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Integrating scientific and local knowledge into pollution remediation planning: An iterative conceptual site model framework

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A B S T R A C T

Pollution remediation decisions in developing communities are often made with limited technical data and stakeholder engagement. Local knowledge of contamination is oftentimes neglected, resulting in efforts that fail to align with community objectives. In this work, we propose a new approach for incorporating local knowledge on contamination into remediation efforts, resulting in a community-informed conceptual site model framework for pollution remediation. This framework uses qualitative and quantitative social science methods to develop a holistic view of contamination as defined by the community, pairing social knowledge with existing technical information about a site. An example of the application of this framework is provided from a field study conducted in a mercury-contaminated artisanal and small-scale gold mining community in Andes, Colombia. We conducted qualitative unstructured and semi-structured interviews and surveys to elicit local knowledge on mercury contamination. We combined this stakeholder input with limited scientific published literature on mercury contamination in artisanal mining communities to develop different conceptual site models that vary based on the level and type of stakeholder input. Our findings demonstrate how local knowledge on contamination varies due to contextual factors within the community, revealed through the engagement. This work also demonstrates how the new framework can be utilized by environmental practitioners to define the needs, wants, and priorities of stakeholder groups throughout a remediation project, ensuring maximum participation in solution development.

1. Introduction

Environmental remediation projects rely on vast amounts of quantitative data, linked with mathematical tools, to develop solutions that limit human and ecological exposure to hazardous contaminants. One tool commonly used to communicate site information to stakeholders and guide decision-making among practitioners around the complex behaviors of a contaminant at a site is a conceptual site model (CSM). CSMs are generally written and/or illustrative representations of the physical, chemical and biological processes

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controlling the fate and transport of contamination to humans and the environment (NJ DEP, 2019). Initial CSMs, which are made during a preliminary site assessment, are highly conceptual, focusing on understanding basic topography, hydrogeology, and surface drainage patterns impacting the transport of a contaminant (US EPA, 2011). However, as knowledge of site conditions progresses, CSM iteration allows for additional refinement, resulting in more quantitative rather than qualitative understanding. CSMs are highly useful because they evaluate the extent of contamination, identify additional site investigation needs, and analyze the sustainability of applied solutions (Li et al., 2019; NJ DEP, 2019; Ouni and Brusseau, 2016; US EPA, 2011). Additionally, CSMs help to facilitate the communication of site contamination issues with stakeholders, especially local communities (Clark et al., 2007).

Currently, CSMs are almost exclusively created by the collection and use of technical, quantitative data, despite the United States Environmental Protection Agency's (US EPA) acknowledgement that stakeholder interviews can inform the development of early iterations of a CSM (US EPA, 2011). The overreliance on technical, quantitative data may impede a CSM's ability to be used as a stakeholder engagement strategy. Some stakeholders do not find purely quantitative information reliable (Rizzo et al., 2016). Others may be unable to understand technical information at the level of technical experts (Bardos et al., 2018). Instead, local community members are often enlisted to make decisions about the end-use of a site or tangential impacts related to community life, such as defining traffic routes (Cappuyns, 2016; ITRC, 2011). Limiting community input early in the project excludes knowledge that could contribute to on-going project activities, such as gathering initial site data, creating project objectives, or defining locations for environmental sampling. Additionally, failure to collaborate with stakeholders early in the remediation project may cause crucial social, economic, or environmental considerations to be disregarded. This lapse threatens the sustainability of remedial solutions by creating objectives from purely scientific forms of knowledge that may not reflect local context, constraints, priorities, and needs.

The primary objective of this work is to develop a framework for environmental practitioners that utilizes methods of stakeholder engagement alongside traditional quantitative data collection and analysis to create conceptual site models. To demonstrate the framework's practical applicability, we apply it to a case study of mercury contamination at artisanal and small-scale gold mining

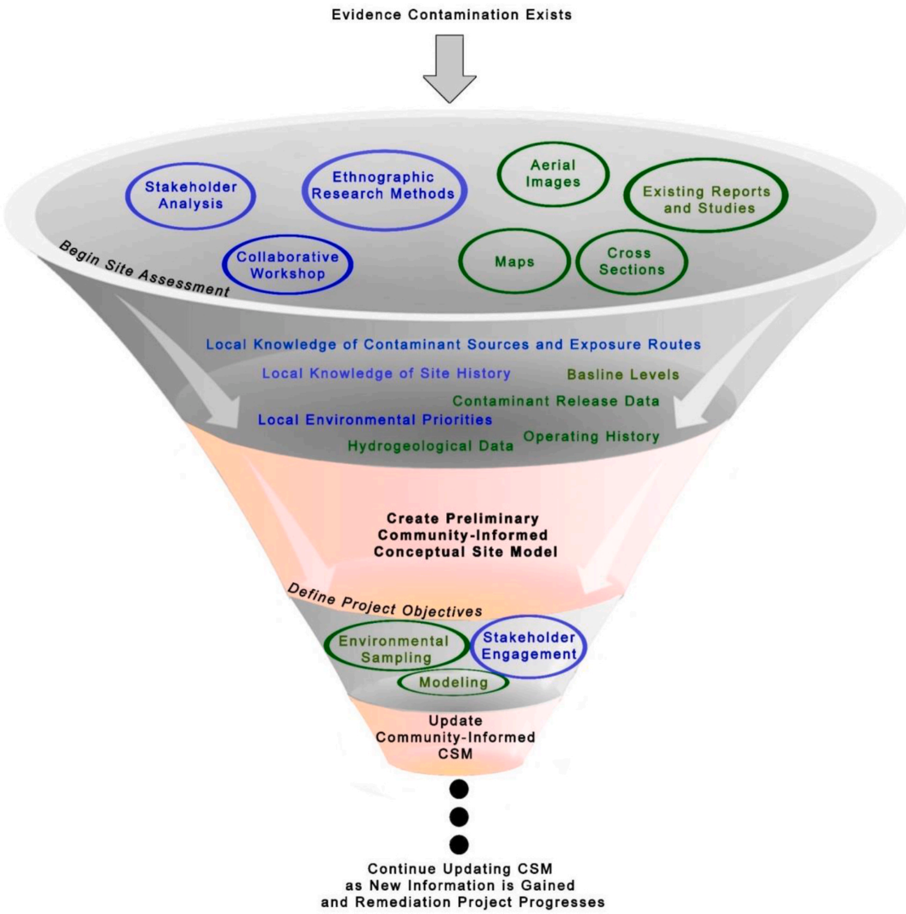


Fig. 1. Adapted framework for creating community-informed conceptual site models (CSMs) using a blend of social and technical knowledge sources during the planning phases of a remediation project. Social data and information are shown in blue. Technical data and information are shown in green. Pink highlights denote when a CSM may be updated, although this framework can be adapted to specific projects and may have more iterations during planning phases. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

(ASGM) sites in Andes, Colombia. This work demonstrates an explicit process that enables socio-technical integration in early pollution remediation efforts, allowing remediation decision-makers to enhance local community involvement in preliminary site assessment efforts.

2. Community-informed conceptual site model

In the field of site remediation, CSMs are used to accomplish three main goals: 1) identify the sources, fate and transport, and receptors of a contaminant; 2) organize existing information and document the evolution of a project; and 3) communicate site information to stakeholders (US EPA, 2011). The accomplishment of these three goals results in an application of robust remediation solutions that meets the needs of the local context and site conditions. Remediation projects, therefore, require conceptual site models to be developed for each individual site. In this section, we present the general framework for the community-informed conceptual site model. Unlike traditional approaches that fail to incorporate key stakeholder engagement early and often throughout the remediation process (Zheng et al., 2019; Ouni and Brusseau, 2016; Li et al., 2019; ASTM, 2014; AECOM, 2017; Jakubick and Kahnt, 2002; U.S. Army Corps of Engineers (USACE), 2003), we propose incorporating local knowledge by applying ethnographic research methods and stakeholder analysis at key stages in the conceptual site model development process. The proposed framework (Fig. 1) focuses on the initial site assessment stage of remediation projects, when the extent of contamination and knowledge of the environmental setting (topography, geology, etc.) are often unknown and early stakeholder engagement is critical but often lacking (Norrman, et al. 2020). The inclusion of this CSM framework has the potential to influence and improve later stages of CSM development that are based on more rigorous quantitative analysis on site data (see Zheng et al., 2019 for an example). Rather, this framework culminates in the creation of project objectives, identification of knowledge gaps that require technical expertise to be answered, and an initial contextual understanding of local communities that enhances effective stakeholder engagement during the project lifespan.

2.1. *Community-informed conceptual site model development*

A remediation project starts with evidence that a contaminant has been released and has the potential to impact (or has already impacted) the environment and human health. This evidence could include information on historical practices, distressed vegetation, water with taste or odor problems, or direct observation of the contaminant in the environment. This evidence triggers a preliminary site assessment, where, traditionally, practitioners find and review existing technical information about the site and contact the existing and former site operators (US EPA, 1991). This information may include documentation about the site history, reports or studies from other agencies about the area, and aerial imagery (ASTM, 2014; ITRC, 2011; Payne et al., 2008; US EPA, 2011). Although site operators may be interviewed (US EPA, 2011), other stakeholder involvement and local knowledge is excluded from the conceptual site model that results from this initial data analysis. The framework (Fig. 1) suggests four main data types (maps, aerial images, cross sections, and previous reports) during the preliminary site assessment, based on a review of technical guidance for conceptual site models (ASTM, 2014; ITRC, 2011; US EPA, 2011; Payne et al., 2008) and case studies (e.g., US EPA, 2006; Ouni and Brusseau, 2016; Palumbo-Roe et al., 2011; Nikolaidis and Shen, 2000; AECOM, 2017).

The community-informed conceptual site model, by comparison, strategically incorporates local knowledge about contamination to supplement missing information about a contaminated site in a much more comprehensive fashion than is typical. This may include documenting community members' ideas about the potential sources of contamination, revealing their experiential observations about the site's history, uncovering their knowledge about exposure routes to human or ecological receptors, and discerning stakeholders' risk perceptions about a contaminant. The community-informed CSM framework (Fig. 1) suggests three primary activities to occur alongside quantitative analysis of existing data. First, a stakeholder analysis can begin to identify the relevant stakeholders in a project. Multiple methods exist for completing a stakeholder analysis (see Reed et al., 2009 for a review of different methods used in natural resource management fields, as well as advantages and disadvantages of each). An effective stakeholder analysis can lead to a minimization of single stakeholder bias and maximize the time and resources spent engaging community members (Reed et al., 2009). It can also help identify different community groups and entities, as well as discover marginalized groups (Shirey, 2012). Second, ethnographic field methods, such as semi-structured interviews and participant observation, can be conducted simultaneously during initial site visits, making effective use of the practitioner's time to engage in social and technical data-gathering. Ethnographic field methods can allow unexpected issues within a community to be uncovered because the central aim of these methods is to provide holistic insight into the perspectives, culture, practices, and beliefs of people within a specific context (Reeves et al., 2008). Although interviewing current and former employees of a site is often conducted at the beginning of a remediation project, additional community members (as identified from stakeholder analysis) can also be included to provide experiential or observational knowledge related to potential contamination. Ethnographic field methods further serve as a natural method for building rapport between project practitioners and local stakeholders. Third, an introductory workshop, focus group, or public forum may be convened to gauge initial interest in project activities, answer community members' questions about the project, and introduce the role of the community in the project.

2.2. *Utility of community-informed conceptual site models*

Early iterations on the preliminary CSM may highlight significant data gaps that create barriers to meeting project objectives (US EPA, 2011). Stakeholder input at this stage can pinpoint cultural and contextual barriers to successful remedial implementation, especially through a comparison of stakeholder needs and priorities. As a remediation project progresses and more technical data are integrated into the CSM, there will be a shift in knowledge base from a heavy reliance on local knowledge to a reliance on quantitative data enriched by stakeholder feedback. Conceptual site models can be updated to reflect this feedback.

CSMs can also be used as a mechanism for fostering dialogue between stakeholders and practitioners. In many countries in the Global South, a strong regulatory structure does not exist, and contamination may result from an informal livelihood sector that cannot pay for the environmental damage it causes. In such cases, remediation is often driven by strong community support and local government collaboration that seek to improve human health (O'Brien et al., 2020); this underscores the importance of strong community engagement efforts and the utility of the community-informed conceptual site model. In contrast, in areas in which there is no community interest or support, a more traditional CSM approach may be more appropriate. Early stakeholder analysis is recommended to determine the applicability of this framework at different sites.

3. ASGM case study

To test the efficacy of the community-informed CSM framework, we applied it to an ASGM community in Andes, Colombia. ASGM is a sector of the mining industry that exists in the Global South and is characterized by rudimentary mining processes and low quantity and quality gold production (Esdaile and Chalker, 2018). Although contributing approximately 20% of the world's gold supply (Morgane et al., 2018), ASGM is frequently only recognized as being the largest anthropogenic source of mercury pollution in the world (Cordy et al., 2011; UN Environment, 2019). ASGM represents a significant source of income for approximately 40 million people across 80 countries around the world (Morgane et al., 2018), making it of significant interest to non-governmental organizations, intergovernmental organizations, local governments for both its environmental impact and its potential for assisting countries in the Global South to reach the UN Sustainable Development Goals (e.g., Laing and Moonsammy, 2021; Maconachie and Conteh, 2021). In Colombia, ASGM accounts for 94% of gold production, employing approximately 300,000 families across the country (World Bank, 2020). An ASGM community was chosen for the focus of this case study for two primary reasons. First, ASGM communities are highly stigmatized, similar to communities located near contaminated sites around the world (Gregory and Satterfield, 2002; Potter et al., 2019; Zhuang et al., 2016). ASGM communities are often perceived as 1) uneducated or uninformed about their own environment (Veiga et al., 2014), 2) polluted and plagued by armed conflict (Cordy et al., 2011; Kornberger et al., 2015), 3) "insane" for utilizing mercury (Cordy et al., 2011), or 4) "dirty" by producing a low-quality gold product that simultaneously contaminates the environment (Kornberger et al., 2015). For example, the Department of Antioquia has earned the unfortunate reputation as the region with the "highest per capita mercury pollution" in the world (Cordy et al., 2011). These stigmas tend to overshadow the raw ingenuity and entrepreneurship that exist in ASGM communities, reinforcing decision-making by experts instead of through participatory strategies (Hilson et al., 2018).

Second, there has been an academic and sustainable-development focus on ASGM (Cordy et al., 2011; Esdaile and Chalker 2018). Since the ratification of the Minamata Convention in 2017, signatory parties have been required to develop National Action Plans (NAPs) to reduce the emission of mercury from this sector by prohibiting open burning of amalgams and the burning of amalgams within residential neighborhoods (Moody et al., 2020). Commitments to the Minamata Convention has encouraged countries to propose legal, technical, and socio-economic strategies to mitigate the use of mercury in ASGM (Selin et al., 2018). Colombia ratified the Minamata Convention in 2013, committing the country to reform policy to reduce mercury emissions from ASGM. Colombia's 2018 law banning mercury in mining activities placed the contaminant at the forefront of the Colombian government's priorities as compared to other contaminants (Paz Cardona, 2018). For more information regarding Colombia's efforts with complying with the Minamata Convention and the challenges with regulating mercury use in ASGM, the reader is referred to Diaz et al. (2020).

Recognizing this global emphasis, this case study focuses on the development of an iterative community-informed CSM for a mercury-contaminated ASGM site within the project-planning stage of remediation. As compared to later stages of remediation, remediation practitioners face the biggest challenges in identifying and engaging stakeholders during the early stages of a project (Norrman et al., 2020). Additionally, this case study demonstrates the observational knowledge that exists within local communities and can aid practitioners during early stages of a remediation project.

3.1. Site description

A municipality called Andes, located in the southwestern part of the Department of Antioquia, was chosen as the focus area for this research. Andes is made up of seven rural areas (*corregimientos)* and an urban area, also named Andes. The dominant livelihood in Andes is the production of Arabica coffee (Zapata et al., 2019; Salazar A., 2014). ASGM predominantly occurs in two corregimientos: Santa Rita and Santa Inés. Santa Rita, the predominant corregimiento with artisanal mining, experienced a revival in ASGM activity in the 21st century, leading to a total population of 4800 inhabitants, the creation of a school with over 800 alumni, and direct transportation to the area (Zapata et al., 2019). Santa Inés, the second largest mining region in the municipality, is the most rural corregimiento*,* claiming 2800 total inhabitants due to the dense natural forests exploited mainly for construction materials (Zapata et al., 2019).

Historically, ASGM activities in Andes and many other regions used mercury to process gold ore. In 2013, the University of Antioquia began an interdisciplinary intervention to address mercury-related problems in Andes' artisanal mining sector through a variety of projects. One key project was the implementation of technical assistance to switch miners to cyanidation, a processing technique that does not use mercury (Servicio Geológico Colombiano, 2017). Since then, Colombian media outlets touted Andes as the municipality with "*cero mercurio*" (zero mercury) (Carrasquilla, 2019).

3.2. Methods

The CSM for Andes developed over several iterations to identify the environmental risks present within an ASGM community. First, prior to conducting fieldwork in Andes, an illustrative, pre-fieldwork CSM was created by compiling and analysing published literature on mercury fate and transport and the Colombian ASGM sector. To create the additional CSMs, we conducted fieldwork in Andes from June to August 2019. Following methodological approaches used in anthropology (Bernard, 2006), we utilized informal, unstructured interviews, semi-structured interviews, and a structured, face-to-face survey to collect data on ASGM history and current operations, environmental issues within the municipality, and local stakeholder knowledge on environmental risk from ASGM and other sectors in Andes. Participant observation, a process of observing and participating in the activities of people under study in their natural setting, was also conducted throughout the duration of the research to become acquainted with the labor practices and lifestyles of both miners and coffee farmers and expand our contextual understandings of the municipality.[1] The combination of ethnographic research methods allowed enough information to develop a CSM that reflected community members' perceptions of environmental risk and gage initial community acceptance of a future remediation project focused on mercury from ASGM.

Information from the unstructured and semi-structured interviews were analysed by dividing any recordings, field notes, and direct transcripts into representative stakeholder groups and manually reviewing each interview for common themes relating to environmental issues within Andes. The structured survey was statistically analysed using chi-squared analysis to find statistically-significant differences in environmental perception and risk perception from different stakeholder groups.

This section describes the methods as they were chronologically applied over the course of the research. Section 3.2.1 describes the development of the pre-fieldwork CSM which supported key research questions answered by the ethnographic fieldwork. Sections 3.2.2-3.2.4 describe the unstructured interviews, semi-structured interviews, and structured survey and any analysis that was completed while fieldwork was ongoing. Section 3.2.5 explains the methods of analysis for the compiled data from fieldwork and how this data was incorporated into the CSM iterations.

3.2.1. Pre-fieldwork CSM development

Prior to fieldwork, we performed a critical review of existing literature on ASGM and mercury use (e.g., Cordy et al., 2011; 2015; Echavarria, 2014; García et al., 2015; Veiga and Marshall, 2019; Veiga et al., 2014; Veiga et al., 2018) and reviewed reports and studies on ASGM in Colombia (e.g., Servicio Geológico Colombiano, 2017). For example, the technical report by Servicio Geológico Colombiano (2017) provides results from limited environmental sampling of soils and rivers that showed the existence of mercury contamination and emphasized the need for future remediation efforts.

The pre-fieldwork CSM provided a baseline for understanding mercury fate and transport in the environment due to releases from the ASGM sector at large and historically within Colombia. However, the pre-fieldwork CSM lacked incorporation of local context. For example, current operating conditions at ASGM sites could not be verified without fieldwork. Although propaganda existed claiming ASGM no longer used mercury (e.g., Carrasquilla, 2019), peer-reviewed literature from ASGM sites around the world have documented continued mercury use even after intense interventions have been pursued to eliminate its application (Clifford, 2015; Esdaile and Chalker, 2018; Smith, 2019; Veiga et al., 2014). Therefore, this initial CSM development created three broad questions for investigation using ethnographic field methods. First, what is the site history and current application of mercury at ASGM sites in Andes? Second, what other environmental issues or contaminants are present in Andes? Third, how do local stakeholders understand the environmental risks from ASGM and/or other sectors in Andes?

3.2.2. Unstructured interviews

Unstructured interviews, whereby a natural conversation occurs between the researcher and the participant without pre-defined questions, are used to build rapport with local community members and can be useful when little is known about the local context and local environmental issues (Bernard, 2006; Gill et al., 2008). Participants in unstructured interviews were selected based on their affiliation with an identified stakeholder group (i.e., coffee farmer, miner, ASGM processing plant manager) and identified using local contacts. The unstructured interviews for this research took place at coffee farms, ASGM mine entrances (*bocaminas)*, and ASGM processing plants (*entables)*. By holding unstructured interviews at locations thought to have greatest environmental impact, the conversation naturally turned towards topics related to the environment and natural landscape, such as the individual's relationship with the environment, the development of multiple livelihoods in Andes, and observed changes to the environment over the participant's lifetime. The unstructured interviews helped the researchers build rapport and determine key informants for more detailed semi-structured interviews. Additionally, differences in perception of environmental risks between stakeholder groups initially became apparent, causing a need for further engagement with a broader range of stakeholders. In total, 40 people participated in unstructured interviews. Data from the unstructured interviews were used to develop a preliminary conceptual site model as well as to help define a guide for semi-structured interviews.

3.2.3. Semi-structured interviewing

Based on common themes identified from unstructured interviews in Andes, we developed an interview guide to gather more information regarding environmental perceptions and contamination. Separate interview guides were created for interviewing coffee

[1] All research activities were pre-approved under IRB protocol #18–0233 under multiple institutions.

farmers, miners, and local government employees to ensure that interview questions were relevant to their livelihoods. However, all interviews contained several common questions that specifically asked about the participant's individual history in Andes, mercury use in ASGM, and the primary environmental issues in Andes (as perceived by the participant). Additionally, for any specific chemicals or compounds listed by the participant as an environmental issue, the participant was asked more specifically about the fate and transport of each compound. This included, but was not limited to, asking the participant to describe the activity that generates the compound, specific locations where it is used, how the participant believes the compound is impacting the environment and/or human health, and if any interventions have been implemented to restrict any contamination. Throughout the course of the fieldwork and the semi-structured interviews, the interview guide was amended based on new information and additional knowledge gaps that needed to be filled.

Participants in the semi-structured interviews were selected based on their participation in the unstructured interviews (e.g., level of interest in research and desire to speak with us in more detail) and participation in life in Andes (e.g., full-time residents engaged in a livelihood physically located in Andes or members of the local government interested in environmental issues in the municipality). We interviewed 18 individuals over the duration of the field session. Seven of the interviews were conducted with miners, mine or entable owners or managers, or representatives of the local mining association. Five interviews were completed with coffee farmers or representatives of the local coffee cooperative. Two interviews were with trout farmers, three were with the wives of trout farmers, and one interview was completed with a representative from Corantiquia, the Antioquian environmental regulatory agency. Overall, five interviews were conducted with women and thirteen with men.

Ongoing participant observation and semi-structured interviews provided enough evidence to create an influence-interest matrix of stakeholders in Andes. An influence-interest matrix is a stakeholder analysis tool that organizes stakeholder groups onto a grid based on their ability to influence a project (x-axis) and interest in project activities (y-axis). It was used in an effort to include all stakeholder groups in the research rather than biasing one group's knowledge and opinions over another. Additionally, the matrix allowed us to proactively challenge the ongoing research efforts to include additional stakeholders. This knowledge supported the development of a structured survey to capture the opinions of less-powerful stakeholders in Andes.

3.2.4. Structured survey

A structured survey was developed after the unstructured and semi-structured interviews took place. This allowed us to specifically focus the survey questions on knowledge uncovered from the interviews. The main portion of the survey asked respondents to rank the level of danger to the environment of 12 different activities in Andes. The 12 activities were mentioned by participants during the unstructured and semi-structured interviews as being destructive to the local environment.

We completed 100 face-to-face surveys across the municipality by meeting local individuals at common places of congregation (e.g., town square on weekends, coffee shops/bakeries on weekdays) in the early mornings prior to the start of the workday and revisiting entables and bocaminas to survey the employees working there (known as a street intercept survey). The surveys asked participants to answers a set list of questions with structured answers to provide comparable data sets (Bernard, 2006). Potential respondents were chosen through this strategic method of sampling to ensure a statistically significant cross section of stakeholders.

4. Results

Four iterations of CSMs were constructed: a pre-fieldwork CSM, Miner-informed CSM, Corregimiento-informed CSM, and a Stakeholder Group CSM. As shown in the pre-fieldwork CSM, this research was motivated by the environmental impacts of mercury contamination in ASGM communities. However, unstructured and semi-structured interviews revealed that stakeholder's perceived a complex set of environmental issues and contaminants in Andes. This results in CSM iterations illustrating mercury pollution alongside other contaminants of interest to community members, from ASGM as well as agricultural livelihood sectors, as revealed through different ethnographic research methods. In other words, using multiple types of ethnographic research methods and incorporating a broader range of stakeholders revealed the existence of multiple contaminants that would require consideration by future remediation projects in the area and the level of concern for each stakeholder group.

4.1. Pre-fieldwork CSM

The pre-fieldwork CSM (Fig. 2) reflects the physical, chemical, and biological processes that control the fate, transport, and potential impacts of mercury in Andes. As shown in the diagram (Fig. 2), mercury is released to the environment through a mineral processing technique known as whole-ore amalgamation. In whole-ore amalgamation, miners add mercury directly to small ball mills, commonly resulting in mercury losses to the environment through 1) direct deposition (i.e., spills), 2) leaching from tailings piles, or 3) volatilization during the heating of mercury amalgams (Cordy et al., 2011; Gibb and O'Leary, 2014). The volatilization of mercury during the heating of the mercury-gold amalgam (also known as amalgam burning) is of particular concern because mercury can enter into cyclical atmospheric transport, where it can be deposited into rivers and sediments through wet or dry deposition, or directly inhaled by individuals near the amalgam burning. This transport in the atmosphere results in the contamination of areas outside the direct proximity of mining areas (Garcia-Sanchez et al., 2006; Gbor et al., 2006).

4.2. Miner-informed CSM

The first iteration of a preliminary CSM draws from the data collected during unstructured and semi-structured interviews at

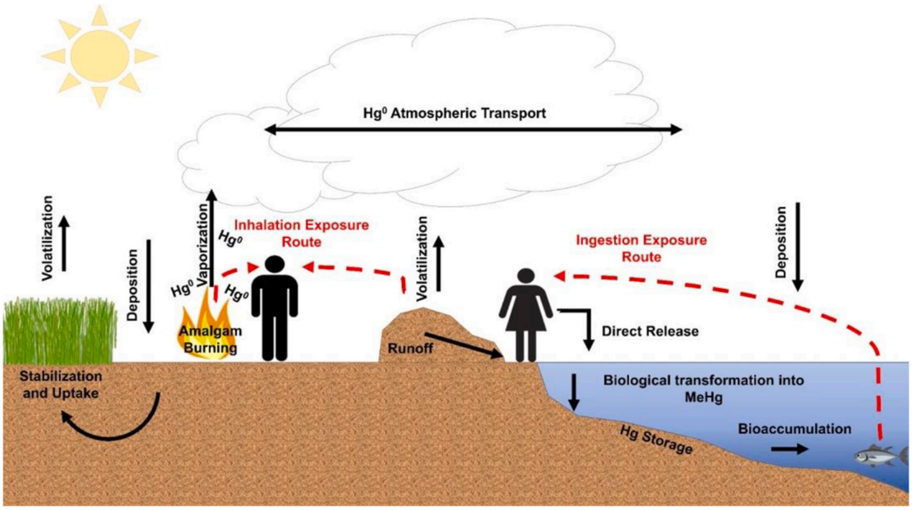


Fig. 2. Pre-fieldwork conceptual site model made from literature review of mercury contamination in ASGM communities, with a specific focus on Colombia. Because few resources were available describing Andes at the time of this CSM's creation, no contextual knowledge is presented in this CSM.

entables. Entables were historically the central locations for mercury use and, potentially, mercury contamination. The miner-informed CSM (Fig. 3) depicts the three core components (i.e., source, transport, and fate of contamination (Digges La Touche et al., 2011) of a traditional conceptual site model, but from the perspective of entable workers.

4.2.1. Occupational exposure of entables

As described in the Site History, since the intervention from the University of Antioquia, Colombian media outlets touted Andes as

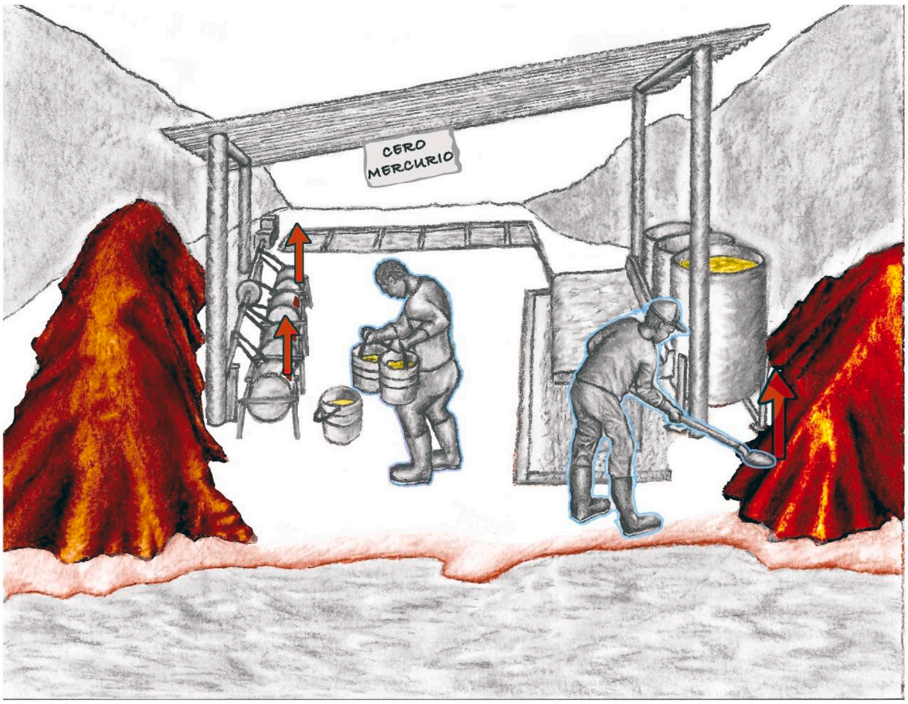


Fig. 3. Miner-informed CSM depicts occupational exposure concerns of local miners at gold ore processing facilities. Red denotes areas potentially contaminated with mercury: old tailings piles, surrounding soils, and ball mills. Yellow represents other substances onsite, including cyanide and "acids" to aid the cyanidation process. Blue highlights around the processing plant workers denote their exposure to mercury from inhaling mercury vapors out of the old ball mills or by disturbing tailings piles. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

the municipality with "*cero mercurio*" (zero mercury) (Carrasquilla, 2019). While the phrasing itself simply suggests a movement away from mercury amalgamation, many miners have adopted it to identify themselves as the antithesis of artisanal mining in Colombia. The distinction the Andes miners drew between themselves and other ASGM regions with regard to mercury use is a key attribute of place-identity (Wester-Herber and Misse, 2004). One miner disparaged an individual who attempted to sell mercury to Andes miners, calling them "very stupid. Mercury is illegal. Go be with your family, not in prison." Miners pushed against the stigmas of mercury use and the ASGM sector to show they were worthy of formalization and sustainable. These individuals believe that these efforts should result in legal recognition and protection to continue their operations, which has not occurred as of the writing of this paper. Presented as an illustrated banner in Fig. 3, whenever we asked about mercury use in the municipality, miners responded that mercury is no longer utilized, the region is "cero mercurio."

Equipped with knowledge about the risks of mercury use, miners emphasized occupational exposure risks from working at an entable that had previously used mercury. Some miners expressed concern over lingering mercury vapors in the small ball mills, known as *cocos*. More entable managers, however, identified old tailings (represented in Fig. 3 by the large red piles on either side of the entable) produced from whole-ore amalgamation by mercury as the primary source of ongoing mercury contamination. These individuals worried that the tailings could be volatilizing mercury that they directly inhale. Entable managers were further able to pinpoint specific locations that they thought might have the highest levels of mercury contamination due to their knowledge of the history of mercury use at the site.

Entables are often located in riparian environments; some backed up to rivers, whereas others were located 20–46 m away from natural bodies of water. Managers of entables located further away from riverbanks were not concerned that tailings located on their sites were leaching mercury into the river. One entable owner discussed his reasoning: "I am not worried [about contamination] because there are five terraces and 45 m between the plant and the river." This statement references a common belief among many community members in Andes that physical proximity was the main method of transport for contaminant. Because rivers run from rural areas to more populated centers, individuals seemed to understand that once in contact with a river, contaminants could be transported. However, other mechanisms of contaminant transport, such as groundwater transport, did not seem to be understood.

As shown by the large yellow tanks and smaller buckets in Fig. 3, potentially hazardous substances like cyanide and acids are present at the site. However, compared to mercury, cyanide was largely perceived as a safe substance,[2] and many miners claimed "cyanidation creates less contamination than mercury." Several miners additionally felt that cyanide posed a smaller inhalation risk than mercury use and was therefore preferable for their own safety. Overall, miners felt they were managing the risks of cyanide effectively. During the semi-structured interviews, only one entable manager identified cyanide as a possible contaminant or hazard to human health. He addressed his concerns by restricting access to the cyanidation process. At other entables, miners did not seem concerned about health impacts from cyanide and dismissed concerns about environmental contamination from improper cyanide use. It seemed that while previous interventions in Andes effectively educated community members on the risks of mercury use, risks from improper cyanide use were either not discussed or not emphasized. Thus, most community members did not express any knowledge about risks from improper cyanide use in ASGM processing operations.

4.2.2. Need for further engagement

The miner-informed CSM presents important information about site history, key players at ASGM sites, and some data about behaviors related to mercury use. The dialogue mostly revolved around occupational exposures for ASGM workers. Generally, participants did not focus on widespread contamination throughout mining areas resulting from mercury transport. It seemed that many managers believed contamination was limited to the physical boundaries of the entables. This pointed to a need to engage community members outside of the ASGM sector, such as coffee farmers and local government officials. These initial interviews provided an entry point into the community that allowed for the initial identification of other stakeholders by observing the day-to-day activities around ASGM sites. This directly contributed to the development of the corregimiento-informed CSM, which included the views of agricultural workers in the rural towns (corregimientos), local government officials, and Corantioquia, and further engagement with ASGM miners.

4.3. Corregimiento-informed CSM

Expanding engagement to include community members beyond ASGM identified a need to more fully understand potential water contamination from mercury use because residents in the mining *veredas* (rural neighborhoods) repeatedly mentioned concerns about surface water contamination. These individuals acknowledged the importance of local topography in contaminant transport, although initially mercury was not discussed as a primary contaminant in the region. Instead, many participants believed mucilage, a waste product from processing coffee, was the primary contaminant in the municipality. The corregimiento-informed CSM (Fig. 4) illustrates the primary physical characteristics that might potentially impact contaminant transport. It also documents additional exposure routes beyond the occupational exposure at an ASGM processing plant. In the municipality of Andes, veredas follow a river or stream out of the center of a corregimiento. Women and children often live and work adjacent to stream banks, across and downstream from mining areas (Fig. 4).

The corregimiento-informed CSM further illustrates local ASGM operations in greater detail. Ore is transported, typically by mule, from the bocaminas to one of the 11 operating entables in the municipality for processing. The individuals working at bocaminas are

[2] Although the interviewed miners did not seem to perceive risks to cyanide use, research on cyanide within gold mining has found that this processing technique poses acute and chronic risks to human health and the environment (Donato et al., 2007; Goltz et al. 2019; Tran et al. 2019).

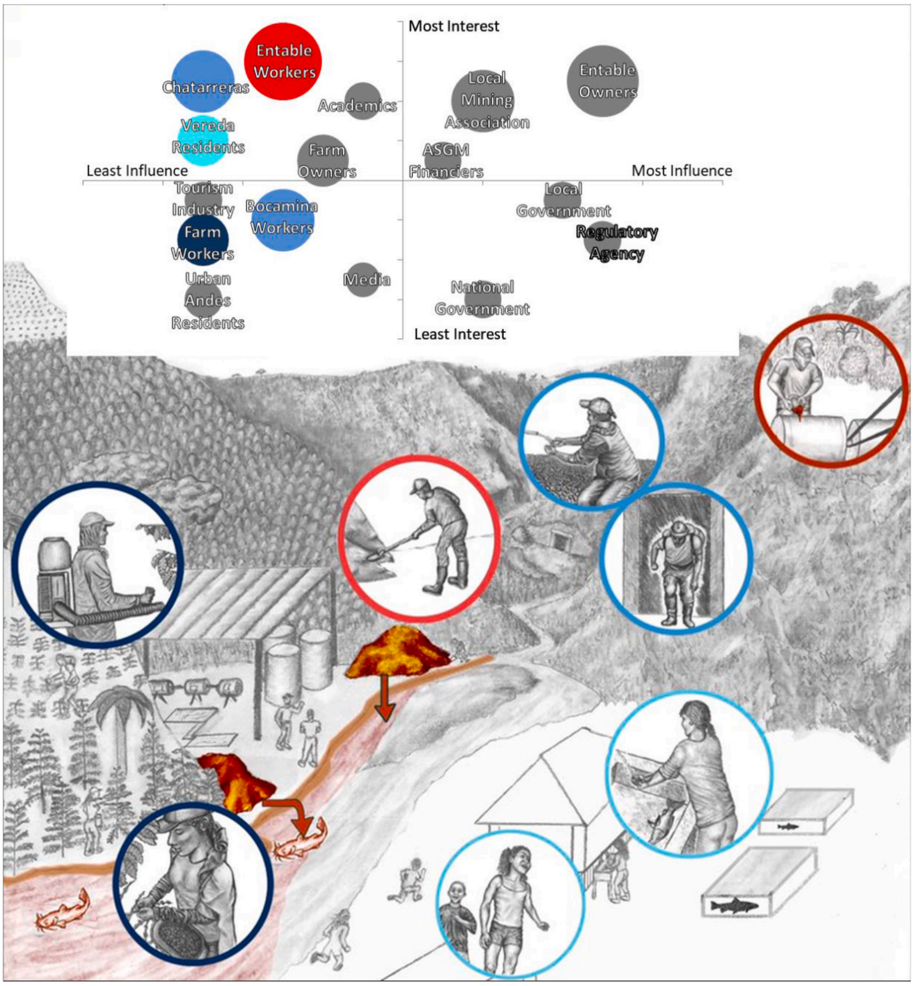


Fig. 4. CSM illustrating the steep-graded topography of Andes impacting runoff patterns. River networks became a common topic of discussion and a central mechanism for mercury contamination, highlighted in red by contamination from old tailings piles at ASGM processing facilities. The diversity of stakeholder groups is represented by varying shades of blue, except for two groups: processing plant workers and "secret" processors. These two groups are shown in red due to their direct exposure to mercury. An interest-influence bubble matrix provides our subjective positioning of stakeholders in relation to their potential interest in and influence over mercury use at the entables. The size of the bubble illustrates a qualitative estimate of stakeholders' exposure risk to mercury pollution. Stakeholders illustrated in the CSM, which is different from the groups with the most influence in the interest-influence matrix, are all at a potential risk for exposure to mercury contamination due to their physical proximity to mining activities, but the only confirmed receptors based on the fieldwork were processing plant workers and "secret" processors. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

not necessarily the same individuals employed at entables – an important distinction for mercury exposure risk assessment. *Chatarreras*, women responsible for sorting through waste rock and processing that ore by themselves, may work at both. There were rumors from local community members that chatarreras continue to use mercury at entables secretly, but we were never able to observe this over two months of fieldwork nor did we receive direct confirmation during formal interviews. One miner, though, confided that individuals at "secret" gold processing facilities hidden in the dense forest of the mountains continue to process gold via whole-ore amalgamation. Other miners later echoed the reality that whole-ore amalgamation by mercury exists, albeit covertly (dark red bubble in Fig. 4 on the top right).

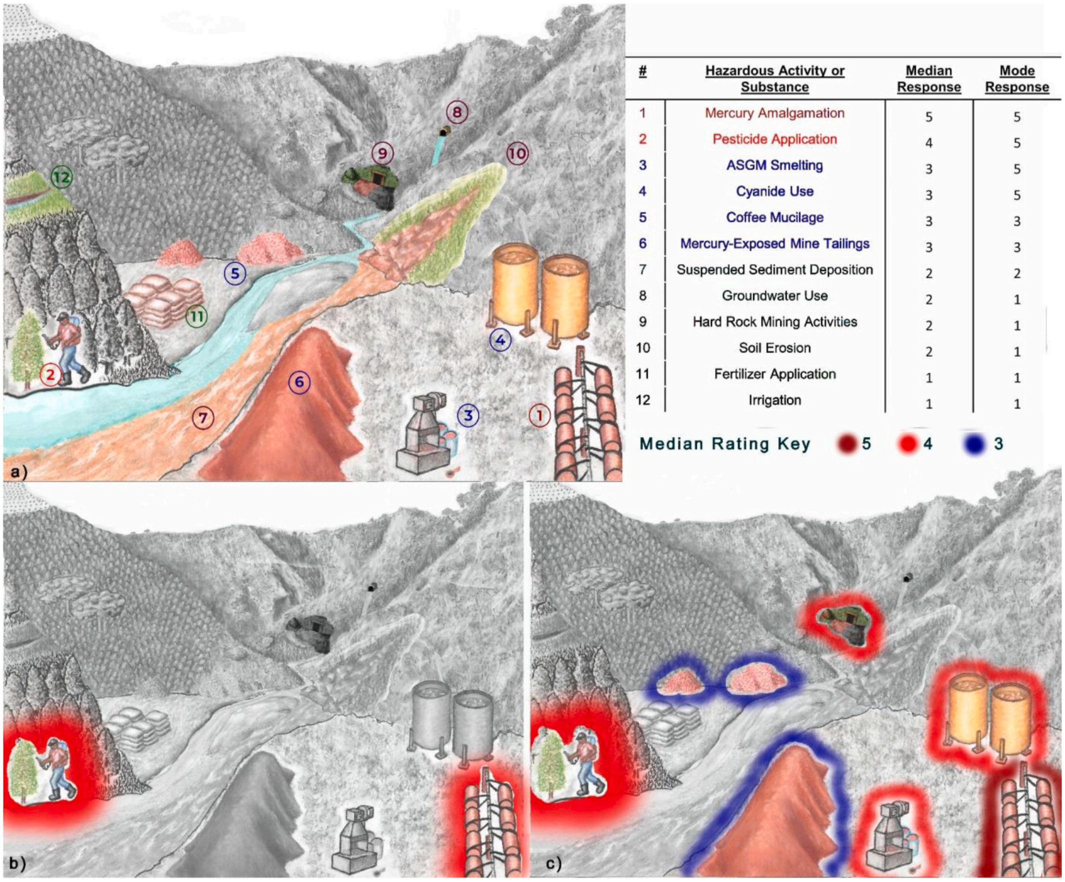
4.3.1. *Mapping stakeholders on an influence-interest matrix*

The influence-interest matrix (Fig. 4) provides a way for organizing stakeholders in Andes. This qualitative matrix was developed to ensure that more marginalized stakeholders were given a chance to voice their knowledge and concerns in the research. As such, the matrix lists more stakeholders than are illustrated. Although other stakeholders may hold more influence over project activities (e.g., governmental entities), the CSM focuses on physical proximity to entables because proximity increases the risk of exposure to mercury contamination (Diringer et al., 2015). Since mining is localized to several veredas within the corregimientos of Santa Rita and Santa Inés, we specifically engaged stakeholders located near mining areas through interviews, rather than convening a single workshop to engage an entire stakeholder group. In this way, we were able to understand how a connection to the physical environment influences perceptions on mercury contamination and behaviors associated with reducing contamination.

4.3.2. *Conflicting priorities*

Engagement with a broader collection of community members exposed competing environmental concerns in Andes. Although historic mercury use appeared to be viewed negatively across sectors, desired priorities for environmental conservation were mixed. Some cafeteros perceived the by-products from agricultural activities as the most severe impact to local water sources. Others viewed ASGM as a main concern. These conflicting priorities may influence the extent to which community members desire to participate in future remedial activities. This would require community involvement to be tailored to the stakeholders concerned with ASGM. Wide dissemination of notices or eliciting participation via community-wide resources may be ineffective because of the diversity of concerns in relation to physical location.

Additionally, the creation of the corregimiento-informed CSM granted wide access to ASGM sites and farms. The influence-interest matrix suggests that many of the interviews, though, were with owners and managers of both sectors, thereby requiring further work to connect with less-powerful workers throughout the municipality. Engagement with these individuals is important because they may be more exposed to contamination (Steckling et al., 2011). Understanding that these community members lack time to dedicate to semi-structured surveying, we developed a structured survey to capture their knowledge of and interest in local environmental issues.



#	Hazardous Activity or Substance	Median Response	Mode Response
1	Mercury Amalgamation	5	5
2	Pesticide Application	4	5
3	ASGM Smelting	3	5
4	Cyanide Use	3	5
5	Coffee Mucilage	3	3
6	Mercury-Exposed Mine Tailings	3	3
7	Suspended Sediment Deposition	2	2
8	Groundwater Use	2	1
9	Hard Rock Mining Activities	2	1
10	Soil Erosion	2	1
11	Fertilizer Application	1	1
12	Irrigation	1	1

Fig. 5. Variations on the third conceptual site model, created from structured survey data where community members quantified their perceived risks from 1 (no risk) to 5 (significant risk). Figure a) shows the ranking of perceived risk of contaminants as compared to other environmental issues in Andes, where 1 corresponds to the highest perceived risk and 12 corresponds to the lowest perceived risk (see adjacent table). Figure b) shows a reduced CSM that illustrates the median ratings of 3 or above for individuals whose primary sector of work is mining. The color outlining the hazardous activity or substance corresponds to the median rating of risk perception among this stakeholder group. Only pesticide application and mercury amalgamation had a high enough rating to be illustrated on the CSM. Figure c) shows the median ratings of 3 or above for individuals whose primary sector of work is agriculture. Mercury-exposed mine tailings and coffee mucilage had ratings of 3 (shown in blue). Pesticide application, hard rock mining, cyanidation, and smelting (fundición) all had ratings of 4 (shown in bright red). Mercury amalgamation had a median rating of 5 (shown in dark red). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

4.4. Stakeholder group CSM

The stakeholder group CSM presents varying models based on the groupings of survey respondents. An ungrouped CSM (Fig. 5a) illustrates the final ranking for all responses, providing a broader understanding of mercury contamination in relation to other perceived environmental issues. Two other diagrams present the rankings by grouping responses by the primary sector of work (Fig. 5b and c). These perspectives compared to the baseline CSM reveal the diversity of knowledge and opinions within the local community through the lens of a single contextually dependent factor: the existence of multiple livelihoods in Andes.

Hazards due to ASGM activities received the highest median ratings, regardless of sector of work or education level. For those individuals who believed mercury amalgamation still occurs in Andes, they consistently ranked mercury amalgamation as the most hazardous activity for the environment. The application of pesticides also consistently received a high median rating across the demographic groupings, but coffee mucilage and other agricultural activities did not receive ratings consistent with concerns expressed in some of the semi-structured interviews. These results suggest that there are opportunities for community-supported remediation projects because community members have a high perception of risk associated with ASGM activities, and, specifically, the history of mercury amalgamation in the sector.

Disparities exist between site owners and employees. Although tailings were cited by managers as the primary source of contamination, the survey results suggest that other occupational exposures are perceived as greater risks, especially whole-ore amalgamation and ore-refining (known as *fundición)* activities. Additionally, individuals who worked in agriculture (compared to individuals in mining) consistently rated mining activities higher in terms of risks than other activities.

5. Discussion

Fieldwork with the use of ethnographic field methods allowed community-informed CSMs to be developed for Andes that document sources of contamination, hypothetical transport routes, and ecological and human receptors of contamination as seen through the eyes of different stakeholder groups. Through the evolution of the CSM, we observed potential benefits, such as understanding how relationships between stakeholder groups influences perceptions of pollution, and weaknesses, such as lack of quantifiable data, within our framework. The importance of community involvement is emphasized by comparing Fig. 5, the third iteration of the CSM, with Fig. 2, the pre-fieldwork CSM. Engagement with community members revealed the competing interests and intersection of multiple livelihoods in Andes, which are excluded entirely from the pre-fieldwork CSM. In practice, an understanding of these livelihoods is critical to further contamination assessment because other industries may present additional sources of contamination, release other contaminants that can comingle with the contaminant of interest, and influence the desire for stakeholders to participate in remediation projects. Such discoveries would not be made using traditional CSM approaches. However, the reliance of qualitative data may create challenges for practitioners, illustrating the limitations of this CSM framework.

5.1. Influence of entable managers and regulatory agencies

The role of entable managers and Corantioquia, the regional regulatory body, in current mining operations is important for remediation practitioners because of the influence these two groups have over the operations of the ASGM sector. Remediation project implementation requires the participation of local community members and, specifically, entable owners and managers. As seen in other risk-perception studies, continuity of management in reducing risky behaviors supports safe behaviors among employees (Rundmo, 1996). During our early observations at entables, employees followed the behaviors and adopted the practices of the owners and managers. For example, one entable manager used signage to communicate safety risks around the entable. Workers at this entable largely complied by wearing hearing protection and staying out of restricted areas. During interviews, workers onsite also reiterated some of the main safety concerns expressed by the entable manager.

The involvement of the local regulatory agency, Corantioquia, further encouraged safe mining practices. Several miners described Corantioquia as “attentive” and “vigilant.” Corantioquia's continued presence at and around ASGM sites in Andes helped to sustain the abandonment of whole-ore amalgamation by mercury, largely due to the threat of forced closure if mercury use was discovered. Corantioquia does not provide capacity building or training to promote the formalization of miners. Their role is limited to regulatory compliance, and their regulatory authority includes closing entables or other mining areas who continue to use mercury. Closure has been witnessed by the miners in Andes. It seems, though, that the miners also believed this regulatory power allows Corantioquia to create and approve new mining processes. As explained by a Corantioquia representative, this belief is mistaken. The agency's obligation is limited to “controlling [mercury use] and monitoring environmental conditions. Corantioquia can offer recommendations to the miners, but [the agency] does not help with formalization [or other projects].” Therefore, miners currently lack support for the development additional practices that may make ASGM safer and more sustainable. While discussing the potential for remediating contaminated tailings, one entable manager remarked, “I would work to decontaminate the tailings. But, right now there is no approved process to do so. I need approval from Corantioquia.” Interestingly, local miners did not reference the involvement of other local, regional, or national government in Andes as motivation for ending mercury use in mining operations.

5.2. Influence of mixed livelihoods

Engagement with a broader collection of community members exposed competing environmental concerns in Andes. This is important to note as practitioners must recognize the diversity that exists within mining communities, especially when trying to bring together community actors to collaborate and make decisions on a project (Warnaars, 2012). In Andes, we found that individuals' physical location influenced how they viewed Andes as a place, with differences in the importance of and concerns about ASGM activities. Coffee farmers, known as *cafeteros,* located adjacent to mining operations perceived ASGM more negatively than did coffee farmers located further away. In fact, one of the largest coffee farmers in Andes, who does not live in one of the mining areas, remarked: "[coffee production] is the biggest threat to the environment in the region" due to improper disposal of coffee mucilage. Cafeteros near mining areas found mining to be far more destructive than did the miners. During interviews, cafeteros expanded on this by noting the disruption of the natural forest due to bocaminas, dangers of working inside mines, and impacts to natural waterways from mineral processing. Furthermore, multiple cafeteros specifically noted negative impacts to fish populations resulting from the reappearance of ASGM in the 21st century. One cafetero attributed feeling sick after consuming catfish that came from rivers in mining areas to mercury contamination from ASGM activity, reflected in the corregimiento-CSM (Fig. 4).

Miners and cafeteros both viewed Andes as an agricultural area, not a "mining town," even though both livelihoods exist simultaneously in some corregimientos. Miners referred to coffee and plantain production as a reason for supporting more sustainable mining endeavors and abandoning whole-ore amalgamation by mercury. One miner described Andes as a "region of coffee farmers," requiring mining activities to protect and preserve the natural environment so that agriculture can thrive. The recognition by miners that Andes' current and future economic development depends upon agriculture, not mining, supported pro-environmental attitudes and behaviors that they then connected to other areas of their lives. For example, one miner described his efforts to reuse mine tailings as a reflection of progressive environmentalism and acknowledgement of the shared environment with agricultural production: "we only have one planet, and everyone shares it. There is no other planet." Another miner in the municipality correlated his decision to adopt cyanidation with "the mindset of the ancients," connecting his family history in Andes to a responsibility to protect the natural environment. Later, he further supported this idea by agreeing that "Andes is a coffee region." The environmental proactiveness of miners in Andes supports future remediation projects. One entable owner was actively trying to remediate old tailings and use the resulting material as an aggregate in construction bricks. As discussed previously, while other miners did not actively try to pursue remediation by themselves, they were open to future remediation projects.

5.3. Limitations and need for technical investigation

The divergence in knowledge represented across the iterative CSMs, and most notably recognized in the Corregimiento-Informed CSM, highlights the areas where quantitative data are essential for implementing remedial activities. The migration of mercury from tailings piles into the environment and primary surface water bodies is a complex issue that requires further analysis to assess the exposure of residents and community members living and working in mining areas. Additionally, project objectives may expand to cover contaminants besides mercury and address other occupational hazards at ASGM sites, such as the inhalation of vapors from fundición and improper neutralization or disposal of cyanide solution.

Additional data gaps require ongoing engagement with stakeholders to ensure effective implementation. For example, if mercury use is ongoing in Andes, as 50% of the survey respondents believe, remedial measures need to be perceived as adequately improving the environment in order for community members to participate in project activities, two-way dialogue, or long-term monitoring activities. Stakeholders can further identify specific areas for environmental sampling and testing to aid in modelling mercury contamination.

6. Conclusion

This research proposed an integration of local stakeholders into early pollution remediation efforts through the creation of community-informed CSMs. We applied this framework to a Colombian ASGM community facing mercury contamination. The CSMs demonstrate how knowledge about a contaminated site can be developed by remediation practitioners from the perspective of local community members over time and through the application of different ethnographic field methods. Although similarities can be found within the local communities, local knowledge and opinion on ASGM risks varied within stakeholder groups. Mining site managers perceive different risks than their workers, and perceived risks vary from profession to profession. Grouping stakeholders by sector of altered the CSMs, with individuals in agriculture perceiving greater hazards than other respondents. Local community members in Andes described some aspects of mercury fate and transport, raised concern over the risks of mercury contamination, and pinpointed locations they felt required further scientific analysis. Taken together, these perspectives of CSMs provide a more holistic depiction of Andes that can aid future remedial efforts. These results raise the possibility of applying the concept of community-informed CSMs to countries' NAPs, as they provide a strategy for identifying mercury-contaminated sites in data-poor regions. The community-informed CSM offers a potential method of stakeholder engagement that is critical for meeting the requirements of Article 12 (Contaminated Sites) of the Minamata Convention as it accounts for common challenges associated with ASGM site identification and characterization (e.g., lack of formal records and informal structure). Such a tool could be used in conjunction with suggested stakeholder engagement methods proposed by UNEP's guidance documents for NAP (see UN Environment, 2017).

Community-informed conceptual site models leverage and recognize the inherent knowledge and skills of local communities in contaminated areas and detail context-specific factors potentially impacting future remedial endeavors. By applying social science methods that are appropriate for the site in question alongside data collection and analysis of quantitative information, CSMs can provide remediation practitioners with a more comprehensive model with which to engage stakeholders and develop sustainable project objectives. This framework is not limited to mercury contamination. Rather, it can be applied to any environmental pollution assessment scenario. The ASGM case study relied substantially upon qualitative, social data due to the limited availability of existing technical data and restricted site access. The quantitative component of site assessments can easily be strengthened during application of this framework modelled through methods such as knowledge-based prediction (see Ongley and Booty, 1999).

Conceptual site models are a versatile tool to aid communication and decision-making in remediation projects. By adapting current methods to create CSMs through the frame-of-reference of different stakeholders, remediation practitioners can enhance overall stakeholder engagement efforts, build trust, and find alternative methods for communication. More importantly, local communities are empowered to participate in early remediation efforts, supporting initial implementation of remediation projects and enhancing decision-making of remedial solutions.

Credit statement

Rosalie M. O'Brien: Conceptualization, Methodology, Data Curation, Software, Formal Analysis; Writing – Original Draft, Visualization; Kathleen M. Smits: Conceptualization, Supervision, Funding Acquisition, Writing – Review and Editing; Nicole M. Smith – Methodology, Supervision, Funding Acquisition, Writing – Review and Editing; Michelle R. Schwartz – Conceptualization, Investigation, Writing – Review and Editing; Thomas J. Phelan – Supervision, Funding Acquisition, Writing – Review and Editing; Dustin R. Crouse – Visualization, Writing – Review and Editing.

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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