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Water pollution and environmental policy in artisanal gold mining frontiers: The case of La Toma, Colombia

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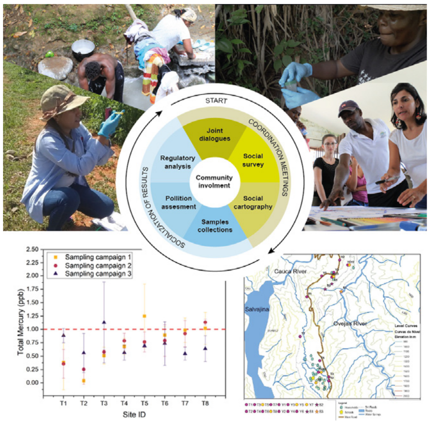
HIGHLIGHTS

- ASGM communities in Colombia are vulnerable to exposure to water pollutants.
- Communities consume natural water sources and lack water treatment infrastructure.
- A participatory research approach was used to engage the ASGM community La Toma.
- Fecal coliforms and mercury levels above regulatory limit for drinking water.
- Regulations must be adapted to the vulnerabilities of rural communities.

GRAPHICAL ABSTRACT

Researching mercury pollution from ASGM in Cauca, Colombia.



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ABSTRACT

Artisanal and small-scale gold mining (ASGM) is the largest anthropogenic source of mercury emissions globally. Concern over mercury pollution increases due to its long-term impacts on human health and aquatic and terrestrial ecosystems. Using a participatory research methodology, we gathered social and behavioral information regarding daily practices and water usage by an ASGM community in Suárez, Colombia. Based on this information, we identified 18 sampling sites of water sources commonly used by the community. The samples were analyzed for total mercury, total coliforms, pH, electrical conductivity, and total dissolved oxygen. Physicochemical and microbiological parameters from the water assessment were compared with the drinking water thresholds set by the Colombian regulatory agencies, the EPA, and the WHO. Our results showed that the majority of the samples do not meet one or more quality and safety standards. On average, the sampling sites showed total mercury levels below the regulatory limits; however, the data had considerable variability, and in many cases, individual observations fell above the maximum concentration limit for drinking water. We discuss these results within the larger framework of the regulatory gaps for human

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Abbreviations: ASGM, Artisanal and small-scale gold mining; WASH, Water, sanitation, and hygiene; CV-AAS, Cold-vapor atomic absorption spectroscopy; HMTL, Heavy metal toxicity load; ATSDR, Agency for Toxic Substances and Disease Registry's; BOD5, Biological oxygen demand; COD, Chemical oxygen demand; TSS, Total suspended solids.

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and environmental protection in ASGM contexts. The total lack of water, sanitation, and hygiene infrastructure, combined with the long-term consumption of sublethal doses of mercury and other water contaminants, constitutes a significant threat to the well-being of communities and territories that necessitates further research and intervention by institutional authorities.

1. Introduction

Artisanal and small-scale gold mining (ASGM) is the largest anthropogenic source of mercury emissions. Approximately 200 metric tons of elemental mercury are commercialized every year for ASGM purposes; this accounts for >30 % of the total mercury used in industrial applications (Gallo Corredor et al., 2021; Yoshimura et al., 2021). Due to the rudimentary gold extraction techniques used in ASGM, a significant fraction of the mercury used in ASGM ends up disseminated in the environment (Gutiérrez-Mosquera et al., 2021; Telmer and Veiga, 2009). Mercury is a pollutant of worldwide concern because of its high potential for complexation with organic material present in the environmental matrix. Complexation can lead to the formation of persistent and highly hazardous compounds such as methylmercury. Organic mercury (e.g., ethylmercury and methylmercury) represents the most toxic forms of this heavy metal to human health. Once released into the environment, mercury can be bio-accumulated and bio-magnified throughout the trophic chain, increasing the risk for terrestrial and aquatic ecosystems (Gallo Corredor et al., 2021; Gutiérrez-Mosquera et al., 2021).

Various studies have documented the harmful effect of mercury in soils, sediments, macroinvertebrates, macrophytes, fish, and humans (Gutiérrez-Mosquera et al., 2021; Laws, 2017; Servicio Geológico Colombiano ; Ministerio de Minas y Energía, 2018). Specific impacts on human health include immunological impairment (Lubick, 2010; Mutter and Yeter, 2008; Sollome and Fry, 2015), teratogenesis (Crespo-López et al., 2009; Nemeh and Longe, 2021), and disruptions to the endocrine and nervous system (Tilley and Fry, 2015). Several studies have shown that ASGM miners and nearby communities are often directly and indirectly exposed to mercury and other highly hazardous pollutants associated with the mining activities (Deheza and Ribet, 2012; Tschakert, 2009; Tschakert and Singha, 2007).

At least 10 million people work in ASGM in approximately 70 countries in Africa, Asia, and South America (Cordy et al., 2011; Diaz et al., 2020; Telmer and Veiga, 2009). South America is the largest emitter of mercury pollution from ASGM (53 %), followed by East and Southeast Asia (36 %) and Sub-Saharan Africa (8 %) (Diaz et al., 2020). Recent analyses by the World Bank and other international agencies suggest that the number of people that have entered ASGM may have increased substantially in the past three years in low- and middle-income countries due to the economic crisis derived from the COVID-19 pandemic. The ongoing global instability has increased market volatility and the use of gold as a safe-haven asset, thus pushing the gold extractive frontier while inviting people in impoverished regions to seek ASGM as an alternative to lessen the economic burden (Hilson et al., 2021; International Labour Organization, 2020; Yoshimura et al., 2021). The increase in ASGM activity will likely be reflected in higher mercury usage and emissions compared to pre-pandemic years.

Colombia is the fifth largest gold producer in Latin America, after Peru, Mexico, Brazil, and Argentina (Diaz et al., 2020). It is estimated that nearly 200,000 people are involved in ASGM in Colombia (Gallo Corredor et al., 2021). Currently, Colombia is ranked third globally for ASGM mercury emissions after Indonesia and Peru (Alcala-Orozco et al., 2021; Arctic Monitoring & Assessment Programme; UN Environment, 2019; Cordy et al., 2011; Gallo Corredor et al., 2021). According to the Colombian Ministry of Mines and Energy, 63 % of the gold-producing units in Colombia are informal (Ministerio de Minas y Energía, 2012). The informal nature of the ASGM sector implies considerable uncertainty in the accountability for mercury trading (Yoshimura et al., 2021). While the uncertainty in mercury trading information hinders the overall assessment of health impacts, it is known that the burden of disease associated with mercury pollution is disproportionately carried by marginalized communities living below the poverty line (Vélez-Torres and Méndez, 2022). In the case of the Cauca region, many artisanal and traditional miners are also disadvantaged members of indigenous and Afro-descendant groups (Le Billon et al., 2020).

This article examines the complex situation of water pollution in a small ASGM community in the northern region of Cauca, Colombia. We perform a cross-sectional investigation of water pollution and discuss the social inequalities and dysfunctional governance in rural territories that make the community highly vulnerable to environmental hazards such as contaminated water. Using mixed methodologies and a participatory research approach, we identified key sampling sites that supply water and fish for the community. Data from water analysis is presented in two categories: i) mercury pollution and ii) microbiological and physicochemical quality. Finally, we discuss the water pollution analysis within the framework of environmental justice to call attention to the urgent needs regarding safe water access and sanitation in ASGM communities.

2. Materials and methods

2.1. Study site and research framework

La Toma is located in the municipality of Suárez, in the northern region of the department of Cauca, Colombia. It has an approximate area of 70 km^2 and an altitude between 1100 and 1500 m.a.s.l (Fig. 1). Approximately 1300 families reside in the territory (Sañudo et al., 2016). La Toma is subdivided into five settlements: La Toma, Yolombó, Gelima, Dos Aguas, and El Hato. In this study, we collected data from the settlements of La Toma and Yolombó, which are the most densely populated, and have the closest proximity to the artisanal gold mines.

Since 2016, our research team has been working with the communities to investigate the impacts of mercury usage in ASGM. Transdisciplinarity and community empowerment through active participation have been the epistemic foundations of our methodological approach. Thus, community involvement was prioritized at all stages of our work. Fig. 2 shows the research framework used in this study.

2.2. Joint dialogues for partnership articulation and decision making

Between 2019 and 2020, the research team and community leaders from Yolombó and La Toma held two annual coordination meetings in the territory to discuss fieldwork logistics and to sort out emerging roadblocks. For example, in one of these joint meetings, we crafted an alternative strategy to continue with the water sampling campaigns, which were disrupted by the municipal mobilization restrictions and city lockdowns from the COVID19 pandemic. The coordination meetings were attended by the project's principal investigators and leaders from the most prominent social organizations in the territory: the Yolombó women's organization (a.k.a., ASOMUAFROYO) and the Community Council of La Toma. Additionally, in 2021, the research team led two community assemblies to socialize preliminary results obtained from the water analyses. The assemblies were attended by 59 people in La Toma (36 females, 23 males) and 75 in Yolombó (53 females, 22 males). In addition, 11 students presented results in these meetings (6 females, 5 males).

2.3. Social cartography

Two social cartography workshops were conducted in 2017 and 2019, with 16 people from Yolombó and 27 from La Toma. Participants were invited under the criteria of (i) having lived in the area longer than 10 years and (ii) having comprehensive knowledge of the mining activities performed

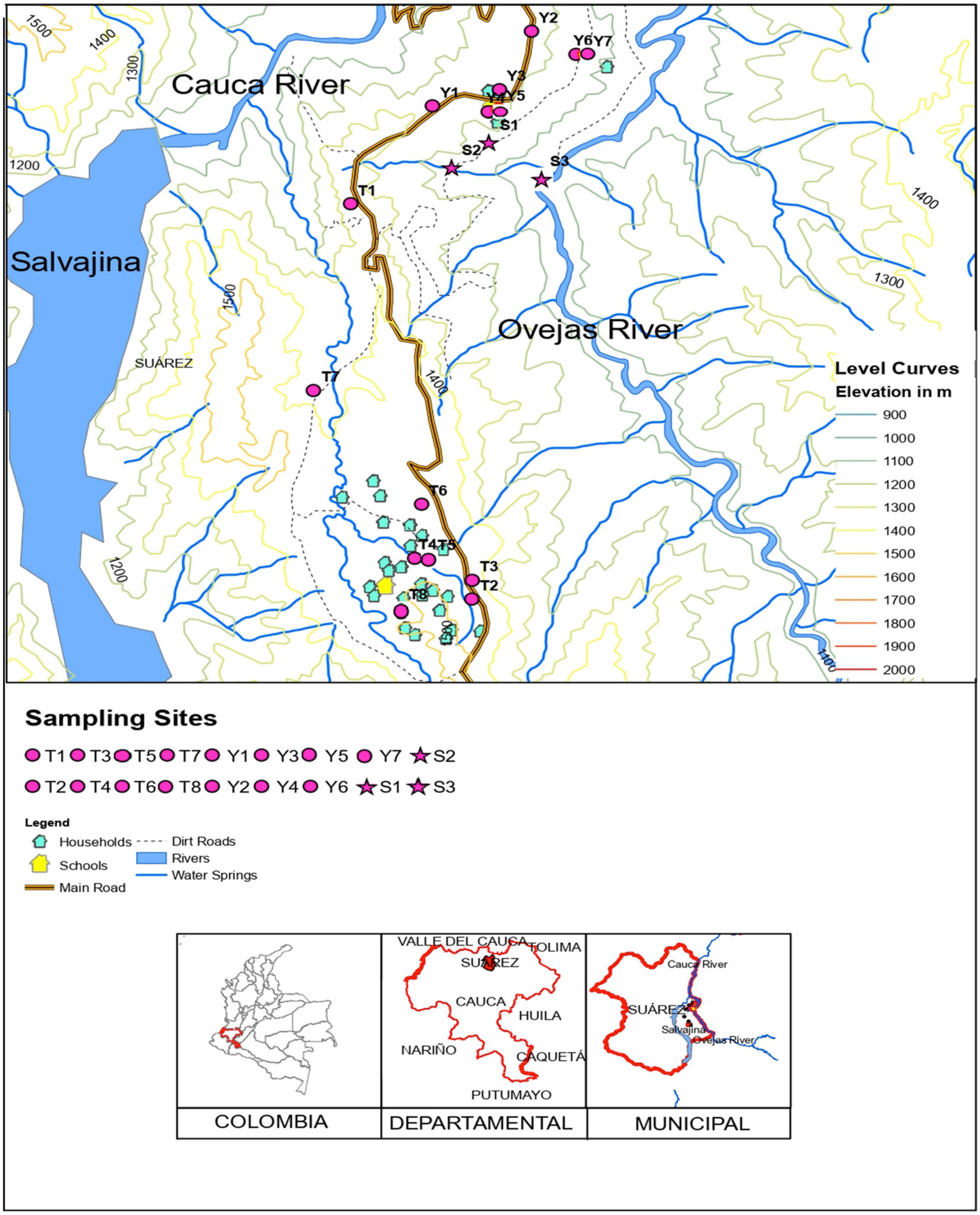

Fig. 1. Topographic map of the territory depicting sampling sites of spring water used for consumption (pink dots) and surface water (pink stars) where fishing and recreational practices take place. “Y” or “T” indicates the location in either Yolombó or La Toma settlements, respectively, and “S” indicates surface water.

in the area. Community members were given verbal and written instructions to reflect three prominent landmarks on the map: community drinking water sources, traditional (mercury-free) gold mining sites, and ASGM facilities currently known to use mercury. Community members worked collectively to draw the maps. These workshops allowed our research team to identify the water sources for human consumption in La Toma and Yolombó and provided valuable information regarding the spatial overlap of the mining sites using mercury and the water sources used for human consumption.

2.4. Social survey

A survey composed of 73 questions was conducted among 160 individuals to characterize the community in terms of (i) general demographics, (ii) water practices, (iii) livelihoods, (iv) mining, (v) fishing, and (vi) gender. The participants' selection was carried out based on spatial criteria aiming to cover the settlements of Yolombó and La Toma. The participants answered each question from a multiple-choice list. The language used in the surveys was adjusted considering the local linguistic variation and the literacy level of the participants; this was done through iterative feedback provided by the social leaders from the women's association of Yolombó and the Community Council from La Toma. Finally, trained surveyors from Universidad del Valle traveled to La Toma and Yolombó to fill out the surveys by conducting face-to-face interviews at the participants' households. All respondents were over 18 years of age and signed informed consent to participate in the study (see IRB information).

2.5. Selection of sampling sites

Based on the information obtained from the joint dialogues and social cartography, we identified 31 collective water capture sites frequently

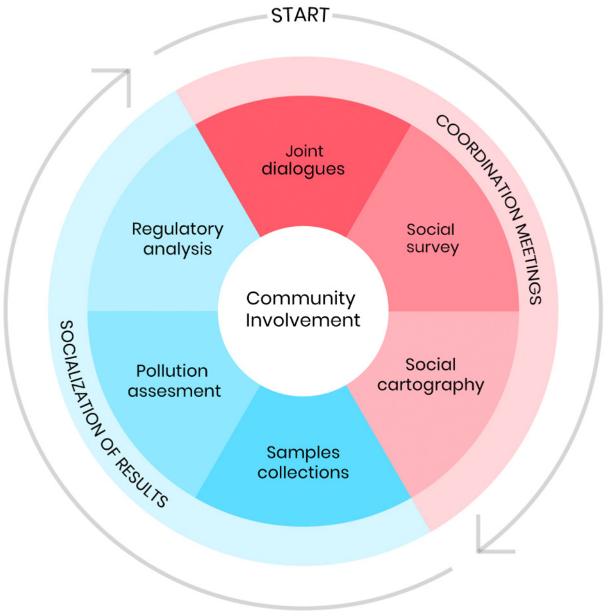

Fig. 2. Participatory research framework. Community participation was emphasized in each stage of the project. Research methodologies from social sciences (red shades) and engineering (blue shades) were integrated into two core phases over a three-year-long project. The first phase focused predominantly on qualitative methods (12 to 6 clockwise orientation), beginning with cogenerative dialogues between community leaders and lead scientists. The second phase focused on quantitative techniques (6 to 12 clockwise orientation). Two events to socialize results were held in the territory to update the community stakeholders on the research progress.

used by the community (12 in La Toma and 19 in Yolombó). Out of these 31 sites, we selected 14 water sources (7 in La Toma and 7 in Yolombó) with the highest perceived importance based on the number of households supplied by the water source (Morgan et al., 2021; Vélez-Torres et al., 2018). Community leaders requested the addition of two sampling sites near La Toma's market. The market is a vital congregation venue for the community and the territory's central mercury and gold trading area.

While the primary concern of our study was spring water used for human consumption, we also analyzed surface water from three sites: two creeks that flow downstream from active mines and one confluence point where these creeks flow into the Ovejas River. These sites were included because local fishers catch most fish from the Ovejas River, and fish is a primary component of people's diet in the municipality of La Toma. Thus, it is essential to inform the risk of mercury bioaccumulation in the trophic chain within the aquatic ecosystem. The community also gathers for recreational activities (e.g., traditional cookouts) at the shoreline and usually bathes in the Ovejas River.

Altogether, 18 sampling sites were screened for total mercury (Fig. 1).

2.6. Assessment of water samples

The water pollution assessment was carried out in two stages. First, total mercury levels were measured in all 18 sites depicted in Fig. 1. Next, 5 of these sites were selected to analyze physicochemical and microbiological parameters further.

With the assistance of two local guides, we performed the sampling campaigns in Yolombó and La Toma between January and September of 2020. Water samples were collected and brought to the laboratory facilities at Universidad del Valle on the same day of the field trip. A total of 242 water samples were analyzed.

2.6.1. Total mercury assessment

Water samples were collected in 60 mL sterile polypropylene containers and stored in coolers with ice packs during the sampling trip (~8 h maximum lag time between sample collection and lab reception). Once in the laboratory, each sample was mixed with 60 uL of a 14 N solution of nitric acid (Sigma Aldrich, USA) and stored at −18 °C until further use. To estimate total mercury levels, the samples were analyzed via cold-vapor atomic absorption spectroscopy (CV-AAS) using a portable mercury analyzer (EMP-3 + Aqua Kit, Nippon Instruments Corporation, Japan). Calibration of the instrument was performed prior to sample processing yielding a relative standard deviation of 3 % and a lower limit of detection of 0.01 μg L^{-1}. The analytical procedure was based on the instruction manual NIC-TD-0000117-01 (Nippon Instruments Corporation, 2019). To estimate total mercury levels, 20 mL of sample was transferred into the instruments impinger and 1 mL of a 6 N solution of sulfuric acid (Sigma Aldrich, USA), and 1 mL of a 0.5 M Stannous Chloride solution (Sigma Aldrich, USA) were added. Mercury in the water sample was reduced to elemental mercury, separated from the aqueous phase via evaporation, and quantified through AAS.

Using the data on mercury concentration, we calculated the heavy metal toxicity load (HMTL), which is defined as the total toxic load of all individual heavy metals in the water that impact human health (Herath et al., 2022; Huang et al., 2021; Saha and Paul, 2018). HMTL is calculated by multiplying the concentration of mercury measured in each water sample by mercury's hazard intensity score (HIS) (Eq. 1). Mercury's HIS was taken to be 1458 from the Agency for Toxic Substances and Disease Registry's (ATSDR) Substance Priority List (ATSDR, 2019).

$$\mathrm{HMTL} = \Sigma_{i=1}^{n}\ \mathrm{C} \times \mathrm{HIS} \tag{1}$$

2.6.2. Physicochemical and microbiological characterization

Based on the outcomes from the total mercury screening and additional population data, sites T5, T6, Y3, Y5, Y7, and S3 were selected for further characterization of water quality parameters. Criteria for selecting these five sites included: (i) higher observed concentrations of total mercury and (ii) frequency of use for human consumption by high-risk populations such as children and the elderly (Morgan et al., 2021). The second criteria were informed by a questionnaire filled out by members of ASOMUAFROYO who have a detailed knowledge of the composition of the households in the community (see Table 2).

To assess the physicochemical and microbiological parameters, all measurements were taken according to Standard Methods for the Examination of Water & Wastewater (Baird and Bridgewater, 2017). Upon collection, samples were stored at 4 °C and shipped in coolers to laboratory facilities at Universidad del Valle. All samples arrived within 8 h of being collected. Parameters such as pH, electrical conductivity, dissolved oxygen, redox potential, and temperature were measured in situ with portable probes and upon arrival at the university using laboratory instruments. Turbidity, biological oxygen demand (BOD5), chemical oxygen demand (COD), and total suspended solids (TSS) were measured only in the lab. Plate counting was executed with EMB selective media for enteric bacteria, Chromocult for total coliforms, and m-FC Agar for fecal coliforms to assess the presence of indicator organisms.

2.7. Statistical analysis

2.7.1. Social survey

To obtain population parameters, the sample size was established based on simple random sampling equations. The goal was to estimate population proportions in relation to the number of respondents that meet attributes such as: (i) residing in a household in which at least one member works in ASGM, (ii) residing in a household connected to certified water treatment infrastructure (aqueduct and sewage), (iii) residing in a household served by municipal trash collection and landfill disposal; etc. Therefore, the minimum sample size was determined to yield the proportion of households that meet the attributes of interest using a confidence level of 95 % and a maximum tolerable error of 7.5 %.

2.7.2. Water analyses

Statistical analysis of the data was done in R software, version 4.0 (R Studio interface 1.2.1335). The data generated in this study is presented in scatter plots and bar diagrams. The statistical difference between sampling points for total mercury content was contrasted through an ANOVA model that considered the sampling campaign a blocking factor. The assumption of normality of the errors of this model was verified. In the case of physicochemical and microbiological data, for which the assumption of normal distribution of errors is not verified, the difference between sampling points was contrasted through Friedman's nonparametric test. A Post-hoc Tukey Test for ANOVA and multiple nonparametric comparisons for Friedman Test was executed on those variables whose null hypothesis was rejected with a significance level ($p<0.05$) to find the statistically significant differences by pair of sampling points.

3. Results

3.1. Characterization of water usage in La Toma

Observations made by researchers during field visits and information gathered from joint dialogues, social surveys, and social cartography confirm that people residing within the municipality of La Toma have no direct access to drinking water from aqueduct systems nor adequate sanitation infrastructure such as sewage. Nearly 92 % of the people in the territory identify as Afro-Colombians who depend on subsistence livelihoods, including small-scale ore mining, artisanal fishing, and family farming. For this reason, daily household practices include manual water collection from natural sources, pit latrine usage, and burning of trash. In fact, among the non-remunerated activities performed in the household, water collection from natural springs is performed by 76.3 % of the population, and 63.1 % of the respondents claimed that water is scarce or insufficient. The survey also shows that the community's access to freshwater is derived from several complementary sources: rainwater (69.4 %), creeks (39.4 %), rivers (2.5 %), and springs (39,5 %); in this case, each participant disclaimed the different sources of water for household usage without mention of relative quantities withdrawn from any given source. Of participants surveyed, 46 % informed that no treatment is done to the natural water prior to household usage. Among the participants that do perform some kind of water treatment, the most frequent methods are water boiling (23 %), decantation (16 %), and chlorination (15 %). Water from springs, creeks, and rivers is collected and shared by multiple households, while rain collectors are located and used at the individual-household level. Based on the communal use consideration, we focused our pollution analysis on springs, creeks, and river water.

The 18 sampling sites considered in this study for detecting total mercury content are shown in Table 1. Table 1 lists the selected sampling locations, consisting of 15 water springs and three flowing surface water sites.

3.2. Total mercury assessment

The social survey results also show that gold mining is currently a fundamental pillar of the family economy in La Toma, where 77.5 % of the people surveyed live on <8 USD per day. Of the people surveyed, 92 % practice some form of gold mining, of which 86 % claim to perform only mercury-free traditional mining, and 14 % admit to the use of mercury in their ASGM work. To understand the effect of local mercury usage in ASGM, we analyzed the community's pollution levels in water sources frequented by the community.

The average total mercury concentrations in water samples collected from different sampling points from La Toma y Yolombó are presented in Fig. 3. Total mercury concentrations in La Toma ranged between 0.28 and 0.93 μg L^{-1} with an average of 0.71 ± 0.38 μg L^{-1}. In Yolombó, the total mercury levels in drinking water were between 0.17 and 0.62 μg L^{-1}, with an average of 0.38 ± 0.34 μg L^{-1}. The total mercury levels in surface water fell between 0.68 y 0.97 μg L^{-1} with an average of 0.71 ± 0.64 μg L^{-1}.

Table 1

Sampling Site identification in two villages: La Toma and Yolombó, located in the municipality of Suárez. The letter T indicates the site is located in La Toma; the letter Y indicates the site is located in Yolombó, and the letter S indicates the site is flowing surface water (creeks and rivers) collected in Yolombó.

Site ID	Source type	GPS coordinates	
T1	Spring	N 02° 56′ 16.73″	W 076° 41′ 35.02″
T2	Spring	N 02° 54′ 19.3″	W 076° 41′ 04.3″
T3	Spring	N 02° 54′ 24.9″	W 076° 41′ 04.2″
T4	Spring	N 02° 54′ 31.4″	W 076° 41′ 18.8″
T5	Spring	N 02° 54′ 31.3″	W 076° 41′ 15.0″
T6	Spring	N 02° 54′ 47.5″	W 076° 41′ 17.1″
T7	Spring	N 02° 55′ 21.3″	W 076° 41′ 44.4″
T8	Spring	N 02° 54′ 16.7″	W 076° 41′ 22.2″
Y1	Spring	N 02° 56′ 45.8″	W 076° 41′ 14.3″
Y2	Spring	N 02° 57′ 08.0″	W 076° 40′ 49.3″
Y3	Spring	N 02° 56′ 50.7″	W 076° 40′ 57.4″
Y4	Spring	N 02° 56′ 44.1″	W 076° 41′ 00.2″
Y5	Spring	N 02° 56′ 44.9″	W 076° 40′ 57.6″
Y6	Spring	N 02° 57′ 01.2″	W 076° 40′ 38.0″
Y7	Spring	N 02° 57′ 01.1″	W 076° 40′ 35.7″
S1	Creek	N 02° 56′ 35.0″	W 076° 41′ 00.2″
S2	Creek	N 02° 56′ 27.6″	W 076° 41′ 08.7″
S3	River	N 02° 56′ 24.3″	W 076° 40′ 47.3″

The results of the analysis of water pollution due to mercury were compared to the maximum mercury values accepted by the Colombian Resolution 2115/2007 (Ministerio de la Protección Social, 2007) (1 μg L^{-1} total mercury), the Guidelines for Drinking Water Quality (WHO, 2017) (6 μg L^{-1} inorganic mercury), and the National Primary Drinking Water Regulations (EPA, 2009) (2 μg L^{-1} inorganic mercury). Considering that the applicable regulatory enforcement from pollution assessment is based on individual measurements (instead of averaged data), it is important to note that sites Y5, Y7, T1, T3, T5, T6, T7, T8, S1, and S3 exceeded the maximum mercury threshold of 1 μg·L^{-1} in more than one observation (Fig. 3). The most concerning results come from site T8, where >4 out of 9 observations (≅44 %) exceeded the regulatory limit.

The ANOVA test indicated statistically significant differences between the mean total mercury at the different sampling points. This test also showed differences in the averages obtained in the sampling campaigns, which had a decreasing behavior over time.

The HMTL values provide information on toxicity levels which can be used to predict the percent removal of mercury needed to ensure the safety of the water. The samples obtained from the municipality of La Toma showed HMTL values ranging from 251.9 to 1414.3 μg L^{-1} (Fig. 3.), with an average HMTL of 849.0 μg L^{-1}. While the average HTML was lower than the permissible toxicity load of 1458 μg L^{-1}, the data variability is high. In la Toma, 12 of the 72 samples exceeded the permissible toxicity load (Table S1); in Yolombó 3 of the 63 samples exceeded the permissible toxicity load (Table S2), and in surface water 4 of the 27 samples exceeded the permissible toxicity load (Table S3). The percentage removal of mercury necessary to reduce levels below the permissible toxicity load ranged from 3 to 50 % in La Toma (Table S4), 6 to 48 % in Yolombó (Table S5), and 16 to 68 % in surface water sites (Table S6).

In this context, it is difficult to elucidate the risk of health impacts for the community exposed to mercury polluted water. It is known that the highest risk of toxicity for humans is associated with exposure to methylmercury. Thus, it is advisable to further explore the bioaccumulation and biomagnification pathways applicable to the region. The scientific consensus used to be that sulfate-reducing bacteria found in anaerobic environments were the principal methylators of mercury (Compeau and Bartha, 1985). However, emerging genomic research looking at the hgcA and hgcB gene clusters (Parks et al., 2013) suggests that the organisms able to carry out methylation are diverse, including sulfate-reducing bacteria, iron-reducing bacteria (FeRB), methanogens, and fermenters (Fleming et al., 2006; Gilmour et al., 2018, Gilmour et al., 2013; Hamelin et al., 2011; Peterson et al., 2020). Additionally, researchers have long suspected abiotic processes contribute to mercury methylation, including methylation

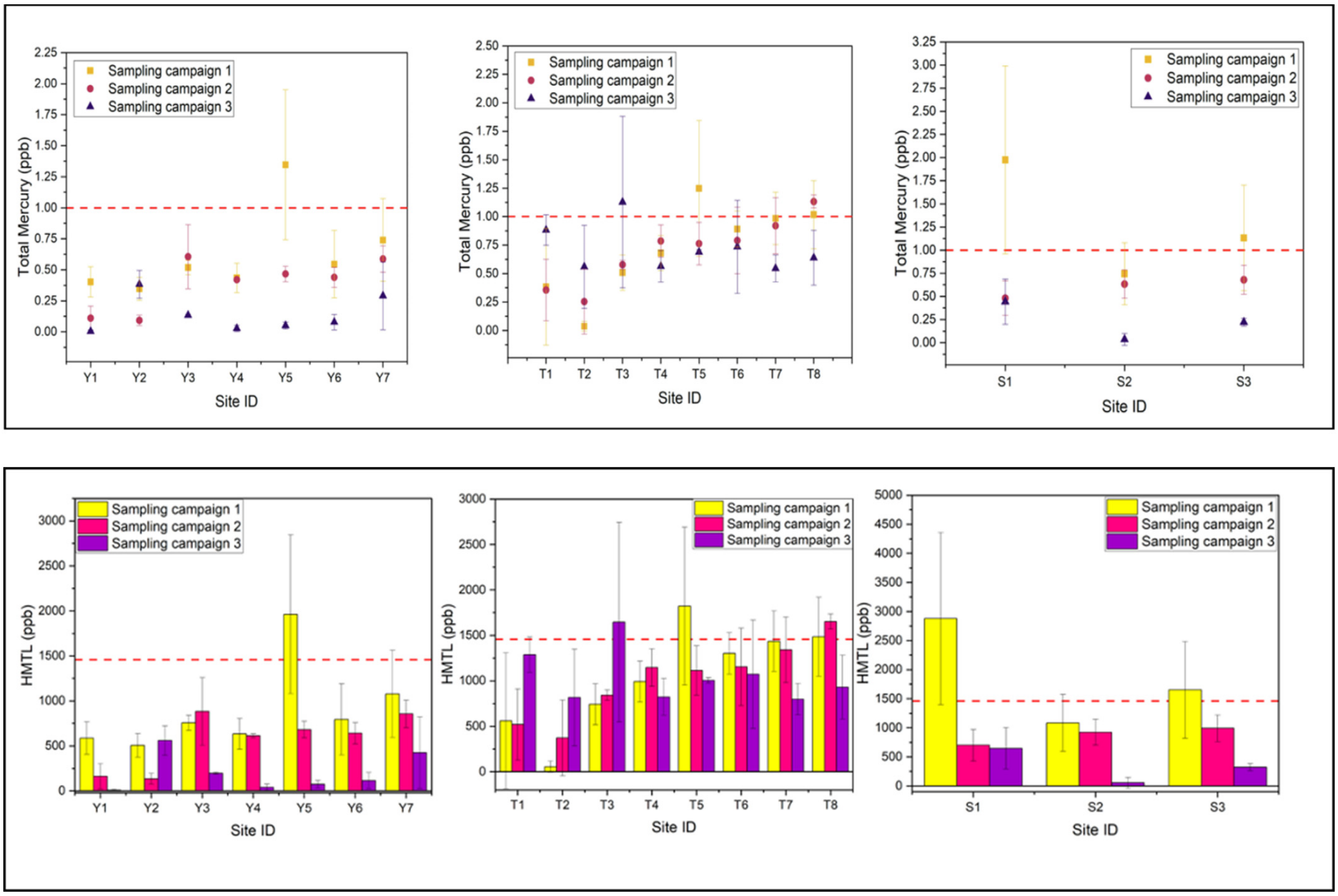

Fig. 3. Total mercury concentration (in the top) and HMTL (in the bottom) in spring water used for human consumption in Yolombó (left panel) and La Toma (middle panel) and surface waterways (right panel) used for fishing, bathing, and recreational activities by the community. Three sampling campaigns were conducted in the territory during weekdays between February and March 2020. Geometric symbols represent the mean mercury concentration in the sample. Error bars represent the standard deviation from the mean ($n = 3$). The red dotted line represents the maximum mercury threshold for drinking water (WHO, 2004).

by methyl iodide, dimethylsulfide, methylcobalamin, methyltin, and methyllead compounds and fulvic and humic acids (Celo et al., 2006; Weber, 1993). Thus, the transformation of mercury from inorganic to organic forms may be mediated via multiple mechanisms in the aquatic ecosystems of La Toma.

3.2.1. Physicochemical and microbiological results from drinking water sources

Table 2 shows the demographic characteristics of the supplied population from the four sites where water assessment was conducted. The table shows that site T8 supplies the largest portion of the population with 417 residents and the highest number of people between 0 and 13 years old (206).

Results of physicochemical parameters measured in the different sampling sites are presented in Table 3. These results show important variations in the pH measurements. Sampling sites T5 and Y7 presented the lowest average pH values of 4.8 ± 0.38 and 5.83 ± 0.22, respectively. All of the sampling sites assessed were relatively acidic and fell under the minimum pH allowed by the national (Res 2115/2007) and international (EPA, 2009; WHO, 2017) regulations for drinking water (between 6.5 and 9 and 6.5 and 8.5, respectively). The moderate acidity in the water could be explained by the physicochemical properties of the local soil. Generally, the sampling sites in La Toma and Yolombó presented low values for turbidity and dissolved oxygen.

The Friedman test showed that there are significant statistical differences. The average pH and dissolved oxygen in sampling point Y5 were higher than T5, T8, and Y7.

The number of fecal coliforms found in the sampling sites is represented in Fig. 4. According to the Colombian (Res 2115/2007) and international regulations (EPA, 2009; WHO, 2017), the presence of fecal coliforms in drinking water must be zero. Therefore, all sites assessed do not comply with these regulations.

Regarding the total coliforms, at a significance level of 0.1, there are significant differences between sites T5 and Y5, Y5 being higher. In the

Table 2
Demographic Characteristics of the supplied population from the sampling sites.

Site ID	Population supplied	Women	Men	Age (years)				
				0–5	6–13	14–18	19–60	>60
T5	41	13	16	1	12	1	25	2
T8	417	194	223	44	162	145	56	10
Y5	69	27	42	9	10	3	43	4
Y7	19	8	11	3	3	0	12	1

Table 3
Summary of physicochemical concentrations of water quality measured sampling sites in La Toma and Yolombó.

Site ID	Physico-chemical parameters					
	pH	T (°C)	CE (μS cm^{-1})	Turbidity (NTU)	Eh (mV)	DO (mg L^{-1})
T5	4.80	21.5	72.8	1.79	223.8	4.3
T8	6.23	22.0	54.5	–	267.6	2.69
Y5	6.28	24.1	75.9	8.68	186.8	5.14
Y7	5.83	24.8	45.5	–	208.3	4.02

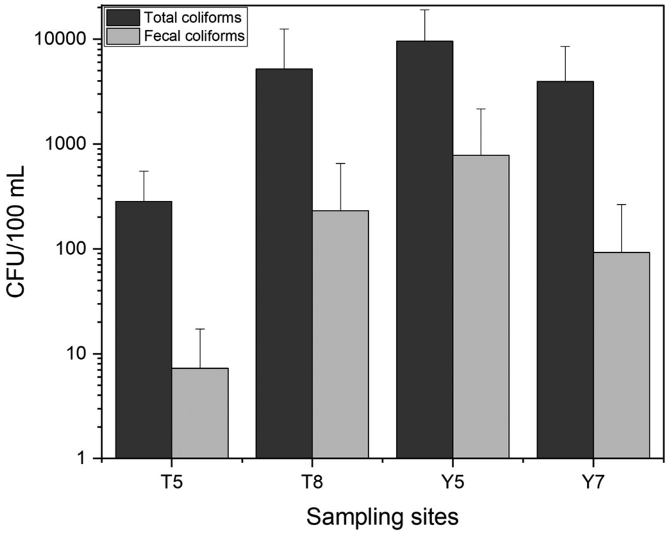

Fig. 4. Microbiological analysis of water samples drawn from sites frequently used by the community for cooking and other household activities.

case of fecal coliforms, the Friedman test found differences at a significance level of 0.1, but when executing the Post Hoc Test, no differences were found. This discrepancy occurred because there was an outlier at every site. The absence of basic sanitation systems to release wastewater produced in houses close to the sampling sites most likely causes the microbiological pollution. According to the data generated from the survey, 9 % of La Toma's population admits to frequently practicing open defecation. This practice may contribute to the microbial contamination of water sources via runoff and percolation.

In the survey, 63 % of respondents said that water was scarce or insufficient, and only 27.5 % believed that they had a sufficient amount of water available for household use. Of those surveyed, 50 % consider the water quality substandard. Additionally, the results from the survey show that in most cases (46 %), there is no water treatment at all. The treatments applied in some cases are boiling water (23 %), sedimentation (16 %), and chlorination (15 %).

3.2.2. Physicochemical analysis of surface water

The physicochemical parameters assessed at the surface water sampling point S3 did not surpass the maximum allowable values under the Colombian regulation Resolution 0631/2015 (Ministerio de Ambiente y Desarrollo Sostenible, 2015), which regulates the surface water sources affected by gold mining activity. The parameters recorded were as follows: pH (7.3), temperature (22.6 °C), conductivity (98.9 $\mu s\ cm^{-1}$), redox potential (207.4 mV), dissolved oxygen (6.8 mg L^{-1}), DBO_5 (<2.5 mg $O_2\ L^{-1}$) and DQO (12.2 mg $O_2\ L^{-1}$. Contrarily, the total suspended solids (319 mg L^{-1}) did not comply with the established reference limit. Upstream of the sampling site, the creek joins with two other creeks and drags a large amount of suspended material from a blast mine.

4. Discussion

This discussion provides an integrated analysis of water pollution based on physicochemical and microbiological factors, focusing on mercury pollution from ASGM. We analyze the results considering current public health and environmental protection regulations and provide insights into the practical gaps and dysfunctionalities hindering the enforcement of these regulations in Colombia. This integrated analysis allows for a comprehensive understanding of the inherent relationship between mining activity and water pollution, environmental degradation, and health risks. It sheds light on more effective policies and institutional strategies to address environmental issues while protecting the welfare of vulnerable communities.

4.1. Inadequate access to clean water

Water stress refers to the pressure put on freshwater resources by use and withdrawal under a multifaceted interaction among socioeconomic factors, the terrestrial hydrological cycle, and climate change (Alcamo et al., 2010; Gao et al., 2018; Haddeland et al., 2014; Kiguchi et al., 2014; Wada et al., 2011). The overall situation in the studied sites fits the description of water stress. Despite having numerous freshwater reserves, available sources have deteriorated, and their quality is not acceptable or safe for consumption. As shown in the results from the perception surveys, residents are aware of this problem. The strain on the community in La Toma and Yolombó is compounded because many people cannot access alternative water sources with more suitable water quality. Vélez-Torres (2012) described the multiple hurdles faced by the community in trying to access clean water from the Salvajina dam, located adjacent to La Toma (see Fig. 1).

Our research findings indicate an urgent need to develop water, sanitation, and hygiene (WASH) infrastructure in La Toma and Yolombó. Previous work in the communities includes qualitative reports on the impacts of mercury pollution due to ASGM on local livelihoods and gender roles, a quantitative analysis of contamination levels in surface water used for human consumption, and worrisome pitfalls of governmental agencies when addressing mercury pollution in the area (Vélez-Torres et al., 2018; Vélez-Torres and Vanegas, 2022).

Approximately 85 % of the water supply systems in the municipality of Suárez, where La Toma and Yolombó are located, are obsolete (Alcaldia de Suarez, 2020). In response to this situation, community members have opted for different treatment alternatives that are rudimentary and, in many cases, insufficient or inadequate to improve water quality. For example, chlorine is used to disinfect the water, thereby reducing adverse health effects related to the consumption of water contaminated by microorganisms. However, at incorrect doses, chlorine can form significant levels of disinfection byproducts, such as trihalomethanes; particularly in water with a high organic matter content. Long-term consumption of trihalomethanes is highly dangerous (Hernandez-Sanchez et al., 2011). Regarding sanitation, the results and information reported by the local government indicate that none of the residents have access to sewer services (Alcaldia de Suarez, 2020). Consequently, wastewater is discharged directly to surface water sources.

These issues correspond to the generalized human and ecological crisis in the rural Global South and water insecurity in particular (Lu et al., 2014; Shah, 2021). In Colombia, 28.46 % of the 11 million people living in rural areas did not have potable water in 2018 (Carrasco Mantilla, 2016). In contrast, within urban areas, only 2.2 % did not have access to water infrastructure (Departamento Nacional de Planeación, 2019). Regarding sewage, according to the Colombian National Development Plan of 2011–2014, in 2008, coverage was 92.9 % in urban areas, while in rural areas, it was only 69.6 % (Useche Melo, 2012).

Water and sanitation gaps between urban and rural areas are also significant worldwide. In 2020, a total of 225 million individuals in rural areas did not have safely managed drinking water services. This means that 8 out of 10 individuals who lack basic services live in rural areas (WHO and UNICEF, 2021), and only 60 % of the rural population have access to a safe source of water. The case of sanitation services is similar, with global coverage in rural areas at barely 44 % and a gap between urban and rural areas of 18 percentage points (WHO and UNICEF, 2021).

4.2. Regulatory landscape in ASGM territories

The use of mercury in the gold extraction process in Colombia has led to contamination of drinking water sources. Out of eighteen water collection sites studied, ten showed mercury levels above the Colombian regulatory threshold in more than one observation. Although the average mercury levels are, for the most part, within the maximum levels allowed, it is important to acknowledge confounding risk factors, such as the poor physicochemical and microbiological quality of the water that the community regularly uses.

One hundred forty countries, including Colombia, pledged to phase mercury usage by signing the Minamata agreement in 2013 (Convenio de Minamata sobre Mercurio, 2018). However, the presence of mercury speaks to the persistent circulation of mercury in illegal markets despite bans imposed by law 1658, framed in the Minamata agreement (Vélez-Torres and Vanegas, 2022). These findings represent a failure to make progress regarding the overall objective of effectively eliminating the use of mercury in production or gold recovery activities (Zapata et al., 2016). These findings agree with evaluations by state control agencies, which also highlight that the official data on mercury trading are not precise (United Nations et al., 2017).

The World Health Organization (WHO) establishes reference values for parameters of drinking water quality to be used globally as guidance for the formulation of local regulations. Each country's government is responsible for adapting these values to local circumstances when developing water quality and safety standards, especially in "countries with limited infrastructure and resources" (WHO, 2018). The United States Environmental Protection Agency (EPA) regulations are frequently adopted or used as a reference for elaborating environmental regulations in Colombia. However, in the United States, the maximum contaminant levels can be adapted to more strict levels according to the specific needs of each state. While WHO and EPA pollutant thresholds are intended to serve as generic guidelines, the direct adoption of these frameworks without regard for context specificity is a relatively common malpractice in Colombian policymaking.

Regulations must evolve as technology improves, more information is obtained on the health effects of pollutants, and analysis methods become more accurate. Likewise, the processes for treating contaminated water must be stricter and guarantee human health. Mercury was included in 1971 international standards due to health concerns, with a maximum allowed value of 1 $\mu g\ L^{-1}$ of total mercury in water. This value was maintained until the 3rd edition of the Guidelines for Drinking Water Quality of 2004 (WHO, 2004). In 2006, an addendum to the newest edition changed the value and type of mercury used as a measurement parameter for drinking water. The new edition suggests 6 $\mu g\ L^{-1}$ inorganic mercury, based on the premise that the mercury found in water for consumption is in its ionic form and not complexed with organic matter, assuming that organic matter levels are diminishable. In other words, "it is unlikely that there is any direct risk of the intake of organic mercury compounds (…) as a result of the ingestion of drinking water" (WHO, 2017). This value is the most up-to-date value available.

In Colombia, the current maximum mercury level in water is set by Resolution 2115 of 2007, based on the third version of the WHO drinking water quality guidelines. In Colombia, there is a lack of political will or scientific support to pursue studies investigating the differential factors that may yield significant impacts on water quality and the health of local ecosystems and rural communities that depend on natural water sources. Thus, despite the flaws associated with the direct adoption of guidelines from international agencies, this approach is perhaps the most scientifically informed strategy available in developing countries such as Colombia.

4.3. Structural inequities, inadequate regulatory enforcement, and environmental mismanagement

Colombia defines drinking water in its legislation in Art. 2, Decree 1575 of 2007 (Departamento Administrativo de la Función Pública, 2007) as: "due to its physical, chemical and microbiological characteristics, is suitable for human consumption, whether treated or natural." This definition of drinking water supposes an ideal where human health is guaranteed, thereby acknowledging the human right to water (United Nations, 2010). However, it is often not applicable in complex natural settings where contaminants interact and enhance or diminish potential toxicity. Furthermore, several physical, social, and economic conditions limit the possibility of accessing safe (treated) water for some rural poor communities (WHO, 2003).

The problem lies in the fact that there is no sufficient commitment by the Colombian institutions to developing water, sanitation, and hygiene (WASH) infrastructure for rural communities. The material conditions have made it virtually impossible to enforce regulations in ASGM contexts. The inequitable outcomes between rural and urban communities are amplified, and institutional avoidance in addressing the root causes of the environmental problems disproportionately affect vulnerable rural communities that often fall into regulatory cracks (Bullard, 2001). Due to this, there is an ongoing and day-to-day violation of the human right to water and sanitation for rural communities. This makes the definition of drinking water not compatible with water consumed in the 30 % of Colombian rural areas that do not have water and sanitation service coverage (Carrasco Mantilla, 2016) and therefore, consume water that does not have suitable microbiological and physicochemical characteristics.

The results of our research demonstrate that the water consumed by the communities in La Toma and Yolombó does not comply with several regulatory parameters. The water is of poor quality because of a lack of appropriate WASH strategies and contamination generated by mining practices (Gallo Corredor et al., 2021; Gasteyer et al., 2016). Furthermore, the regulations designed for drinking water do not account for the actual environmental conditions in rural Colombia. Standard analytical methods used for assessing total mercury (i.e., the sum of all forms of mercury present in the sample) involve additional pretreatment steps and reagents for samples suspected of containing organic mercury (e.g., environmental water with a significant content of dissolved organic matter) compared to water samples that are less likely to contain it (e.g., purified drinking water). The organic load found in the communities water suggests that chemical analyses must be carried out with methods designed for water with significant total organic matter contents (EPA, 1994). This bias in the method may imply underestimation in the values found because mercury is not quantified in organic form, which implies underestimated risk.

Shortcomings in infrastructure and public policies, together with the socioeconomic conditions of rural marginalization, affect the right of communities to access quality water. This study indicates a systemic failure, which can be understood as environmental racism by constituting a deliberate decision of allowing or not preventing contamination in rural territories, and in this case, Afro-descendant territories (Vélez-Torres and Vanegas, 2022). Therefore, we propose that the problems related to water pollution in the mining sites studied here should be addressed from the water justice framework. Water justice is part of the Environmental Justice perspective that encompasses the differentiated exposure to environmental hazards, access to natural resources and social determinations of toxic exposure, and lack of services by vulnerable communities (Bullard, 2001; Holifield, 2013; Kiguchi et al., 2014; Sundberg, 2013; Taylor, 2014). This approach is essential given that this territory is sustained and raised by the water. The main economic activities revolve around it, and its inhabitants are mainly fishermen, miners, and farmers.

5. Conclusions

Our physicochemical and microbiological analysis shows that drinking water in La Toma and Yolombó does not comply with national and international water quality standards for human consumption. This situation is not surprising given the total lack of water and sanitation infrastructure in the territory. Concerns over water pollution in this region have increased in the past decade due to the incursion of new gold mining practices involving mercury amalgamation. The uncontrolled usage of mercury in ASGM has led to mercury dispersion in the local waterways. All water samples analyzed in this study contained some measurable level of mercury. Since these samples were collected from the most frequented water supply sites used by the community, people's exposure to mercury via ingestion of polluted water is a reasonable concern. A previous water assessment performed in 2018 by the regional environmental protection authority (CRC) showed mercury presence in water samples collected from Yolombó. This suggests that the community's exposure to contaminated water could be chronic at this point since there are no alternative safe water sources accessible to them. Bioaccumulation of mercury in local aquatic ecosystems is another factor of concern since our results show that water from creeks and the river used for fishing and recreation by the community also contain detectable levels of mercury. Locally caught fish is the primary source of protein in the community's diet; thus, pollution of the aquatic environment in La Toma deserves further research to better understand the health and environmental impacts of mercury usage in ASGM.

We have discussed that the lack of WASH solutions is an expression of the absence of support, technical assistance, and training from responsible governmental entities. The lack of WASH solutions leads to a violation of the right to water and sanitation, which was celebrated as an advance in the struggle for environmental and water justice and a change in the development discourse about water and sanitation coverage. In the circumstance of our research, where Afro-Colombian communities are being exposed and violated, we frame the case in environmental racism. The lack of WASH solutions also implies a continuing non-compliance with international commitments such as the Sustainable Development Goals (e.g., Goal 6: Clean Water and Sanitation). This situation demonstrates the need for community science and participatory research to inform policy strategies that take into consideration the social, cultural, and environmental characteristics of the territory.

From a water justice perspective, confronting this environmental racism in La Toma and Yolombó means addressing these five fundamentals: (i) correct the deficiencies in WASH infrastructure, (ii) guarantee appropriate education on water use and preservation, (iii) ensure technological access and law enforcement for water protection and management, (iv) empower local communities in local water governance and schemes for environmental protection under the principles of territorial ethnic autonomy, and (iv) recognize and protect cultural practices that enforce water as a cultural milestone.

This approach will allow the inclusion of the precautionary principle with pollution prevention as the primary strategy (elimination of the threat before harm occurs) (Bullard, 2001; Cole and Farrell, 2006) by creating normative frameworks that recognize the specificities of rural and ethnic communities. Also, this approach can help to determine the real conditions in which these people and places find themselves. Knowing the state of contamination in these territories is essential for the communities that inhabit them and for public knowledge. In addition, it is the first step in taking action against contamination and helps develop solution strategies.

CRediT authorship contribution statement

Lisseth Casso-Hartmann: Formal analysis, Investigation, Writing-Original Draft, Visualization; **Paulina Rojas-Lamos:** Investigation, Writing- Original Draft, Writing- Review & editing; **Irene Vélez-Torres:** Conceptualization, Methodology, Validation, Investigation, Resources, Writing- Review & editing, Supervision, Project administration, Funding acquisition**; Claudia Lorena Montes:** Formal analysis**; Kelli McCourt:** Formal analysis, Writing- Original Draft, Writing- Review & editing**; Jaime Mosquera:** Validation, Formal analysis, Data curation; **Byron Wladimir Bolaños:** Investigation**; Luz Edith Barba-Ho:** Conceptualization, Supervision**; Diana Vanegas:** Conceptualization, Methodology, Validation, Resources, Data curation, Writing- Review & editing, Visualization, Supervision, Funding acquisition.

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Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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