ENHANCING SOCIO-TECHNICAL INTEGRATION OF REMEDIATION EFFORTS IN ARTISANAL AND SMALL-SCALE GOLD MINING COMMUNITIES

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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science (Civil and Environmental Engineering).

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ABSTRACT

Artisanal and small-scale gold mining represents the largest source of anthropogenic mercury contamination in the world, creating long-term exposure risks to miners and communities in which these operations exist. Eliminating these health and environmental risks requires the implementation of remediation projects in coordination with local communities. Yet, current remediation frameworks lack thorough guidance on integrating local knowledge with technical data, and projects therefore emphasize technical forms of knowledge over local knowledge. This research bridges this gap by first analyzing previous remediation projects in developing countries. The review concluded that stakeholder engagement leads to greater project success by enhancing communication and creating project goals that meet the needs of different stakeholders. Yet, stakeholder engagement with a diverse range of individuals and organizations is not pursued by the majority of remediation projects. This critical need for stakeholder engagement led to the redevelopment of a common decision-making tool in remediation: the conceptual site model. During a field visit to an ASGM community in Antioquia, Colombia, three iterations of preliminary conceptual site models were created by integrating ethnographic research methods and existing technical information. The framework for creating community-informed conceptual site models further offers opportunities for engineering students to engage with stakeholder engagement within site remediation course curriculum, thereby equipping students to solve complex engineering problems prior to entering their professional career. The culmination of this research presents a comprehensive reform of the engineering discipline within remediation by exposing opportunities for local knowledge to enhance remedial endeavors and offering methods for incorporating local knowledge directly into remediation projects.

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ABET – Accreditation Board for Engineering and Technology

ASM – Artisanal and small-scale mining

ASGM – Artisanal and Small-Scale Gold Mining

ASTM – American Society for Testing and Materials

CBL – case-based learning

CSM – Conceptual Site Model

DDT- dichlorodiphenyltrichloroethane

PCBs - polychlorinated biphenyls

GEF – Global Environment Facility

HE – Humanitarian Engineering

ITRC – Interstate Technology Regulatory Council

NGO – Non-governmental organization

POP – persistent organic pollutant

SuRF – Sustainable Remediation Forum

ULAB – Used lead acid battery

UN – United Nations

UNDP – United Nations Development Programme

US EPA – United States Environmental Protection Agency

USAFA – United States Air Force Academy

USD – United States dollars (in reference to currency)

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to my son, Augustine Kolbe Crouse -

CHAPTER 1

INTRODUCTION

Engineers in remediation projects often rely solely on technical knowledge to identify contamination, determine the extent of contamination, and implement remediation solutions. This emphasis on the technical aspects of the project, rather than utilizing socio-technical knowledge to form decisions and guide project activities, represents a severe flaw in the remediation process. This lapse can directly result in the inadequate clean-up of contaminated sites. For example, the concluding paragraph from a project completion report for a mercury-contaminated site in Kyrgyzstan states:

> Additional source of contamination was identified in conversations with local people. Turns out [sic] some old pipes from the factory were used by local residents as construction materials, particularly for irrigation. As a result several other places in town were contaminated with mercury. (Pure Earth 2017b)

A failure to engage local community members during the initial remedial investigation of the site led to an incomplete analysis, and, therefore, inadequate application of remediation solutions to eliminate the exposure of mercury to local communities. This example represents a common transgression of current remediation processes to focus on technical issues and constraints, rather than leveraging local knowledge to create contextually-appropriate project objectives and empower local stakeholders to help direct project activities (Huysegoms and Cappuyns 2017).

The incorporation of local knowledge into technical engineering systems is further critical in artisanal and small-scale gold mining (ASGM): the largest anthropogenic source of mercury contamination in the world (Esdaile and Chalker 2018). During mineral processing, artisanal and small-scale miners often add mercury directly to unconcentrated gold ore to form a mercury-gold amalgam. This amalgam is then heated, leaving behind low-quality gold (Cordy et al. 2011). Processing gold ore in this way releases mercury through several mechanisms, including direct deposition into natural waterways from spilling mercury, potential runoff from contaminated mine tailings, and volatilization of mercury vapors from heating the amalgam (Garcia-Sanchez et al. 2006; García et al. 2015; Cordy et al. 2015). Individuals exposed to mercury contamination in ASGM communities experience a range of documented medical problems, including kidney and autoimmune dysfunction and neurological disorders (Gibb and O'Leary 2014). Existing mercury contamination in ASGM communities creates an urgent need for remediation to eliminate human and ecological exposure to mercury. Many environmental projects related to the abatement of mercury in ASGM communities have experienced limited success, due, in part, to a lack of engagement and collaboration with local community members (Childs 2014; Hirons 2011; Spiegel et al. 2015).

1.1 Problem Definition

In remediation projects, a lack of engagement with local stakeholders stems from broader remediation guidance that excludes or limits the involvement of these groups. One example is the Sustainable Remediation Forum (SuRF), a framework developed from the international collaboration of researchers and practitioners invested in supporting sustainability during remediation projects:

> While the sustainability assessment work carried out so far does not yet include widespread stakeholder engagement, it is already evident that there are some significant 'missing' items in the social element of the SuRF-UK indicator guidance, namely: cultural impacts and public health. (Bardos et al. 2018)

The creators of the SuRF-UK framework reflect on their development, noting that cultural elements of sustainability are neglected in remediation. Other frameworks also fail to identify essential components of stakeholder engagement work, instead limiting stakeholder engagement to consultative opinions. The Interstate Technology & Regulatory Council (ITRC), for example, limits stakeholder collaboration to addressing tangential impacts to community life and defining end-uses of a site:

> *Baseline stakeholder engagement*—Conduct early in the remedy evaluation and selection phase to capture key points from the community and other interested stakeholders regarding site reuse preferences and constraints during the remedy construction phase (e.g., truck traffic, scheduling, etc.). (ITRC 2011, 33)

Thus, while many sustainable remediation frameworks embrace stakeholder engagement as an essential project activity, they do not fully empower stakeholders to make decisions throughout the remediation process. The ITRC framework suggests baseline engagement during remedy evaluation, only after project objectives are established and remedial investigations complete. Superfund projects in the United States potentially include the greatest stakeholder engagement due to the use of a Community Involvement Coordinator, an individual assigned to a local community and tasked with overseeing all community involvement efforts (US EPA 2015). Yet participation is inconsistent. For example, some Superfund projects limit engagement to distributing notifications and holding public forums, thereby limiting local community engagement to communicative and consultative, instead of participatory means (Graves 2015).

During the early stages of a remediation project, known as the preliminary assessment or preliminary evaluation, practitioners examine existing data about a contaminated site. For Superfund projects, the preliminary assessment utilizes the Hazard Ranking System (HRS) to "assess the relative potential of sites to pose a threat to human health or to the environment" (US EPA 2016). The HRS, in particular, groups site conditions into one of three categories: 1) likelihood that a hazardous substance has been released or may be released into the environment; 2) waste characteristics; and 3) people or environments impacted by the release (US EPA 2016). Guidance for conducting preliminary assessments relies exclusively on the analysis of historical technical data. The only stakeholders potentially contacted are site operators or workers, who are asked to provide information about disposal practices and past environmental problems (US EPA 1991). The experiential and observational knowledge of local communities, examination of local culture and context, and all other social factors are excluded. Yet, recent studies have concluded that practitioners continue to struggle with identifying and contacting all impacted stakeholders (Norrman et al. 2020). Additionally, projects suffer from cultural and language barriers that create communication difficulties over the course of a project (Laurian 2004).

Technical facets of remediation projects are essential to the successful implementation of remedial solutions for contaminated sites. However, by focusing only on technical information during early project activities, remediation practitioners overlook essential contributions from local community members. Current frameworks to guide the structure of remediation projects continue to emphasize technical considerations over economic or social considerations (Cappuyns 2016). Therefore, the available guidance for remediation practitioners disregards local knowledge in defining project objectives, creating goals and plans for additional site assessments, developing solutions, implementing effective designs, and monitoring the site.

Furthermore, sustainability work in remediation is focused in industrialized nations, despite the reality that 92% of pollution-related mortality occurs in developing countries (Landrigan et al. 2018). As of 2019, 11 countries have developed sustainable remediation frameworks under SuRF, including Brazil, Taiwan, and Colombia (SuRF 2019). Yet, only professionals from industrialized nations have published on the framework's use and methods for implementation. Many developing countries face challenges in implementing remediation projects and other kinds of environmental initiatives due to technological barriers (Evans and Kantrowitz 2002), required socio-economic tradeoffs (Atash 2007; Bartrem et al. 2014; Hilson 2002), political instability (Bartrem et al. 2014), and poor regulatory capacity of local, regional, and national governments (Beckers and Rinklebe 2017; Lupi and Hoa-Nghiem 2015).

Three main problems challenge the implementation of sustainable remediation. First, practitioners lack adequate guidance to integration local and technical knowledge in projects. Second, these efforts are particularly lacking during preliminary site assessment stages. Finally, improvements in stakeholder engagement are discussed in industrialized nations, neglecting the contexts of developing countries.

1.2 Primary Research Goal and Thesis Layout

The primary aim of this work is to enhance the long-term sustainability of remediation projects, especially in developing communities, by providing alternatives for seamless integration of local knowledge into traditional remediation processes. Accomplishing this goal requires research and innovation in two ways: adapting the tools remediation practitioners currently use and integrating socio-technical thinking in site remediation curricula for undergraduate engineering students. Both methods are developed to not only enhance the practitioner, but to better equip the future leaders in site remediation with the skills necessary to create sustainable solutions. This thesis accomplishes this goal through several tasks (Figure 1.1 on page 6). First, an initial literature review (Chapter 2) develops the theories of stakeholder engagement, previous stakeholder engagement efforts in remediation projects, the role of conceptual site models as a decision-making tool in remediation, and socio-technical thinking in engineering education. Given the lack of analysis in a developing country context, we further pursued a thorough literature review of remediation projects in developing countries (Chapter 3), with a focus on stakeholder engagement methods applied in real-world projects. We then integrated social and scientific knowledge in remediation projects by redesigning the development of a conceptual site model and applied it to a mercury-contaminated ASGM community (Chapter 4). Widening the scope of this research, we further develop a series of student learning outcomes, assessments, and lesson plans to help students understand the role of stakeholder knowledge in remediation projects (Chapter 5). Finally, we discuss the future applications of this research and ways forward to continue improving the long-term sustainability of remediation projects.

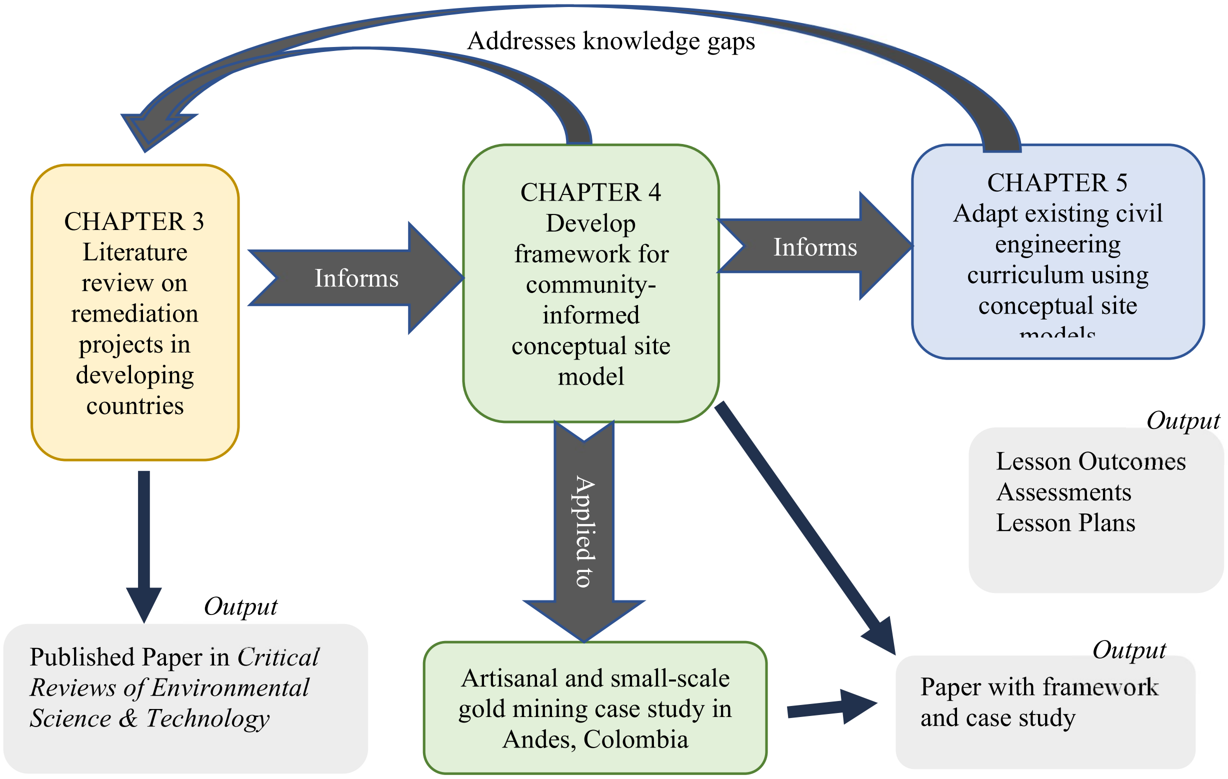

Figure 1.1 Flowchart of main thesis contributions and progression

CHAPTER 2

LITERATURE REVIEW

2.1 Stakeholder Engagement

A stakeholder is an individual, group, or organization that is impacted by or may impact the activities of a project. The process of identifying and including stakeholders in project activities, known as stakeholder engagement, varies. Rowe and Frewer (2005) created a typology that divides stakeholder engagement into one of three categories: communication, consultation, and participation. “Communication” refers to one-way information flows from project teams to stakeholders. “Consultation” refers to one-way information flows from the stakeholders to project teams. Finally, “participation” refers to two-way dialogue between the stakeholder groups and technical project teams. Empowering stakeholders to actively participate in projects (rather than providing consultation or receiving communication) allows “the act of dialogue and negotiation…to transform opinions in the members of both parties” (Rowe and Frewer 2005, 255–56). In this way, stakeholders have a greater likelihood of becoming valued decision-makers in projects, instead of passive recipients of project activities and decisions.

Early critics of stakeholder engagement worried that stakeholder participation and decision-making led to lower-quality decisions by shifting the focus away from rigorous, scientific judgements (Yosie and Herbst 1998). More recent scholarship in stakeholder engagement refuted these claims, instead providing evidence to support more inclusivity of stakeholders (Beierle 2002; Reed 2008; Reed et al. 2018). Normative arguments in support of stakeholder engagement contend that participatory mechanisms lead to broader societal benefits beyond the confines of a specific project. If completed effectively, participation helps ensure that marginalized populations are empowered to not just make decisions on a specific project, but can further bring recognition and validity to the knowledge and opinions of these groups by other stakeholders (Reed 2008). Participation can promote public trust and increases the perception that project decisions are both holistic and fair because it accounts for diverse values and perspectives (Beierle and Konisky 2000). It enhances social learning, promoting long-term benefit within communities by fostering cooperation between diverse groups (Blackstock, Kelly, and Horsey 2007).

Pragmatic claims for stakeholder participation include the creation of project activities that are adapted to local socio-cultural and environmental contexts, thereby enhancing the adoption and continuation of these activities (Brocklesby and Beall 2018). Additionally, by including other forms of knowledge, such as local knowledge, in decision-making, research and project decisions will be more robust and comprehensive (Bell et al. 2013). Practitioners can arbitrate negative externalities with the impacted parties before severe consequences to the project occur (Manetti 2011). As remediation is a type of environmental management project, remedial strategies can similarly benefit from stakeholder participation and, more specifically, local community participation.

Although the normative arguments for pursuing stakeholder engagement are worth noting, this research conforms with the pragmatic arguments for stakeholder engagement in remediation projects. It seeks to identify and incorporate applicable local knowledge into existing technical frameworks. Through this exploration, the outcomes from this research offer tangible opportunities for local stakeholders to become involved in early remediation endeavors.

2.2 Stakeholder Engagement in Remediation

Remediation projects in industrialized nations have utilized a variety of communicative, consultative, and participatory stakeholder engagement mechanisms, with a greater emphasis on communicative and consultative methods. Maco et al. (2018) suggested implementing a vulnerability assessment in remediation, where vulnerability is defined as understanding a community's "ability to cope with and adapt to any external stress placed on livelihoods and well-being" (11). This assessment largely focused on technical aspects regarding resiliency, including climate change impacts, physical security measures, and communication methods (Maco et al. 2018). Beyond noting a need to discuss plans and engage local communities, methods to incorporate local community participation into resiliency planning and remediation efforts are not discussed. Stakeholder consultation has been heavily implemented through the use of stakeholder analysis and stakeholder values assessments (Apitz 2018; Pollard et al. 2004), checklists (Greenberg et al. 2002) and surveys (Li et al. 2016; Harclerode, Macbeth, et al. 2016; Prior and Rai 2017; Prior, Hubbard, and Rai 2017; Drottz-Sjöberg and Sjoberg 1990; Hanahan 1996; Greenberg and Schneider 1994; Greenberg, Mayer, and Powers 2011; Kocher, Levi, and Aboud 2002). Additionally, local community communication has been applied in the form of educational programs (Focht and Albright 2009).

Some methods of local community consultation have tried to better understand the impact of local knowledge and culture on contamination issues. Focus groups have drawn out intricacies in local residents' discourses on contaminated land and pollution and identified marginalized stakeholders (Burningham and Thrush 2004; Foran et al. 2015). An analytic hierarchy process followed by ethnographic research methods revealed the complex cultural context of a community in Fiji and showed flexibility and adaptability in stakeholder perceptions about contamination, as well as the power of institutions to make decisions in the project (Plant et al. 2017). Other kinds of stakeholder engagement that do not fit into the typology of communication, consultation, and participation included hiring local community members to carry out project activities, such as manual labor (Sam, Coulon, and Prpich 2016; Sam and Zabbey 2018; Zabbey, Sam, and Onyebuchi 2017).

Mechanisms of stakeholder participation included the creation of stakeholder groups, consultative community meetings, community advisory committees, or citizen juries (Bubna-Litic and Lloyd-Smith 2007; Beierle 2002; Greenberg et al. 2002; Beierle and Konisky 2000; Pollard et al. 2004; Foran et al. 2015). In these methods, a group of stakeholders is convened (often after completing stakeholder analysis) to establish project objectives and provide recommendations to the project team, representing a narrow area of remediation pursuing active stakeholder participation.

Effective application of stakeholder participation requires consideration of the local context and constraints in which a project lies (Brocklesby and Beall 2018). Ethnographic research methods, whereby the researcher is used as the research tool (Bernard 2006), offer flexibility in engaging local community participants. The use of qualitative ethnographic research methods, such as interviews and focus groups, can provide detailed contextual narratives about a site (Gill et al. 2008). A sole reliance on qualitative methods may be unable to identify a breadth of knowledge required in stakeholder engagement. Therefore, triangulation of quantitative and qualitative methods offers the best opportunity for practitioners to understand and incorporate local knowledge into project decision-making (Jick 1979).

The published literature on stakeholder engagement in remediation projects showcased existing knowledge on ways to gather information about local communities. Additionally, methods already exist regarding how stakeholders can participate in projects (e.g., citizen advisory committees). However, the existing sustainable remediation frameworks and studies about specific engagement methodologies fail to demonstrate how this knowledge might augment existing project activities. As described by Plant et al. 2017 (30), “stakeholder deliberation is a common way of eliciting people’s held and assigned values; however [sic] incorporating these into remediation decision-making remains challenging.”

2.2.1 Stakeholder Engagement in Remediation Projects in Developing Countries

Currently, stakeholder engagement advancements in the field of remediation are limited to discussion within industrialized nations. As of 2019, 11 countries have implemented SuRF frameworks, including Brazil, Taiwan, and Colombia (SuRF 2019). Yet, only professionals from industrialized countries such as the United States, United Kingdom, or Australia have published on the framework’s use and methods for implementation.

In industrialized nations, governmental bodies such as the United States Environmental Protection Agency oversee clean-up of contamination and regulate industries to prevent pollution. However, many developing countries already struggle with political instability, economic frailty, and weak regulatory structures (Atash 2007; Bartrem et al. 2014; Lupi and Hoa-Nghiem 2015; Evans and Kantrowitz 2002; Müezzinogˇlu 2003). Governmental support and regulation is often weak or nonexistent, requiring local communities to take more responsibility for remedial efforts (Fuller and DiMarco 2015). Especially in developing countries, the integration of local community knowledge into existing remediation processes becomes an essential action.

Yet, there has been a lack of analysis in understanding how stakeholders contribute (or, alternatively, do not contribute) to project activities in developing countries. Sustainable development literature and environmental management have embraced stakeholder engagement as an essential action for successful projects (e.g., Reed et al. 2018; Callaghan and Colton 2008), but remediation projects have largely been neglected from this analysis and discussion.

2.3 Conceptual Site Models

A conceptual site model (CSM) is a representation of known and hypothesized information at a contaminated site. It demonstrates how a contaminant moves through environmental media, documents sources and exposure routes of a contaminant, and facilitates strong decision-making among remediation practitioners (Rizzo et al. 2016; Holland et al. 2011). Traditionally, CSMs are created through the analysis of technical, quantitative data. However, researchers in the field of sustainable remediation have suggested that CSMs can be developed to include more aspects of sustainability, including land reuse and stakeholder well-being (Holland et al. 2011). These existing frameworks fail to specify how “stakeholder well-being” is defined and evaluated. Moreover, adapting the CSM to sustainability has been unexplored by the literature with regard to stakeholder engagement and participation.

Conceptual site models have further been used to describe sustainability linkages for a project (Bardos and Menger 2013; Li et al. 2019), but have continued to emphasize more technical angles of remediation and utilize graphical methods of representation. For rural communities in developing countries, this method limits the number of individuals who may be able to interact and discuss the conceptual site model due to low literacy abilities. These research advances still emphasize technical forms of knowledge over local knowledge, excluding early stakeholder input from key decision-making at the onset of a remediation project. This therefore neglects the needs, wants, and priorities of local communities in defining project objectives and determining preferences for investigative stages of the project.

2.4 Translating Stakeholder Knowledge to the Engineering Classroom

Greater use of stakeholder engagement amongst remediation professionals requires a greater emphasis on cultivating socio-technical skill development within engineering education. Monteiro, Leite, and Rocha (2019) broadly view the engineering profession through three different perspectives: 1) the transfer of scientific knowledge into practical application, 2) technical innovation, and 3) a public service to society. In engineering disciplines such as remediation, all three perspectives may be true simultaneously. Yet, traditional engineering education focuses on the first two perspectives, largely excluding the role of society in engineering. Recently, ABET's Engineering Accreditation Commission has addressed this lapse with revisions to the Criterion 3 Student Outcomes, which now include (emphasis added):

> (1) an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics; (2) an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as *global, cultural, social, environmental, and economic factors.* (ABET 2020)

whereby "complex engineering problems" are defined as

> involving wide-ranging or conflicting technical issues, having no obvious solution, addressing problems not encompassed by current standards and codes, involving diverse groups of stakeholders, including many component parts or sub-problems, involving multiple disciplines, or having significant consequences in a range of contexts. (ABET 2020)

Therefore, ABET requires accredited engineering curriculum to prepare students for interacting, involving, and empowering stakeholders to become involved in engineering projects.

2.4.1 Integration of Social Sustainability Skills into Site Remediation Courses

Incorporating these skills into undergraduate engineering curricula can happen through vertical or horizontal integration. Vertical integration is more common, where students receive these skills through specialized classes in community development or humanitarian engineering (Harsh et al. 2017). Yet, horizontal integration actually leads to longer attainment of these skills by integrating social dimensions of engineering directly into applied technical courses (Barrella and Watson 2016). Further, there is a lack of research on 1) the integration of nontechnical skills into specific programs of study and 2) assessment of programs incorporating social and other sustainability criteria into a course (Sivapalan 2015; J. Smith, Tran, and Compston 2020). This gap is consistent within courses specific to contaminant fate and transport and site remediation. Textbooks used in remediation-focused classes reinforce quantitative technical skills by blending theory, engineering concepts, and case studies, and may include discussions of applicable legislation (Dunnivant and Anders 2019; Payne, Quinnan, and Potter 2008). Stakeholder engagement may appear as part of a case study (see Sarni 2010 for examples) but is often excluded as a core component of remediation. While stakeholder engagement is more fully introduced in remediation textbooks focusing on sustainability and sustainable development (e.g. Hou 2020; William Sarni 2010), guidance does not exist on what stakeholder or community involvement looks like or how community involvement can directly contribute to project activities. Therefore, site remediation course curricula need further development so that students develop the requisite knowledge, skills, and attitudes necessary to incorporate stakeholder engagement in remediation projects.

2.5 Research Objectives and Hypotheses

As stated in Section 1.2, The primary aim of this work is to enhance the long-term sustainability of remediation projects, especially in developing communities, by providing alternatives for seamless integration of local knowledge into traditional remediation processes. Four research objectives and three hypotheses are presented that guide Chapters 3, 4, and 5.

2.5.1 Objective 1 and Hypothesis 1

The first research objective, developed in Chapter 3, is to understand both the barriers and opportunities of environmental remediation projects performed within the social, economic, and political context of developing communities.

Based on the detailed literature review of stakeholder engagement in remediation projects and several well-known sustainable remediation frameworks, there is a need to understand how projects are implemented in a developing country context. This chapter investigates previously implemented projects for a range of contaminants, solutions, and contexts within developing countries with a focus on how stakeholder engagement and participation benefits or hinders remediation efforts.

The hypothesis for this objective is two-fold: 1) remediation projects in developing countries face constraints that are different to that of industrialized nations, and 2) stakeholder engagement is not consistently pursued in remediation projects in developing countries.

2.5.2 Objective 2 and Hypothesis 2

The second objective guiding Chapter 4 is to integrate local knowledge into pre-existing remediation tools during the preliminary assessment stage of a contaminated site.

This thesis developed chronologically, where the development of Chapter 4 followed the literature review in Chapter 3. Therefore, the main results from Chapter 3 (broadly, that stakeholder engagement is important for project success in developing countries, but not widely implemented) motivated this research objective. The hypothesis developed from an examination of literature on conceptual site models (see Section 2.3). The null hypothesis would support the current development and use of conceptual site models through strict technical knowledge, rather than socio-technical integration.

The second hypothesis contends that local knowledge can be used to create preliminary conceptual site models alongside existing technical knowledge about a contaminated site, thereby creating socio-technical integration in early remediation efforts.

2.5.3 Objective 3 and Hypothesis 3

The third objective of this research, also in Chapter 4, is to test the framework of a community-informed conceptual site model by applying it to a contaminated site in an ASGM community.

Frameworks are structures to guide decision makers on a project. The full realization of a framework is in application. Because of the founding work on remediation projects in developing countries (Chapter 3) and the critical need of remediation in ASGM communities from historic gold processing using mercury, field work implemented the framework in Andes, Colombia.

The third hypothesis is that organizing local knowledge into a community-informed conceptual site model allows the opinions, needs, and context of an ASGM community to guide project planning for future remedial efforts.

2.5.4 Objective 4

The final objective developed in Chapter 5 is to improve socio-technical thinking in undergraduate site remediation courses through the use of conceptual site models in a course-long project.

The goal of engineering education is to equip students with the skills and tools necessary to efficaciously complete professional engineering work. If engineering systems are inherently socio-technical, but the classroom only focuses on technical information, students will be unprepared to work in the real-world context of remediation. As conceptual site models are flexible tools, they offer a mechanism to engage students' socio-technical thinking skills. This chapter seeks to guide engineering educators by developing specific course objectives, assessment mechanisms, and lesson plans on introductory site remediation material with a socio-technical focus.

2.6 Scope

Although this research applies to the broader remediation community, the scope of this research is limited in two ways. First, it focuses on remediation projects in developing countries, rather than a focus on industrialized nations. The preliminary assessment stage corresponds to early remedial investigations of a site, prior to setting project objectives, environmental sampling, or heavy technical modeling. Second, this research applies the novel framework for developing CSMs to a single artisanal and small-scale gold mining community in Colombia where the availability of technical data was limited to a single report. In this way, this research was forced to rely on stakeholder knowledge to develop an understanding of local mercury contamination. Engineering principles and a technical understanding of mercury fate and transport were essential to understanding where local knowledge aligns with, or diverges from, scientific reality.

In terms of engineering education, the scope of this work is limited to developing strategic learning outcomes and assessments for engineering educators. The learning outcomes and assessments are designed through the application of Bloom's Taxonomy (Bloom 1956). A study of the efficacy of these lesson plans or examples of student work from applying the lessons are also beyond the scope of this project.

CHAPTER 3

REMEDIATION IN DEVELOPING COUNTRIES: A REVIEW OF PREVIOUSLY IMPLEMENTED PROJECTS AND ANALYSIS OF STAKEHOLDER PARTICIPATION EFFORTS

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3.1 Introduction

In 2010, lead contamination from artisanal and small-scale gold mining (ASGM) killed over 400 children in six months and exposed over 17,000 people to lead poisoning in northern Nigeria (Agence France-Presse 2010; Tirima et al. 2016). Public attention to this epidemic spawned both medical and clean-up assistance for the impacted communities, resulting in a massive remedial effort to reduce ongoing lead exposures and develop Nigeria's capacity to prevent future catastrophes. Clean-up and capacity building efforts included lead removal, clean soil replacement, institutional controls, and health advocacy campaigns from various non-governmental organizations (NGOs) and government agencies worldwide (Tirima et al. 2016).

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Nigeria’s 2010 lead poisoning crisis is far from the only example of the risks posed to human health and the environment due to pollution and contamination worldwide, much of which targets people in developing communities. In fact, in 2016, pollution-related diseases were the cause of premature death for over nine-million people in the world (World Health Organization 2018). Of these nine-million deaths, approximately seven-million people died from exposure to indoor and outdoor air pollution, and an additional two million died due to a combination of unsafe drinking water, sanitation practices, and unintentional poisonings: the result of exposure to hazardous chemicals and environmental contamination (World Health Organization 2018). These high mortality rates prompted the creation of one of the World Health Organization’s Sustainable Development Goals to substantially reduce “the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination by 2030” (World Health Organization 2018).

Ninety-two percent of pollution related mortality occurs in low- and middle-income countries, threatening poor communities around the world (Hardoy, Mitlin, and Satterthwaite 2001; Landrigan et al. 2018). This is due, in part, to unsafe work practices, technological barriers (Evans and Kantrowitz 2002; Lupi and Hoa-Nghiem 2015), socio-economic tradeoffs (Atash 2007; Bartrem et al. 2014; Evans and Kantrowitz 2002; Hilson 2002; Raza et al. 2017), political instability (Bartrem et al. 2014), poor appropriation of funds (Atash 2007; Lupi and Hoa-Nghiem 2015; Müezzinogˇlu 2003), and insufficient capacity for regulation and supervision from government and local institutions (Atash 2007; Beckers and Rinklebe 2017; Lupi and Hoa-Nghiem 2015; Müezzinogˇlu 2003; Tirima et al. 2016). Vulnerabilities created by these factors ultimately result in disproportionate exposure to contamination (Evans and Kantrowitz 2002;

Raza et al. 2017). Thus, there is an urgent need to implement strategies to both prevent and clean-up contamination in these regions.

Remediation, the removal of hazardous contaminants from soil, groundwater, sediment, and surface water, provides an opportunity to reduce pollution and, thereby, pollution-related deaths (Landrigan et al. 2018; World Health Organization 2018). Although remedial efforts have occurred in developing communities, such as the clean-up of lead contamination in Nigeria in 2010, most efforts have been confined to developed communities due to the difficulty in overcoming the abovementioned barriers (e.g., social, economic, etc.). Efforts specifically focused on developing communities have often been poorly documented or communicated. Published literature has largely focused on improving remedial technologies and strategies (Garelick et al. 2005; Li 2010; Li et al. 2012; Phillips 2009) rather than examining the implementation of these strategies within the communities themselves (Erakhrumen 2011). Additionally, little analysis has been performed in an effort to synthesize our understanding of context-specific issues that may differ from projects in industrialized nations.

Previous studies on other environmental projects in developing communities, such as water treatment, highlight the importance of stakeholder engagement and participation to a project (Luyet et al. 2012; Reed 2008). As demonstrated by Reed (2008), stakeholder engagement and participation fosters solutions that can be adapted to a local socio-cultural context. Additionally, stakeholder engagement can uncover health and environmental information that may not be immediately evident from traditional techniques of environmental sampling and field testing by integrating local knowledge with technical knowledge. For remediation projects, specifically, this knowledge blending can reveal existing contamination and priorities to local community members, whose context-dependent knowledge results from collective experience, often derived through observation (Reed 2008). In other words, community members can be important sources of information in remediation projects. In this paper, we distinguish between stakeholder engagement and stakeholder participation, following the definition of participation from The World Bank. Stakeholder participation is a “process through which stakeholders influence and share control over development [in this case, remediation] initiatives and the decision and resources which affect them” (Luyet et al. 2012; World Bank 1996). By comparison, stakeholder engagement represents a broader collection of activities that encompasses stakeholder participation, but also includes activities such as consultation and active listening whereby stakeholders do not necessarily influence decisions. Rather, these activities provide information to decision-makers. These non-participation activities are important initial steps in a project that can lead to stakeholder participation. However, because actual stakeholder participation results in greater ownership and sustainability of projects (World Bank 1996), it is worth distinguishing from broader stakeholder engagement efforts.

The purpose of this work is to understand both the barriers and opportunities of environmental remediation projects performed within the social, economic, and political context of developing communities. Results can be used as both a reference for remediation practitioners working in developing communities and a roadmap for future efforts. After a brief explanation of the methods used in this review, we classify previous efforts by contaminant, industry practice, project cost, and remedial strategy. The results of this classification expose a need to analyze stakeholder engagement and participation within the remediation projects. In addition to environmental remediation, findings can be applied to other intervention efforts in developing countries, particularly those that require behavior changes from community members and local acceptance of project activities.

3.2 Methods

Environmental remediation efforts (hereafter referred to as *remediation projects*) in developing countries are often conducted by national governments, sometimes in collaboration with local authorities and NGOs. Information on these projects is typically reported in unpublished reports or project webpages, and little to no information is available in the form of peer-reviewed literature. Consequently, this review combines both peer-reviewed literature and grey literature in the form of websites and unpublished reports from NGOs or government authorities. For a clean-up effort to be included in this review, a formal document, either in the form of a project report, article, working paper, or a summary webpage must be available.

This review targets implemented remediation projects in developing communities. Therefore, the review excludes studies involving the following:

(1) preventive strategies for pollution, instead of remedial processes for existing contamination;

(2) policy and governmental capacity building;

(3) existing and emerging remedial technologies but do not address practical applications within a developing country context;

(4) a project location exclusively in China.

Because there are several literature reviews focused specifically on remedial efforts within China, we excluded projects located in China alone from this review (Li et al. 2017; Sun et al.

2018; Tang et al. 2016; Xie and Li 2010). These reviews concluded that policy improvements in China can enhance existing contaminated site management efforts, such as remediation, as well as greater inclusion of stakeholders and the public in projects.

We used several methods to identify remediation projects. For example, we conducted two different Web-of-Science queries. The first search returned 350 results by using the search terms “remediation,” “clean-up,” “contaminated land,” and “developing countries.” The second search returned 1125 results by using the search terms of “remediation,” “clean-up,” “contaminated land,” “polluted ground,” “polluted land,” and “polluted soil,” excluding results with “experimental study,” “pilot-scale” and “field study.” After reading all abstracts from these two searches, we excluded most of the papers because the focus was on policy, technological advances at the laboratory scale, or field trials of a technology rather than actual clean-up. Other articles were excluded because the authors used samples taken from a developing country for laboratory analysis, but no follow-on remedial efforts were included. We also searched the project repository from the Global Environment Facility (GEF) and the World Bank using the search terms mentioned above, resulting in six additional projects. Excluded projects from the GEF and World Bank searches mentioned remediation but rather focused on policy related to the environment or mining reclamation.

The majority of remediation projects were found through searching the project repository on the Pure Earth website. Pure Earth is an NGO focused on reducing pollution-related health risks though environmental clean-up in developing communities and is therefore involved in many remediation efforts around the world. Specifically, Pure Earth was involved in some capacity in about 70% of the projects covered in this review. We reviewed all 159 “Completed Projects” listed on Pure Earth’s website (as of September 24, 2019). From this list, 29 projects were included based on the above-mentioned criteria. Finally, the citations contained in each of the sources were checked for additional studies or reports that were not found in the preceding search. One additional project was found (through a citation to a government website). Overall, we identified 38 relevant projects from 20 countries (Figure 3.1).

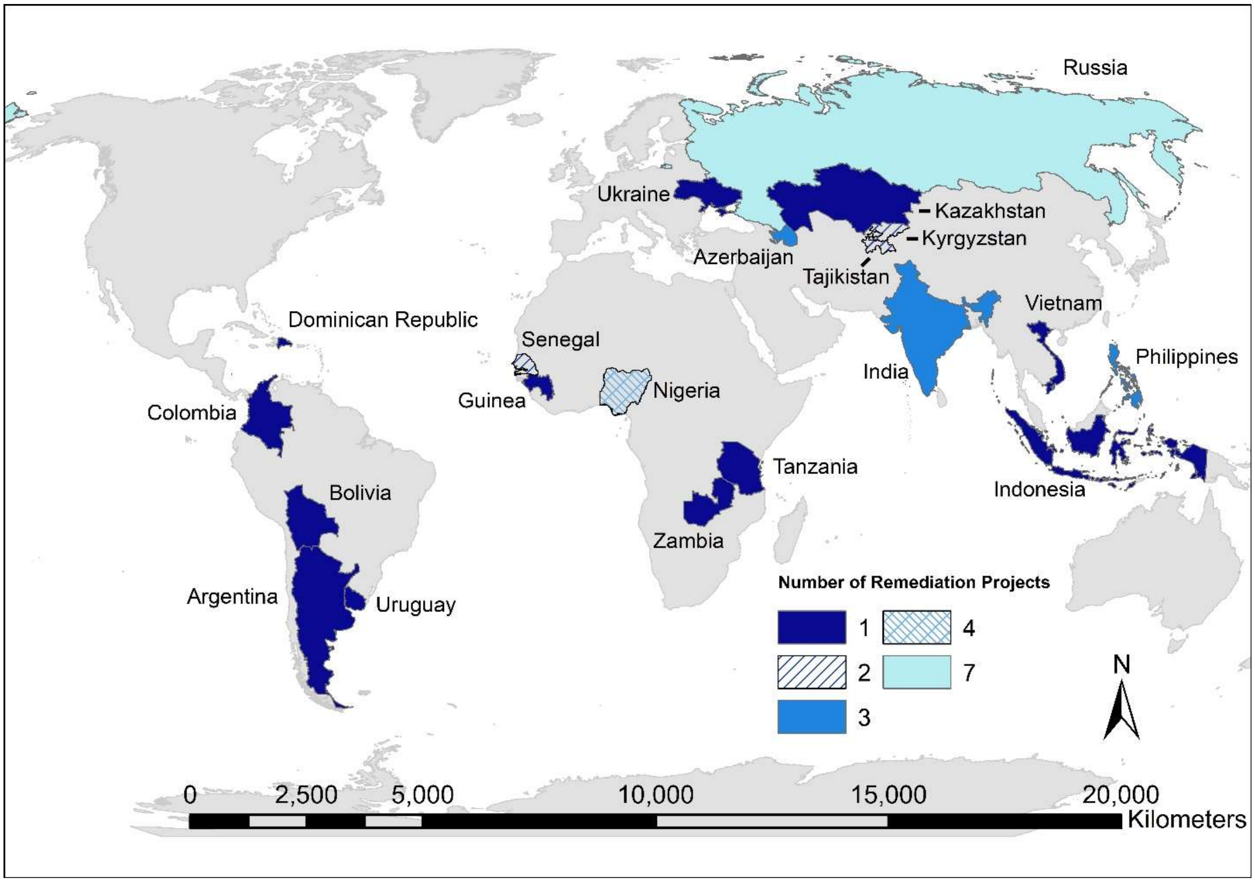

Figure 3.1 Map showing the location and number of remediation projects included in this report. The color scale corresponds to the number of projects identified in each country. Data source: ArcWorld Supplement for continent shapefiles and Esri, Garmin for country shapefiles. The map was created using ArcGIS software by Esri. ArcGIS and ArcMap are the intellectual property of Esri and are used herein under license. Copyright Esri. All rights reserved.

It is important to note the limitations of this work due to the limited literature available on remediation projects in developing countries. Unlike developed countries, there are no standardized reporting requirements for projects. Therefore, although well intentioned, many documents were missing key details (like the type of contaminant being targeted) or contained vague language to describe the remedial strategy. Our other classifications of project cost and responsible sector faced similar barriers during analysis. In addition to limiting the review, poor project reporting propagates confusion for practitioners seeking information about a specific contaminant and applicable remedial technologies for future remedial efforts.

3.3 Project Classifications

To understand the state of remediation in developing countries, projects were first identified by contaminant, responsible sector, project cost, and remedial strategy. Overall, the projects spanned 23 different contaminants from over 14 different sectors, and a wide range of costs and clean-up efforts.

3.3.1 Contaminant Categories

Remediation projects were sorted based on contaminant category (Figure 3.2). Projects targeted heavy-metal contamination, persistent organic pollutants (POPs) (e.g., polychlorinated biphenyls (PCBs), dichlorodiphenyltrichloro-ethane (DDT), and other pesticides), hydrocarbons (e.g., crude oil or benzene), and radionuclides. Other contaminants included tannery waste, aluminum, cyanide, and fluoride. Notably, lead was targeted in 13 remediation projects, more than double any other contaminant. This was due, in part, to the known health effects of acute lead poisoning (Blacksmith Institute 2007a; Haefliger et al. 2009; Tirima et al. 2016). Moreover, in communities with used lead-acid battery (ULAB) recycling, lead contamination critically endangered the local population because of the proximity of lead operations to households, schools, and public gathering spaces (Blacksmith Institute 2014b). In fact, except for one project that did not provide enough information to be evaluated (UNDP 2016), all lead remediation projects reported successful completion of the clean-up effort. Similarly, contaminants such as

DDT and mercury motivated remedial efforts when in proximity to a human population.

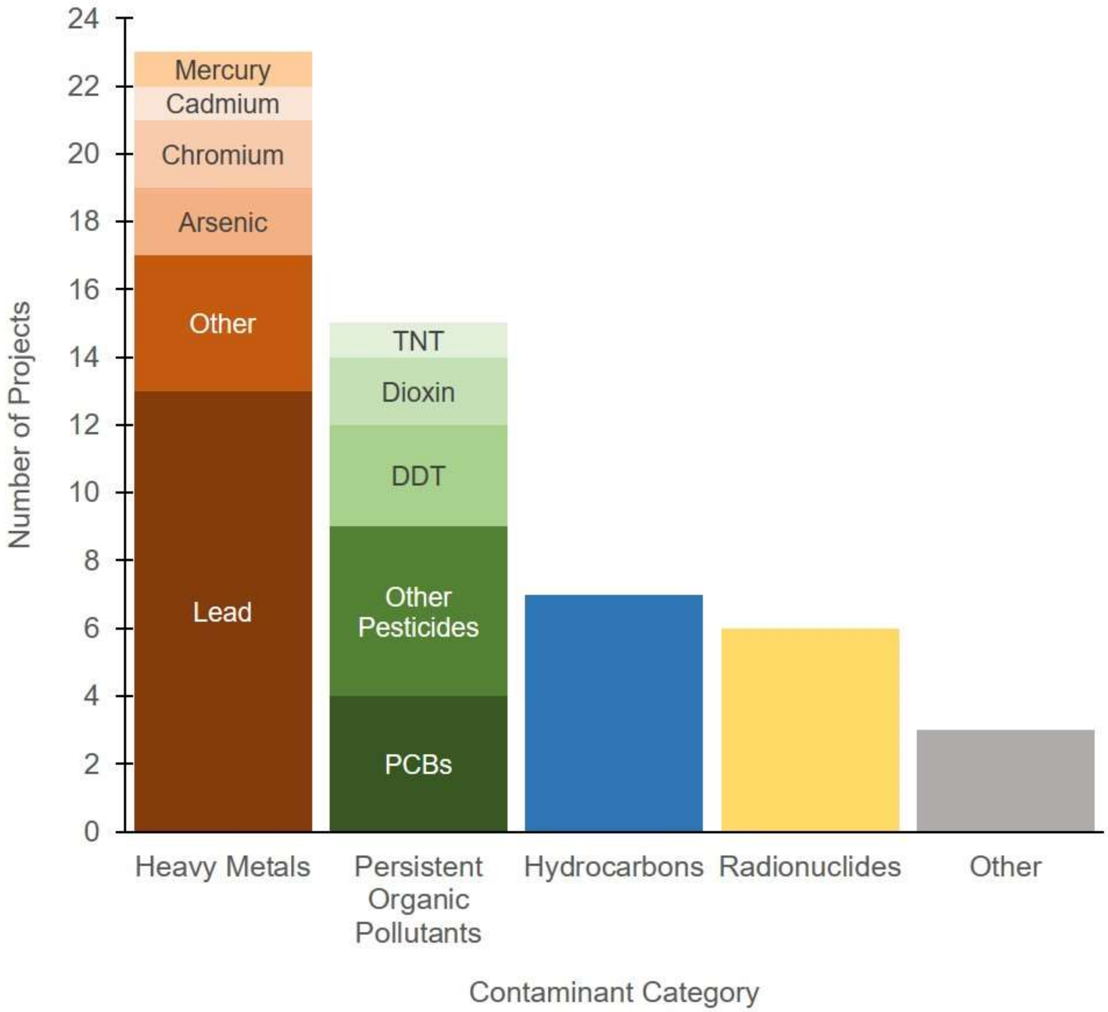

Figure 3.2 Number of remediation projects sorted by targeted contaminant, representing 23 different contaminants. Heavy metals and Persistent Organic Pollutants (POPs) are segregated into more specific contaminants due to differentiation within project reporting. Radionuclides consist of cesium, strontium, plutonium, and uranium contamination (approximately one project each). Other contaminants include tannery waste, aluminum, nickel, cyanide, and fluoride.

3.3.2 Responsible Sectors linked with Project Cost

Although remediation projects are critical endeavors for the health and well-being of local communities, knowledge of responsible party(s) (or lack thereof) often limits implementation and support. The majority of contamination targeted by previous remediation projects originated from four broad categories: mining, recycling, chemical-related industries, and other sectors. These sectors are delineated into more specific activities within each category (Table 3.1 on page 30). The third column lists the various contaminants due to the corresponding activities, with citations to project reports and other literature. Most of these sectors are affiliated with some of the world's most polluting industries of nonferrous metal production and industrial chemicals (Mani and Wheeler 1998; Binder 2001). However, work in these sectors has developed beyond traditional mining and manufacturing of products to include low-income individuals and small groups informally engaged in recycling activities of used products. These sectors include artisanal and small-scale mining (Environmental Law Institute 2014), electronic waste (e-waste) recycling (Ackah 2017), and ULAB recycling (Daniell et al. 2015). Six projects (16%) in this review targeted contamination caused by an informal sector (Figure 3.3).

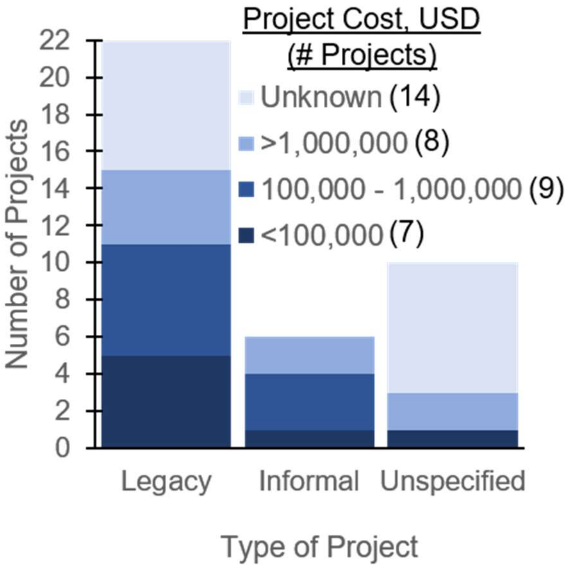

Figure 3.3 Remediation projects sorted by whether the project targeted legacy contamination or was caused by an informal sector. These categories are further partitioned by project cost as reported by the available project reports.

Although informal sectors, such as ASGM and ULAB recycling, contributed to contamination, 58% of the projects targeted legacy contamination from formal operations (Figure 3.3 on page 28). Legacy pollution results from historic activities where the responsible parties are either unknown, bankrupt, or now-obsolete state agencies (World Bank 2011a; 2012). Working with this definition, projects were classified as “legacy contamination” if the responsible party was unknown, did not perform remediation, or was not held liable for the contamination. Of the legacy remedial sites, 40% were attributed to the mining industry. Due to poor project reporting, 11% of the projects failed to specify the responsible sector and therefore could not be classified as legacy or non-legacy contamination (Blacksmith Institute 2005b; 2014d; Pure Earth 2018c; CSIR-NEERI 2015).

In terms of remedial costs, only 60% of projects reported total project cost, the majority of which were classified as legacy contamination (Figure 3.3 on page 28). Sixty-six percent of projects with legacy contamination had a project cost over 100,000 USD, four of which cost over 1,000,000 USD. As highlighted by the World Bank (2004), municipalities and national governments lack the financial resources and economic stability to support these legacy projects with high price tags, creating a funding barrier for remediation projects. Due to the high clean-up costs from legacy contamination and the inability to hold responsible parties accountable, outside funding from organizations such as the Global Environment Facility (GEF) and the United Nations Development Programme, among many others, supported over 60% of the projects in this review.

Informal sectors experienced similar funding barriers for remediation projects due to the informal nature of their operations and a lack of regulatory mechanisms required to hold them accountable. The average cost of remediation projects targeting informal contamination was

Table 3.1 (next page) Activities responsible for contamination in reviewed remediation projects. Four broad categories of mining, recycling, chemical-related industries, and other sectors are further delineated into more specific activities within each category. The third column lists the various contaminants due to the corresponding activities, with citations to project reports and other literature.

Sector Categories for Contamination	Specific Activities within Each Sector	Contaminant and Citations
Mining	Large and Medium-Scale Mining Activities	Lead (Blacksmith Institute 2014c; Ericson and Dowling 2016; Sharov, Sinitsky, and Temnikova 2017) Mercury (Pure Earth 2017b) Radionuclides ("Russia (Bolshoi Balchug) – Riverbank of Nuclear Waste" n.d.; Blacksmith Institute 2014; Ferl 2017) Unspecified Contamination in Copper Tailings (World Bank 2004)
	Artisanal and Small-scale Gold Mining	Lead (Tirima et al. 2016)
	Smelting Activities	Lead (Blacksmith Institute 2008a; 2009; Pure Earth 2017a)
Recycling	Used lead-acid battery recycling (ULAB)	Lead (Blacksmith Institute 2009; 2008c; 2014b; Pure Earth 2016; UNDP 2016)
	E-waste recycling	Lead (Pure Earth 2015b)
Chemical-Related Industries	Chemical and Explosives Manufacturing	Benzene (Pure Earth 2015a) Benzo [a] pyrene (Pure Earth 2015a) Chromium (Blacksmith Institute 2006a) Lead (Blacksmith Institute 2006a) Mononitrochlorobenzene (Blacksmith Institute 2014a) PCB (Pure Earth 2015a) Radionuclides ("Russia (Bolshoi Balchug) – Riverbank of Nuclear Waste n.d.) TNT (Blacksmith Institute 2014a)
	Chemical Weapons Dismantling	Arsenic (Blacksmith Institute 2008b) Dioxin (Blacksmith Institute 2008b) Lead (Blacksmith Institute 2008b)
	Pharmaceutical Industry	Aluminum (Blacksmith Institute 2005a) Cyanide (Blacksmith Institute 2005a) Lead (Blacksmith Institute 2005a; 2009) Nickel (Blacksmith Institute 2005a) Unspecified POPs (Blacksmith Institute 2005a)
	Leather Tanning	Arsenic (Blacksmith Institute 2009) Cadmium (Blacksmith Institute 2009) Chromium (Blacksmith Institute 2009)
Other Sectors	Oil and Gas Industry	Hydrocarbons (World Bank 2007; UNEP 2011; Chikere, Azubuike, and Fubara 2017; Ola, Fadugba, and Uduebor 2018) Radioactive Waste Oil (MES 2008)
	Military Operations	Dioxin (Lupi and Hoa-Nghiem 2015) Lead/other Heavy Metals (Blacksmith Institute 2007b) PCB (Blacksmith Institute 2007b)
	Abandoned Capacitor	PCB (Pure Earth 2018b)
	Nuclear Reactor	Radionuclides (Devell et al. 1986; "Russia (Bryansk) – Chernobyl Radiation Remediation" n.d.)
	Pesticide Storage Facility	DDT (Blacksmith Institute 2006b; 2011; Pure Earth 2017c) Unspecified Pesticides (Blacksmith Institute 2006b; Pure Earth 2018a)
	Unspecified	Fluoride (CSIR-NEERI 2015) Tannery Waste (Blacksmith Institute 2005b) Unspecified Heavy Metals (Blacksmith Institute 2014d; Pure Earth 2018c) Unspecified Pesticides (Pure Earth 2018c)

approximately 80,000 USD. Three of the projects cost between 100,000 and 1,000,000 USD, and two projects cost over 1,000,000 USD (Figure 3.3 on page 28). Development agencies, such as the United Nations, World Bank, and Asian Development Bank, were the financers of such clean-up efforts.

The dependency on development agencies further demonstrates the contexts of economic fragility, political instability, and regulatory vulnerabilities in which projects operated. For example, two of the projects classified as "unspecified" (i.e., not legacy or informal) still cost over 1,000,000 USD (Figure 3.3 on page 28). Both remedial initiatives were part of larger projects that simultaneously sought to strengthen regulatory capacity within the countries, restructure or improve the responsible state-controlled extractive companies and provide needed financial resources that were otherwise unavailable (World Bank 2004; 2007). In fact, during rehabilitation of the Uzen Oil Fields in Kazakhstan, remedial activities were not originally planned. Instead, they were added onto existing project activities based on technological availability and potential profitability (World Bank 2007).

3.3.3 Remedial Strategies

From the thirty-eight projects, fifty different remedial strategies grouped into four main categories were employed to clean-up twenty-three different compounds (Figure 3.4 on page 34). Projects targeted all environmental media, including water (30%), soil (78%) and air (7%). The most common remedial strategy applied was excavation and safe storage (a source recovery and removal method), where contaminated soil was physically removed and stored in an alternate location, typically off-site. Encapsulation, in which soil is surrounded by impermeable barriers in situ, was the only method that applied isolation and containment as a remedial strategy. Four projects explored source and plume treatment options such as bioremediation or in-situ chemical oxidation. As previously discussed, many projects targeted lead remediation using source recovery and removal (i.e., excavation and safe storage). The utilization of excavation and safe storage requires an appropriate storage method for the hazardous waste to reduce the risk of recontamination. For example, during a pesticide clean-up in Azerbaijan, Pure Earth selected a hazardous waste facility location "situated away from any residential areas," and used appropriate containment measures such as concrete lined pits and the overpacking of liquid pesticides in plastic (Pure Earth 2018a). Proper containment reduces the risk of recontamination by preventing groundwater migration (Lombi, Wenzel, and Adriano 1998). In the event the containment fails, locating the hazardous waste facility away from people reduces the risk of contaminant exposure. However, a hazardous waste disposal facility may not be available. For example, during the remediation of mercury-contaminated soils in Kyrgyzstan, contaminated soil was stored at a nearby tailings facility (Pure Earth 2017b). Disposal location selection is critical to the success of projects that utilize excavation and safe storage. When a hazardous waste storage facility is not available, other options may need to be considered, including other remediation technologies (for a discussion on different remediation technologies see Lombi, Wenzel, and Adriano 1998 and Li 2010).

Many projects implemented institutional controls alongside other remedial strategies. Institutional controls included dissemination of information through mass media outlets, informational pamphlets or children's books, and educational programs and workshops created for communities and schools. Fourteen projects (~40%) utilized institutional controls as part of the remedial activities. Institutional controls rely on the adoption and compliance of local communities to be effective, necessitating adequate stakeholder participation efforts (US EPA 2012). Yet, out of these fourteen projects, four failed to document any form of stakeholder engagement, and only two noted collaboration with local governmental authorities. Four other projects noted some kind of coordination with the local community but lacked evidence to suggest that local community members actively participated within the remedial process. For example, during the Nigeria Lead Poisoning Crisis described earlier in this review, two institutional controls were implemented. One prohibited the employment of women in ore

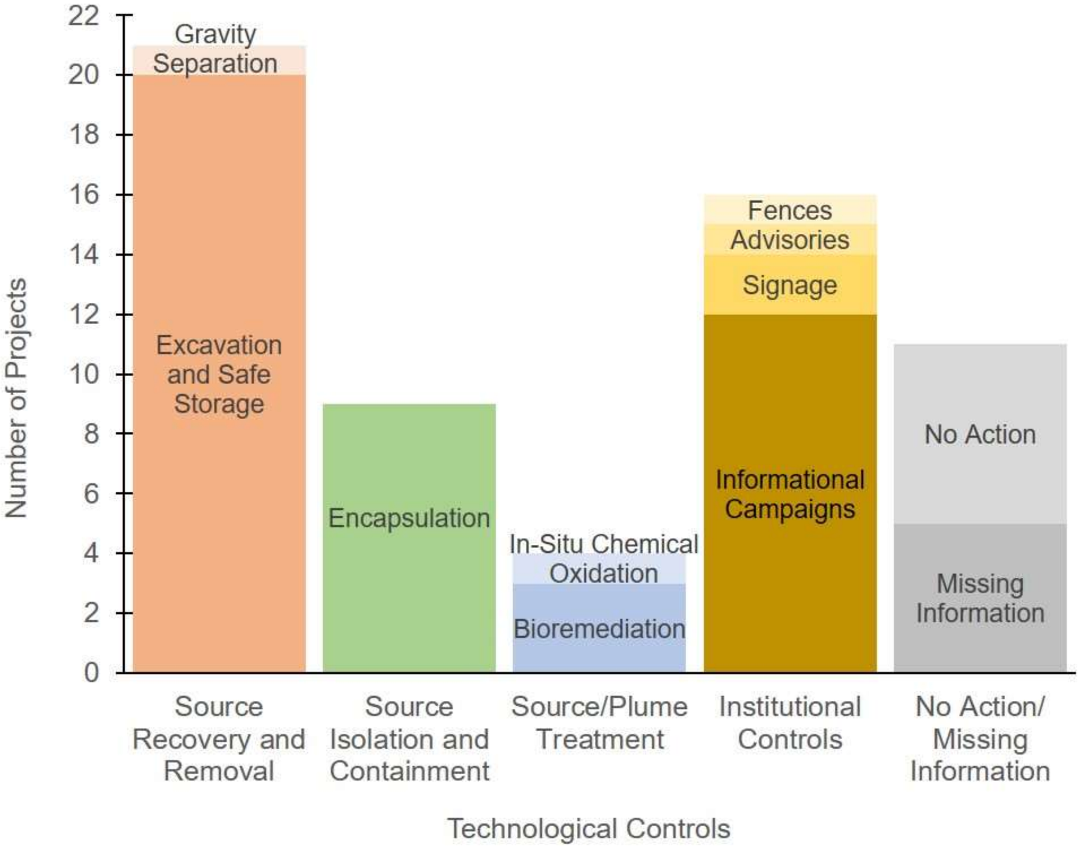

Figure 3.4 Remediation projects sorted by employed remedial strategy. Projects often utilize more than one remedial strategy. Therefore, the total number of remedial strategies (50) exceeds the 38 projects included in this report. The category of Missing Info identifies projects that lacked enough information in the report to identify the remedial strategy employed. The category of No Action identifies projects that never employed a remedial strategy due to various barriers to implementation.

processing, and the second required active artisanal miners to remediate any re-contaminated media from their activities (Tirima et al. 2016). However, there was no information describing whether community members complied with these institutional controls or how cooperation with local community members created these institutional controls. Because the investigated projects lacked analyses and reflections on stakeholder engagement or participation, the effectiveness of institutional controls could not be evaluated, and insights on the proper utilization of institutional controls could not be determined from these projects.

3.4 Stakeholder and Community Participation

Because stakeholder engagement and participation is an important component in creating effective solutions in environmental projects (Chess and Purcell 1999; Luyet et al. 2012; Reed 2008), the investigated remediation projects were analyzed against criteria for effective stakeholder participation developed by Reed (2008): engagement and acknowledgement of a diverse range of stakeholders, skilled facilitation of stakeholder engagement and participation efforts, and early engagement and continuous participation of impacted stakeholders. For the projects investigated, stakeholder participation efforts that included multiple groups were limited. Forty-four percent of the projects failed to document any stakeholder engagement or participation. Twenty-one percent of the projects listed some kind of local government collaboration but failed to note any additional stakeholder engagement or participation in the project. Only thirty-two percent of the projects reported diverse stakeholder engagement, which included activities such as creating stakeholder groups or committees, community mapping, and household surveying. We did not consider education and informational campaigns delivered to local community members to be a form of stakeholder engagement since these activities are types of institutional controls, discussed previously. Moreover, only four projects (10%)

provided evidence of involving local community members (individuals not necessarily part of an NGO, governmental authority, or other institution). Three of these four projects utilized a stakeholder group for stakeholder participation, and one project utilized a combination of consultations and workshops. Only one project mentioned the use of stakeholder mapping to identify the impacted stakeholders in the project (Blacksmith Institute 2005b). Overall, projects often failed to document details about stakeholder engagement within reporting. This included a failure to provide or explain initial stakeholder analysis to ensure all impacted stakeholders were, at least, engaged in the project. Given the limited information available, the following excerpts and discussion summarize existing stakeholder engagement and participation efforts.

Poor stakeholder participation, often caused through inadequate facilitation, led to project delays and failure. For example, in the Msimbazi River project in Tanzania, several stakeholder groups were involved in pursuing clean-up efforts for heavy metal and pesticide contamination, but the project did not leverage the collective action of the various groups and the remedial efforts were left incomplete:

> efforts [of the various stakeholder groups] are isolated…and primarily prevent further contamination more than remediate the problem such that it currently exists. It is necessary at this point to synchronize the efforts of all interested parties, to maximize their overall effect…The community stakeholders know best the history of their surroundings and the sources of the water pollution. But, due to lack of efficient communication channels to the government, this resource has previously not been effectively utilized. (Pure Earth 2018c)

While local stakeholders were equipped with knowledge on local environmental conditions, without proper coordination and facilitation of these groups, this knowledge could not be properly leveraged to assist with remedial efforts. Poor coordination further contributed to confusion about responsibility: in the Msimbazi River project, community stakeholders considered the river clean-up to be the government's responsibility. As a result, they hesitated to take action, stalling remedial efforts. By comparison, adequate facilitation of stakeholder participation drove greater project success. During the remediation of heavy metals and PCBs in the Clark and Subic Bay area of the Philippines, Pure Earth coordinated the utilization of a stakeholder group, local technical experts, and staffed local partners to monitor day-to-day operations of the project. This allowed multiple institutions and groups to direct project activities in varying ways: local institutions provided additional evaluation of remediation proposals, local technical experts recommended sampling locations and site selection, and the stakeholder group - made up of local community members, local government, and redevelopment authorities - helped to facilitate project management over the course of remediation activities (Blacksmith Institute 2007b). In addition to including a diverse range of stakeholders in the project, the ability to manage and direct these diverse stakeholders' efforts led to effective sampling and site selection, efficient clean-up of contaminated soil, and the scheduling of thirteen additional contaminated sites for remediation (Blacksmith Institute 2007b).

In addition to the need for skilled facilitation and inclusion of a diverse selection of stakeholders, defining common goals and expectations for a project required early engagement and continuous participation of all stakeholders (Chess and Purcell 1999). In the previous example of remediation in Clark and Subic Bay, early engagement of local officials and technical experts produced effective sampling procedures and established communication early among different stakeholders. Additionally, local community members and government officials understood the existence of contamination near them and supported project activities

(Blacksmith Institute 2007b). Because these stakeholders were also given responsibilities pertaining to remedial efforts, communication continued as all stakeholders actively participated in project activities. By contrast, failure to engage stakeholders early in project activities resulted in miscommunication and project failure during a World Bank-sponsored project in Bolivia. Project authorities removed funding for remediation of contaminated mine sites within two years of the project start date due, in part, to a lack of agreement from the community on the proposed solutions (World Bank 2004). Over 3 million USD, allotted for remedial activities, were either transferred to pay for laboratory upgrades, used to create technical assistance programs for municipalities affected by mining, or were cancelled altogether. An additional 3 million USD were further spent on studies that did not result in a remediation project (World Bank 2004).

One project assessed, in detail, the methods of its stakeholder participation and effectiveness of these processes, demonstrating how early engagement without continuous participation may compromise project success. The Copperbelt Environment Project in Zambia utilized a detailed stakeholder participation plan and envisioned utilizing stakeholders in the identification, selection, and design of remedial subprojects. A Midterm Review workshop convened 62 different stakeholders to discuss the project part-way through implementation, and stakeholder consultations continually provided feedback to the project (World Bank 2011b). Unfortunately, portions of the project team failed to recognize community participation as an essential component of the remediation project, arguing that a “community component would make this already very ambitious Project [sic] too complex and implementation possibly even slower” (World Bank 2011b). While the local community was intended to be included in selection and identification of subprojects, the technical environmental coordination unit made most of these decisions. During the Midterm Review, community members provided feedback to project members, but did not actively participate in decision-making that directed project activities. Thus, while local community members were involved early in the project and allowed to provide recommendations, they did not implement remedial subprojects as the project had envisioned. At the conclusion of the remedial activities, the project reported limited sustainability and local ownership of clean-up efforts because local communities did not actively participate throughout the remedial process.

Overall, some remediation projects struggled in effectively facilitating diverse groups of stakeholders and allowing active participation of stakeholders throughout the entire remediation process. By comparison, other projects prospered when efforts were made to include stakeholders. They experienced success when diverse groups of stakeholders were engaged early in planning phase of the remediation process. In many cases, even if full stakeholder participation was never reached, early engagement and skilled facilitation of stakeholders still led to enhanced communication and the creation of shared goals, knowledge, and expectations among the various stakeholders.

3.5 Conclusions

Driven by a need to reduce or eliminate human exposures to hazardous contaminants, remediation projects play a critical role in maintaining the health and quality of life for developing communities. This review synthesized information from 38 implemented remediation projects in developing countries, both from academic and grey literature. Remediation projects primarily targeted contamination of soil media due to heavy metals (the majority of which were lead contamination), followed by persistent organic pollutants. Due to the dominance of soil contamination within the remediation projects, source recovery and removal strategies were the primary method of clean-up, despite concerns about long-term contamination resulting from ineffective storage solutions. Three main sectors were responsible for contamination: mining, recycling activities, and chemical production. Over seventy percent (70%) of the projects were due to either informal livelihood occupations or legacy pollution, the majority of which were classified as legacy pollution. The dominance of legacy pollution and informal livelihood occupations in remediation projects created a funding and responsibility gap specific to developing countries because of limited governmental capacity to regulate and clean-up this kind of contamination. Development organizations therefore provided funding and support for remediation, and projects operated in fragile contexts that required commitment from local stakeholders to be successful. Additionally, many projects employed a series of institutional controls as part of the clean-up solution. Institutional controls relied on compliance and participation from the public, offering additional support to include local stakeholders within project activities.

Because remediation projects relied on cooperation between remediation practitioners and local stakeholders, we analyzed stakeholder engagement and participation efforts within the projects, finding a lack of strategic and successful engagement efforts. Overall, the investigated projects ignored stakeholder engagement and participation as a core part of the remediation process. When some form of stakeholder participation or engagement was present, project delays, wasted financial resources, and project abandonment were due, in part, to failed stakeholder participation efforts. Efforts were hampered due to a lack of skilled facilitation, inability to engage stakeholders early in project activities, or neglect of stakeholder participation throughout the entire project. By contrast, projects that more successfully pursued stakeholder participation experienced enhanced communication between different stakeholders, acknowledgement of shared goals and resources, and identified additional information pertaining to project activities.

Poor documentation of historic remedial efforts in developing countries continues to present a challenge for future projects and practitioners because of an inability to learn from past failures and successes. Thorough and accessible reporting, even if unpublished, is necessary for remediation projects to improve in the future, both in technical feasibility and stakeholder participation. Finally, this lack of documentation presents uncertainty in evaluating the effectiveness of remediation efforts.

Drawing from other development fields, stakeholder participation can begin with an initial “community appraisal” that asks a series of questions to identify sociocultural, technical, economic, political, environmental, institutional, and educational factors within a local community (Amadei 2014). These efforts can be complemented with stakeholder analysis to ensure all impacted stakeholders are identified and engaged early in the remediation process. After an initial community appraisal is completed, individuals leading a remediation project can select appropriate engagement strategies to enlist local community members and other stakeholders within the project, ensuring the empowerment of different stakeholder groups to make decisions and contribute to the remediation project for its entire duration (Reed 2008). We further recommend that future work explores a framework for incorporating diverse stakeholder engagement and participation within remediation projects. This framework can expand upon the criteria developed by Reed (2008) for effective stakeholder participation and apply it towards remediation. These criteria, used in this study to analyze remediation projects, include the engagement and acknowledgement of a diverse range of stakeholders, skilled facilitation of stakeholders, early engagement of stakeholders at the beginning of a remediation project, and continuous participation of stakeholders throughout remediation. Especially for projects utilizing institutional controls or operating in an area with informal livelihoods, remediation projects must employ strategic, informed stakeholder participation efforts to reveal context dependent solutions that ensure the health, well-being, and development of communities in developing countries.

CHAPTER 4

INTEGRATING SCIENTIFIC AND LOCAL KNOWLEDGE THROUGH COMMUNITY-INFORMED CONCEPTUAL SITE MODELS

Modified from a manuscript in preparation for publication in *Science of the Total Environment*

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4.1 Introduction

Scientists and engineers rely on vast amounts of quantitative information to guide the clean-up of a contaminated site. One tool commonly employed to guide decision-making around the complex interaction of these data sets is a conceptual site model (CSM). A CSM is a versatile, iterative representation of the known and hypothesized information at a site. Early iterations of a CSM are very conceptual and help project teams identify significant data gaps and define project objectives (US EPA 2011). As a project progresses, they evolve to incorporate new data, demonstrate the application of remedial solutions, and lead operation and monitoring activities. Conceptual site models can come in many forms, from graphical or pictorial representations (Ouni and Brusseau 2016; Palumbo-Roe, Banks, and Fleming 2011) to descriptive narratives (Jakubick and Kahnt 2002). Recently, some innovation has occurred within the development and use of CSMs. For example, they have been developed to assess end-use sustainability at contaminated sites (Bardos and Menger 2013; Holland et al. 2011; Li et al. 2019). They have also been used as a key communication tool in facilitating dialogue between

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stakeholder groups (Clark et al. 2007; Schultz 2001; US EPA 2011). Regardless of format, CSMs evolve to represent the comprehensive state of a contaminated site and ensure that the project progresses in accordance with project objectives.

When CSMs are used for collaborative decision-making between stakeholders and project teams, several challenges may arise. Currently, CSMs are almost exclusively created by the examination and use of technical, quantitative data, despite acknowledgement by the United States Environmental Protection Agency (US EPA) that stakeholder interviews can inform the development of early iterations of a CSM (US EPA 2011). As a tool for early stakeholder communication, this is problematic when stakeholders view information and their environment differently from technical experts. Some stakeholders do not find purely quantitative information transparent or reliable (Rizzo et al. 2016). Others may be unable to understand technical information at the level of technical experts (Bardos et al. 2018). Local expertise is also challenging to interpret by technical experts, particularly when it is tied to rich cultural traditions and heritage (Fazey et al. 2013). People tend to overvalue or strengthen forms of knowledge that resonate the most to them individually. When scientists and engineers are in positions of power to make decisions, as they are in remediation projects, they tend to favor scientific, quantitative knowledge – thereby negating or suppressing social knowledge (Raymond et al. 2010). Currently, local knowledge is not used in the creation of a CSM, and local knowledge is often excluded entirely over the course of a remediation project (Booth 2015).

Local community members are often enlisted only 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). This kind of decision-making typically occurs mid-way through the project, when remedial solutions are being determined. Limiting community decision-making in this way inhibits their contribution early in the project and excludes any knowledge they could contribute to ongoing project activities, such as gathering initial site data, creating project objectives, or defining locations for environmental sampling. 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.

Ideally, stakeholders are engaged throughout a project life cycle to enhance the viability and sustainability of implemented solutions (Bardos et al. 2018; Cappuyns 2016; HM Treasury 2018; O'Brien et al. 2020; Reed 2008). True stakeholder engagement is a long-term strategic process of building rapport, obtaining feedback, and collaboration between project practitioners and stakeholders, often utilizing a variety of methods. Prior to successful stakeholder engagement, projects must be able to identify stakeholders and elicit their initial input. Practitioners in the field of remediation struggle with these first steps in pursuing long-term stakeholder engagement because initial stakeholder analysis is often completed in an *ad hoc* manner (Norrman et al. 2020; Booth 2015; Reed et al. 2009).

Qualitative and quantitative methods from the social sciences offer ways to enhance the identification of stakeholders and provide detailed information about local culture, context, and other social factors that may influence remediation projects (Harclerode et al. 2015; Jick 1979). These methods can provide information about stakeholders' risk perceptions (Harclerode, Lal, et al. 2016) as well as offer flexible options for engaging stakeholders through an application of different methods. Application of only one method requires all stakeholders to convey their knowledge in a certain way, which ignores the reality of competing time constraints and power hierarchies that favor some stakeholders over others. Therefore, it is imperative that remediation projects adapt early methods of receiving stakeholder input to fit the needs of the local community. Yet, the use of social science methods by non-social scientists may appear a daunting and complex task as engineers and scientists receive little direction to apply these methods. Socio-technical processes that promote re-evaluation of local and scientific knowledge throughout a project life-cycle offer the greatest opportunities for effectively integrating social and technical forms of knowledge into remediation (Raymond et al. 2010).

Because CSMs are an evolving tool used in decision-making between stakeholders and remediation practitioners, we argue that CSMs can be this vehicle for integrating local knowledge into traditional remediation processes. Focused on the preliminary site assessment stage of remediation, we propose a framework for creating a community-informed conceptual site model that links data from social science methods to limited technical information. This provides a socio-technical perspective of contamination to guide project objectives and early project decision-making. We apply this framework to an artisanal and small-scale gold mining community context. Specifically, the paper describes the iteration of three community-informed conceptual site models for mercury-contaminated sites in the rural municipality of Andes, Colombia. We argue that conceptual site models can illustrate local knowledge and alter the frame-of-reference for contamination, leading to early decision-making by community members and more inclusive remediation efforts.

4.2 Framework for Community-Informed Conceptual Site Models

A socio-technical framework is proposed for integrating stakeholder knowledge into early remediation project activities via a CSM (Figure 4.1 on page 48). A remediation project starts with evidence that a contaminant has been released to the environment. This evidence could range from information on historical practices to distressed vegetation to water with taste and odor problems to direct observation of the contaminant in the environment. Remediation practitioners then undertake an initial site assessment (or remedial investigation) where they analyze existing data about a site. This may include documentation about the site history, reports or studies from other agencies about the area, a limited sampling plan, and aerial imagery (ASTM 2014; ITRC 2011; Payne, Quinnan, and Potter 2008; US EPA 2011). The preliminary CSM resulting from this data analysis serves as the foundation for defining project objectives. Therefore, this initial data inquiry stage offers a prime opportunity for initiating contact with local stakeholders.

Early iterations of 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. Early identification of and contact with stakeholders is therefore necessary for the development of project objectives that meet the needs of local communities, further emphasizing the importance of early stakeholder analysis at the beginning of a project. Early stakeholder integration allows for practitioners to receive feedback along the project life cycle, ensuring the initial project objectives are met.

As a remediation project progresses and more technical data are integrated into the CSM, the knowledge base will shift from a heavy reliance on local knowledge to a reliance on quantitative data enriched by stakeholder feedback. Conceptual site models can be revised to reflect this feedback and continually used as a mechanism for fostering dialogue between stakeholders and practitioners.

In industrialized nations, environmental laws and regulations drive the initiation of a remediation project and determine what mechanisms will be used to remediate contamination. For example, when the US EPA initially assesses a site, the agency determines whether the

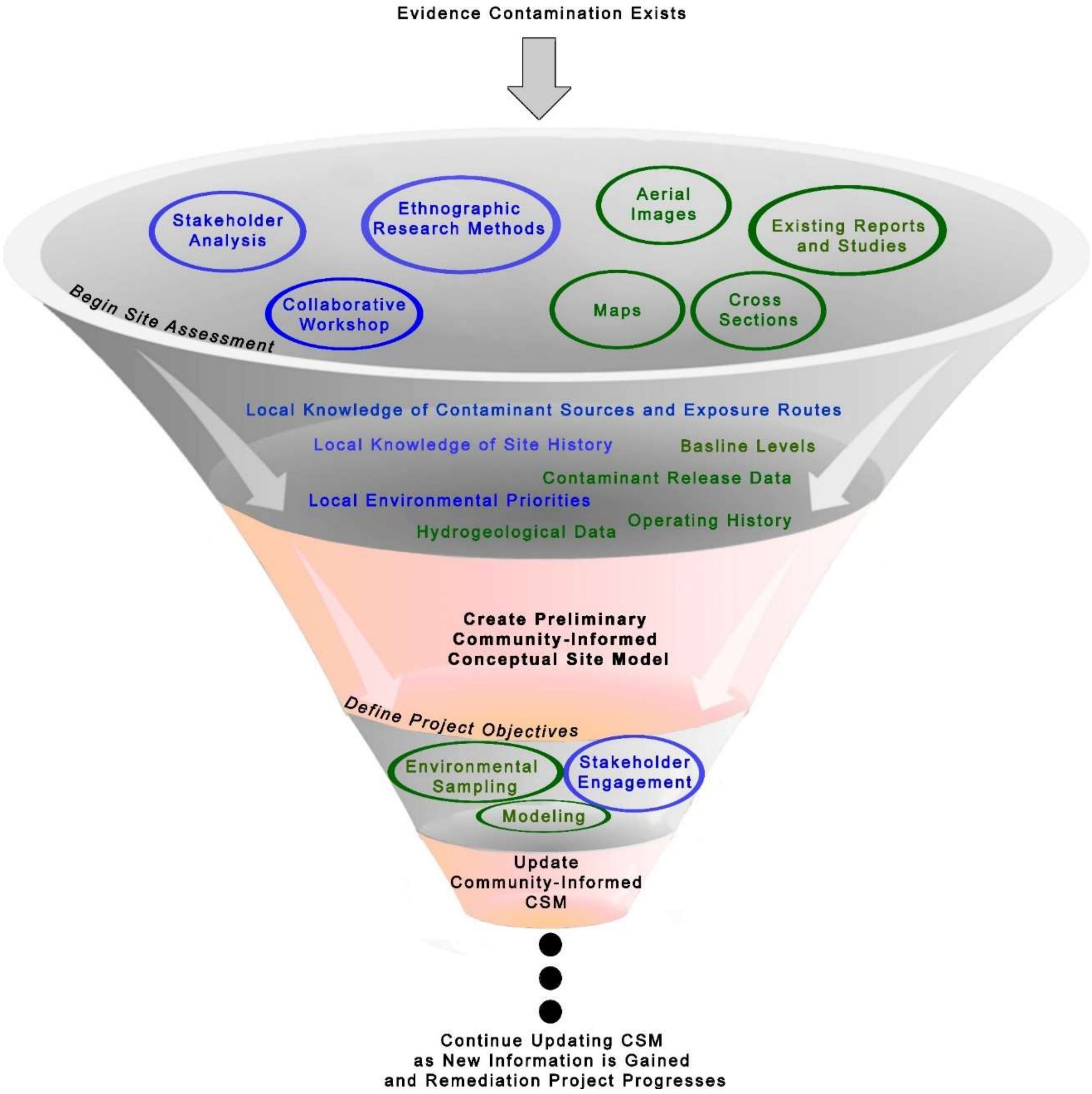


Figure 4.1 Adapted framework for creating community-informed conceptual site models (CSMs) using a blend of social and technical knowledge. Social data and information are shown in blue. Technical data and information are shown in green. Pink highlights denote when a CSM may be updated, although this framework can be adapted to specific projects and may have more iterations during planning phases. Although not explicitly shown in the figure, regulations are consulted throughout the initial stages of a remediation project.

extent of contamination is cause for placing the site on the National Priorities List (NPL), motivated through an analysis of whether or not the site requires a response under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Only sites on the NPL qualify to receive funding from the Superfund Trust Fund to remediate contaminated areas (US EPA 1991). Sites not listed on the NPL must receive funding through other mechanisms. In many developing countries, though, this 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 through strong community support and local government collaboration that seeks to improve human health (discussed in greater detail in Chapter 3). Due to the regulatory differences from country to country, the framework does not specifically address the role of regulations.

4.3 ASGM Case Study in Andes, Colombia

This case study synthesizes findings from fieldwork undertaken in the municipality of Andes, located in the southwestern part of the Department of Antioquia, Colombia in June – August 2020. An artisanal and small-scale gold mining (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, Angeloci-Santos, and Meech 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). Although raw ingenuity and entrepreneurship exist within ASGM communities, policies and projects aimed at intervening in the sector have largely failed to account for the contextual factors that offer opportunities for improving livelihoods at the community level (Hilson, Hilson, and Maconachie 2018).

Second, there has been an academic and sustainable development focus on ASGM, in large part due to the fact that the sector represents the largest source of anthropogenic mercury pollution in the world (Cordy et al. 2011; Esdaile and Chalker 2018). Specifically, Colombia's 2018 law banning mercury in mining activities places the contaminant at the forefront of the Colombian government's priorities as compared to other contaminants (Paz Cardona 2018). Recognizing this global emphasis, the case study focuses on evolving CSM development 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 in the early stages of a project (Norrman et al. 2020).

4.3.1 Pre-Fieldwork CSM Development

A pre-fieldwork CSM was created to reflect initial knowledge about mercury contamination in Andes. Because the researchers had never visited the community before and little is written about Andes in published literature, the CSM neglects contextual information. Instead, this CSM reflects general knowledge about mercury transport and contamination more broadly in Colombian ASGM communities (e.g. Cordy et al. 2011; 2015; Echavarria 2014; García et al. 2015; Veiga and Marshall 2019; Veiga, Angeloci-Santos, and Meech 2014; M. M. Veiga et al. 2018). Apart from a single technical report from about the local geology in Andes (Servicio Geologico Colombiano 2017), there is little evidence that mercury contamination was considered a hazard in the area. Historically, miners use mercury during whole-ore amalgamation. In this process, miners add mercury directly to small ball mills without pre-concentrating the ore, commonly resulting in mercury losses to the environment through 1) direct deposition (i.e., spills), 2) tailings piles (Cordy et al. 2011; Gibb and O'Leary 2014), or 3) to the air during the burning of mercury amalgams (Figure 4.2). Knowing this CSM lacked local context, we initially thought its creation may be useful for educational purposes about the risks and contamination routes of whole-ore amalgamation by mercury for miners in Andes.

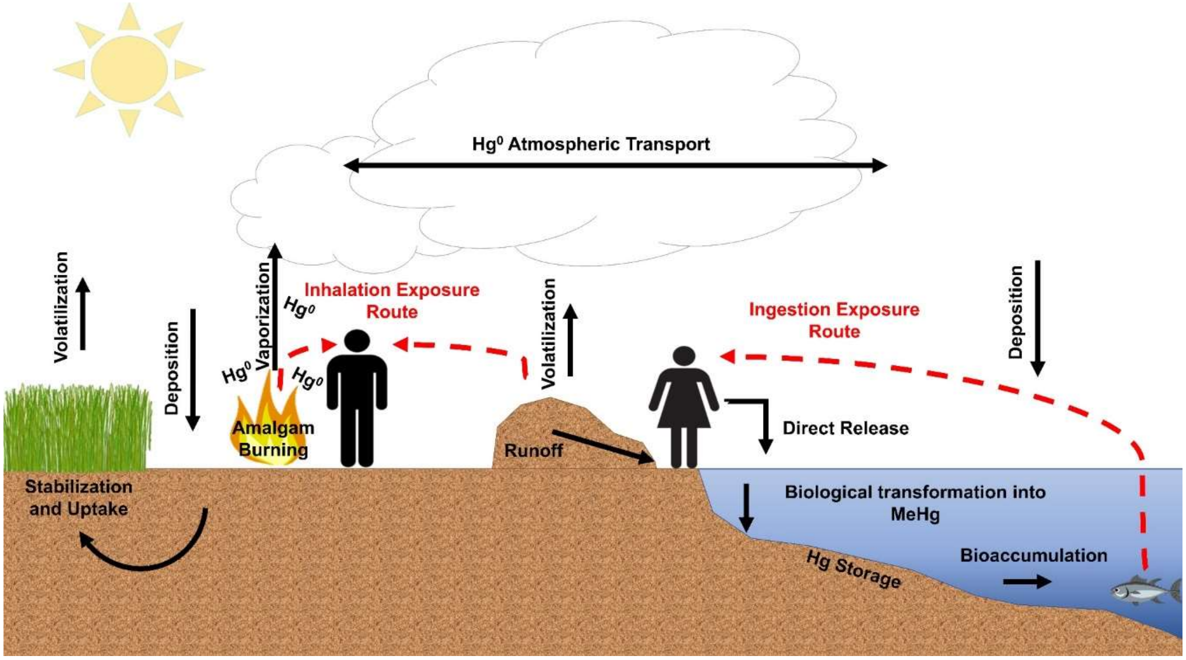


Figure 4.2 Pre-fieldwork conceptual site model made from extensive literature review of mercury contamination in ASGM communities, with a specific focus on Colombia. Because few resources were available describing Andes at the time of this CSM's creation, no contextual knowledge is presented in this CSM.

4.4 Case Study Field Methods

Interviews and surveys were carried out with miners, coffee and plantain farmers, trout farmers, and representatives from the local government and environmental regulatory agency. Following methodological approaches used in anthropology (Bernard 2006), we utilized informal, unstructured interviews, semi-structured interviews, and a structured, face-to-face survey. All interviews were conducted by a fluent Spanish speaker and often took place over several hours or days at a field location. Handwritten notes were taken during interviews and transcribed as soon as possible following the conclusion of the interview. Only a few of the interviews were audio recorded when individuals gave their consent. Participant observation was also conducted throughout the duration of the research to become acquainted with the lifestyles of both miners and coffee farmers and expand upon the contextual understanding of the municipality.

4.4.1 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). The unstructured interviews for this research took place at coffee farms, ASGM mine entrances (*bocaminas)*, and ASGM processing plants (*entables)* and often included a tour of the site. This allowed the conversation to naturally turn towards topics related to the environment and natural landscape. 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.

4.4.2 Semi-Structured Interviews

After two weeks of unstructured interviews in Andes, the initial interview guide created prior to fieldwork was amended to reflect the latest contextual knowledge of the researchers and address specific knowledge gaps about mercury contamination. Additionally, separate interview guides were created for interviewing coffee farmers and local government employees. Throughout the duration of fieldwork, the interview guide was amended based on new information and additional knowledge gaps that needed to be filled. The researchers memorized each interview guide to ensure a natural and fluid interview.

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 Corantioquia, the local, departmental-level, environmental regulatory agency. Overall, five interviews were conducted with women and thirteen were with men.

4.4.3 Structured Survey Development

The structured survey was developed after approximately six weeks of unstructured and structured interviewing and participant observation in Andes. From semi-structured interviews, we curated a list of environmental issues from community members, ranging from improper disposal of coffee pulp to the use of mercury in gold ore processing. A total of 12 anthropogenic and natural events were listed in the final survey, as well as questions about a respondent's sector of work, education level, and gender. The final structured survey is found in Appendix A (in English) and Appendix B (in Spanish). Full survey results are attached as a supplemental file to this thesis. The codebook to interpret the raw data is provided in Appendix C.

Because our survey was intended to target the working population in agriculture and artisanal mining in Andes, we ensured the whole survey took less than 20 minutes and could be completed face-to-face as these individuals walked to work. Therefore, we limited the number of questions on the survey, including the demographic variables. This ensured the researchers were respectful of the respondent's time. Additionally, by creating a survey based on information gathered through interviews and participant observation, the questions on it were acknowledged as representing immediate threats to the community. We vetted the survey through several key contacts in Andes prior to implementing it with trained undergraduate research assistants from Colombia.

Our analysis of the survey data departs from traditional survey assessment in risk perception. Instead of trying to identify predictors or causal explanations for risk perception, we simply wanted to create a ranking of hazards to understand how mercury contamination compared to other environmental issues in the region. Additionally, we wanted to analyze if the groupings of individuals (by sector of work, education level, and gender) resulted in differences in the ranking of these hazards. For these reasons, we utilized numerical rating scales to quantify the environmental hazards (see the example question in Table 4.1). A thorough explanation for determining the sample size of the survey and the statistical methods used to analyze the survey are provided in Appendix D.

Table 4.1 Example of a numerical rating scale question on a topic related to the Andes survey

Numerical rating scale How hazardous do you think the existence of mine tailings are for the environment?				
Not hazardous – 1	2	3	4	5 – Extremely hazardous

As explained in Appendix D, statistically analyzing the survey results required the use of non-parametric statistics suitable for nonexperimental designs, which reflect the nature of the survey and the use of numerical rating scales. The results were interpreted using the Kruskal-Wallis test in MATLAB (Bedoya-Marrugo et al. 2017; MATLAB 2020b), a common software package used in civil engineering. Sample MATLAB code for interpreting the results is provided in Appendix E.

4.5 Miner-Informed CSM

The first iteration of a preliminary CSM focuses on unstructured and semi-structured interviewing at gold ore processing plants, known as *entables*. *Entables* were historically the central locations for mercury use and, potentially, mercury contamination. The miner-informed CSM is depicted by an illustration (Figure 4.3) that shows the three core components (i.e., source, transport, and fate of contamination (Digges La Touche, Culshaw, and Lansley 2011)) of a traditional conceptual site model, but from the perspective of *entable* workers.

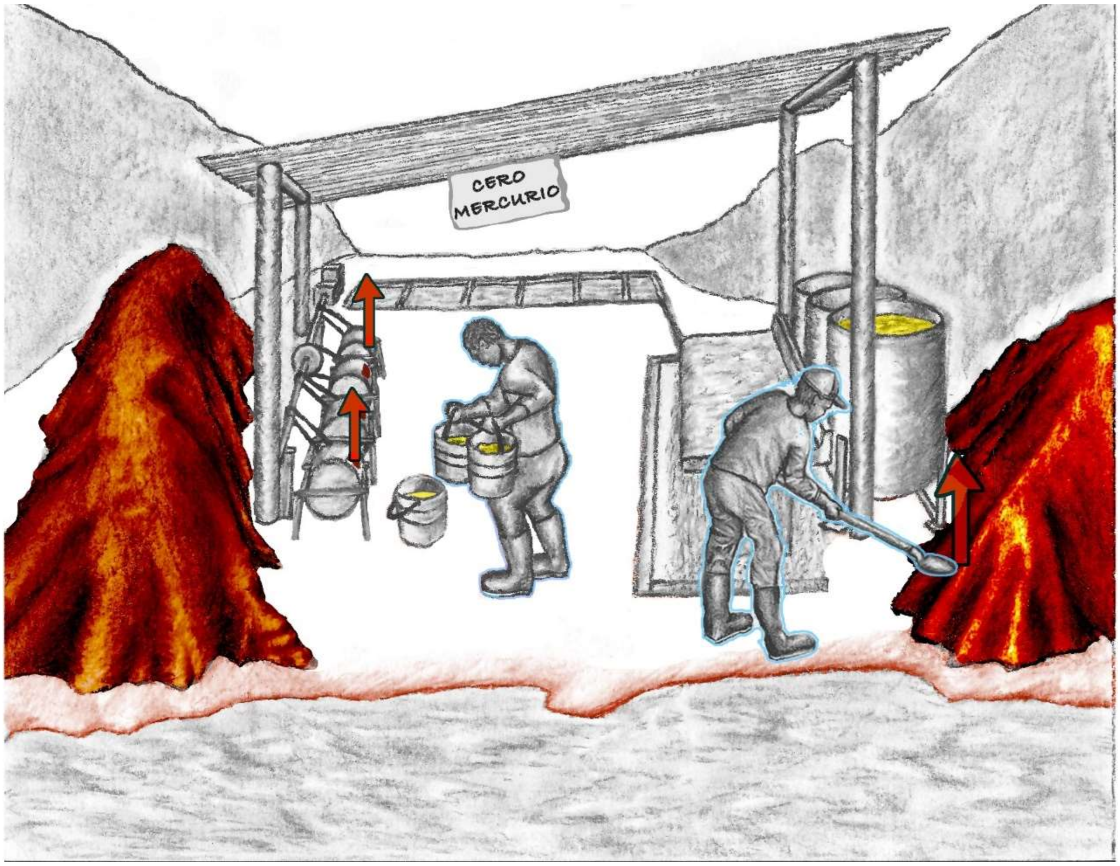


Figure 4.3 The miner-informed CSM depicts occupational exposure concerns of local miners at gold ore processing facilities. Red denotes areas potentially contaminated with mercury: old tailings piles, surrounding soils, and ball mills. Yellow represents other substances onsite, including cyanide and “acids” (miners used the term acid to signify a range of other compounds, including sodium hydroxide, that aid the cyanidation process). The 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.

4.5.1 Site History and Occupational Exposure

Several years ago, the University of Antioquia began an interdisciplinary intervention to address mercury-related problems in the Andes' artisanal mining sector through a variety of projects. One key project was the implementation of technical assistance to switch miners to mineral processing using cyanide, which does not use mercury. Since the intervention from the University of Antioquia, Andes has been touted as the municipality with "*cero mercurio*" (zero mercury) (Carrasquilla 2019). While the phrasing itself simply suggests a movement away from mercury amalgamation, many miners adopt it to identify themselves as the antithesis of artisanal mining in Colombia. Presented as an illustrated banner (Figure 4.3), whenever we asked about mercury use in the municipality, miners responded that mercury is no longer utilized, the region is "*cero mercurio*," and "cyanidation creates less contamination than mercury." As shown by the large yellow tanks and smaller buckets (Figure 4.3), hazardous substances like cyanide and other acids are present at the site. During our semi-structured interviews, only one *entable* manager identified cyanide as a possible contaminant or hazard for human health. He addressed his concerns by restricting access to the cyanidation process. At other *entables*, miners did not seem concerned about any health impacts from cyanide and dismissed concerns about environmental contamination from improper cyanide use. Compared to mercury use or the safety conditions within the actual mines, cyanide use was largely perceived as a safe substance.

Equipped with knowledge about the risks of mercury use, miners emphasized occupational exposure risks from working at the *entable.* Some miners expressed mild concern over lingering mercury vapors in the small ball mills, known as *cocos.* More *entable* managers, however, identified old tailings (represented in Figure 4.3 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. *Entable* managers pinpointed 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.

A reoccurring concern was the variable proximity of *entables* to river networks. Some backed up to rivers, where 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 contaminating the river. One *entable* owner discussed his reasoning: "I am not worried [about contamination] because there are five terraces and 45 meters between the plant and the river." Yet, when discussing the transition to cyanidation from whole ore amalgamation by mercury, he noted the impacts to water bodies, but re-emphasized occupational risks from inhalation. He stated that the transition to cyanidation was "easy. It was easy to change because there are impacts to the water. Mercury is a contaminant. It's also better for breathing." All the interviewees recognized the risk of exposure due to inhalation, citing this as a primary reason for switching to cyanidation. Yet, there seemed to be more concern about inhalation exposure than water contamination. Dermal exposure was not a concern.

4.5.2 Influence of *Entable* Managers and Regulatory Agencies

Implementation of a remediation project would require the adoption by local community members and, specifically, *entable* owners and managers. As seen in other risk perception studies, continuity of management in reducing risky behavior supports safe behavior in employees (Rundmo 1996). During our early observations at *entables*, *entable* employees followed the behavior and adopted practices supported by the owners and managers. For example, one *entable* manager used signage to communicate safety risks with employees. Workers at this *entable* largely complied with the requests to wear hearing protection and stay out of restricted areas due to the manager’s concerns about the toxicity of cyanide exposure. 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 supported safe mining practices. Several miners described Corantioquia as “attentive” and “vigilant.” Their continued presence at and around ASGM sites in Andes supported the abandonment of whole ore amalgamation by mercury, but also challenged some miners to reuse mine tailings or pursue remediation endeavors of the tailings. One *entable* manager stated: “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 agencies in Andes.

4.5.3 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 and largely excluded potential transport and exposure of other community members. These initial conversations therefore do not reflect the views of the broader community in Andes well. They did, however, provide an entry point for engagement with community members and allowed for the initial identification of other stakeholders by observing the day-to-day activities at 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, and further engagement with ASGM.

4.6 *Corregimiento*-Informed Preliminary CSM

Expanding engagement to include community members beyond ASGM identified a need to more fully understand potential water contamination from mercury use. Local individuals acknowledged the importance of local topography in contaminant transport, although initially mercury was not discussed as a primary contaminant in the region. The *corregimiento*-informed preliminary CSM (Figure 4.4 on page 64) 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,* or rural neighborhoods, follow a river or stream out of the center of a *corregimiento*. Women and children live and work adjacent to stream banks, across and downstream from mining areas (Figure 4.4 on page 64). The dominant livelihood in Andes is the production of Arabica coffee (Zapata Restrepo and Mejia Aramburo 2019; Salazar A. 2014). ASGM in Andes is the second-most predominant livelihood for two *corregimientos*: Santa Rita and Santa Inés (Zapata Restrepo and Mejia Aramburo 2019). Operating and abandoned mines are scattered throughout the mountains. Ore is transported, typically by mule, from the mines to one of the 11 *entables* in the entire municipality for processing. The individuals working at the mines are not necessarily the same individuals employed at *entables*. *Chatarreras*, women responsible for sorting through waste rock and processing 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.

4.6.1 Mapping Stakeholders

An influence-interest matrix (Figure 4.4 on page 64) was developed to organize stakeholders impacted by or able to impact mercury contamination in Andes. The diagram lists more stakeholders than are illustrated. The CSM is represented in this way because the physical proximity to *entables* increases the risk of exposure to mercury contamination (Diringer et al. 2015). Because mining is localized to several *veredas* (rural neighborhoods) 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.

4.6.2 Influence of Mixed Livelihoods

One factor seemingly impacting both the risk perceptions of mercury contamination and behaviors toward mercury use is the competing existence of coffee production and ASGM in Andes. There is a distinction between a broader collection of stakeholders and those physically located near mining areas. Coffee farmers, known as *cafeteros*, adjacent to mining operations perceived ASGM more negatively compared to 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 the miners did. During interviews, *cafeteros* expanded on this by noting the disruption of the natural forest due to the mines, dangers of working inside the 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* reported feeling sick after consuming catfish that came from rivers in mining areas. Miners also 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.

4.6.3 Place-Identity Driving Environmental Behavior

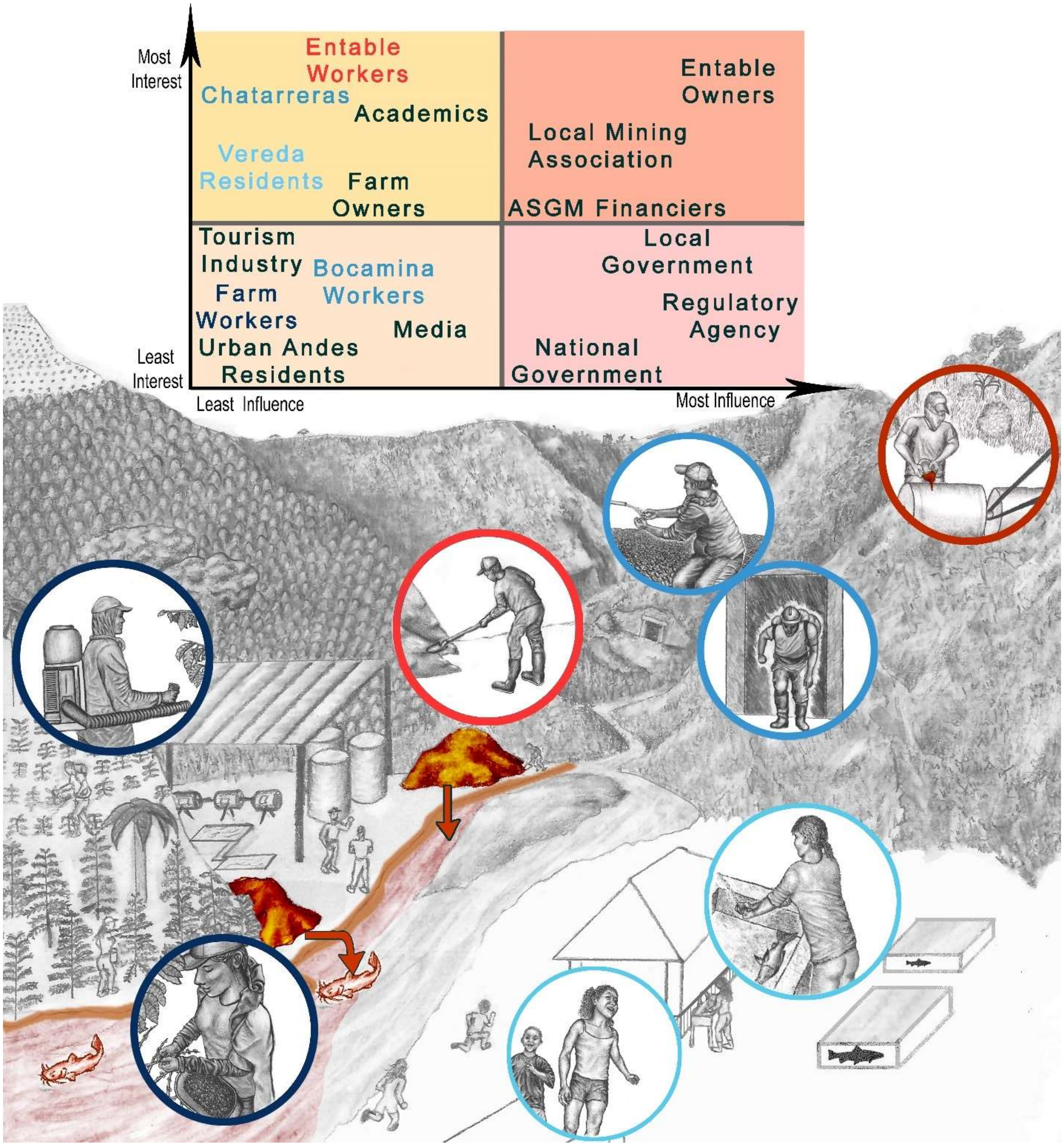
By expanding engagement to a diverse range of stakeholders, this research suggests that a strong "sense of place" or place-identity impacts environmental behaviors from both the agricultural and ASGM sectors. A remediation project could leverage place-identity to bring consensus among varying stakeholder groups. The distinction the Andes miners draw between themselves and other ASGM regions with regards to mercury use is a key attribute of place-identity (Wester-Herber 2004). This fed miners' ambitions to protect the environment and discontinue mercury use. 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 popular stigma of the ASGM sector as being "dirty" to show they are worthy of formalization and operating sustainably. This miner further confided with disdain that individuals at "secret" gold processing facilities hidden in the dense forest of the mountains continue to process gold via whole ore amalgamation by mercury. Other miners interviewed later echoed the reality that whole ore amalgamation by mercury exists, albeit covertly. The facilities are represented in the bubble on the right side of the diagram in red (Figure 4.4 on page 64).

For some miners, the choice to live in Andes supported pro-environmental behavior. Of the *entable* owners we interviewed, most had migrated to Andes from other ASGM regions in Colombia (e.g., Buriticá, Segovia, Chocó). This choice to live and work in Andes resulted in a perceived responsibility to pursue sustainable operations. One miner described his efforts to reuse mine tailings as a reflection of progressive environmentalism: “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. The environmental proactiveness of miners in Andes support 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.

4.6.4 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 coffee farmers perceived the by-products from agricultural activities as the most severe impact to local water sources. Others viewed ASGM as the 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. For this case study, the research suggests these individuals live and work within *corregimientos* that contain mining. Dissemination of notices or participation via community-wide resources may be ineffective because the priorities in protecting the environment vary based on the proximity to mining locations.

Figure 4.4: This evolution on the CSM illustrates 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 covert processors, shown in red due to their direct contact with mercury. A stakeholder rainbow diagram for mercury contamination in the municipality of Andes provides a comparison of methods for organizing stakeholder groups. In the rainbow diagram, stakeholders are sorted into two criteria. First, stakeholders impacted the most are listed in the inner circle, with decreasing level of impact on outer circles. Second, stakeholders are sorted left to right depending on whether they have the power to affect the situation or are affected by mercury contamination.


Most Interest
Least Interest
Least Influence
Most Influence
Entable Workers
Chatarreras
Academics
Vereda Residents
Farm Owners
Entable Owners
Local Mining Association
ASGM Financiers
Tourism Industry
Bocamina Workers
Farm Workers
Media
Urban Andes Residents
Local Government
Regulatory Agency
National Government

Additionally, the creation of the *corregimiento*-informed preliminary CSM granted the researchers wide access to ASGM sites and farms. 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. These individuals lie on the "impacted" quadrants of the matrix, indicating a lack of power that marginalizes their voices. Yet, these individuals 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 and interest in local environmental issues.

4.7 Stakeholder Group CSM

The stakeholder group CSM presents several varying models based on the groupings of survey respondents. An ungrouped CSM (Figure 4.5 on page 68) 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 (Figure 4.5 on page 68). These perspectives on 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 the 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.

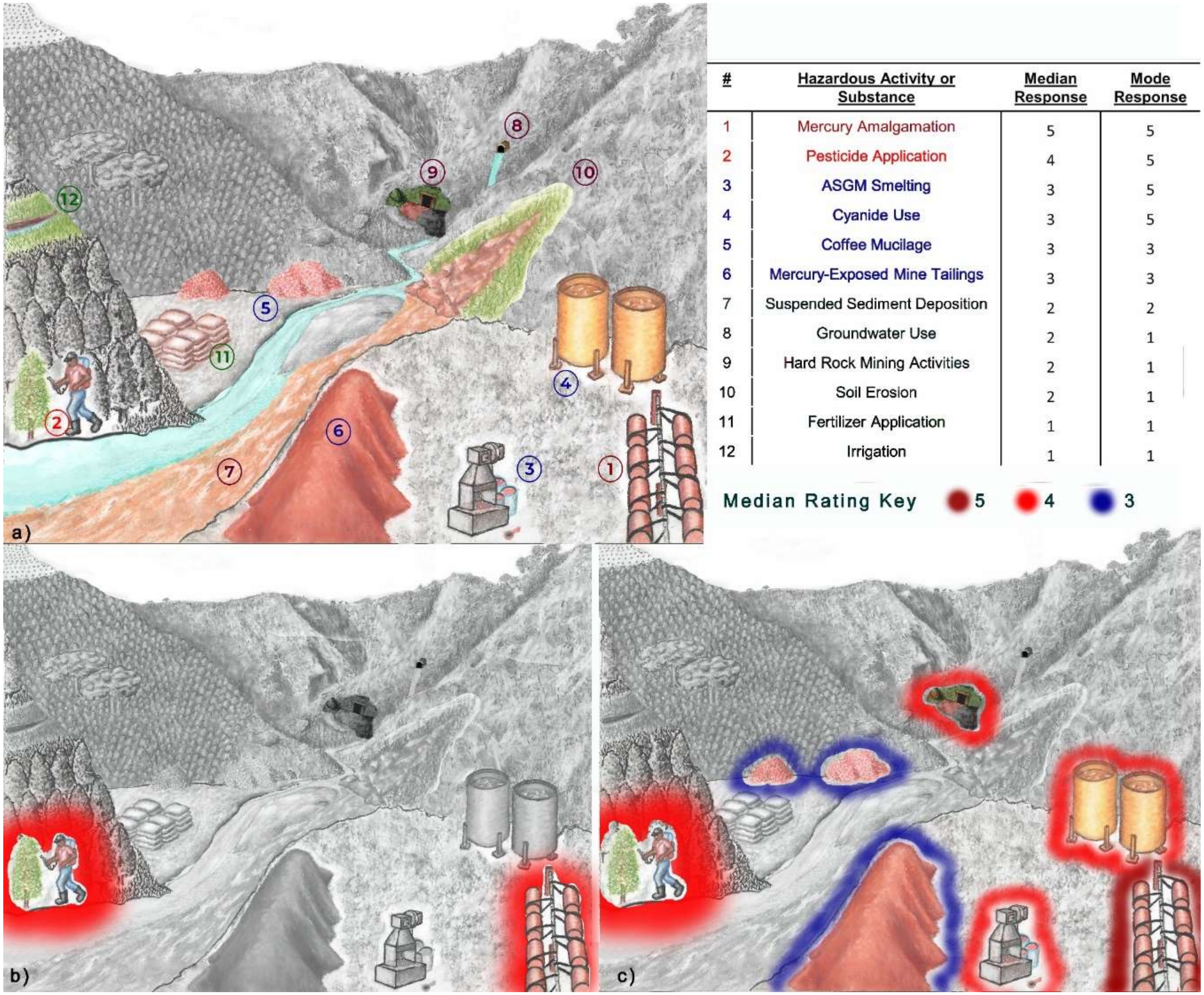
Disparities exist between site owners and employees. Although tailings were cited by managers as the primary source of contamination, the survey results suggest that other occupational exposures are perceived as greater risks, especially smelting activities. Additionally, individuals who worked in agriculture (compared to individuals in mining) consistently rated mining activities higher than other impacts (Figure 4.5 on page 68).

4.7.1 Significant Data Gaps and Defining Project Objectives

The divergence in knowledge represented across the iterative CSMs, and most notably recognized in the community-informed baseline CSM, highlights the areas where quantitative data are essential for implementation of remedial activities. The migration of mercury from tailings piles into the environment and primary surface water bodies, a complex issue, 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 smelting activities 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 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 modeling development of mercury contamination.

Figure 4.5 (next page): These variations on the third conceptual site model, created from structured survey data, show the relative level of risk of contaminants as compared to other environmental issues in Andes. The three CSMs in this image show the overall CSM without grouping analysis (a), the perspective of individuals who work in mining (b) and the individuals who work in agriculture (c). a) This CSM presents the overall median ratings (from 1-5), with 1 having the highest median rating (5) and 12 having the median rating (1), representing the most hazardous and least hazardous activities for the environment, respectively. b) This CSM presents the median ratings of 3 or above for individuals whose primary sector of work is mining. Only pesticide application and mercury amalgamation, had a high enough rating to be illustrated on the CSM. c) This CSM presents 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. Pesticide application, hard rock mining, cyanidation, and smelting all had ratings of 4. Mercury amalgamation had a median rating of 5.



#	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

Median Rating Key ● 5 ● 4 ● 3

4.8 Conclusion

Communities located near contaminated sites and remediation projects are plagued by stigmas and projects that only incorporate strict quantitative data collection to make decisions. Rather, local communities near contaminated areas may have valuable information to contribute to project activities, especially during early planning stages of remediation projects. This research aimed to provide a mechanism for blending social and technical forms of knowledge at the onset of remediation projects. 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 alongside data collection and analysis of quantitative information, the evolution of early CSMs provides remediation practitioners with a more comprehensive model with which to engage stakeholders and collectively decide project objectives.

We applied this framework to a Colombian artisanal and small-scale gold mining 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 social science methods. Although similarities can be found within the local communities, local knowledge and opinion on ASGM risks varied when stakeholders were viewed through different lenses. Site managers perceive different risks than their workers, although managers have a strong ability to influence operating conditions and limit occupational exposures. Grouping stakeholders by sector of work also altered the CSMs, with individuals in agriculture perceiving greater hazards than other respondents. Local community members in Andes described some aspects of mercury transport, expressed concern and knowledge over the risks of mercury contamination, and pinpointed locations they felt required scientific analysis. Taken together, these perspectives of CSMs provide a holistic depiction of Andes that can aid future remedial efforts.

Future work might explore how initial site assessments may be altered by utilizing stakeholder knowledge at the onset of a remediation project or analyze how stakeholders collaborate with remediation practitioners through different CSMs. Additionally, we hope that remediation practitioners adapt these methods to fit the specific context of their remediation projects. 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.

CHAPTER 5

COMMUNITY-INFORMED CONCEPTUAL SITE MODELS TO AUGMENT EXISTING REMEDIATION COURSE CURRICULUM

5.1 Introduction

Current techniques in undergraduate site remediation and fate and transport courses offer multiple opportunities for innovation to adequately prepare students to work in remediation. Specifically, students must know how to “address the social and cultural links between environmental quality and economic vitality” in remedial solutions (Tansel 2008, 201). This interdisciplinary approach to engineering problems, known as socio-technical thinking, in the engineering disciplines is important for ensuring long-term sustainability of applied solutions. The ability to effectively communicate with a broad range of stakeholders is especially important in projects where the central focus is to improve community life or a user’s needs (Dym et al. 2005). As the core purpose of remediation is to reduce human exposure to contamination, remediation practitioners need to know how to collaborate and involve local community members into existing project methods (US EPA 2015). Therefore, engineering education needs to prepare its students for solving complex engineering problems, which includes understanding how community engagement and input can benefit remediation projects.

Within engineering education, socio-technical skills have largely been enhanced through an implementation of extra-curricular activities, courses, seminars, and degree paths dedicated to social and economic dimensions of engineering. This is evidenced by the expansion of humanitarian engineering, engineering ethics, and other similar programs within higher education (Gilbert et al. 2015). In a study of several engineering institutions across the United

States, Lattuca et al. (2017) found a strong relationship between a professor's belief in fostering interdisciplinary skills in the classroom and the self-efficacy of students in possessing interdisciplinary skills. Additionally, professors who believe in the importance of interdisciplinary skills tend to incorporate it more into their classroom (Lattuca, Knight, and Brown 2014). These studies support the integration of interdisciplinary skills (such as those required to foster socio-technical thinking) into traditional classrooms, as opposed to solely providing these skills in separate classes or extra-curricular opportunities. Yet, engineering educators do not have the experience or training necessary to teach interdisciplinary skills, especially when those skills are related to community engagement, social justice, or the social sciences (Wolcott et al. 2011; Gilbert et al. 2015).

Little to no research has been performed on site remediation courses, specifically. Yet, their reliance on case-based learning offers opportunities for incorporating socio-technical thinking directly into the course. Site remediation courses have traditionally utilized case studies as a core to their teaching method. Case studies can demonstrate the interdisciplinary, complex nature of remediation projects and encourage students to consider decision-making dilemmas that come from these projects (Leal Filho and Nesbit 2016; R.L. Miller and Olds 1995). Incorporating social and cultural elements into case-study learning therefore offers students the ability to consider stakeholders and their knowledge in a real-world application, instead of a simulated or forced scenario. In essence, site remediation course material can be augmented through case-based learning to promote socio-technical thinking in undergraduate engineering students.

Conceptual site model development is also a component of remediation course material (e.g. Payne, Quinnan, and Potter 2008; Dunnivant and Anders 2019). Therefore, a combination of case-based learning and community-informed conceptual site models may provide an avenue for adapting current course material to encourage socio-technical thinking in students. This work provides a series of learning outcomes and assessment techniques for engineering educators.

5.1.1 Curricula Promoting Socio-Technical Thinking

Several particular challenges face educators in creating curricula that helps engineering students adopt socio-technical thinking (Harsh et al. 2017). A common issue is access to and synthesis of community input. Remediation projects often incorporate anecdotal information regarding local culture and context. Students struggle with understanding how anecdotal information can be interpreted and used in engineering projects that traditionally rely on more quantitative information (Hariharan et al. 2015). Additionally, much literature in stakeholder engagement is filled with jargon, which forces students to focus on defining terms and understanding previous literature instead of finding practical applications of stakeholder engagement to their respective fields (Harsh et al. 2017). Finally, course curricula need to address common struggles students face in stakeholder engagement; namely, how differences in culture and context can be interpreted in a project and how to deal with conflicting needs of different stakeholders (Hariharan et al. 2015).

Curricula from humanitarian engineering offer multiple lessons for site remediation courses to consider. Socio-technical thinking can be considered under three broad categories: technology, people, and broader context (Mazzurco and Daniel 2020). Within these three domains, students have tended to neglect long-term technical considerations, collaboration and co-design processes with local communities, ethical considerations, and laws (Mazzurco and Daniel 2020). Conversely, students have expressed strong skills related to early project development, such as problem definition, brainstorming, prototyping, and client communication

(Oehlberg and Agogino 2011; Miller and Olds 1994; Daniel and Mazzurco 2019; Mazzurco and Daniel 2020). Humanitarian engineering courses often use active learning environments to promote socio-technical thinking and other interdisciplinary skills (DeTurris 2012; Miller and Olds 1994; Hariharan et al. 2015). They also draw from historical blunders and successes to provide students with opportunities for reflection within their engineering discipline (Harsh et al. 2017). These two factors support the use of case-based learning within remediation courses to enhance socio-technical thinking and understanding stakeholder knowledge.

5.1.2 Case-based learning

Case-based learning (CBL) relies on the experiential knowledge of others through story-telling or recording events in a case study (Jonassen and Hernandez-Serrano 2002). The civil and environmental engineering discipline has utilized case studies to show the implementation of engineering designs and concepts (Chinowsky and Robinson 1997; Leal Filho and Nesbit 2016) and provide ethics training to undergraduate students (Delatte and Gisemba Bagaka's 2014). CBL supports a variety of learning styles (Vivas and Allada 2006) and shifts the classroom to an active learning environment (Walter 2013). It further offers students a comprehensive examination of engineering techniques, evolving technologies, and interdisciplinary requirements of engineering projects (Chinowsky and Robinson 1997).Additionally, CBL promotes self-directed learning, an essential skill for modern engineers to tackle problems in a rapidly changing technological environment (Smith and Biswas 2001).

CBL extends constructivist learning theories. A constructivist approach to learning, where students consider their own knowledge of engineering through experience, offers ways to expand engineering education beyond traditional lectures and assignments (Mihelcic, Phillips, and Watkins 2006). In such a way, students can connect their ideas to the experience of others and retain knowledge and lessons-learned from the course by associating it with a descriptive story. During a case-based course, modules are designed to introduce students to the context of the case while withholding the actual decisions made by practitioners in the case. Students are asked to make and defend their own decisions given the context and available information (Lynn 1999).

5.2 Use of Learning Outcomes in Teaching

A learning outcome is “a very specific statement that describes exactly what a student will be able to do in some measurable way” (Hartel and Foegeding 2006, 69). Creating defined learning outcomes is the first step in developing effective course material to meet certain objectives. In this case, the defined learning outcomes help meet the objective for students to understand how remediation projects can involve and utilize local stakeholders. This section details several learning outcomes for a site remediation course. It also suggests potential assessment mechanisms for these learning outcomes. These outcomes are provided to aid educators in creating effective site remediation course material, adaptable to various teaching methods and classroom orientations.

5.2.1 Bloom’s Taxonomy

Well-defined learning outcomes utilize action verbs that help students comprehend the specific skills obtained through a course. Simultaneously, learning outcomes help teachers construct effective assessment mechanisms (Harden 2002). Bloom’s Taxonomy (Bloom 1956) is one tool used by educators to create measurable learning outcomes. It provides a classification system of six categories for student learning, with example verbs for each level of the taxonomy (Table 5.1).

Table 5.1 Bloom’s Taxonomy (Forehand 2005)

Original Taxonomy	Definition	Example Verbs
Knowledge	Remembering information	Identify, Define, List
Comprehension	Explaining the meaning	Describe, Summarize
Application	Using abstract ideas in concrete ways	Implement, Chart, Brainstorm
Analysis	Breaking down complex ideas	Distinguish, Differentiate
Synthesis	Bringing ideas together	Organize, Design, Plan
Evaluation	Judging the merits of a topic or idea	Critique, Judge, Evaluate

5.2.2 Learning Outcomes with Conceptual Site Models

The learning outcomes for a future remediation course build off one another. Early outcomes aim to meet the knowledge and comprehension levels of the taxonomy. Learning outcomes were developed for the first three one-hour lessons of a site remediation course. These lessons provide introductory material to students and are separated based on the day of instruction (Table 5.2). Additionally, each learning outcome shows the applicable Bloom's Taxonomy level (Table 5.2).

Table 5.2 Learning outcomes for a three-day course that introduces remediation, conceptual site models, and stakeholder knowledge. Associated Bloom's Taxonomy levels are listed.

Day	**Student Learning Outcomes**	**Bloom's Taxonomy**
1	1) Define remediation 2) Define a conceptual site model	Knowledge
	3) Identify phases of a remediation project 4) Identify key components of a conceptual site model	Comprehension
2	1) Brainstorm/sketch an initial CSM for Wells G & H in Woburn, Massachusetts	Application
	2) Compare CSMs to create a list of known and unknown information about the site	Analysis
	3) Argue which CSM is the most complete and why	Evaluation
3	1) Define stakeholder engagement as it applies to remediation projects 2) List the methods previously used by remediation projects to implement stakeholder engagement	Knowledge
	3) Discuss the ways stakeholder knowledge can impact the development of the conceptual site model	Comprehension
	4) Revise the CSMs from Day 2 using *A Civil Action: Woburn: Summer 1966*	Application

The learning outcomes (Table 5.2) consider the utilization of remediation case studies and conceptual site models in its development. Educators can provide students with a specific case study or students can select a case study on their own. Because the objective of these courses is to help students understand the role of stakeholders in remediation, students may benefit from pre-selected case studies that discuss different stakeholders. The example used in the provided learning outcomes is the well-known Wells G & H Superfund Site in Woburn, Massachusetts. Along with the availability of technical data, the novel *A Civil Action* (Harr 1995) follows the civil litigation brought by the families impacted by alleged trichloroethene contamination in the city drinking water wells G and H. The opening chapters of the novel provide a potential example of real stakeholder narratives that show the qualitative and uncertain nature of stakeholder knowledge. *A Civil Action* and the case study site of Wells G and H have been used in other educational applications. Broadly, educators have used the case study to teach legal dimensions of business (McEvoy 1998), environmental health (Backus, Hewitt, and Chalupka 2006), technical processes critical in determining the fate and transport of contaminants (Bair 2000; Bair 2005), quantitative risk assessment (Du, Butkus, and Starke 2016), and communication skills through mock trials that mimic the events in *A Civil Action* (Bair 2000). The site has further been proposed for constructing an environmental education center (Berry 1999).

As previously described in this thesis, conceptual site models (CSMs) are key decision-making tools for remediation practitioners. Understanding how to develop CSMs are important objectives for a remediation course overall. These outcomes address this objective by using CSMs as the main method of organizing information about a site, hypothesizing transport mechanisms, and integrating local knowledge about contamination.

5.3 Assessments for Learning Outcomes

Assessment methods ensure that students achieve the desired learning outcomes in a course. The theoretical ground for creating assessments suggests three processes (Black and Wiliam 2009). First, educators establish where students are in their learning. Second, educators decide “where they [students] are going” (Black and Wiliam 2009). Finally, educators determine how to move their students from their current learning state to the desired end point, as measured by the learning outcome. Formative assessments are one method used to ensure this continuity of learning is reached. Formative assessments consist of five key elements (Black and Wiliam 2009):

1. Clarifying and sharing learning outcomes
2. Providing effective classroom discussions and other tasks to promote student understanding
3. Providing feedback to students
4. Utilizing students as instructional resources for one another
5. Empowering students to take control of their own learning

Formative assessments rely on feedback among the students, as well as between the teacher and the student (Sadler 1998). In many activities, the teacher becomes a mediator within student discourse on a topic. Although formative assessments are not always appropriate in engineering education, the use of conceptual site models in remediation requires self-reflection and deliberation among peers.

5.3.1 Formative Assessment of Creating Conceptual Site Models

Relying again on the Wells G and H case study from Woburn, Massachusetts, a two-period (50 minutes per period) classroom activity serves as the main assessment mechanism for the course. This activity accomplishes several goals:

1. Assess initial socio-technical thinking in students
2. Assess Day 1, 2, and 3 learning outcomes
3. Promote student-to-student feedback
4. Foster decision-making in students

After introductory instruction on CSMs and the field of remediation, students will be asked to create a preliminary CSM for the case-study, which serves as the main project for the course. Appendix F provides a handout explaining the activity to students and introductory information about the case study. Students are reassured that this CSM is will be largely hypothetical as they do not currently possess the technical skills needed to scientifically assess contamination at the site. Prior to the class, students are instructed to read the first section of *A Civil Action,* "Woburn: Summer 1956". This section of *A Civil Action* introduces the families involved in the litigation. Readers shadow the families as their children suffer from leukemia and they grow increasingly concerned about the safety of water coming from Wells G and H.

By reading this section of *A Civil Action*, students are introduced to the qualitative, observational knowledge of local community members. The activity prompts students to create a conceptual site model with their project partner, and asks them the following question: "What considerations do you need to consider to create a more complete conceptual site model? List and describe all considerations and justify their inclusion." Students have stakeholder observations about water quality from *A Civil Action*. The educator can evaluate whether students utilize this knowledge in developing their CSM and see whether collaboration with stakeholders is listed as a consideration for the development of a more robust CSM. Therefore, educators can assess the initial socio-technical thinking within their students.

Learning outcomes are assessed through the development of the CSM. During the classroom discussion, students can debate a series of questions among themselves in determining the strengths and weaknesses of their preliminary CSMs (Table 5.3). Educators can directly prompt these questions or mediate the dialogue to help students evaluate one another’s work.

Table 5.3 (next page) Learning outcomes and questions for educators to consider to ensure that students meet learning objectives from the formative CSM assessment activity. Blue-highlighted questions note specific changes between Day 2 and 3 of the activity. On Day 2, these questions assess initial student understanding of stakeholder engagement. On Day 3, student learning is reassessed to ensure students understand the role of stakeholder knowledge in remediation and CSM development

Day	Learning Outcome	Educator Question for CSM Activity
1	1) Define a conceptual site model	How do students represent the CSM? How do they organize the information about a contaminated site? Do students attempt to hypothesize information about the site?
	2) Identify key components of a conceptual site model	Do the CSMs contain the three primary components (source, transport, and exposure) of a conceptual site model? Do students distinguish between known and hypothesized information in their CSM?
	3) Identify phases of remediation	How do students describe their CSM? Do they use the words hypothetical or preliminary? Which phases of a remediation project do the listed considerations correspond to?
2	1) Brainstorm/sketch an initial CSM for Wells G & H in Woburn, Massachusetts	Did students create a CSM for Wells G and H (as opposed to, more generally, groundwater contamination)
	2) Compare CSMs to create a list of known and unknown information about the site	What considerations are listed for developing a more robust CSM? Do students distinguish between known and hypothesized information in their CSM?
	3) Argue which CSM is the most complete and why	What criteria do students use to evaluate each other's CSMs? (e.g., socio-technical, purely technical, problem-definition based)
3	1) Define stakeholder engagement as it applies to remediation projects	Do students consider stakeholder engagement in their list of considerations for the CSM? After discussing stakeholder engagement, do students revise their CSMs and list of considerations to incorporate stakeholder knowledge?

Table 5.3 continued

Day	Learning Outcome	Educator Questions
3	2) List the methods previously used by remediation projects to implement stakeholder engagement	Which methods do students list in their revised considerations? Why do they prefer these methods?
	3) Discuss the ways stakeholder knowledge can impact the development of the conceptual site model	After discussing stakeholder engagement, do students revise their CSMs and list of considerations to incorporate stakeholder knowledge? How do the CSMs change?

The questions highlighted blue (Table 5.3) can be used for educators to document and understand students' initial socio-technical thinking prior to a discussion of stakeholder knowledge. The second period of the activity asks students to reassess their CSMs following a discussion of stakeholder engagement and presentation of the community-informed conceptual site models. Depending on the preferences of the educator, the same activity can be repeated, or the students can be asked to update the CSM using a different colored pen, sticky notes, or other annotating tools.

5.3.2 Sample Summative Assessments and Lesson Plans

The flexibility and adaptability of the classroom to aiding student learning promotes the use of formative assessments for meeting the defined learning objectives. However, other assessment methods exist. Summative assessments provide a summary of student learning at a specific point in time, allowing students to see a representative snapshot of their current knowledge on a topic (Harlen and James 1997). Appendix H provides sample summative assessment questions for a test, using free material in the public-domain. These test questions correspond to Knowledge and Comprehension levels of Bloom's Taxonomy (Table 5.4). Finally, basic lesson plans, in the form of slides, are proposed in Appendix I to aid educators in constructing classroom lessons that meet the learning objectives.

Table 5.4 Learning outcomes and summative assessment examples, listed in Appendix H

Day	Student Learning Outcomes	Summative Assessment Example
1	1) Define remediation 2) Define a conceptual site model	Matching Question (Q7) Matching Question (Q8)
	3) Identify phases of a remediation project 4) Identify key components of a conceptual site model	Short Answer Question (Q 12) Multiple Choice Question (Q 1-3)
3	1) Define stakeholder engagement as it applies to remediation projects 2) List the methods previously used by remediation projects to implement stakeholder engagement	Matching Question (Q4-6) Matching Question (Q9-11)

5.4 Conclusions

This chapter provided engineering educators with learning objectives, assessment options, and lesson plans to incorporate socio-technical thinking into site remediation courses. It relied on the use of a well-known contaminated site, Wells G and H in Woburn, Massachusetts, as the primary case study for analysis and utilized conceptual site models in an active learning environment. It is recommended for engineering educators to adapt the lesson plans to fit the needs of their respective classrooms. This may include adding anecdotes from an educator's personal industry experience to contextualize site remediation and conceptual site models, emphasizing alternate stakeholder engagement mechanisms, or limiting the introductory material discussed during class time by assigning additional homework assignments.

The use of conceptual site models can be applied to other sectors as well. Concept mapping is similar in theory to a conceptual site model but can be applied to a range of disciplines, problems, and contexts. Combined with the socio-technical rubric, these two mechanisms offer methods for enhancing socio-technical integration in any case-based project.

CHAPTER 6

CONCLUSIONS AND OPPORTUNITIES FOR FURTHER RESEARCH

During the mercury remediation project in Kyrgyzstan, mentioned in Chapter 1, technical experts failed to adequately eliminate mercury exposure to local community members because they relied solely on their own knowledge, rather than engaging local stakeholders to understand the extent of contamination. As demonstrated through the literature review, stakeholder engagement is critical to creating sustainable remediation designs, especially in developing countries where financial, economic, and regulatory constraints already threaten project success. Yet, pursuing stakeholder engagement can be a daunting task to technical experts, especially when local, experiential knowledge may seem unrelated to the technical knowledge required to create effective remediation plans. The development of community-informed conceptual site models offers a mechanism for local knowledge to directly contribute to fundamental questions about a contaminated site, such as identifying sources of contamination, explaining site history, and documenting local risk perception. Simultaneously, this process yields valuable information about the context and culture in which a contaminated site lies. Conceptual site models were further incorporated into an undergraduate engineering course to enhance socio-technical thinking of traditional course curriculum. Therefore, this work approached the lapse in socio-technical remediation design by adapting existing practitioner tools and improving the education of future practitioners.

Within stakeholder engagement, a particular concern is the empowerment of marginalized voices to participate in project activities. For example, in artisanal and small-scale gold mining, occupational exposures often differ depending on the gender of the individual engaged in mining activity (Steckling et al. 2011). Future research may include gender analysis to create conceptual site models that are informed through the lens of women in the community. This may help remediation practitioners understand differences in exposure to mercury or other contaminants in a community due to gender differences. Additionally, eliciting further input from other women in the community not directly engaged with mining offers an alternate frame-of-reference to understanding contamination at this site.

Collaboration in creating and revising conceptual site models with community members offers additional research opportunities. Disparities may exist between the illustrations and community members' own perceptions because of differences in how local community members view their environment. Community members may connect with tangible impacts of contamination and wish for these attributes to play a more central role in discussing further work for assessing contamination or remedial solutions. Further research can explore the risk perceptions of local community members and compare local risk perceptions to quantitative risk assessments. This could provide remediation teams with specific knowledge gaps that could be addressed through educational outreach and provide an additional mechanism for ensuring that remediation objectives and solutions align with community concerns and needs.

Since conceptual site models have not been previously developed using social science research methods, researchers can apply this method at other contaminated sites around the world. One comparison could be for contamination near an urban area. Because local stakeholders may be less dependent on the environment for supporting their livelihoods, local knowledge of environmental issues may present a stark contrast from the knowledge of rural communities. Another comparison could be drawn between developing countries and communities in industrialized nations, who benefit from strong central governments and regulatory structures.

Finally, the culmination of this research would result in the use of community-informed conceptual site models alongside remediation endeavors. Particular focus can immediately be given to stages preceding remedial design, such as remedial investigations, site testing, and feasibility studies. The full development of a community-informed CSM can be expressed along the progression of a full remediation project. Alternatively, research may reveal how a community-informed CSM becomes one piece of an aggregate CSM that integrates all technical and social knowledge of a site. The proposed framework can be extended and elaborated for other stages of a remediation project. Therefore, full utilization of this research offers opportunities to create specific, tangible guidance for remediation practitioners to integrate stakeholder knowledge into existing remediation processes.

6.1 Engineering Education Experiment Opportunities

The incorporation of social and sustainability considerations into a technical class offers multiple opportunities for contributing to the literature on engineering education. Future studies may compare this course integration to other remediation courses that have alternate class options to teach about social integration and sustainability. Additionally, future studies may compare the three-course integration to remediation courses focused on community development and developing countries. Through the development of socio-technical rubrics (Mazzurco and Daniel 2020), this altered curriculum can be evaluated for its ability to incorporate social and technical factors into student projects. This development could be a stand-alone study, or an objective evaluation of these socio-technical skills could be compared to student self-efficacy.

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APPENDIX A

ANDES ENVIRONMENTAL CONTAMINATION KNOWLEDGE SURVEY (ENGLISH)

Gender:

Occupation in: Mining:

Coffee:

Plantain:

Other:

Education level: Primary/Secondary/Technical/Professional/None

1. Do you believe that Andes is a region with zero mercury? Yes/No
2. On a scale of 1-5, with 5 being extremely harmful and 1 being not harmful, how harmful do you think the following products or activities are on the environment in Andes at the current time?

Activity	Not harmful				Extremely harmful	Does not understand
Coffee mucilage	1	2	3	4	5	
Tailings	1	2	3	4	5	
Cyanidation	1	2	3	4	5	
Pesticides/Insecticides	1	2	3	4	5	
Fertilizing	1	2	3	4	5	
Irrigation	1	2	3	4	5	
River Sediment Deposition	1	2	3	4	5	
Mine Entrances	1	2	3	4	5	
Groundwater Use	1	2	3	4	5	
Soil Erosion	1	2	3	4	5	
Smelting Activities	1	2	3	4	5	
If respondent answered NO to Question 1, ask about mercury use for processing gold	1	2	3	4	5	

3. For each response above that has a 4 or a 5, do you think it is a danger to (yes/no):
    a. Plants
    b. Fish
    c. Other Animals
    d. People
    e. Air
    f. Water
    g. Soil
4. Which sector has the greatest environmental impact?
    a. Mining
    b. Coffee Farming
    c. Other agriculture (specify crop)
    d. Trout Farming
    e. Other:____

APPENDIX B

ANDES ENVIRONMENTAL CONTAMINATION KNOWLEDGE SURVEY (SPANISH)

Lugar de cuestionario:

Sexo:

Trabajo: Minería:

Café:

Plátano:

Otro:

Durante un año, ¿en cual trabaja más?

Nivel de educación: Primaria/Bachillerato/Técnico o Tecnólogo/Profesional/Ninguna

1. ¿Cree que Andes es una región con cero mercurio? Si/No
2. En una escala de 1 a 5, con 5 siendo un gran peligro y 1 no siendo un peligro, cuán peligrosas son las siguientes actividades o productos para el medio ambiente en Andes por este momento?

Actividad	No peligro				Gran peligro	No entiendo
Miel(pulpa) de café/mucilago	1	2	3	4	5	
pacivos ambientales/colas/relaves/ lodo antiguo	1	2	3	4	5	
Cyanidación	1	2	3	4	5	
pesticidas/insecticidas	1	2	3	4	5	
fertilizante/abono	1	2	3	4	5	
irrigación	1	2	3	4	5	
sedimentos con los rios	1	2	3	4	5	
entradas de minas	1	2	3	4	5	
usa de agua subterráneo	1	2	3	4	5	
erosión del suelo (de avalanchas)	1	2	3	4	5	
Fundición después cyanidación	1	2	3	4	5	
(Si NO a numero uno, pregunta: aprovechamiento de mercurio para el beneficio de oro)	1	2	3	4	5	

3. Para cada respuesta con 4 o 5, ¿piensa que es un peligro para (si/no):
    a. Plantas?
    b. Pescado?
    c. Otros animales?
    d. Personas?
    e. Aire?
    f. Agua?
    g. Suelos?
4. Cual actividad tiene el mayor impacto ambiental?
    a. Minería de Gran Escala
    b. Minería Artesanal y Pequeña Escala
    c. Café
    d. Otra Agricultura
    e. Truchera
    f. Otro:____

APPENDIX C

ANDES SURVEY CODE BOOK

This code book describes the raw data results for the Andes Survey, described in Appendix F.

Key-

Variable Name

Data Type (continuous, discrete, nominal, or ordinal)

Item Value Description

Demographic Question 1: Sex

Nominal

1. Male
2. Female

Demographic Question 2: Sector of Work

Nominal

1. Mining
2. Agriculture
3. Other
4. Mining and Agriculture

Demographic Question 3: Primary sector of work

Nominal

1. Mining
2. Agriculture
3. Other

4. Equal time between mining and agriculture

Demographic Question 4: Education Level

Ordinal

1. None
2. Primary
3. Secondary
4. Technical
5. Professional

Question 1: Do you believe that Andes is a region with zero mercury?

Nominal

1. Yes
2. No

Question 2a: How harmful do you think coffee pulp is to the environment in Andes at the current time?

Ordinal

0. Do not understand
1. Not harmful
2. Slightly harmful
3. Moderately harmful
4. Very harmful
5. Extremely harmful

Question 2b: How harmful do you think old tailings are to the environment in Andes at the current time?

Ordinal

0. Do not understand
1. Not harmful
2. Slightly harmful
3. Moderately harmful
4. Very harmful
5. Extremely harmful

Question 2c: How harmful do you think cyanidation is to the environment in Andes at the current time?

Ordinal

0. Do not understand
1. Not harmful
2. Slightly harmful
3. Moderately harmful
4. Very harmful
5. Extremely harmful

Question 2d: How harmful do you think pesticides/insecticides is to the environment in Andes at the current time?

Ordinal

0. Do not understand
1. Not harmful

2. Slightly harmful
3. Moderately harmful
4. Very harmful
5. Extremely harmful

Question 2e: How harmful do you think using fertilizing is to the environment in Andes at the current time?

Ordinal

0. Do not understand
1. Not harmful
2. Slightly harmful
3. Moderately harmful
4. Very harmful
5. Extremely harmful

Question 2f: How harmful do you think irrigation is to the environment in Andes at the current time?

Ordinal

0. Do not understand
1. Not harmful
2. Slightly harmful
3. Moderately harmful
4. Very harmful
5. Extremely harmful

Question 2g: How harmful do you think sediment deposition is to the environment in Andes at the current time?

Ordinal

0. Do not understand
1. Not harmful
2. Slightly harmful
3. Moderately harmful
4. Very harmful
5. Extremely harmful

Question 2h: How harmful do you think mine entrances are to the environment in Andes at the current time?

Ordinal

0. Do not understand
1. Not harmful
2. Slightly harmful
3. Moderately harmful
4. Very harmful
5. Extremely harmful

Question 2i: How harmful do you think the use of groundwater is to the environment in Andes at the current time?

Ordinal

0. Do not understand
1. Not harmful

2. Slightly harmful
3. Moderately harmful
4. Very harmful
5. Extremely harmful

Question 2j: How harmful do you think the soil erosion is to the environment in Andes at the current time?

Ordinal

0. Do not understand
1. Not harmful
2. Slightly harmful
3. Moderately harmful
4. Very harmful
5. Extremely harmful

Question 2k: If answered No to Question 1, how harmful do you think the usage of mercury in gold processing is to the environment in Andes at the current time?

Ordinal

0. Do not understand
1. Not harmful
2. Slightly harmful
3. Moderately harmful
4. Very harmful
5. Extremely harmful

Question 3a: If you answered very harmful or extremely harmful to questions 6 – 16, do you think it is a danger to plants?

Nominal

1. Yes
2. No

Question 3b: If you answered very harmful or extremely harmful to questions 6 – 16, do you think it is a danger to fish?

Nominal

1. Yes
2. No

Question 3c: If you answered very harmful or extremely harmful to questions 6 – 16, do you think it is a danger to other animals?

Nominal

1. Yes
2. No

Question 3d: If you answered very harmful or extremely harmful to questions 6 – 16, do you think it is a danger to people?

Nominal

1. Yes
2. No

Question 3e: If you answered very harmful or extremely harmful to questions 6 – 16, do you think it is a danger to the air?

Nominal

1. Yes
2. No

Question 3f: If you answered very harmful or extremely harmful to questions 6 – 16, do you think it is a danger to the water?

Nominal

1. Yes
2. No

Question 3g: If you answered very harmful or extremely harmful to questions 6 – 16, do you think it is a danger to the soil?

Nominal

1. Yes
2. No

Question 4: Which sector has the greatest environmental impact?

Ordinal

1. Mining
2. Coffee Farming
3. Other Agriculture
4. Trout Farming
5. Other

APPENDIX D

STATISTICAL ANALYSIS OF THE ANDES SURVEY

D.1 Sample Size Calculations

Surveys are intended to gather responses about a subject that are representative of the population. Because an entire population can rarely be surveyed in its entirety, a researcher calculates the sample size needed to derive statistics to a pre-determined confidence level (in this case, 0.1, although 0.05 is a common convention), variance, and margin of error. The formula used for calculating sample size in our survey, Cochran's formula (Bartlett, Kotrlik, and Higgins 2001), is based on a determination of error due to the variables that exist in the survey. It is often beneficial, and recommended, to perform sample size calculations on the most important variables in the survey, examine the range of resulting sample sizes, and choose an appropriate sample size from those data. This includes a consideration of the "real-world" constraints of survey collection, including restrictions in time and financial resources. For demonstration purposes, we limit the sample size calculation to the dichotomous categorical variable of gender, because it often produces the largest sample size (Bartlett, Kotrlik, and Higgins 2001). The use of Cochran's formula can estimate the ideal sample size of the population (Bartlett, Kotrlik, and Higgins 2001):

$$n_0 = \frac{t^2(p)(q)}{d^2} = \frac{1.65^2(0.25)}{0.05^2} = 272 \tag{D.1}$$

where n_0 is the sample size for categorical data, t is the t-statistic from Student's T-test for the selected confidence level of 0.05 in each tail (0.1 overall), set due to the nature of the introductory research and acknowledgement that critical decisions impacting human or ecological life will not be made due to the results of the analysis, $(\mathrm{p})(\mathrm{q})$ is the estimate of variance, set at 0.25 by the dichotomous variable of gender (Bartlett, Kotrlik, and Higgins 2001), and d is the acceptable margin of error, set at 0.05 as is customary for categorical data in the social sciences (Bartlett, Kotrlik, and Higgins 2001)

Cochran's formula does not use the population size to calculate the sample size. Rather, it is based on pre-determined margins of error by the researcher, which can vary between variables, academic disciplines, and context surrounding the survey. A secondary formula exists to correct the first calculation based on the population size. The population size for our survey was 405, based on information from an informed local contact as to the number of artisanal miners employed in Andes. Because n_0 exceeds 5% of the population size of 405, Cochran's correction formula can be applied to calculate the final desired sample size of 163:

$$\mathrm{n}_1 = \frac{\mathrm{n}_0}{\left(1+\frac{\mathrm{n}_0}{\mathrm{Population}}\right)} = \frac{272}{\left(1+\frac{272}{405}\right)} = 163 \tag{D.2}$$

where n_1 is the final sample size.

The constraints of time and access to research participants limited the ability to achieve the desired sample size of 163. Over six days of field work with two research assistants, we were able to obtain 100 completed surveys. This corresponds to a 7% margin of error, compared to the 5% used in the sample size calculations. Since our survey is exploratory, we proceeded with statistically analyzing the survey results with this margin of error.

D.2 Background on Statistical Methods

The Andes survey is a nonexperimental design. The independent variables of sex, sector of work, and education level were not randomly selected or manipulated by the researchers. The Andes survey further employs a comparative design in that two or more groups (based on the separation of demographic variables) are compared. Nonexperimental designs cannot explain causal relationships (Lohmeier 2010) because compounding variables cannot be controlled. For example, the sector of work for an individual might be determined by other variables, such as skills, interests, and educational background (Lohmeier 2010). Additionally, other circumstances uncaptured in the survey may also be informing an individual's response, such as local history or current events. A difference in perception of environmental hazards may be due to one of the variables captured in the survey, or it may be due to other factors not discussed. In our case, a nonexperimental survey design was further necessary given that the target population for the survey (lower-level workers in ASGM and agriculture) was relatively small and hard to access. The completion of qualitative interviews prior to the implementation of the Andes survey allowed us to create a more holistic understanding of the factors impacting risk perception for ASGM communities in Andes. This allowed the survey to instead focus on ranking, not predicting behavior or perception.

Numerical rating scales, while using numbers, are ordinal: they represent attitudes on an ordered structure, but the physical numbers do not represent a well-defined mathematical size. A previous example (Table 4.1 on page 54) explains this further, using the numerical rating scale to provide a range of values to assess the level of hazard. It is important to note that each number does not have a specific value. Rather, what the numbers represent is an order. A score of 5 is higher than 4, which is higher than 3, and so forth. The calculation of information like means (where data needs to be added and divided to get a result) is meaningless in ordinal data sets since the numbers themselves are not of value (Siegel 1956). Any five set of values could be used as long as they correspond to the same ordered structure as the example given. Therefore, statistical methods based on arithmetic calculations (such as analysis of variance or linear regression) are inappropriate ways to analyze the data (Svensson 2001).

The statistical method of choice further requires an understanding of the limitations of the (non)experimental design. For nonexperimental research, it is unlikely that the population under study has a normal distribution. Many parametric statistical methods, such as analysis of variance (ANOVA) or linear regression assume a specific distribution of the population(Gao 2010). Nonparametric statistical methods, by comparison, do not carry this assumption. Because we draw our data from a nonexperimental design, nonparametric statistical methods are more appropriate to analyze the survey results. Nonparametric statistical methods can further be used in small sample sizes, such as the Andes survey (N = 100) (Siegel 1956).

D.3 Chi-Squared and Kruskal-Wallis Tests

Prior to any statistical analysis, the survey data was cleaned to remove responses where the question was not understood. Then, the chi-squared test of independence was used to determine if any of the categorical demographic variables were related. We used the crosstab function(MATLAB 2020a) to compare the three demographic variables of sex, primary sector of work, and education level (see the sample script provided in the supplementary material). After concluding that the demographic variables are unrelated using an alpha level of 0.1, we then proceeded to use the Kruskal-Wallis test to determine if any of the categorical variables create differences in the median responses of the numerical rating scale data. The Kruskal-Wallis method has been used by other surveys with categorical variables (Bedoya-Marrugo et al. 2017; Hassan et al. 2012).

We placed all of the p-values from the Kruskal-Wallis tests into a table to compare the p-values across the different categorical variables for each environmental hazard. If the p-values for at least half of the hazards was statistically significant ($p<0.1$). For the "statistically significant" categorical variables, we then calculated group statistics of medians and modes (MATLAB 2020c). After compiling all the median and modes into an Excel spreadsheet, a ranked list under each group of the categorical variable was created. First, each column was sorted in ascending values based on median, the middle value of the responses. If multiple hazards had the same median, the results were further ranked based on descending values of the mode, since it denotes the amount of times a rank was chosen for a given hazard. Any remainder ties for both mode and median were noted as such and listed in alphabetical order.

APPENDIX E

SAMPLE MATLAB CODE FOR SURVEY ANALYSIS

```
%%Example Script for Analyzing Numerical Rating Scales Using Kruskal-Wallis

%Import data into MATLAB using the 'Import Data' button on the Home Tab

%First, remove the responses from the survey data where people did not
%understand the question, denoted by a zero in the data.

load SurveyData

Mucilagedata = SurveyData(:,1:5);
Mucilage = Mucilagedata(:,5);
Mucilage2 = table2array(Mucilage);
indices = Mucilage2==0;
Mucilagedata(indices,:)=[];
clear Mucilage
clear Mucilage2
clear indices

Tailingsdata = SurveyData(:,[1:4 6]);
Tailings = Tailingsdata(:,5);
Tailings2 = table2array(Tailings);
indices = Tailings2==0;
Tailingsdata(indices,:)=[];
clear Tailings
clear Tailings2
clear indices

Cyanidedata = SurveyData(:,[1:4 7]);
Cyanide = Cyanidedata(:,5);
Cyanide2 = table2array(Cyanide);
indices = Cyanide2==0;
Cyanidedata(indices,:)=[];
clear Cyanide
clear Cyanide2
clear indices

Pestdata = SurveyData(:,[1:4 8]);
Pest = Pestdata(:,5);
```

```
Pest2 = table2array(Pest);
indices = Pest2==0;
Pestdata(indices,:)=[];
clear Pest
clear Pest2
clear indices

Fertilizerdata = SurveyData(:,[1:4 9]);
Fertilizer = Fertilizerdata(:,5);
Fertilizer2 = table2array(Fertilizer);
indices = Fertilizer2==0;
Fertilizerdata(indices,:)=[];
clear Fertilizer
clear Fertilizer2
clear indices

Irrig_data = SurveyData(:,[1:4 10]);
Irrig = Irrig_data(:,5);
Irrig2 = table2array(Irrig);
indices = Irrig2==0;
Irrig_data(indices,:)=[];
clear Irrig
clear Irrig2
clear indices

SuspSeddata = SurveyData(:,[1:4 11]);
SuspSed = SuspSeddata(:,5);
SuspSed2 = table2array(SuspSed);
indices = SuspSed2==0;
SuspSeddata(indices,:)=[];
clear SuspSed
clear SuspSed2
clear indices

Bocaminadata = SurveyData(:,[1:4 12]);
Bocamina = Bocaminadata(:,5);
Bocamina2 = table2array(Bocamina);
indices = Bocamina2==0;
Bocaminadata(indices,:)=[];
clear Bocamina
clear Bocamina2
clear indices

GWUsedata = SurveyData(:,[1:4 13]);
GWUse = GWUsedata(:,5);
GWUse2 = table2array(GWUse);
```

```
indices = GWUse2==0;
GWUsedata(indices,:)=[];
clear GWUse
clear GWUse2
clear indices

SoilErosdata = SurveyData(:,[1:4 14]);
SoilErosion = SoilErosdata(:,5);
SoilErosion2 = table2array(SoilErosion);
indices = SoilErosion2==0;
SoilErosdata(indices,:)=[];
clear SoilErosion
clear SoilErosion2
clear indices

CyanideAmalgamdata = SurveyData(:, [1:4 15]);
CyanideAmalgam = CyanideAmalgamdata(:,5);
CyanideAmalgam2 = table2array(CyanideAmalgam);
indices = CyanideAmalgam2 == 0;
CyanideAmalgamdata(indices,:) = [];
clear CyanideAmalgam
clear CyanideAmalgam2
clear indices

%Because the survey was specific to Andes, a precursor question asked
%respondents if they believed Andes was a region free from mercury. If they
%answered yes, they were not asked about the hazard of mercury amalgamation
%(because it theoretically no longer exists in the area)

MercuryAmalgamdata = SurveyData(:, [1:4 16]);
MercuryAmalgam = MercuryAmalgamdata(:,5);
MercuryAmalgam2 = table2array(MercuryAmalgam);
indices = MercuryAmalgam2 == 0;
MercuryAmalgamdata(indices,:) = [];
clear MercuryAmalgam
clear Mercury Amalgam2
clear indices

%% Complete a chi-squared test of independence for the categorical variables
sex = table2array(SurveyData(:,2)); %Sex (Male or Female)
PSofW = table2array(SurveyData(:,3)); %Primary Sector of Work
Edu = table2array(SurveyData(:,4)); %Education Level

%Use the crosstab function to run the chi-squared test, where p1, p2, and
%p3 denote the p-values for the test. Compare the p-values to the alpha
%level (0.1 in this study)
```

```
[~,~,p1] = crosstab(sex, PSofW, Edu); %runs a test using all three variables
[~,~,p2] = crosstab(sex, PSofW);
[~,~,p3] = crosstab(PSofW, Edu);
[~,~,p4] = crosstab(sex, Edu);

%create an exported file with the p-values and labeled tests
p_values={p1,p2,p3};
ChiSquaredResults = {'3-way comparison' p1; 'sex and Primary Sector of Work' p2;
   'Primary Sector of Work and Education' p3; 'Sex and Education' p4};
filename = 'ChiSquaredResults.xlsx';
writecell(ChiSquaredResults,filename);
%% Run Kruskal-Wallis tests

%Store the variable names for the original table in a cell
VarNames = SurveyDataStatistics.Properties.VariableNames;


KWmatrix = cell(13, 5); %Create an open matrix for the p-values
counts = zeros(1,5); %creates a double matrix to count the number of times the p-value is
significant
for k = 1:5 %label the open matrix columns
   KWmatrix(1,k) = VarNames(k);
end

for k = 1:12 %label the matrix rows
   KWmatrix(k+1,1) = VarNames(k + 5);
end

   for j=2:5
      [p,~]=kruskalwallis(Mucilagedata.(5), Mucilagedata.(j), 'off');
      KWmatrix(2,j) = num2cell(p);
      if p < 0.1 %compares to the alpha value
         counts(1,j) = counts(1,j) + 1; %tallies the number of times the p-value is statistically
significant
      end
   end

   for j=2:5
      [p,~]=kruskalwallis(Tailingsdata.(5), Tailingsdata.(j), 'off');
      KWmatrix(3,j) = num2cell(p);
      if p < 0.1
         counts(1,j) = counts(1,j) + 1;
      end
   end

   for j=2:5
```

```
    [p,~]=kruskalwallis(Cyanidedata.(5), Cyanidedata.(j), 'off');
    KWmatrix(4,j) = num2cell(p);
    if p < 0.1
      counts(1,j) = counts(1,j) + 1;
    end
end

for j=2:5
    [p,~]=kruskalwallis(Pestdata.(5), Pestdata.(j), 'off');
    KWmatrix(5,j) = num2cell(p);
    if p < 0.1
      counts(1,j) = counts(1,j) + 1;
    end
end

for j=2:5
    [p,tbl]=kruskalwallis(Fertilizerdata.(5), Fertilizerdata.(j), 'off');
    KWmatrix(6,j) = num2cell(p);
    if p < 0.1
      counts(1,j) = counts(1,j) + 1;
    end
end

for j=2:5
    [p,tbl]=kruskalwallis(Irrig_data.(5), Irrig_data.(j), 'off');
    KWmatrix(7,j) = num2cell(p);
    if p < 0.1
      counts(1,j) = counts(1,j) + 1;
    end
end

for j=2:5
    [p,~]=kruskalwallis(SuspSeddata.(5), SuspSeddata.(j), 'off');
    KWmatrix(8,j) = num2cell(p);
    if p < 0.1
      counts(1,j) = counts(1,j) + 1;
    end
end

for j=2:5
    [p,~]=kruskalwallis(Bocaminadata.(5), Bocaminadata.(j), 'off');
    KWmatrix(9,j) = num2cell(p);
    if p < 0.1
      counts(1,j) = counts(1,j) + 1;
    end
end
```

```
    for j=2:5
      [p,~]=kruskalwallis(GWUsedata.(5), GWUsedata.(j), 'off');
      KWmatrix(10,j) = num2cell(p);
      if p < 0.1
        counts(1,j) = counts(1,j) + 1;
      end
    end

    for j=2:5
      [p,~]=kruskalwallis(SoilErosdata.(5), SoilErosdata.(j), 'off');
      KWmatrix(11,j) = num2cell(p);
      if p < 0.1
        counts(1,j) = counts(1,j) + 1;
      end
    end

    for j=2:5
      [p,~]=kruskalwallis(CyanideAmalgamdata.(5), CyanideAmalgamdata.(j), 'off');
      KWmatrix(12,j) = num2cell(p);
      if p < 0.1
        counts(1,j) = counts(1,j) + 1;
      end
    end

    for j=2:5
      [p,~]=kruskalwallis(MercuryAmalgamdata.(5), MercuryAmalgamdata.(j), 'off');
      KWmatrix(13,j) = num2cell(p);
      if p < 0.1
        counts(1,j) = counts(1,j) + 1;
      end
    end

%Export these results to an excel file
filename = 'KruskalWallisPvalues.xlsx';
writecell(KWmatrix, filename);

%% Calculate the Medians and Modes of the Grouped Datasets for sorting

%create a cell matrix and label the columns
PSoWMandM = cell(13,9);
PSoWMandM(1,1) = cellstr('NA');
PSoWMandM(1,2) = cellstr('Mining Medians');
PSoWMandM(1,3) = cellstr('Mining Modes');
PSoWMandM(1,4) = cellstr('Agriculture Medians');
PSoWMandM(1,5) = cellstr('Agriculture Modes');
```

```
PSoWMandM(1,6) = cellstr('Other Medians');
PSoWMandM(1,7) = cellstr('Other Modes');
PSoWMandM(1,8) = cellstr('Mining and Agriculture Medians');
PSoWMandM(1,9) = cellstr('Mining and Agriculture Modes');
for k = 1:12 %label the cell matrix rows with the hazard names
   PSoWMandM(k+1,1) = VarNames(k + 5);
end

%start computing group medians and modes and place into the matrix
%This can be repeated with any other categorical data by changing the
%second reference inside grpstats (e.g. Mucilagedata.(3) may become
%Mucilagedata.(2))
medians = grpstats(Mucilagedata.(5), Mucilagedata.(3), @median);
modes = grpstats(Mucilagedata.(5), Mucilagedata.(3), @mode);
for k = 0:3
   PSoWMandM(2, 2*k+2) = num2cell(medians(k+1));
   PSoWMandM(2, 2*k+3) = num2cell(modes(k+1));
end

%Mucilagedata.(6) is the hazard ranking by the individual
%Mucilagedata.(4) is the categorical variable group
%@median is the function to calculate
%the for loop writes the results into the corresdponding columns

medians = grpstats(Tailingsdata.(5), Tailingsdata.(3), @median);
modes = grpstats(Tailingsdata.(5), Tailingsdata.(3), @mode);
for k = 0:3
   PSoWMandM(3, 2*k+2) = num2cell(medians(k+1));
   PSoWMandM(3, 2*k+3) = num2cell(modes(k+1));
end
medians = grpstats(Cyanidedata.(5), Cyanidedata.(3), @median);
modes = grpstats(Cyanidedata.(5), Cyanidedata.(3), @mode);
for k = 0:3
   PSoWMandM(4, 2*k+2) = num2cell(medians(k+1));
   PSoWMandM(4, 2*k+3) = num2cell(modes(k+1));
end
medians = grpstats(Pestdata.(5), Pestdata.(3), @median);
modes = grpstats(Pestdata.(5), Pestdata.(3), @mode);
for k = 0:3
   PSoWMandM(5, 2*k+2) = num2cell(medians(k+1));
   PSoWMandM(5, 2*k+3) = num2cell(modes(k+1));
end
medians = grpstats(Fertilizerdata.(5), Fertilizerdata.(3), @median);
modes = grpstats(Fertilizerdata.(5), Fertilizerdata.(3), @mode);
for k = 0:3
   PSoWMandM(6, 2*k+2) = num2cell(medians(k+1));
```

```
    PSoWMandM(6, 2*k+3) = num2cell(modes(k+1));
end
medians = grpstats(Irrig_data.(5), Irrig_data.(3), @median);
modes = grpstats(Irrig_data.(5), Irrig_data.(3), @mode);
for k = 0:3
    PSoWMandM(7, 2*k+2) = num2cell(medians(k+1));
    PSoWMandM(7, 2*k+3) = num2cell(modes(k+1));
end

medians = grpstats(SuspSeddata.(5), SuspSeddata.(3), @median);
modes = grpstats(SuspSeddata.(5), SuspSeddata.(3), @mode);
for k = 0:3
    PSoWMandM(8, 2*k+2) = num2cell(medians(k+1));
    PSoWMandM(8, 2*k+3) = num2cell(modes(k+1));
end
medians = grpstats(Bocaminadata.(5), Bocaminadata.(3), @median);
modes = grpstats(Bocaminadata.(5), Bocaminadata.(3), @mode);
for k = 0:3
    PSoWMandM(9, 2*k+2) = num2cell(medians(k+1));
    PSoWMandM(9, 2*k+3) = num2cell(modes(k+1));
end
medians = grpstats(GWUsedata.(5), GWUsedata.(3), @median);
modes = grpstats(GWUsedata.(5), GWUsedata.(3), @mode);
for k = 0:3
    PSoWMandM(10, 2*k+2) = num2cell(medians(k+1));
    PSoWMandM(10, 2*k+3) = num2cell(modes(k+1));
end
medians = grpstats(SoilErosdata.(5), SoilErosdata.(3), @median);
modes = grpstats(SoilErosdata.(5), SoilErosdata.(3), @mode);
for k = 0:3
    PSoWMandM(11, 2*k+2) = num2cell(medians(k+1));
    PSoWMandM(11, 2*k+3) = num2cell(modes(k+1));
end
medians = grpstats(CyanideAmalgamdata.(5), CyanideAmalgamdata.(3), @median);
modes = grpstats(CyanideAmalgamdata.(5), CyanideAmalgamdata.(3), @mode);
for k = 0:3
    PSoWMandM(12, 2*k+2) = num2cell(medians(k+1));
    PSoWMandM(12, 2*k+3) = num2cell(modes(k+1));
end
medians = grpstats(MercuryAmalgamdata.(5), MercuryAmalgamdata.(3), @median);
modes = grpstats(MercuryAmalgamdata.(5), MercuryAmalgamdata.(3), @mode);
for k = 0:3
    PSoWMandM(13, 2*k+2) = num2cell(medians(k+1));
    PSoWMandM(13, 2*k+3) = num2cell(modes(k+1));
end
```

```
%Export the results to a new Excel file
filename = 'Primary Sector of Work Medians and Modes.xlsx';
writecell(PSoWMandM, filename);
```

APPENDIX F

ANDES SURVEY SUPPLEMENTAL FILE

This supplemental file provides the raw survey data results for the Andes survey, used Chapter 4 of this thesis. The data can be interpreted using the codebook in Appendix C. The Andes survey results are stored in an Excel file, which were imported into MATLAB for analysis, using the code provided in Appendix E.

APPENDIX G

CONCEPTUAL SITE MODEL CLASSROOM ACTIVITY HANDOUT

Jonathan Harr’s book *A Civil Action*, and the movie of the same name that followed, brought national attention to the trichloroethene (TCE) groundwater contamination case in Woburn, Massachusetts.

In the mid-1960s, the city of Woburn installed two new municipal wells (Wells G and H) to provide water to its residents. Within a few years of these wells going online, a number of childhood leukemia cases were reported. Anne Anderson, whose 3-year-old son was one of those diagnosed, believed that the drinking water from the two new wells was responsible for the childhood leukemia. The suspected sources of contamination were Riley Tannery, Unifirst Properties. and a chemical plant owned by W.R. Grace.

Your task is to create a preliminary conceptual site model (CSM) of contamination for Woburn, Massachusetts. Right now, your CSM will be largely hypothetical. The rest of this course is designed to equip you with the technical knowledge necessary to create a more robust conceptual site model and analysis of contamination in Woburn. Your CSM can be graphical, pictorial, written, or a combination of those. As you create your CSM, answer the following question:

What considerations do you need to consider to create a more complete conceptual site model? List and describe all considerations and justify their inclusion.

APPENDIX H

SUMMATIVE ASSESSMENT EXAMPLES

Note: Questions 1-3 all refer to the diagram of Rocky Flats below. Answers withheld. Below is an edited version of the human health conceptual site model for Rocky Flats, a 6,241-acre Department of Energy facility used for nuclear weapons manufacturing in Boulder, Colorado. The site was contaminated with a variety of hazardous substances, including radionuclides, organic solvents, and metals. Below is an excerpt from the human health conceptual site model from the US EPA's Record of Decision for Rocky Flats, publicly available at https://semspub.epa.gov/work/08/1020363.pdf.

1) Some of the column headers are hidden for the conceptual site model. What component of a conceptual site model is column a?
    a) Site Assessment
    b) Primary Source
    c) Exposure Route
    d) Site History
2) What component of a conceptual site model is column b?
    a) Exposure Route
    b) Human Receptor
    c) Occupational Risk
    d) Fate of Contaminant

3) The US EPA developed this human health conceptual site model to aid in the development of a wildlife reserve on the Rocky Flats site. Given this knowledge and the CSM above, who are the potential receptors of contamination in this model?
    a) Wildlife Reserve Visitors
    b) Wildlife Reserve Workers
    c) Wildlife – birds, animals, insects
    d) All of the above
    e) a) and b) only

Questions 4 – 11 would be placed in a matching section, with the right column scrambled. Currently, the list is unscrambled (Table H.1 on page 138).

12) List the progression of a remediation project from initial evidence of contamination to evaluation. Provide brief descriptions of each step or stage alongside a listed progression.

Table H.1 Questions 4-11 intended as matching questions on a summative assessment

4) Stakeholder	a) an individual, organization, or other party who may be impacted by or have the power to impact a project
5) Consultative Engagement___	b) One-way communication where practitioners elicit ideas and opinions from impacted stakeholders
6) Public Participation	c) Two-way communication where people are empowered to make decisions on project activities
7) Remediation _______	d) removal of contaminants or reduction of exposure to contaminations from environmental media
8) conceptual site model	e) iterative decision-making tool used by remediation experts to represent the known and hypothesized information of a contaminated site
9) Citizen Advisory Board	f) representatives of a local community who are tasked with providing input and feedback to a project
10) Social Network Analysis	g) method of understanding and organizing stakeholders based on their connection to a project and/or ability to influence project activities
11) Structured Survey	h) method of eliciting stakeholder knowledge by asking participants questions with restricted answers.

APPENDIX I

SITE REMEDIATION LESSON SLIDES

The supplemental files to this thesis provide base lesson slides for guiding the three-day course structure described in Chapter 6. The lesson titles for the lesson plans are as follows:

1. Lesson 01 – Introduction to Remediation and Conceptual Site Models
2. Lesson 02 – Building CSMs
3. Lesson 03 – Stakeholder Engagement and Remediation

The slide progression is guided by the lesson outcomes, which are listed before and after each section pertaining to a particular outcome. In this way, students and educators can ensure the lesson outcomes are met during each classroom period. It is intended for each presentation to be delivered over a 50-minute time slot.