribution of quantitative information [6]. The results of ESI are especially aimed at proposing solutions to those ecosystems that have been anthropogenically altered or analyzing the surrounding information for decision making [3].

This classification technique is often used to create thematic maps, where regions are shaded or colored based on the values of a specific attribute within each region. The calculation of ESI is done using methods such as Natural Breaks Classification (NBC) or the Jenks optimization method[3], in order to determine the class limits that best represent the patterns of the data.

The formula for calculating the ESI is as follows (Equation 3):

$$ESI = \sum_{i=1}^{n} w_i * f_i (3)$$

*Where* $w_i$ *is the weight of the subcriterion and* $f_i$ *is the rating of the subcriterion* [6].

The application of this method in ArcGIS allowed for efficient segmentation of the data. This technique allows for identifying the division points by selecting the class cuts that group similar values and optimizing the differences between the classes [6], allowing for effective segmentation of the data. In the present study, the environmental sensitivity index (ESI) was divided into three levels or homogeneous classes, which represented the high, medium and low sensitivity categories, as detailed in Table 7.

Table 7. ESI scale classification

| Level | ESI | Description |
|---|---|---|
| **Low** | ≤0.28 | No significant impacts on the environment are observed |
| **Half** | 0.47-0.29 | A moderate imbalance caused by human activities is evident |
| **High** | 0.47> | The environment is significantly affected |

## 3. RESULTS AND DISCUSSION

*Level of consistency*

After processing the qualitative data provided by the judges, individual matrices were created that allowed the consistency of the judgments to be analyzed. However, a notable discrepancy was observed, since each judge presented at least one inconsistent matrix out of the four required (criteria and subcriteria). According to Merino & Bojórquez [23], finding a matrix obtained at random from one that is logically reasoned implies that the consistency index works through the transitivity property. So, if A ≥ B and B ≥ C, then A ≥ C. This property not only implies direction, but also magnitude; that is, if A ≥ 2B and B ≥ 4C, then A ≥ 8C. Therefore, based on the above, inconsistent judgments of one or more matrices of a judge were not taken into account (Table 8).

Table 8. Consistency of individual judgment matrices

| Expert | Half | | Biotic | | Abiotic | | Socioeconomic | |
|---|---|---|---|---|---|---|---|---|
| | CR | *Classification* | CR | *Classification* | CR | *Classification* | CR | *Classification* |
| **1** | 1.65 | *IN* | 0.21 | *IN* | 0.84 | *IN* | 0.66 | *IN* |
| **2** | 0.05 | *IN* | 1.58 | *IN* | 0.16 | *IN* | 0.21 | *IN* |
| **3** | 1.32 | *IN* | 0.01 | *C* | 0.01 | *C* | 0.15 | *IN* |
| **4** | 0.01 | *C* | 1.70 | *IN* | 0.35 | *IN* | 0.10 | *C* |
| **5** | 2.72 | *IN* | 2.78 | *IN* | 0.07 | *C* | 0.45 | *IN* |
| **6** | 0.04 | *C* | 0.59 | *IN* | 0.46 | *IN* | 0.34 | *IN* |
| **7** | 0 | *C* | 0.10 | *C* | 0.45 | *IN* | 1.99 | *IN* |
| **8** | 0.33 | *IN* | 0.01 | *C* | 0.45 | *IN* | 0.24 | *IN* |
| **9** | 0.01 | *C* | 1.09 | *IN* | 0.01 | *C* | 0.25 | *IN* |
| **10** | 0.33 | *IN* | 0.23 | *IN* | 3.85 | *IN* | 1.89 | *IN* |
| **11** | 0.41 | *IN* | 0.10 | *C* | 0.11 | *IN* | 0.45 | *IN* |
| **12** | 0 | *C* | 0.10 | *C* | 0.45 | *IN* | 0.61 | *IN* |
| **13** | 0.19 | *IN* | 0.23 | *IN* | 0.15 | *IN* | 1.31 | *IN* |
| **14** | 0 | *C* | 0.01 | *C* | 0.33 | *IN* | 0.80 | *IN* |
| **15** | 0 | *C* | 0.15 | *IN* | 1.05 | *IN* | 0.18 | *IN* |
| **16** | 4.38 | *IN* | 0.23 | *IN* | 4.88 | *IN* | 1.97 | *IN* |
| **17** | 0 | *C* | 0.15 | *IN* | 0.30 | *IN* | 0.30 | *IN* |
| **18** | 1.40 | *IN* | 2.34 | *IN* | 1.13 | *IN* | 0.02 | *C* |
| **19** | 0.14 | *IN* | 0.07 | *C* | 0.13 | *IN* | 0.06 | *C* |
| **20** | 0.14 | *IN* | 0.07 | *C* | 0.15 | *IN* | 0.06 | *C* |
| **21** | 0 | *C* | 0.10 | *C* | 0.35 | *IN* | 0.05 | *C* |
| **22** | 0.33 | *IN* | 0.07 | *C* | 0.00 | *C* | 0.35 | *IN* |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **23** | 0.04 | *C* | 0.23 | *IN* | 0.11 | *IN* | 1.52 | *IN* |
| **24** | 0.78 | *IN* | 0.53 | *IN* | 0.02 | *C* | 0.40 | *IN* |
| **25** | 0.08 | *C* | 0.85 | *IN* | 0.01 | *C* | 0.28 | *IN* |

Note: CR: Consistency radius; C: Consistent; NC: Inconsistent.

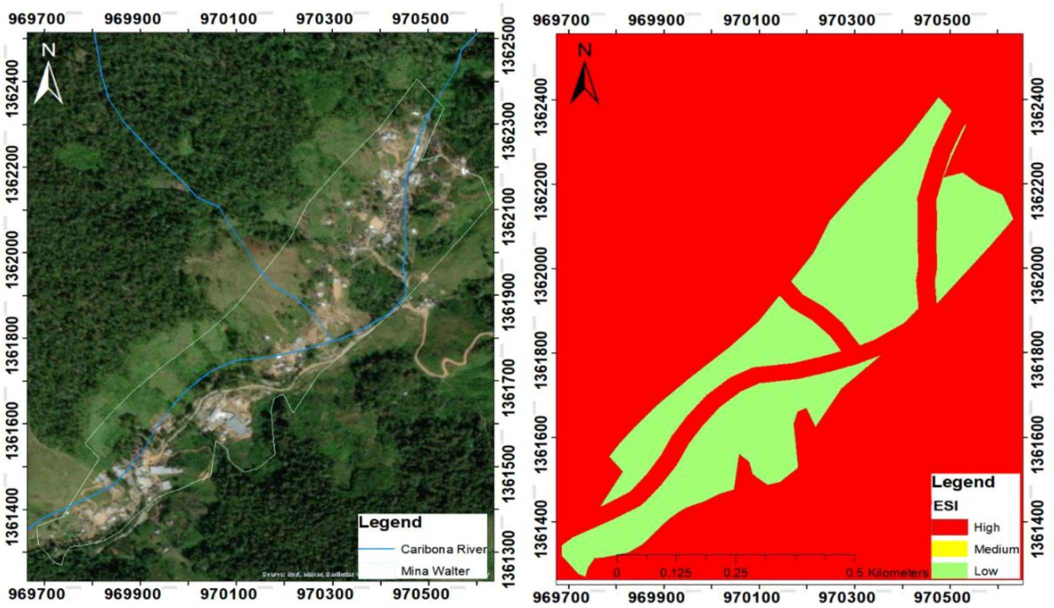
*Prioritization of weights according to AHP*

3.1.Sensitivity Level of Criteria

After carrying out the calculation process to obtain the weights of the criteria and subcriteria (Table 9), the sensitivity levels of each variable were determined according to the ESI scale. As a result, it was found that the environment with the greatest tendency to suffer damage is the biotic environment, followed by the abiotic environment and then by the socioeconomic environment, which, unlike the two previous variables, has low sensitivity.

According to the above, the biotic environment is the most heavily weighted because it shows high complexity, especially in terms of biological diversity, defined according to Law 165 of 1994 as the diversity of living beings that ranges from aquatic ecosystems, terrestrial ecosystems and other ecological complexes in which they are integrated. The components of this environment are intrinsically related and any alteration in one species can significantly impact others, which can unbalance the ecosystem (Image 3). That is why anthropogenic activities such as deforestation, pollution and overexploitation of resources drastically impact ecosystems, affecting their survival [2].

Image 3. Current sensitivity index of Mina Walter.




Note: Image on the right-current state of the area of interest, extracted from Google Earth; Image on the left-ESI obtained in the study area.

Table 9. Weights of AHP hierarchy levels.

| N1 | N2 | ω | N3 | ω |
|---|---|---|---|---|
| Environmental sensitivity | BI | 0.374 | AP | 0.22 |
| | | | CV | 0.09 |
| | | | PF | 0.67 |
| | AB | 0.346 | GE | 0.18 |
| | | | CU | 0.19 |
| | | | CRH | 0.61 |
| | HE | 0.278 | DP | 0.21 |
| | | | AP | 0.26 |
| | | | CS | 0.30 |
| | | | IF | 0.20 |

Note: N1: first level, N2: second level (criteria), N3: third level (subcriteria), and ω: weights.

Mining activity is often carried out in areas with high biodiversity because it is related to the presence of mining deposits [23]. Montecristo, Bolívar, is no exception, because until 2016 the geographic area was part of the protected area under the classification of the Magdalena River forest reserve. However, this area was removed in 2016 under resolution 0666 of 2016 to carry out gold mining under the supervision of the ANLA. That generated a significant change in the ecosystem due to the permissibility of exploration and exploitation of mining projects in the area, additionally the different sub-activities of exploitation such as assembly, construction, extraction and closure of areas. Likewise, the ecosystem presents a greater demand for resources, due to the displacement of communities that generate settlements near the area, as a result of the impact on local employment.

The abiotic criterion exhibits a value similar to the biotic one, also presenting medium sensitivity due to the relationship between both, since mining influences geological aspects of the environment. That is, mining can affect the quality of soil and water, generating changes in erosion and sedimentation, impacting geological processes. Furthermore, in its generation of erosive processes, unstable areas increase, which lead to an extend in the impact on the abiotic environment. Therefore, this result shows the need to take preventive actions to prevent these variables from being significantly affected in the long term due to mining activities developed in the area of interest.

Regarding the socioeconomic criterion, although it has the lowest weighting compared to the other criteria, it is still relevant. The result obtained is supported by the research of Arias et al. [24], who mention that due to the social conditions of the area, there has been an excessive growth of the population in search of economic stability, in a context where the different legal and illegal dynamics in the study area exacerbate this situation. It is important to consider this criterion in the formulation of management strategies in order to minimize its impact on the other criteria as well as to ensure the integration of the population in the face of the different decisions that may be taken.

## 3.2 Sensitivity level of the Subcriteria

3.2.1. Biotic criterion

It was mentioned beforehand that the biotic criterion had the greatest weight compared to the other criteria. This criterion is made up of protected areas, vegetation cover and loss of fauna. According to the applied methodology, the subcriterion that registered the greatest sensitivity in the evaluation was the loss of fauna (0.67), also indicating that it has a high sensitivity index, that is, it is significantly affected. This result indicates that the biota (microfauna, mesofauna and macrofauna), which is responsible for the maintenance, regulation and stabilization of ecosystem services, is being significantly affected by anthropogenic activities in the area, which not only include mining, also livestock, agriculture, deforestation, uncontrolled urban expansion, armed conflict, among others [25].

Protected areas have a relevant weight within the generated evaluation, because the zones are highly sensitive to anthropic transformations, which generates a great impact that in most cases is irreversible. Almonte et al., [26]mention that the category of protected area prevents environmental deterioration, however, the various processes of subtraction of protected areas lead to eliminating the figure of protection. Such is the case of the surrounding area of Mina Walter, which under resolution 0666 of April 2016, an area of mining interest equivalent to 150 ha was subtracted, which leads to fragmentation, loss of ecosystem services and deterioration of ecological corridors. Some authors such as Acevedo & Maya [27], highlight that these mechanisms cause protected areas to be left without the figure of conservation and sustainable use of the territory.

Regarding vegetation cover, it is evident that it has changed due to deforestation for mining activities. This change in vegetation leads to soil erosion, because vegetation is crucial in water retention and soil protection. Without the vegetation cover characteristic of the area, the soil becomes more susceptible to erosion. In short, the removal of the area of interest nullifies its protection against the impact generated by gold mining and activities associated with its development. This exposes endemic species and the ecosystem to a greater risk of irreversible damage.

3.2.2. Abiotic criterion

The subcriterion with the highest weight is the quality of the water resource (0.6148), which indicates a sensitivity to gold mining in the study area. According to the review of databases, the Caribona River originates in the San Lucas mountain range, which corresponds to the area where Mina Walter is located. It passes through the mining polygon, whose water resource is highly vulnerable due to changes in soil cover and contamination of its water body. Any alteration in the environmental conditions of this river will not only affect the local population, also many more communities downstream. Pollutants such as cyanide and mercury significantly impact the environment and health of nearby inhabitants.

The extraction of minerals generally requires the use of chemicals, specifically, gold requires the use of cyanide and mercury in processes different from this mining, cyanide leaching leads to creating a cyanide solution in which the gold is dissolved and with respect to mercury, it is used in amalgamation, that is, mercury is mixed with gold to form an alloy [28].

A study carried out in the area by the Colombian Geological Service highlights that in 2019, a concentration of approximately 15 mg/kg of mercury (Hg) was recorded in the area [12]. This figure is significantly higher than the international recommendation of 0.18 mg/kg due to its toxicity. This situation highlights the serious situation of the Caribona River as a result of mining activity. It is important to note that mercury not only remains on the surface, it´s move throughout the water and soil matrix, preventing its encapsulation. In addition, it can bioaccumulate in aquatic organisms throughout the food chain, putting aquatic life at risk and the communities dependent on this resource for food and sustenance [29].

As for the remaining sub-criteria evaluated, which have similar weights, they are the conflict due to land use and geology. On the one hand, the area of interest does not present a conflict due to land use, and on the other, the geology of the area is classified as granodiorite biotite porphyritic, that is, igneous rocks widely used in construction and mining due to their high resistance. This suggests that the geological formation of the area is suitable for carrying out underground mining, as it has been carried out to date [30].

3.2.3. Socioeconomic Criterion

The socioeconomic sub-criterion with the greatest weight is the armed conflict, because natural resources frequently become an articulating element due to the dynamics of exploitation, with a high impact on the local ecosystem [31]. The effects of this damage are reflected in the overexploitation of resources, such as deforestation, loss of biodiversity, soil erosion, forest degradation and contamination of water sources, in addition to generating other significant consequences such as forced displacement, illicit crops, land theft or hoarding, among other significant social impacts [32].

The presence of illegal groups in Mina Walter has generated a dispute over mining rights with the local community that has been carrying out mining activities for more than thirty years. Initially, this activity was run by peasants on an artisanal basis, but it has now been legalized and is carried out on a medium scale. Despite its legalization and operation, according to a report by the Ombudsman's Office, guerrilla groups have influenced this conflict through attacks due to non-payment of "security fees" generating forced displacement and significant damage to mining facilities as well as the surrounding ecosystem [33]. This situation contributes to growing social tension that is aggravated by the minimal institutional presence given the difficult geographical conditions of the area, which makes it even more difficult to exercise control over the situation.

The second sub-criterion with the greatest weight is productive activities, which are closely related to mining activity and include aspects such as transportation, trade in food and supplies, rental of housing, sale of food and places of recreation such as bars, billiards, soccer fields, among others. These activities can have a positive or negative impact on the environment and on local communities because they generate employment and economic opportunities for the local population, facilitating the acquisition of goods and services.

Economic activities can give rise to problems such as environmental pollution and conflicts related to resources and land use. It is crucial to involve local communities in decision-making in order to adequately address the needs and concerns of all stakeholders because this allows for more effective management of the socioeconomic impacts generated by such activities. On the other hand, infrastructure although it has a relatively low weight within the analysis of the AHP methodology, remains a crucial variable in economic development. Its relevance lies in aspects such as education, health, recreation, housing and transportation. In other words, a good structure guarantees a better quality of life.

In the specific case of Mina Walter, there is a level I medical center for emergencies, which is essential to deal with possible eventualities. However, access to this area is limited to just one road of more than 45 kilometers that takes approximately 3.5 hours of travel starting from the municipality of Santa Rosa del Sur in the department, the closest population center where all the necessary social and legal services procedures for the community are carried out [12].

This road is constantly deteriorating due to vehicle traffic and weather conditions. For this reason, mining companies in the area, together with the local community, carry out regular maintenance activities to compact and fill the soil in order to ensure the safety of the movement of communities and mining operations. In addition, the area faces limitations in education since it only has primary education, which forces children to travel long distances to receive secondary education. Connectivity is medium to low, with limited access to stable telephone services and dependence on satellite Wi-Fi. As for housing, more than 90% of it is built of wood, which has implications in terms of structural resistance to disaster threats.

Finally, the subcriterion with the least weight is population density, which is defined as the number of individuals per area. This measure is fundamental because it allows us to understand population dynamics and establish monitoring and conservation strategies. According to Vargas [34], population is an active measure that indicates how much pressure is being put on an ecosystem while allowing us to observe the economic growth of the region.

However, since the number of inhabitants per area is not known with certainty, it is difficult to determine the population growth that the area has had over the years unless local sources of information are used. Nevertheless, it was estimated that for 2016, 25% of the area's population corresponds to the floating category [14], whose value increases according to mining demand. Although this data corresponds to previous years, but it underlines an important point, which is that the greater the productivity, the greater the population. This implies an increase in the consumption of resources as economic activity intensifies, so the distribution of people in the territorial space will directly or indirectly affect environmental degradation [34].

Finally, productive activities, population density and, therefore, the infrastructure of these communities will inevitably be limited by the armed conflict. The presence of this conflict will negatively affect the economic and social development of the region, and this dependent relationship will directly and indirectly impact the ecosystem of the region.

## 4. CONCLUSION

This research focused on determining the level of environmental sensitivity of the gold mine in the municipality of Mina Walter. This analysis was carried out thanks to the application of the AHP methodology. The results revealed a medium level of sensitivity for the area of interest, highlighting the sensitivity of the biotic environment, specifically the fauna and the quality of the water resource due to mining activity. This situation poses a risk of the disappearance of species that provide stability to the local ecosystem, affecting environmental services such as food chains.

The applied methodologies offer an essential tool for environmental agencies and governments, allowing a comprehensive assessment of complex territories. This approach considers the interrelations generated between the biotic, abiotic and socioeconomic environments, with the purpose of preventing and mitigating the environmental impacts associated with human activities in each area. The main intention of this tool is to identify and prevent the sensitivity of the ecosystem from reaching high and irreversible levels. This comprehensive approach will allow both biodiversity and the well-being of local communities to be protected, thus ensuring a sustainable balance between human development and environmental conservation.

## RECOMMENDATIONS

Initially, it was thought that it was possible to improve the input matrices to improve their consistency to reduce the number of inconsistent matrices. Therefore, a literature review was conducted in order to explore how to address inconsistencies in judgments. However, according to Pascoe [36]online surveys conducted by judges, tend to have the highest levels of inconsistency, i.e., only 1 in 3 judgments is consistent. One way in which this probability can be decreased is by using a maximum of 7 criteria. Furthermore, the algorithms that have the probability of improving matrix inconsistency recommend that these should not be larger than 4x4 and smaller than 2x2, suggesting that the best option to optimize the results are 3x3 matrices. However, this restriction does not guarantee improving the consistency of all matrices evaluated according to the same author. Finally, the inconsistency error can be significantly reduced with a well-structured hierarchical design from the start, since as the size of the pairwise comparison matrix increases, so does the probability of it being inconsistent [36]. The best option is to have the judges present when they give their opinions.


## DATA AVAILABILITY STATEMENT

Data will be available upon request.

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