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TECHNICAL COMMUNICATION

Prospective Analysis of Artisanal Mining in the Santa Rita Village: Municipality of Andes, Antioquia

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Abstract

Artisanal and small-scale mining (ASM) of gold has adversely affected the environment and human health for decades, mostly due to excessive use of mercury. With the enactment of the zero mercury law, miners in Columbia began to replace mercury with cyanide and improve their processes. We analyzed the extraction dynamics, based on what had been identified in the municipality of Andes (Colombia) and indexed the pollutant loads of discharges from different small-scale mining gold plants. Gold production for the year 2022 in the municipality of Andes is predicted to total 9811.4 g. None of the sampled small-scale mines currently complies with the permissible parameters for ions and metals in industrial discharges; however, the contamination levels have been reduced for the: La Y mine by 18%, Dorado mine by 13.3%, El Molino by 8.6%, and La Soledad mine by 2.7%. This shows that the ASM operators in the municipality of Andes are beginning to implement cleaner production strategies.

Keywords Socio-environmental conflicts · Artisanal and small-scale mining · Subsistence · Extraction · ARIMA

Introduction

Artisanal and small-scale mining (ASM) is a subsistence activity that generates income for low-income families (Halland et al. 2016), According to the Intergovernmental forum on mining, minerals, metals and sustainable development (2018), ASM has grown substantially to become an economic activity of global importance; according to the World Bank (2019), the number of individuals working has increased to more than 40 million in developing countries. In Latin America and the Caribbean, it directly involves 2 million people compared to the 650,000 miners reported in 1999; which in most cases carry out this activity clandestinely in vulnerable areas that are difficult to access, thus making rigorous monitoring by the competent authorities difficult (D'Souza 2007).

The processes involved in small-scale gold mining generate environmental externalities (Rodriguez et al. 2019). Data reported by the UNEP (2013) indicate that the mercury emissions generated by small-scale gold mining in the world correspond to 727 t/year, with a range of 128—465 t/year specifically for Latin America. Some of the countries included in this region are implementing measures to combat this environmental problem; for example, Colombia ratified Law 1658/2013 (Government of Colombia 2013)., which establishes the implementation of cleaner production strategies and the elimination of mercury in mining processes within a period not exceeding 5 years from the law's enactment.

Traditionally, mercury has been used in artisanal gold mining worldwide; however, the efficiency achieved does not exceed 30% (Seccatore et al. 2014). Due to its effects on health and the environment, the Minamata Convention was ratified in 2013, which includes within its guidelines control of ASM of gold, strategic planning and programs to protect the populations at risk, performance of research on sustainable alternative practices, setting of limit values for discharge to the environment from sources, and management of mining waste under the Basel Convention (PNUMA/ORPEALC 2014). With law 1892/2018 (Government of Colombia 2018), Colombia ratified its approval and linkage with the Minamata Convention, starting with the presentation of a national base line that showed that alarming

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amounts of mercury (699 t) were used in the country's mining processes in 2018 to produce 49 t of gold, mainly in departments such as Bolívar, Chocó, Antioquia, and Cauca (MINAMBIENTE/PNUMA 2012).

The Colombian government included gold mining as one of the drivers of development for the 2018–2022 period (PND 2018). The mining sector in Colombia is categorized into formalized mining (mining title), artisanal, and large-scale. Small-scale mining involves processes with higher risks and impacts, compared to large-scale mining that uses more technical processes and implements greater security protocols (Betancur et al. 2018).

In Colombia, the departments with the highest number of mining titles for gold mining are Antioquia (35%), Bolívar (13%), Caldas and Tolima (11%), and Chocó (6%) (MINMINAS/UPME 2017). According to the 2018 Natural Resources and Environment Report, the competent authorities in Colombia began a process with the objective of formalizing 400 illegal mining activities in the country. However, the authorities only managed to legalize 38 activities, corresponding to 9.5% under the national regulation established. Similarly, the annual goal for inspecting 1,417 mining titles was not reached, with 1,328 carried out in 2018.

In addition, the national government defined planning tools for municipal administrations to counteract the problems of ASM with integrated management of solid waste and liquid dumping (CGA 2018), which is significant since until relatively recently, there was no established policy for managing environmental liabilities from mining (Government of Colombia 2010). The department of Antioquia has been a pioneer in gold extraction in Colombia for decades, and this economic activity has generated cumulative, residual, and synergistic impacts (Guiza 2013).

The municipality of Andes, the focus of this study, is located at north latitude: 05° 39′ 29″ and west longitude: 75° 52′ 51″, with ≈ 45,000 inhabitants (Goverment of Antioquia—UDEA 2012). Gold mining in the municipality of Andes comes from 13 small mining plants and people who participate in gold mining in the Quebrada Santa Rita (Santa Rita Stream). However, it is worth noting that gold mining is carried out as temporary work, once the coffee harvest has been completed, since the main economic activity of the municipality is agriculture, mainly coffee and banana crops.

Small-scale mining in the territory of the municipality of the Andes traditionally used mercury for the benefit of gold, adversely affecting human health and the environment. After the ratification of Law 1658/2013, which came into force in 2018, Andes committed to become the first zero-mercury municipality in the department. The miners began a transition process, replacing mercury with cyanide and incorporating improvements in their processes. This research reports on the progress of the ASM operations in the municipality of Andes with respect to meeting Law 1658 (Government of Colombia 2013) and Columbia's Resolution 631/2015 (Government of Colombia 2015), which regulates mining discharges. Due to the high extractive demand for gold in the area, a prospective analysis was carried out to provide a tool for planning and government decision-making to quantify the impacts generated associated with mining extraction.

Methodology

The research developed in two phases, first in a quantitative way, based on the gold extraction data in Colombia that was available at the Energy Mining Planning Unit (UPME), and second, using descriptions of the general extractive behavior in the department of Antioquia, within the municipalities of Andes and El Bagre.

To forecast the future of gold mining in the municipality of Andes, the ARIMA (autoregressive integrated moving average) methodology proposed by Box and Jenkins, which provides a set of time series prediction tools, was used by Faircheallaigh and Corbett (2016). This prediction method is based on the analysis of the probabilistic or stochastic properties of the time series, and assumes that the response (y_t) can be expressed as a function of its previous values ($y_{t-1}, y_{t-2}, \cdots$), regardless of any causal relation apart from a relationship with the past values of the series, which is why they are called atheoretical models.

The objective of the ARIMA methodology is to identify and estimate a statistical model that can be used to generate a time series. That is to say, if the model is used for forecasting, the characteristics of the series are assumed to be relatively stable and keep this pattern over time, thus making it possible to forecast future periods.

To estimate the parameters of an ARMA model, it is necessary that the original series be stationary with respect to the mean and variance, so that it does not present a trend and presents a similar dispersion over time. A classic method of eliminating a trend is to assume that it evolves slowly over time, so that at time t, the trend must be close to the trend at t − 1. Thus, if we subtract each value in the series the previous value, the resulting series will be approximately trend-free. This operation is called differentiation of the series and can be done several times if the trend is very marked.

The stages followed in using the ARIMA model for forecasting purposes are: Identification, Estimation, Verification, and Forecasting. It is necessary to define that d indicates the number of times the series had to be differentiated, AR is the autoregressive part of order p, and MA is the fraction of moving average of order q.

Table 1 Physicochemical parameters Resolution 631 of 2015

Parameter	Units of analysis	Effluent limits 631/2015
General		
pH	Units of pH	6.0–9.0
COD	mg/L O_2	150
BOD5	mg/L O_2	50
Total suspended solids	mg/l	50
Sedimentary solid	ml/L	2.0
Hydrocarbons	mg/L	10
Ions		
Total cyanide	mg/L	1
Chloride	mg/L	250
Sulphate	mg/L SO_4	1200
Metals and metalloids		
Silver	mg/L	0.5
Arsenic	mg/L	0.1
Chrome	mg/l	0.5
Mercury	mg/L	0.002
Iron	mg/L	2
Cadmium	mg/L	0.05

- The *Identification* stage consists of detecting the type of stochastic process that has generated the data. This means finding the appropriate values of the parameters of the ARIMA model (*p, d,* and *q*), for which purpose the patterns that appear in the simple auto-correlation function and the partial auto-correlation function are used.
- *Estimation* consists of determining the coefficients of the autoregressive and moving average terms included in the model, whose number of lags p and q are identified in the previous stage. The model is estimated for the series after it has been verified to be stationary. In practice, the most common models are autoregressive; in particular, economic series can be represented by means of an AR model. However, the ARMA model should be the first option, considering that inclusion of additional MA terms can improve the statistical properties of the estimate. Since in practice it is difficult to accurately identify the order p and q of the ARMA model, two or more plausible models are usually proposed, and the most appropriate one is used after being estimated.
- Stage 3, *Verification*, is intended to assess whether the estimated model fits the observed data in the series reasonably, as there may be another ARMA model that does as well. For validation or diagnostic verification, some tests or indicators are carried out to determine the goodness of fit before proceeding to use the model for forecasting. To determine the best model among the possible candidates, the Akaike information criterion (AIC) was used (World Bank 2019), The model with the lowest AIC value is considered as best fit.
- Finally, in the fourth stage, *Forecasting*, the best model obtained in the previous stages is used to obtain the estimated values of the time series for future periods $(\hat{y}_{t+1}, \hat{y}_{t+2}, \cdots)$.

Characterization of a Small Mining Plant

As a second phase of this study, the indicator was assessed based on article 10 of Resolution 631 (2015). The parameters fell into one of three categories (general parameters, ions, and metals; Table 1).

The parameters measured in the small-scale mining plants were arsenic, cadmium, total cyanide, chlorides, chromium, BOD 5, COD, calcium hardness, hydrocarbons, iron, mercury, pH, silver, sedimentary solids, suspended solids, and sulfate. The samplings were carried out using the methodology established by the Water Monitoring Protocol (MINAMBIENTE/IDEAM 2007) and the Standard Methods for the Examination of Water and Wastewater (Rice et al. 2012). The corresponding maps are presented in the (Figs. 3, 4, and 5).

The data was reported by an environmental laboratory, which operates under the guidelines of NTC/ISO 17025 (NTC/ISO 2005), in the city of Medellin (Colombia), which was the closest city for the correct conservation of samples. Each of the analyzed parameters was denoted with the x_i: value of the ith physicochemical characteristic found in the sample, together with the

Table 2 Specific weights for Metals, Ions, and General

Metals	Weight	Ions	Weight	General	Weight
Total Arsenic	0.30	Total Cyanide	0.30	BOD 5	0.20
Total Cadmium	0.20	Chlorides	0.30	COD	0.20
Total Chromium	0.10	Sulfates	0.40	Sediment solids	0.10
Mercury	0.30	Total	1.00	Suspended solids	0.20
Iron	0.10			pH	0.25
Total	1.00			Fats and oils	0.05
				Total	1.00

respective maximum permitted value (X_i); these figures were compared by constructing an indicator based on the percentage deviation with respect to the maximum permitted, as follows:

$$d_i = \left(\frac{x_i - X_i}{X_i}\right)100\% \quad (1)$$

This indicator has two properties: sign and magnitude. If it is negative, the physicochemical parameter being evaluated is below the limit; otherwise (parameter above the maximum tolerated), the indicator will be positive. On the other hand, the magnitude indicates how large the deviation is in percentage terms; for example, if the indicator for total cyanide is 10%, it can be concluded that in small-scale mining gold plants the measured cyanide is 10% above the permitted limit. Accordingly, it is desirable that this indicator show small and negative values; when the measured values are just above the limit, the indicator is zero.

To examine the patterns of the small-scale mining plants, the physicochemical characteristics under investigation were grouped into three categories:

- Metals (total arsenic, total cadmium, total chromium, mercury, iron).
- Ions (total cyanide, chloride, sulfate)
- General (BOD 5, COD, sedimentary solids, suspended solids, pH, fats, and oils)

For each category, an indicator (metals, ions, general) was calculated using an average that weighted the importance of each item in the category. This weighting (p_i) was agreed with the direct and indirect actors of the study area (mining union, data from health authorities, and an academic panel of experts); for each parameter within each category, using the specific weights in Table 2.

The indicator for each category obeys the following calculation scheme, adjusting itself to the aforementioned weights. In this way, three indicators were obtained to describe and analyze the impact of each ranch according to the category of interest: Metal indicator (I_m), Ions indicator (I_i), and Indicator of other general parameters (I_g).

$$I = \sum d_i \times p_i \quad (2)$$

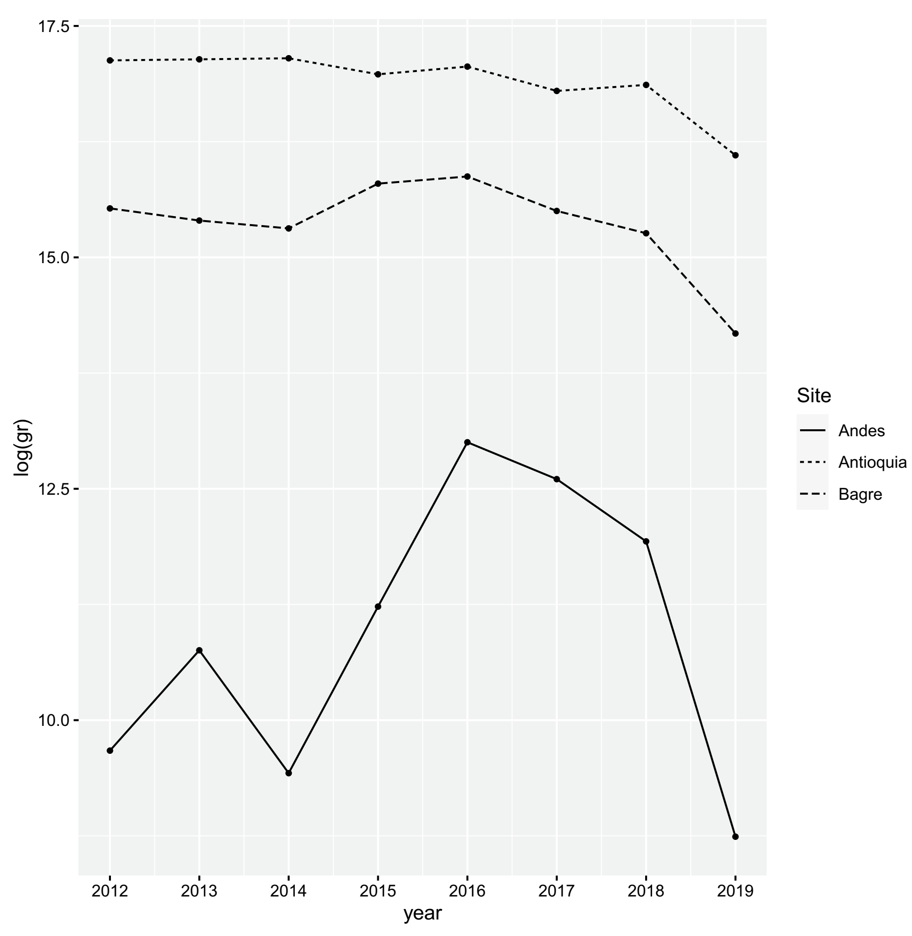

Fig. 1 Annual series of gold mining (gr) for Andes, El Bagre, and Total Antioquia

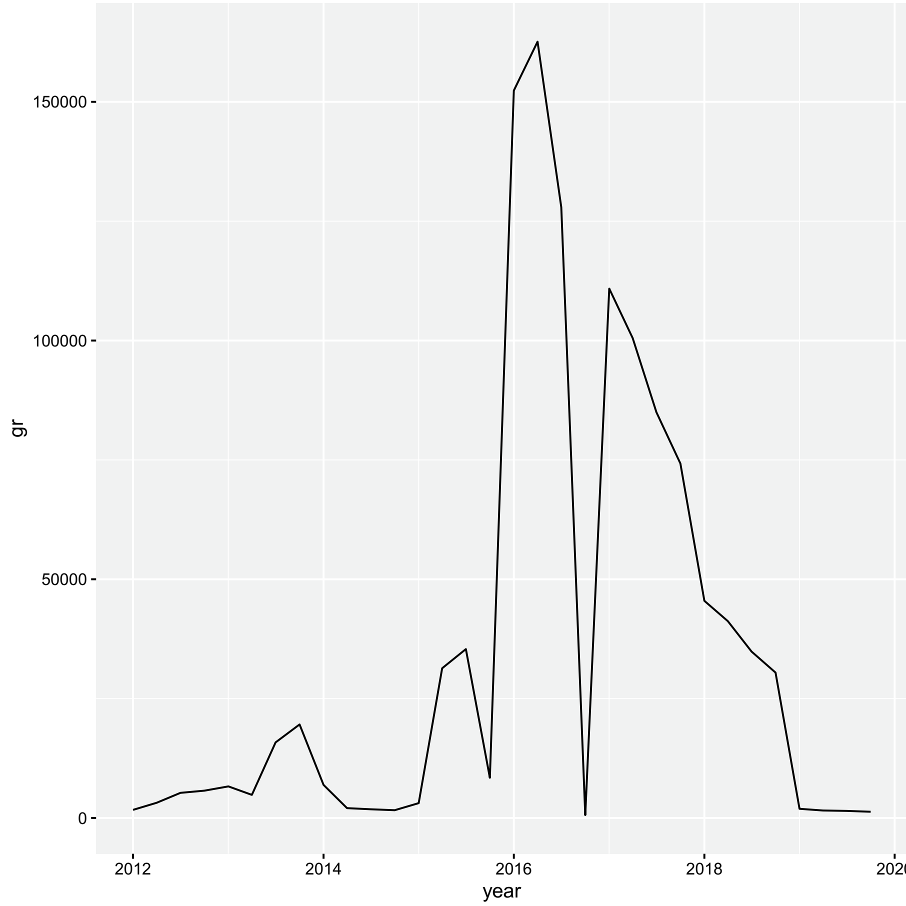

Fig. 2 Quarterly series of gold mining (gr) for the municipality of Andes (Antioquia)

Table 3 Quarterly estimate of gold mining (gr) for the municipality of Andes (Antioquia)

Year	Quarter 1	Quarter 2	Quarter 3	Quarter 4
2020	3475	5762	7469	8533
2021	9136	9462	9634	9723
2022	9769	9793	9805	9811

Results

Forecasting Mining in Andes

First, large-scale mining was considered, based on the municipality of Bagre (Antioquia), the municipality with the highest generation of gold in Colombia (Fig. 1). Next,

Table 4 Impact rate for small-scale mining

	Ions M1*	Metals and Metaloids M1	Generals M1	Ions M2*	Metals and Metaloids M2	Generales M2	Ions M3*	Metals and Metaloids M3	Generales M3
Point 1									
La Y	0.9	34.4	4.3	12.0	24.9	3.3	21.6	58.6	1.1
Point 2									
El Dorado	35.7	8.5	0.8	35.0	4.2	− 3.2	30.6	7.6	− 0.3
Point 3									
El Molino	17.9	5.9	59.0	22.4	6.8	21.8	22.2	4.2	16.3
Point 4									
La Soledad	45.5	51.2	36.0	30.7	64.1	78.2	25.6	29.5	83.0

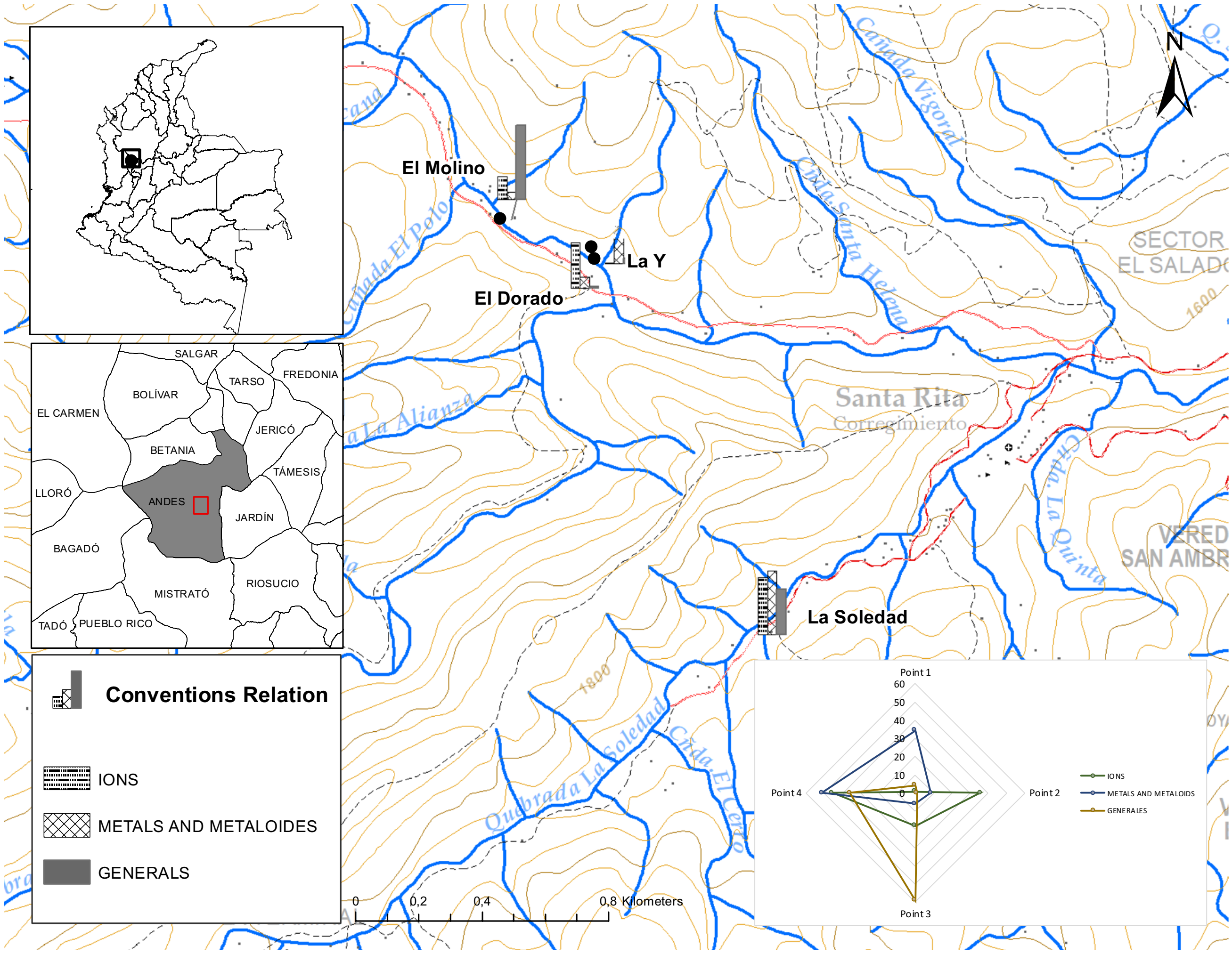

Fig. 3 Index Affectation Sample 1

the municipality of Andes was examined as an example of small-scale mining. In this way, mining level curves for the department of Antioquia was demonstrated be trending downward.

The specific series for the volume of gold mining in the municipality of Andes required the imputation of data for the years 2017 and 2018, periods for which no information was available at UPME. The estimate was made using moving averages. According to the results (Fig. 2), in the third and fourth quarters of 2016, gold extraction drastically decreased, as a consequence of Law 1678 (2015), as the transition to zero mercury began, requiring equipment changes and plant shutdowns, which caused gold extraction volumes to decrease. However, gold beneficiation processes were subsequently reactivated using cyanide, so that by the second quarter of 2017, the extraction projection was again achieved.

Applying the Box-Jenkins methodology, it was found that the best model to estimate gold mining in this municipality was adjusted to an autoregressive model of order 1 and denoted AR 1 (Table 3), thus obtaining the following mining volumes per quarter for the years 2020 to 2022.

Determination of Indicators for Small-scale Mining Plants

A weighting range was set that was conditioned by different factors according to the needs of the municipality (domestic use, agricultural use, and mining) and the opinion of the main stakeholders. A categorical level was assigned to each

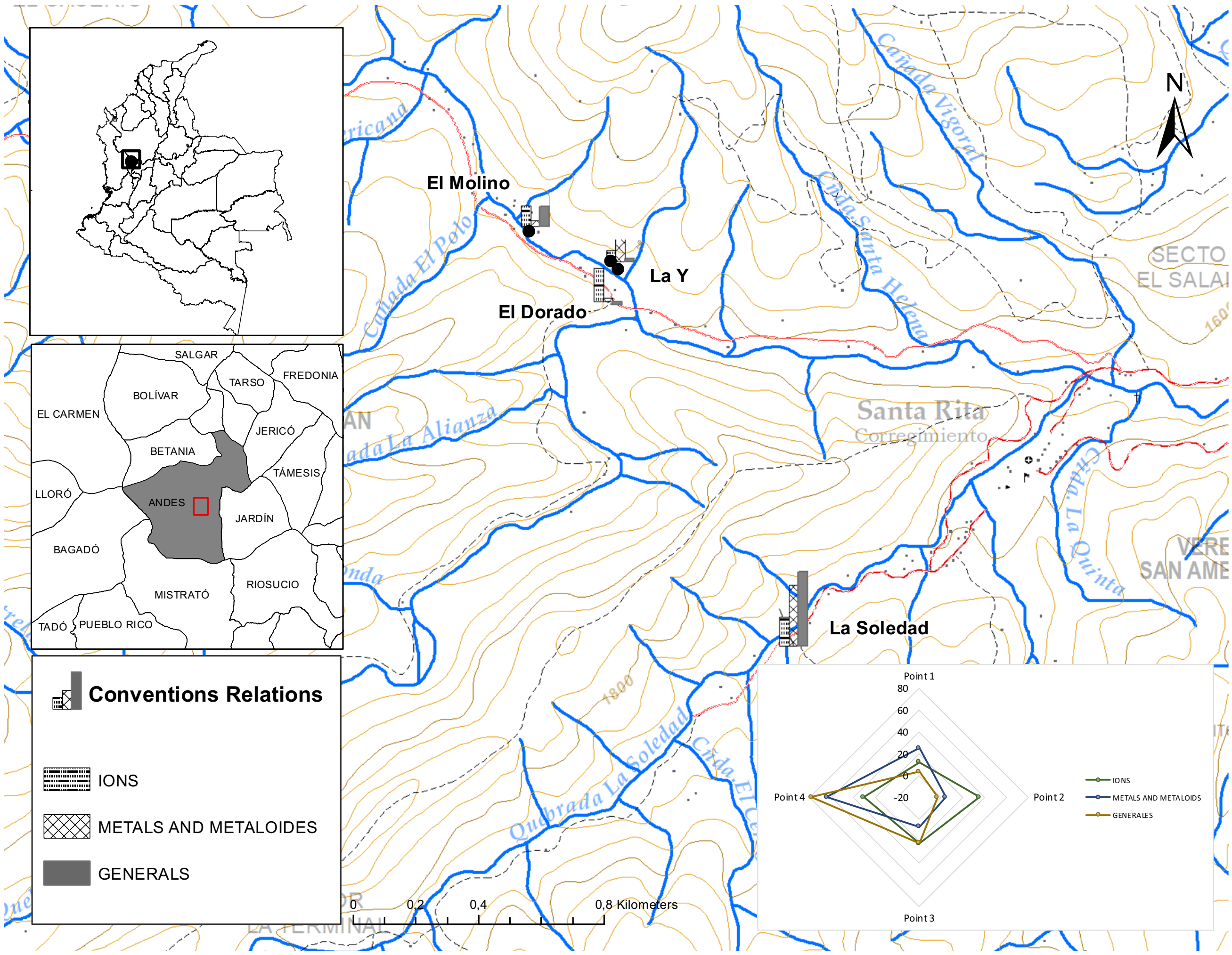

Fig. 4 Index Affectation Sample 2

according to the impact to those needs. Table 4 characterizes each of the establishments studied (Table 4), for the figures in each category:

According to the indices obtained from the ratio of the moving average per small-scale mining plant, a normalization was carried out to generate a comparative analysis by categories, using the water quality results carried out during the year, leading to the dynamics of the physicochemical parameters of Figs. 3, 4, and 5.

Segment diagrams were made according to the physicochemical characteristics in each of the samplings during the study period. In Fig. 1, it is evident that El Molino and La Soledad are having the greatest effect, generating an index above 80% in the General category; however, La Soledad had the most effect, > 50% in the three categories.

In sample 2, the index values decreased for La Y, El Dorado, and El Molino (< 40%), while Soledad had the greatest impact in two categories: general with 78% and metals with 64%. Improvement can be seen in the third sampling; however, La Soledad continued to have the greatest adverse effect (in the General category), mainly due to its high sulfate concentrations. It is important to note that the progress observed in the discharge water quality of small-scale mining plants, although not representative, is evidence that the changes made in traditional mining processes have mitigated the environmental impacts caused by mine water discharges.

Discussion

The projected increase in gold extraction in the Andes is linked to improvement in the artisanal processes, due to the guidelines established in the National Mining Policy (MINMINAS 2016), in accordance with the Methodological Guide for Productive Improvement of Gold Extraction in Andes (MINMINAS/SGC (2018), the mining actors began to implement best practices, focused

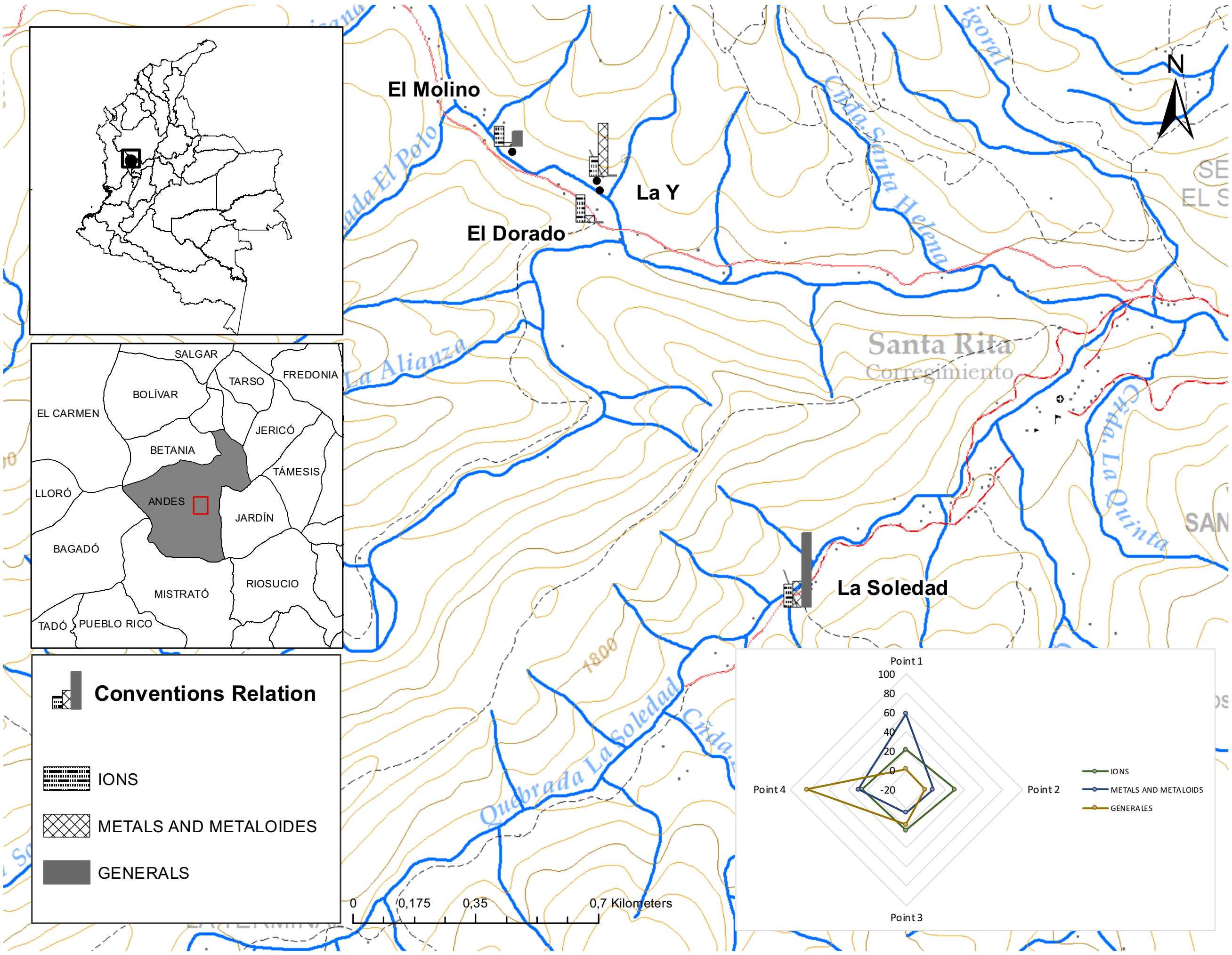

Fig. 5 Index Affectation Sample 3

on increasing the volume of extraction by increasing the efficiency of the process, which is evident in the health of the miners, in the aspect of the small-scale mining plants, and water quality.

Since 63% of the gold extraction in Andes-Antioquia is carried out in an artisanal way, the value of the extraction volume was made by tabulating the activity of legal mining titles, while the projection was made using input from artisanal miners. It is important to remember that this depends on the grade of a mine, considering the relationship between the mass of gold with respect to the volumetric amount of ore.

One of the relevant points in a small-scale mining plant are the work areas, which are still rudimentary, despite process improvements, potentiating some environmental impacts, specifically in aspects of water quality, land use, and the health of the population. However, one of the most significant results caused by the mining transition is the improved Risk Index of the Quality of Water for Human Consumption (IRCA), which includes physical, chemical, and microbiological characteristics, which fell from 24% in the years prior to the validity of the Zero Mercury law to 12.4% in 2019. This supports the results obtained in this study of some improvement in the gold extraction processes, which corresponds to improved water quality (INS/SIVICAP 2019). The results indicate possible improvement in the Quebrada Santa Rita, because the work areas in the small-scale mining plants are not demarcated and isolated from each other and are located ≈ 5 to 20 km from the water source, causing water pollution and affecting the flora and fauna.

Conclusions

ASM should no longer be considered as a source of subsistence economy, since it generates economic development and contributes to sustainability for the benefit of society.

Gold mining in the Andes—Antioquia area is expected to continue to increase by 12 to 20% for the next three years, according to the AMIRA-based model. ASM is a means of subsistence, whereby residents seek an economic balance in their daily lives; however, it is essential that this activity incorporate strategies for continuous improvement.

None of the small-scale mining gold plants in this study met the permissible levels for ions and metals in Resolution 631 (2015), which regulates industrial discharges in Columbia. It is evident, however, that the impact rates have been reduced (by 18% at La Y, 13.3% at El Dorado, 8.6% at El Molino, and 2.7% at La Soledad), indicating some improvement within the context of artisanal mining.

The small-scale La Y and La Soledad mining gold plants still have values between 1000% and 3000% of excess metals such as iron, because the levels of cyanide used cause very stable complexes to form. A cyanide dosage analysis should be contemplated, which guarantees that the presence of ammonia in the effluents is conditioned to cyanide hydrolysis; this would inhibit the precipitation of metal ions in the effluents from these plants.

The sulfide ion parameter reflects the acidification of the discharge and generates anoxic levels in the water. And due to the acidity, it is necessary to add $Ca(OH)_2$ to prevent the pH of the solution from decreasing considerably.

The mining sector should focus on supervision of the ASM processes, to ensure adequate rational use of resources in every process and to make the processes more sustainable.

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