Groundwater Arsenic in Chimaltenango, Guatemala

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THESIS

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LIST OF ABBREVIATIONS

ADD	Average Daily Dose
AIHA	American Industrial Hygiene Association
AT	Averaging Time
BW	Body Weight
C	Concentration
CSF	Cancer Slope Factor
CTE	Central Tendency Exposure
ECR	Excess Cancer Risk
ED	Exposure Duration
EF	Exposure Frequency
EPA	U.S. Environmental Protection Agency
EWB-UIC	University of Illinois at Chicago Student Chapter of Engineers Without Borders
FEV1	Forced Expiratory Volume in 1 Second
FVC	Forced Vital Capacity
GPS	Global Positioning System
HQ	Hazard Quotient
IARC	International Agency for Research on Cancer

LIST OF ABBREVIATIONS (continued)

IR	Ingestion Rate
IRIS	EPA's Integrated Risk Information System
LADD	Lifetime Average Daily Dose
LOD	Limit of Detection
MCL	Maximum Contaminant Level
MRL	Method Reporting Limit
NOAEL	No Observed Adverse Effect Level
PRB	Permeable Reactive Barriers
R*f*D	Reference Dose
RME	Reasonable Maximum Exposure
WHO	World Health Organization

SUMMARY

Arsenic is a highly toxic substance capable of contaminating groundwater drinking sources and causing serious adverse health effects. In the community of Cerro Alto, in the municipality of Chimaltenango, Guatemala, we collected water samples in 2009 from two wells. Arsenic concentrations found were greater than four times the World Health Organization (WHO) provisional guideline value for arsenic in drinking water of 0.01 mg/L. As a result, we returned to work with local public health authorities and characterized the presence of arsenic in the groundwater of the entire municipality.

A total of 42 samples were collected from 27 of the 62 (43.5%) wells in the municipality in January 2012. Well sites were chosen to ensure a representative sampling for both rural and urban areas and from pumped systems, spring fed systems, and artesian well systems. Global positioning system (GPS) coordinates were recorded at each sampling site. Upon analysis, the only site found to have a concentration above the 0.01 mg/L WHO guideline was Cerro Alto, where the average concentration was 0.0475 mg/L, similar to our initial finding in 2009.

Arsenic contamination of groundwater can often be attributed to a naturally high presence in the area. Using data from the US Geological Survey and our GPS data of the sample locations, we found Cerro Alto to be the only site sampled within the tertiary volcanic rock layer, the likely source of arsenic in Guatemala due to the linkage between volcanic rock and naturally occurring arsenic.

A risk assessment based on the arsenic levels found in Cerro Alto showed an increase in noncarcinogenic and carcinogenic risk for residents there. Recommendations are described to eliminate or lower the levels of arsenic found in the community's drinking water.

1. INTRODUCTION

1.1 Background

Contamination of groundwater drinking sources with arsenic is a problem that faces many parts of the globe. Arsenic is naturally distributed throughout the earth's crust, soils, sediment, water, and air. It is the 20th most abundant element in the earth's crust (Mandal and Suzuki, 2002) and as a result can easily infiltrate groundwater. The mobilization of arsenic in groundwater is typically the result of natural processes including weathering reactions, and microbiological activities (Smedley and Kinniburgh, 2002), although it can result from anthropogenic activities. While arsenic concentrations in freshwater typically range from 1–10 µg/L, they can reach greater than 5000 µg/L (Mandal and Suzuki, 2002). The greatest known exposure to arsenic in drinking water is in Bangladesh and West Bengal, India. In 1998, the British Geological Society performed an extensive survey of Bangladesh wells and found that 35% of them had arsenic concentrations above 50 µg/L, and 8.4% had levels above 300 µg/L (Smith et al., 2000). Groundwater arsenic concentrations above 50 µg/L have been found in Argentina, Chile, northern China, Hungary, Mexico, Romania, Taiwan, and the southwest United States (Smedley and Kinniburgh, 2002). Few studies have documented elevated groundwater arsenic concentrations in Guatemala. The first published findings of elevated groundwater arsenic levels in Guatemala were not until 2007 when a well in the municipality of Mixco was found to have an average concentration of 15 µg/L (Bundschuh et al., 2012). Other studies in Guatemala have found arsenic in surface waters as a result of mining activities (Basu and Hu, 2010). Although surface water arsenic levels were all below 10 µg/L, the study found that individuals residing closer to the mine had higher levels of urinary arsenic compared to those further from the mine. In a more comprehensive study of the same mine site that included long-term monitoring, arsenic concentrations in surface water were found to be as high as 120 µg/L, and as high as 261 µg/L in groundwater wells (E-Tech International, 2010). The differences found in the two studies

could be explained by seasonal variation, with a greater infiltration of surface arsenic into the groundwater during the rainy season. Another study in Guatemala found a potential for ceramic pot filters to leach arsenic as a result of the arsenic contaminated soil used to produce them (Archer et al., 2011). While the full extent of the global arsenic problem is not yet clear, it is known that millions of people are currently exposed to levels that are known to be detrimental to human health. With the growth in the use of groundwater globally, it is increasingly important to ensure its safety.

The two most significant anthropogenic sources of arsenic pollution are the smelting of non-ferrous metals and the tailings from metal mining, with other sources including use of arsenical pesticides and wood preservatives, and the production of energy from fossil fuels (WHO, 2001). There has also been recent research into the possibility of groundwater sources being contaminated as a result of arsenic additives used in livestock feed (Fisher et al., 2011). While this process uses organic arsenic, the nontoxic form, it has the potential to transform to the inorganic form after being released to the environment (Jackson and Miller, 1999).

Arsenic is classified as a Group 1 carcinogen by the International Agency for Research on Cancer (IARC) (IARC, 2004), meaning there is sufficient evidence for carcinogenicity in humans. Arsenic ingestion through groundwater has been linked to skin as well as internal cancers including bladder, kidney, lung, and liver (Tseng, 1977; Chen et al., 1985; Wu et al., 1989). Critical health effects seen at the lowest doses of exposure are hyperpigmentation of the skin, keratosis and vascular complications (EPA, 1998).

The WHO provisional guidance value of 50 µg/L was lowered to 10 µg/L in 1993 to reflect research based evidence of arsenic's carcinogenic potential (WHO, 1993). This was followed by the EPA in 2001 who also established a 10 µg/L maximum contaminant level (MCL), the highest level legally permitted in drinking water in the United States (EPA, 2001). While a number of developing countries have maintained a national standard for arsenic in drinking water of 50 µg/L due to the difficulty of

achieving lower concentrations (Vasak et al., 2006), Guatemala has a maximum permissible limit of 10 µg/L (COGUANOR, 1999).

1.2 Study Location and Population

This study was performed in the Municipality of Chimaltenango, Guatemala, a 212 km^2 area with a population of 74,077 according to the 2002 census (XI Censo Nacional de Población y VI de Habitación, 2002). The city of Chimaltenango is the main urban center within the municipality of the same name, and Cerro Alto is one of several small rural communities surrounding the city. The municipality is located in the central highlands of Guatemala, with the city of Chimaltenango at an elevation of 1,786 meters. Unpublished data from the Cerro Alto community in 2009 estimated the population to be 1,283 and the area to be 4.5 km^2.

Guatemala as a whole is a very poor country having a gross domestic product roughly one-half that of other Latin American and Caribbean countries with 54% of the population living below the poverty line (CIA, 2012). Along with persistent poverty, Guatemala has the highest prevalence of chronic malnutrition in the Latin America and the Caribbean region at 44 percent in the year 2000 (Marini and Gragnolati, 2003), a condition that may aggravate the effects of arsenic exposure (WHO, 2001b).

In the study region there are three types of well systems. Artesian wells rely on groundwater under naturally high pressure and as a result require no mechanical pump to bring the water to the surface. Fully mechanical systems that do not have a pressurized groundwater source rely on a pump to transport the water from below ground to the surface, and constitute the majority of the well systems in the study region. Spring fed sources are available at the ground surface and require no extraction. Springs, however, are often located at the bottom of valleys and away from communities; as a result, a mechanical pump is required to bring the water from the surface to a storage tank and delivery system.

1.3 Previous Test Results

The impetus for this current study came from drinking-water testing for metals performed in Cerro Alto in 2009 as part of ongoing work in the community by the University of Illinois at Chicago Chapter of the organization Engineers Without Borders (EWB-UIC). Three samples were taken from the community's shallow well (28 meters depth, which is no longer in use), and five samples from a second deeper well (244 meters depth). Samples were shipped to the United States and analyzed by two independent laboratories. Results showed an average total inorganic arsenic concentration of 48.97 µg/L for the deep well and 55.15 µg/L for the shallow well. Since these levels were approximately five times in excess of the WHO and EPA standards, the results and their potential health implications were discussed both with the community and with Chimaltenango Ministry of Health officials. It was agreed that further testing of other wells in the area would be prudent to determine the extent of the contamination and how many people were affected. As a result, systematic sampling of drinking-water sources was performed in January 2012.

1.4 Study Objectives

The overall objective of this study was to characterize the presence of arsenic in groundwater drinking sources in the Municipality of Chimaltenango, Guatemala, and estimate the risk for adverse health outcomes for residents consuming that water. Specific objectives included measuring spatially representative arsenic concentrations, capturing well information including depth, flow rate, and operation, and conducting a risk assessment based on the measured arsenic levels.

2. METHODS

2.1 Sample Collection

Over a three day period, groundwater samples were collected throughout the Municipality of Chimaltenango. A total of 55 samples (14.5% blanks) were collected at sites reflecting spatial representation and the different types of source systems in use; sites were chosen in part due to convenience (e.g., well accessibility, road conditions, and time constraints). In the study region, the majority (N=38) of the wells were located within the city of Chimaltenango, while the remaining (N=24) were in rural communities outside of the city (see Figure 2, Appendix A). Samples were collected at 14 of the 24 (58.3%) rural wells and at 13 of the 38 (34.2%) urban wells. In all, 27 of the 62 (43.5%) wells in the municipality were sampled.

Samples were collected in 950 mL polyurethane bottles (VWR®, Radnor). The site of sample collection at each location was a water faucet used for drinking water purposes (see Figure 1). Faucets were turned on and water allowed to flow for two minutes to purge the system prior to sample collection following EPA guidance (EPA, 1982). New gloves were worn at each sampling site to avoid sample contamination. Collected samples were stored in a box and out of direct sunlight until shipment back to the United States for analysis. Duplicate samples were taken at the majority (N=20/27) of the sites. Eight blank samples were prepared in the field and stored and shipped alongside the other samples. The water used for the blanks was 500 mL bottles of Evian® water, the only non-domestic bottled water available in the area, which was purchased at the time of sampling.

Figure 1: Example Household Faucet.

2.2 Sample Analysis

Samples analysis for total inorganic arsenic was performed by an American Industrial Hygiene Association (AIHA) accredited laboratory (Travelers Insurance Risk Control Laboratory, Windsor, Connecticut) using modified EPA Method 200.8 "Determination of Trace Elements in Waters and Wastes by Inductively Coupled Plasma-Mass Spectrometry". The method reporting limit (MRL) for this analysis was 0.40 µg/L.

2.3 Supplemental Well Data Collection

At each sampling site a handheld GPS device was used to record latitude, longitude, and elevation (Trimble®, Sunnyvale). Well depth, well diameter, pumping schedule, and well type (i.e., artesian, mechanical or spring) were captured at most sites, typically reported by either the well system operator or someone else familiar with the system. Well diameter was measured directly when accessible. Flow rate was recorded at 10 of the 27 sites, again either as reported by someone knowledgeable of the water system or measured using a 5-gallon bucket and stopwatch.

2.4 **Risk Assessment Model**

The model developed by the National Academy of Sciences (1983) was used to determine the potential for adverse health effects for residents in Chimaltenango as a result of consuming groundwater. Risk calculations were made for both carcinogenic and noncarcinogenic effects as a result of exposures occurring at multiple life stages (0–1 year, 1–2 years, 2–11 years, 11–16 years, 16–21 years, 21–70 years), as well as cumulative lifetime exposure. Risks were calculated separately for Cerro Alto and the rest of the municipality based on the concentrations found in these two areas.

The EPA's Integrated Risk Information System (IRIS) publishes toxicity values based on studies of the dose-response relationship for many chemicals found in the environment. The reference dose (R*f*D), used for noncarcinogenic effects, is an estimate of the daily exposure likely to be without an appreciable risk of deleterious effects during a lifetime. The R*f*D established by IRIS for inorganic arsenic is 3E-4 mg/kg-d, based on a no observed adverse effect level (NOAEL) of 0.0008 mg/kg-d and uncertainty and modifying factors of three and one, respectively. The cancer slope factor (CSF) for inorganic arsenic is 1.5, and is used to estimate the risk of cancer associated with exposure to a carcinogenic substance. Per EPA's "Supplemental Guidance for Assessing Susceptibility from Early-Life Exposure to Carcinogens" (EPA, 2005), the CSF was multiplied by a factor of 10 for exposures occurring in the first two years, and multiplied by 3 for exposure occurring between the ages of two and sixteen. These multiplicative factors adjust for the generally higher cancer risks from early-life exposures than from similar exposures later in life.

The average daily dose (ADD), used for noncarcinogenic effects, and the lifetime average daily dose (LADD), used for carcinogenic effects, for the oral ingestion of drinking water was calculated using the following equation (EPA, 1992):

$$ADD/LADD = C*IR*EF*ED / BW*AT,$$

where;

- ADD/LADD is the estimated daily intake of arsenic (milligrams per kilogram per day);
- C is the concentration of arsenic in water (milligrams per liter);
- IR is the ingestion rate of water (liters per day);
- EF is the exposure frequency (days per year);
- ED is the exposure duration (years);
- BW is the body weight (kilograms);
- and AT is the averaging time (days).

The ADD/LADD was calculated using appropriate exposure parameters for each age group (EPA, 2011). Two values for each exposure parameter were used to calculate risk–the reasonable maximum exposure (RME), which is the upper bound of the exposure distribution (roughly the 95th percentile), and the central tendency exposure (CTE), which represents an average exposure. Specific values used for the exposure parameters and a further explanation of their selection can be found in Appendix C. The EPA's *Exposure Factors Handbook* (EPA, 2011) was used in determining the parameters. There is published literature (Kuzawa et al., 2012; Smith et al., 2003) that indicates both water ingestion rates and body weights are on average lower for Guatemalans; however the values from the *Exposure Factors Handbook* were used in all cases to remain consistent with standard risk assessment procedures.

3. RESULTS

3.1 Results of Arsenic Analysis

Arsenic concentrations for each site are reported in Table I. The concentrations ranged from below the MRL to 47.5 µg/L; six (22.2%) sites were below the limit of detection (LOD). Seven of the eight blank samples had non-detectable arsenic concentrations with one having a value of 0.43 µg/L. Among the samples with detectable amounts, all but one were below the 10 µg/L WHO and EPA standard. Only Cerro Alto had notably elevated arsenic levels, consistent with our initial 2009 findings.

On average, spring fed systems had the lowest concentrations, with all three sites samples having levels below the limit of detection. Excluding Cerro Alto, average arsenic concentrations in artesian and mechanical systems were similar, having concentrations of 0.89 µg/L and 0.87 µg/L, respectively. Urban systems had slightly higher concentrations (0.87 µg/L) compared to rural systems (0.67 µg/L) (again, excluding Cerro Alto), although the difference was not significant ($p = 0.37$).

TABLE I

GROUNDWATER ARSENIC CONCENTRATIONS IN CHIMALTENANGO, GUATEMALA

Site	Arsenic Concentration (µg/L)		
	Sample 1	Sample 2	Average
Monte Cristo	LOD	LOD	LOD
Agua Viva Puerto Rico	LOD	LOD	LOD
Puerto Rico	LOD	LOD	LOD
Fundación El Castillo	LOD	LOD	LOD
Hierba Buena	LOD	LOD	LOD
Residenciales Las Margaritas	LOD	—	LOD
Santa Isabel	0.47	0.44	0.46
Leonidas Mencos	0.44	0.47	0.46
El Rosario	0.52	0.51	0.52
San Rafael (well 1)	0.53	—	0.53
Residenciales La Cañada	0.55	—	0.55
Santa Isabel (well 2)	0.62	0.60	0.61
Bodega Municipal	0.64	0.60	0.62
Alameda A	0.69	0.72	0.71
Las Victorias	0.78	—	0.78
El Durazno	0.84	0.80	0.82
Hospital Nacional	0.85	0.90	0.88
Bosques del Porvenir	0.88	0.87	0.88
Alameda B 1 T. Concreto	0.90	—	0.90
San José Bethania	0.91	—	0.91
Cienaga Grande	1.00	1.10	1.05
Santa Ana Cooperativa	1.30	1.30	1.30
El Esfuerzo	1.40	—	1.40
Monte Cristo (instituto)	1.50	1.50	1.50
El Refugio	1.90	1.80	1.85
La Pedrera Municipal	2.10	2.10	2.10
Cerro Alto	46.0	49.0	47.5

* Limit of detection (LOD), 0.40 µg/L

3.2 **Results of Risk Assessment**

The calculated values for the hazard quotient and excess cancer risk are given in Tables II and III for each age group in both Cerro Alto and the rest of the Municipality of Chimaltenango. Highlighted values represent a risk likely to be associated with adverse health effects. For both RME and CTE conditions, the hazard quotients (HQs) are greater than one for all age groups in Cerro Alto. The excess cancer risks (ECRs) for Cerro Alto are elevated in all age groups under RME conditions and all ages except 16–21 years under CTE conditions. Using groundwater arsenic concentrations found in the rest of the municipality did not result in either the HQ or the ECR being elevated for any age under RME or CTE conditions. For ECR, the age groups represent the contribution of exposures that occur during that age period to the overall lifetime cancer risk. The sum of these individual risks gives the total lifetime cancer risk at 70 years of age (see Table IV). In Cerro Alto, under RME and CTE conditions, the lifetime ECR is significantly increased. In the rest of the municipality, using RME conditions, the lifetime ECR is elevated as well, but not significantly.

TABLE II

ECR AND HQ CALCULATIONS FOR RME

Age	0–1 year		1–2 years		2–11 years		11–16 years		16–21 years		21–70 years	
Population	Cerro Alto	Chimal	Cerro Alto	Chimal	Cerro Alto	Chimal	Cerro Alto	Chimal	Cerro Alto	Chimal	Cerro Alto	Chimal
HQ	19.59	0.39	11.15	0.22	6.86	0.14	4.87	0.10	4.53	0.09	5.57	0.11
ECR	1.26E-03	2.50E-05	7.17E-04	1.42E-05	1.19E-03	2.36E-05	4.69E-04	9.31E-06	1.45E-04	2.88E-06	1.75E-03	3.48E-05

TABLE III

ECR AND HQ CALCULATIONS FOR CTE

Age	0–1 year		1–2 years		2–11 years		11–16 years		16–21 years		21–70 years	
Population	Cerro Alto	Chimal	Cerro Alto	Chimal	Cerro Alto	Chimal	Cerro Alto	Chimal	Cerro Alto	Chimal	Cerro Alto	Chimal
HQ	6.27	0.10	3.61	0.06	2.24	0.04	1.39	0.02	1.35	0.02	1.98	0.03
ECR	4.03E-04	6.54E-06	2.32E-04	3.76E-06	3.88E-04	6.29E-06	1.34E-04	2.17E-06	4.35E-05	7.05E-07	6.24E-04	1.01E-05

TABLE IV

LIFETIME CANCER RISK

Exposure	RME		CTE	
Age	0–70 years		0–70 years	
Population	Cerro Alto	Chimal	Cerro Alto	Chimal
ECR	5.54E-03	1.10E-04	1.82E-03	2.96E-05

* Chimal stands for Chimaltenango (all sites in municipality minus Cerro Alto)

4. DISCUSSION

4.1 Location of Contamination

Only a single site, Cerro Alto, was found to have groundwater arsenic levels greater than the WHO and EPA standard of 10 µg/L. The levels found in Cerro Alto in the current study (47.5 µg/L) were similar to those found in our previous measurements (48.95 µg/L). All other locations tested had levels below exposure guidelines.

Given the close spatial proximity of urban sites to one another, it can be reasonably concluded that arsenic levels in the drinking water in the city of Chimaltenango do not exceed exposure guidelines. With the exception of Cerro Alto, rural locations sampled do not have elevated groundwater arsenic levels; however, it is possible that a site not tested may show elevated arsenic levels. The differences between the different types of systems in use were also not related to arsenic levels.

4.2 Potential Sources of Arsenic Contamination

While most arsenic contamination of groundwater drinking sources is the result of natural deposits, due to the isolated nature of contamination in the study location, other potential sources of contamination should be considered. The common anthropogenic sources of arsenic pollution such as smelting operations and mining are not present in this area, and arsenical pesticides or other agricultural sources would be minor and more widely distributed given the low-scale farming present in the region.

Recent studies have looked at arsenical compounds used in poultry feed and their potential to contaminate groundwater drinking sources (Denver et al., 2004; Fisher et al., 2011). Arsenical compounds may be used in chicken feed to prevent disease, improve growth, and improve pigmentation (Fisher et al., 2011). While the compounds fed to animals contain organic arsenic (the nontoxic form), arsenic in animal waste may be converted to the inorganic form in the environment (Gabarino et al.,

2001). The conversion process is believed to result from microbial and photo-degradation (Cortinas et al., 2006; Rosal et al., 2005). A recent review of published studies concludes that arsenic from animal waste has little, if any, effect on groundwater levels, even in shallow aquifers (Fisher et al., 2011). Surface water, however, can be contaminated by field runoff after a rainfall event. The availability of studies on the subject is limited, however, and cannot be ruled out as a possible source of groundwater contamination. Since a large-scale poultry facility is located adjacent to Cerro Alto, this potential source deserves further investigation.

A likely source may be derived from the fact that Cerro Alto is situated within an area of volcanic rock, and all other sites sampled are located outside of this geological zone. As shown in Figure 3, Appendix B, Cerro Alto is the only site sampled that lies in the tertiary volcanic rock zone. All other sites sampled are in the quaternary pumice fills and pyroclastic mantles region. It has been recognized that volcanic rocks can contribute to elevated arsenic levels in water, including in many areas of Central America (López et al., 2012; Bundschuh et al., 2012).

4.3 **Significance of Risk Assessment**

In reviewing the outcomes of the risk assessment, it can first be concluded that outside of Cerro Alto, there is no concern with the levels of arsenic causing either carcinogenic or noncarcinogenic adverse health outcomes. Although the cumulative lifetime excess cancer risk is elevated under RME conditions, 1.10E-04, it is only very slightly elevated. Within Cerro Alto, however, our risk assessment calculations indicate that there is increased risk for both noncarcinogenic effects and carcinogenic effects. Using both the RME and CTE exposure parameters, all age ranges had hazard quotients well exceeding one, and ECRs greater than 10^{-4} for nearly all groups as well. When added together, the lifetime excess cancer risk under RME conditions in Cerro Alto was 5.53E-03, or greater than 5 in 1000.

The highest risks for noncarcinogenic effects are among the younger age groups. While the HQ is not directly proportional to risk of developing an adverse health outcome, as values increase greater than one, there is generally increased risk and greater cause for concern. The ECR on the other hand does represent the probability that an exposed individual will develop cancer because of that exposure by age 70. The EPA considers an ECR less than 10^{-6} to be negligible and an ECR greater than 10^{-4} sufficiently large to make remediation advisable. An ECR in the range of 10^{-4} to 10^{-6} is considered acceptable (EPA, 2012). The risks calculated in this study represent values that should cause concern and prompt the discontinuation of drinking from the contaminated source until the arsenic levels can be brought down satisfactorily.

4.4 **Study Limitations**

Although the Municipality of Chimaltenango was thoroughly sampled for arsenic, the extent of the arsenic presence that was found in Cerro Alto has yet to be fully characterized. The site nearest to Cerro Alto, Bola de Oro, was not sampled and may likely have similarly elevated arsenic levels in its water. While multiple sites were sampled to the south, east, and west of Cerro Alto, no sites were sampled to the north; therefore, this region remains largely uncharacterized. The scope of our study was to characterize arsenic concentrations in the Municipality of Chimaltenango, and sites further north were located in a different municipality. Information collected, including well depth and flow rates were often reported by someone in those areas familiar with the system, and lacks completeness and definitive documentation to examine relationships with arsenic levels.

4.5 **Recommendations**

It is evident that the arsenic levels in the drinking water supply of Cerro Alto have the potential to cause adverse health effects. The first option should be to find an alternative water source free of arsenic. This strategy has the advantages of not having to maintain or pay for treatment processes. Although it has now been documented that other areas in the municipality are free of arsenic, acquiring access to another water source for the residents of Cerro Alto may not be feasible. This is due mainly to the economic and geographical constraints of the community. If treatment is thus deemed necessary, several low scale remediation strategies have been developed that may be appropriate in this context to reduce arsenic concentration in the water. The simplest of these is the use of zerovalent iron, the materials for which, any metallic iron, are typically easily accessible. Other options include photochemical/solar technologies, coagulation/flocculation and adsorption, and the use of natural adsorbents (Bundschuh et al., 2010).

Further arsenic sampling should also be done in Bola de Oro, the community that lies nearest to Cerro Alto, as this is a potential location to have similarly high arsenic levels. It would also be advisable to take samples to the north of Cerro Alto and in surrounding regions in the same geologic zone to determine if that is indeed the source of arsenic and help identify the extent of the contamination. The likelihood that the nearby poultry farm is the source of the contamination is uncertain, further information regarding arsenical compounds use in feed would help understand this aspect.

5. CONCLUSION

Our measurements confirmed the elevated arsenic levels in Cerro Alto, but did not find any other location in the Municipality of Chimaltenango that exceeded the WHO and EPA standard of 10 µg/L. Although without further sampling, a source of the arsenic cannot be confirmed, it appears likely that the presence of volcanic rock in Cerro Alto is the reason for the high levels found there. As this geologic zone extends to other municipalities in the region, it is possible that other populations are using water with similar arsenic levels as those in Cerro Alto. Risk calculations show that at the level of arsenic found in the drinking water of Cerro Alto, 47.5 µg/L, there are significant increases in the potential for noncarcinogenic and carcinogenic adverse health outcomes. Immediate measures need to be taken to reduce or eliminate the arsenic levels in the water of Cerro Alto. Low-tech options for doing so, such as the application of iron into the water, are feasible in this situation and likely to reduce arsenic levels. Further work will be done with public health officials and the community to better understand the health impacts of the arsenic contamination in Cerro Alto and determine what steps can be taken to reduce or eliminate the exposure.

6. REVIEW OF RELATED LITERATURE

6.1 Use of Groundwater Globally

Groundwater use is a major portion of the worldwide use of water in all its forms. It is estimated that 50% of the world's drinking water supply is provided by groundwater and that irrigation uses are responsible for 70% of the world's freshwater withdrawal (UN, 2003). Over the past half century, the use of groundwater has increased significantly due in large part to improvements in technology, making its extraction more affordable. While this trend has leveled in some parts of the world, in others, like South Asia and China, it continues to grow (Shah, 2005). A crucial resource to so many, it is important to understand the benefits that have led to its intensive use, and the challenges that need to be dealt with to ensure groundwater as a sustainable resource into the future.

The increase in groundwater use over the past half century is largely attributable to the economics of groundwater extraction in comparison to other methods such as the use of surface water. Several factors have decreased the cost of using wells, particularly for irrigation purposes, in many parts of the world. Improvements in well-drilling techniques as well as improved submersible pumps have reduced the time and costs traditionally associated with well usage (Llamas and Martínez-Santos, 2005). An additional benefit for farmers is the relative stability of groundwater compared to surface water that may vary in quantity from year to year based on climate (e.g., drought). Such benefits have contributed greatly in the progression of many farmers into middle class status (Llamas and Martínez-Santos, 2005). Shah (2005) estimates that this drastic increase in groundwater use has been more beneficial for the poor than all poverty eradications programs. While the benefits of groundwater use to the farmer and other users are clear, the environmental impact is also being felt in many parts of the world. As more and more groundwater is abstracted, the water table has the potential to deplete, in turn costing well users more as they have to drill deeper and deeper for water. The increase in its use has led

groundwater to be a chief component in poverty eradication around the globe, but effective management strategies need to be put in place to sustain the resource. Such strategies are yet realized in many developing countries where they are most needed.

6.2 **Worldwide Groundwater Arsenic Presence**

6.2.1 **Introduction**

Arsenic in the environment may be found in the atmosphere, soil, surface waters, and groundwater. Instances of elevated arsenic levels in groundwater have been found in many parts of the world. While the full extent of groundwater arsenic contamination and the populations exposed is still unknown, it is believed that approximately 140 million people are exposed to arsenic through drinking water at levels greater than 10 µg/L (Ravenscroft, 2007). While average levels in most countries are less than 10 µg/L, reported values range from undetectable to greater than 5000 µg/l (Mandal and Suzuki, 2002). In most areas where there is a high presence of groundwater arsenic, it is the result of a natural occurrence, whereas pollution sources such as from mining tend to be more localized and less common (Smedley and Kinniburgh, 2002). There are several parts of the world where groundwater aquifers contain concentrations of arsenic above 50 µg/l, including Argentina, Bangladesh, Chile, northern China, Hungary, India (West Bengal), Mexico, Romania, Taiwan, and the southwest United States (Smedley and Kinniburgh, 2002). Table V shows the ranges of arsenic in some of these higher concentration areas.

TABLE V

ARSENIC CONCENTRATIONS AROUND THE WORLD (SMEDLEY AND KINNIBURGH, 2002)

Country/Region	Area (km^2)	Population Exposed	Concentration range (µg/l)
Bangladesh	150,000	$3x10^7$	<0.5 to 2500
West Bengal	23,000	$6x10^6$	<10 to 3200
Taiwan	4000	105	10 to 1820
China:			
Inner Mongolia	30,000	—	<1 to 2400
Xinjiang	38,000	—	40 to 750
Hungary, Romania	110,000	29,000	<2 to 176
Argentina	106	$2x10^6$	<1 to 5300
Chile	125,000	500,000	100 to 1000
South-west USA:			
Arizona	200,000	$3.5x10^5$	up to 1300
California	5,000	—	<1 to 2600
Nevada	1,300	—	up to 2600
Mexico	32,000	$4x10^5$	8 to 620

6.2.2 **Bangladesh**

The contamination of drinking water with arsenic in Bangladesh is the most widespread arsenic exposure in the world. The arsenic contamination originally came to light in the 1980s due to the increased use of tube-wells installed with a goal of increasing access to “safe” drinking water (Smith et al., 2000). Shortly after, in 1983, the first cases of skin cancer related to arsenic were identified. In 1998, the British Geological Society performed an extensive survey of the country’s wells and found that 35% had arsenic concentrations above 50 µg/l and 8.4% had levels above 300 µg/l (Smith et al., 2000). In 2000 it was estimated that between 35 and 75 million people in Bangladesh were at risk (Smith et al., 2000). Although steps have been taken in recent years including increased monitoring and treatment options, it is a problem that is still very present for the millions affected.

6.2.3 **Central America and Mexico**

Arsenic has been found at levels greater than 10 µg/L in groundwater in parts of Mexico, El Salvador, Nicaragua, and Guatemala. It is believed that many of these occurrences are due to the presence of volcanoes and volcanic rocks that are often rich in arsenic and leach into the groundwater (Bundschuh et al., 2012). In Mexico, arsenic has been found in 13 of 31 states, with an estimated 450,000 people exposed to concentrations greater than 50 µg/L (Castro de Esparza, 2006). Arsenic has also been detected in surface waters and groundwater in El Salvador, where it is naturally occurring and believed to be resultant from the many volcanoes in the region and other geothermal surface manifestations (Bundschuh et al., 2012). In Nicaragua, arsenic was first detected in May of 1996 in the community of El Zapote, with an artesian well having a measured arsenic concentration of 1320 µg/l (Bundschuh et al., 2012). Further studies have determined that the contamination is a problem that spreads into surrounding communities as well. Studies performed between 1996 and 2001 in the region around El Zapote found 33% of the samples had arsenic concentrations greater than 10 µg/L with a maximum concentration of 289.2 µg/L (Bundschuh et al., 2012).

The first findings of elevated groundwater arsenic levels in Guatemala came in 2007 when a well in the municipality of Mixco was found to have an average concentration of 15 µg/ l (Bundschuh et al., 2012). A previous study of the village of San Sebastian de Lemoa in the Guatemalan Highlands (Elmore et al., 2005) found no instances of arsenic above 10 µg/l, the limit of detection on their equipment. Other arsenic studies have been done in Guatemala, but not on naturally occurring arsenic in groundwater. The most well-known of these is that of the discharge waters from the Marlin Mine. In a study performed on residents in the area who consume that water (Basu and Hu, 2010), researchers found that individuals living closer to the mine had higher levels of urinary arsenic than individuals living further away, but could not conclude if these elevated levels pose a significant health threat. Lastly, in a

study from the area of Antigua, Guatemala, researchers found that ceramic pot filters used to treat drinking water leached arsenic, a result of contaminated soils in the area (Archer et al., 2011).

6.3 **Sources of Arsenic**

6.3.1 **Natural Sources of Arsenic**

Arsenic is present as a major constituent in more than 200 minerals, the most abundant being arsenopyrite (Smedley and Kinniburgh, 2002). In igneous, metamorphic, and sedimentary rocks, arsenic concentrations tend to be less than 10 mg/kg (Ure and Berrow, 1982; Smedley and Kinniburgh, 2002; Webster, 1999). In soils, an average worldwide concentration was estimated by Boyle and Jonasson (1973) to be 7.2 mg/kg. A higher concentration was estimated by Ure and Barrow (1982) at 11.3 mg/kg, although individual locations may have much higher values as evidenced by Dudas (1984), who reported concentrations as high as 45 mg/kg in pyrite-rich shales in Canada. The levels of arsenic in groundwater are related to the geochemical environment and the hydrogeology of the area; however, are not necessarily linked to high arsenic concentrations in the source rocks (Smedley and Kinniburgh, 2002). In Central America, most cases of arsenic contamination of water sources have been linked to the highly present volcanic rocks of the region (López et al., 2012; Bundschuh et al., 2012). While volcanic rocks may not necessarily have higher amounts of arsenic compared to other rock types, the arsenic that is present in the rocks is more readily transferred to the water (Spencer, 2002).

6.3.2 **Anthropogenic Sources of Arsenic**

Arsenic is produced and used commercially, with 97% of the arsenic ending up in manufactured goods and 3% as metallurgic additives (Mandal and Suzuki, 2002). In industry, a significant source is the smelting of non-ferrous metals and the production of fossil fuels (WHO, 2001). It is estimated that smelting processes are the single largest anthropogenic contributor to arsenic pollution (Chilvers and Peterson, 1987). Arsenic is also used as a cotton desiccant and a wood preservative. In agriculture, arsenic has traditionally been used for the production of pesticides, herbicides, and insecticides, although use has declined in recent years (Mandal and Suzuki, 2002). Arsenic contamination resultant from the tailings of metal mining, particularly gold, has also been reported in several areas such as topsoil, surface waters, and groundwaters (Basu and Hu, 2010).

Another potential source of environmental arsenic contamination is the use of arsenical additives in poultry feed to prevent disease, promote growth, enhance feed utilization, and improve meat pigmentation (Fisher et al., 2011). While the arsenic additive is in the organic form and nontoxic, it has been shown to transform to the inorganic form in the environment, typically through microbial processes (Garbarino et al., 2001; Stolz et al., 2007). In areas where these arsenical additives are used, studies have reported soil arsenic levels higher than the background levels (Kingery et al., 1994; Han et al., 2000), and have shown that the arsenic can accumulate over time eventually reaching levels requiring remediation (Fisher et al., 2011). Few studies have looked at groundwater arsenic concentrations in areas where there is use of arsenical additives in poultry feed, but those that have, have found no clear association between the two (Focazio et al., 2000; Denver et al., 2004); although it is difficult to differentiate background versus pollutant contributions.

6.4 Oral Exposure Health Outcomes

6.4.1 Introduction

Arsenic is an extremely toxic naturally occurring metal that can negatively impact human health in many ways. The health effect of the most concern is carcinogenicity (Raitnake, 2003), and it has been designated by IARC as a Group 1 carcinogen, meaning there is sufficient evidence linking it to cancer (IARC, 2004). Arsenic is present in two oxidation states in the environment: arsenite or As(III), and arsenate or As(V). According to Raitnake (2003), arsenite is 60 times more toxic than arsenate. In water, arsenic is found mainly in the inorganic form, whereas the organic form is more prevalent in seafood. The organic form is less harmful and readily eliminated from the body (WHO, 2010). Organic arsenic exposure will not be discussed in this review.

6.4.2 Death

Death from oral ingestion of arsenic can be an acute effect, the result of either fluid loss and circulatory collapse or tissue damage, or a chronic effect, typically from cardiovascular disease or cancer (ATSDR, 2007). Many of the acute cases of death are the result of intentional poisoning (Levin-Sherz et al., 1987; Saady et al., 1989; Uede and Furukawa, 2003); however, there are also reported cases of ingestion of drinking water with high enough levels of arsenic to lead to death. Armstrong et al. (1984) described an incident where two family members died as a result of drinking water with an arsenic concentration of 108 ppm for one week. Another case (Zaldivar et al., 1981) involved a 22-year-old man who had ingested arsenic-contaminated water over a 14-year period at an estimated 0.25 ppm. After suffering bouts of abdominal pain and vomiting for years, the patient suffered increased incidents in combination with constipation, jaundice, and fever. He died seven days after admission to a hospital and an autopsy revealed pulmonary and liver damage. In four cases where the ingested arsenic amount was known, the lethal dose ranged from 22–121 mg As/kg (ATSDR, 2007).

6.4.3 **Respiratory Effects**

Respiratory effects have been found in cases of acute arsenic poisoning by the oral route, with symptoms including respiratory distress, bronchitis, and pulmonary edema (Civantos et al., 1995; Fincher and Koerker, 1987). Respiratory effects have also been noted in cases of chronic exposure to arsenic at high levels, with symptoms presenting as bronchitis and chronic cough (Milton and Rahman, 2002; Tsai et al., 1999). In West Bengal, India, von Ehrenstein (2005) found decreased lung function among those who had arsenic exposure through drinking water at levels less than 500 µg/l. Reductions in forced expiratory volume in 1 second (FEV1) and forced vital capacity (FVC) were observed in males who had also shown other signs of arsenic poisoning. Another study by Ahmad et al. (1997) in Bangladesh found that among those with chronic arsenic poisoning in the study population, 25% had cough as one of their symptoms. All individuals had been using drinking water with an arsenic concentration above the WHO limit of 10 µg/L. Ingestion of arsenic at low doses has not been widely associated with respiratory effects (ATSDR, 2007).

6.4.4 **Cardiovascular Effects**

Both acute and chronic cardiovascular effects due to arsenic ingestion often include myocardial depolarization and cardiac arrhythmias (Cullen et al., 1995; Goldsmith and From, 1986). A case study reported by Little et al. (1990) notes observations of serious ventricular arrhythmias and other cardiovascular effects including QT-U interval prolongation in two individuals as a result of arsenic poisoning. Further, a dose-response relationship was found between QT prolongation and water arsenic concentration with an increased sensitivity among women (Mumford et al., 2007). Arsenic exposure can also lead to damage to the vascular system and a particular manifestation known as “Blackfoot Disease” (ATSDR, 2007). In a study by Tseng (1977) in an area of Taiwan with well water arsenic concentrations of 0.01–1.82 ppm, the investigator found a dose-response relationship for Blackfoot Disease and arsenic,

and an increased susceptibility of men over women. Another study in Bangladesh looking at arsenic exposure through well-water consumption and hypertension found a clear dose-response relationship between the two (Rahman et al., 1999). These results were similar to those of Chen et al. (1995), whose study found a 1.5 fold increase in hypertension among those exposed to arsenic-contaminated water of 0.7–0.93 mg/L compared to those not exposed. A study by Zierold et al. (2004) found that individuals exposed to arsenic concentrations in their well water of greater than 2 µg/L were more likely than those with levels less than 2 µg/l to report high blood pressure, circulation issues, and to have had bypass surgery.

6.4.5 **Hematological Effects**

At acute and intermediary levels of exposure, both anemia and leukopenia have been reported. Franzblau and Lilis (1989) reports two case studies of individuals who consumed well water contaminated with arsenic at levels as high as 10,900 µg/L. One of the two individuals was noted to have anemia and leukopenia. Armstrong et al. (1984) reports of a case where nine family members suffered subacute arsenic poisoning, seven of whom later developed leukopenia. Similar results have been found in chronic cases as well, such as Hopenhayn et al. (2006) who found that pregnant women who consumed water with an arsenic concentration of 40 µg/L were more likely to be anemic than those women consuming arsenic-free water. It was also reported that the prevalence of anemia increased as the pregnancy progressed.

6.4.6 **Gastrointestinal Effects**

In nearly all cases of acute arsenic exposure and in many chronic exposure cases as well, gastrointestinal symptoms including nausea, vomiting, diarrhea, and abdominal pain are present (ATSDR, 2007). Arsenic doses below 0.01 mg As/kg/day typically do not have observable gastrointestinal effects associated with them (ATSDR, 2007). In instances of acute exposure, more severe

gastrointestinal symptoms have been reported (Civantos et al., 1995; Fincher and Koerker, 1987; Levin-Scherz et al. 1987).

6.4.7 **Hepatic and Dermal Effects**

In a study of residents of West Bengal, India consuming drinking water with arsenic levels 0.2–2 mg/L, researchers found increased incidents of hepatic damage (Guha Mazumder, 1998). This is consistent with other studies that have noted swollen and tender livers associated with arsenic ingestion (ATSDR, 2007). Elevated levels of hepatic enzymes were found in individuals at arsenic concentrations as low as 0.1 mg/L (Hernández-Zavala, 1998).

A common and widely reported effect of arsenic ingestion is pigmentation changes and other dermal effects particularly to the palms and soles of feet (ATSDR, 2007). Cutaneous effects, in particular skin lesions, are often one of the first symptoms of long-term arsenic exposure. This can take the form of pigmentation changes often on the face, neck, and back; and palmar and plantar keratosis, hard patches on the hands and soles of the feet, respectively. Due to their early presence in individuals suffering from chronic arsenic intoxication, clinical diagnosis is often based on dermal effects (Raitnake, 2003; ATSDR 2007).

Evidence for an association between consumption of arsenic contaminated water and dermal lesions comes from a number of epidemiological studies. A study performed in a series of villages in Bangladesh (Ahsan et al., 2000), found a three-time greater risk for developing skin lesions compared with the exposure estimates. This study also found that 13.9% of the cases of skin lesions were in patients drinking water below the 10 µg/L EPA and WHO standard. Another study (Rahman et al., 2005) in the nearby area of West Bengal, India, where more than 90% of the wells had arsenic concentrations greater than 10 µg/L, similarly found an elevated prevalence of skin lesions among residents. A comparative study of two villages in Chile (Borgoño et al., 1980) as well as one in Mexico (Cebrián et al.,

1983) both found a positive association between increased levels of arsenic in water sources and the manifestation of dermal symptoms including pigmentation changes, and palmoplantar keratosis. A number of other studies have affirmed these findings (Ahmad et al., 1997; Guha Mazumder et al., 1998).

6.4.8 **Neurological Effects**

Several studies have reported neurological symptoms as a result of both acute high-dose exposure and repeated exposures at lower doses. Armstrong et al. (1984) describes an incident of acute arsenic poisoning among a family of nine people, four of which developed encephalopathy. Bartolomé et al. (1999) also described a case of acute arsenic poisoning where the patient developed neurological deterioration and impairment of consciousness. Other common symptoms in cases of acute ingestion include headache, blurred vision, and confusion (Armstrong et al., 1984; Uede and Furukawa, 2003; Vantroyen et al., 2004). Similar symptoms are also common in cases of chronic exposure at lower doses. Several case studies have reported signs of peripheral neuropathy (Chakraborti et al., 2003; Franzblau and Lilis, 1989). Symptoms usually include a tingling, numbness, weakness, and pain in the lower extremities that advances upward through the thighs and upper extremities. In some cases, wrist or foot drop was noted. With chronic exposure to low concentrations of arsenic, neurological effects are typically not found when doses are 0.006 mg As/kg/day or less (ATSDR, 2007).

Recent studies have begun to look at the association between arsenic exposure and effects to the intellectual abilities of children. Wasserman et al. (2004) found that intellectual scores for children using drinking water with an arsenic concentration greater than 50 µg/L were significantly lower than children whose water had less than 5.5 µg/L of arsenic. A study by von Ehrenstein et al. (2007) found small decrements in intellectual testing in school-aged children associated with arsenic concentrations in urine, but no associations between long-term water concentrations and intellectual function. Another study out of Bangladesh by Wang et al. (2007) concluded that the intelligence and growth of children

can be affected by consumption of high concentrations of arsenic. The authors compared IQ tests and anthropometric measurements of children in villages with arsenic in the drinking water to unexposed villages.

6.4.9 **Reproductive Effects**

Several studies have linked chronic arsenic exposure through drinking water to a number of reproductive effects. In a study comparing a group with chronic arsenic exposure to a non-exposed group, Ahmad et al. (2001) found that spontaneous abortion, stillbirth, and preterm birth rates were significantly higher in the exposed group relative to an unexposed group. Similar findings were reported by Milton et al. (2005) who found excess risk of spontaneous abortion and stillbirth among those chronically exposed to higher arsenic concentrations in their drinking water. The author also concluded that chronic arsenic exposure may increase the risk of fetal and infant death. An association between high chronic arsenic exposure during pregnancy and increased risk of still birth was also found by von Ehrenstein et al. (2006).

6.4.10 **Cancer**

Arsenic is an IARC group 1 carcinogen (IARC, 2004), meaning there is sufficient evidence to be classified as carcinogenic to humans. This classification is supported by a wealth of literature correlating arsenic exposure, including through drinking water, to various cancers including skin, bladder, and lung. A survey of an area of Taiwan was performed (Tseng, 1977) where residents have long-term arsenic exposures. Results showed increased arsenic content in the water led to an increased prevalence of skin cancer. Arsenic concentrations in the study area ranged from 0.01 ppm to over 1.00 ppm. Along with many of the other symptoms herein described, a case study of a 35-year-old patient exposed to arsenic occupationally and through drinking water (Cöl et al., 1999) was reported to have Bowen's disease, a known precursor to development of skin cancer. In contrast to the positive correlation between skin

cancer and arsenic found in many other studies like those mentioned here, a US based study (Morton et al., 1976) found no correlation between the two. However, water arsenic concentrations were much lower than in other studies, average of 8.6 ppb, and the author concluded that their study does not necessarily contradict the positive association found in other studies.

An association between lung cancer and "low to moderate" arsenic concentration in drinking water was found in a study (Heck et al., 2009), although the author recommends further large-scale studies to be performed to affirm that conclusion. Arsenic concentrations in the study ranged from 0.1 to 749 µg/L. A retrospective study of cancer cases in Taiwan (Chen et al., 1986) found a positive dose-response relationship between arsenic levels in drinking water from wells ranging from 0.35 to 1.14 ppm, and bladder, lung and liver cancer.

6.5 **Remediation/Mitigation Strategies**

6.5.1 **Introduction**

With the adoption of the current provisional guideline for arsenic in drinking water of 10 µg/l in 1993 by the WHO (WHO, 1993), many parts of the world that before were in compliance found themselves with arsenic levels above the new guideline. The US EPA, which adopted the same standard in 2001 (EPA, 2001) estimated that in the United States, 97% of the water systems out of compliance were small systems with less than 10,000 people (EPA, 2002). Today there are many options for the removal of arsenic from water, many of which were developed for use in public drinking water systems and treatment plants in the United States and other developed countries. The fact that many parts of the world affected by arsenic contaminated groundwater are in areas not supplied by centralized water systems has led to the need to adjust existing technologies to be applicable on a small-scale with

reduced cost, as well as research into appropriate new technologies. The problem can be particularly difficult for developing countries that lack the resources to reduce arsenic levels below 10 µg/l. As a result, many have decided to leave national arsenic standards at the already established 50 µg/l (Appelo, 2006).

There are five principle arsenic mitigation strategies (EPA, 2003); abandonment, seasonal use, blending, sidestream treatment, and treatment.

Abandonment is when the water from an arsenic contaminated source is no longer used and residents switch to other drinking water sources. This is the simplest strategy for arsenic mitigation, especially if arsenic-free sources are readily available. Small communities that do not have the ability to switch to another existing source can either install a new well or other type source, or purchase water from neighboring areas. Even if drilling a new well is financially viable, it may produce similar arsenic levels if being drilled into the same aquifer.

Seasonal use refers to the changing of source use from full-time to seasonal or occasional use. When the high-arsenic source is used it would have to be blended with other sources free of arsenic to lower the overall arsenic level in the water mixture.

Blending is the dilution of the arsenic levels in the source water by combining it with other water sources which are free of arsenic.

Sidestream treatment is treatment of only a portion of the arsenic-contaminated water and subsequently blending it with the untreated portion to lower the overall arsenic level. If capable of treating the water to acceptable levels only using sidestream treatment, it may be more economical than full treatment of the water source.

Treatment of the water is the processing of the water using any of several technologies to remove arsenic to below established limits. There are many conventional treatment technologies as well as alternative options that may be more suitable for specialized applications.

6.5.2 **Conventional Treatment Technologies**

The EPA has developed detailed reviews of technologies for US drinking water systems (EPA, 2000; EPA 2003; EPA, 2005b) that are suitable for the removal of arsenic. Treatment technologies can be grouped into four categories: precipitative processes, adsorption processes, ion exchange processes, and separation or membrane processes.

Precipitative processes involve converting the soluble arsenic to an insoluble form and allowing it to fall out of solution. Precipitative processes include coagulation/filtration, iron/manganese oxidation, and lime softening. These processes can have arsenic removal efficiencies of greater than 90% but are often only capable of removal of As(V) and not As(III). Therefore pretreatment processes are often required to convert all the arsenic to the pentavalent form.

Adsorption processes work by passing water through packed adsorptive media that remove the contaminant. In the case of arsenic the adsorptive media is often activated alumina. This method similarly only works for As(V) but has shown to have removal efficiencies of greater than 98%.

Ion exchange is a method by which arsenic-contaminated water is passed over a media containing a large amount of ionizable groups. The As(V) ions are exchanged for the ions on the media thereby reducing the arsenic level in the water.

Membrane processes describe any of a number of processes in which the arsenic-contaminated water is passed through a barrier that is capable of removing the arsenic from solution. This can be in the form of a filter, of which there are several types depending on the pore size. Reverse osmosis is a

special type of membrane technology that produces “nearly pure” water, having a removal efficiency of greater than 97% for As(V) and 92% for As(III).

Several of these treatment technologies can be adapted for point-of-use applications, including activated alumina, reverse osmosis, and iron-based sorbents. Limitations to these approaches are their inability to convert As(III) to As(V), thereby reducing the efficiency of such systems which in turn may not be capable of reducing arsenic concentrations to acceptable levels.

6.5.3 **Alternative Treatment Technologies**

Due to the cost associated with most conventional technologies, these are often not viable options for areas of the world with arsenic contamination that do not have large-scale public water systems (Bundschuh et al., 2010). Recent efforts have focused on developing new arsenic remediation strategies or modify existing strategies for small-scale usage.

In-situ remediation strategies are those that seek to remove arsenic from water prior to pumping it out of the ground. The advantages of in-situ strategies are the elimination of the need for a treatment facility and the absence of treatment waste or sludge. Lindberg et al. (1997) further highlight some advantages of in-situ remediation as water conservation, low energy consumption, and the lack of need for continuous maintenance. Such treatments however are not household level technologies. One of the most efficient methods of in-situ removal is with permeable reactive barriers (PRB) (Litter et al., 2010). In this process, iron-oxide materials are placed in the ground and water passing through is removed of arsenic. Drawbacks to PRBs are long-term durability, corrosion, and a decrease in the permeability of the PRB (Litter et al., 2010). This technology is often used with zerovalent iron to increase removal efficiency (Gibert et al., 2003; Su and Puls, 2003).

Use of zerovalent iron is a technology that can be applied at the household level and has several advantages compared to other adsorption methods, including its low cost and the wide availability of necessary materials. The process itself can oxidize As(III) to As(V), thereby eliminating the pre-oxidation need, and the iron corrosion products are strong arsenic adsorbents (Bundschuh et al., 2010). Material availability comes from the ability to use any metallic iron such as packing wire or steel wool (Bundschuh et al., 2010). Laboratory testing has proven these methods effective at removing arsenic (Su and Puls, 2001). In San Juan, Argentina, a similar method was applied that can work well in small-scale applications, and is able to get removal efficiencies of greater than 90% (Litter et al., 2010). The use of zerovalent iron has also been shown to be improved by the use of solar technologies (Bundschuh et al., 2010).

The principal benefit of solar technologies is the ability of solar light to facilitate the oxidation of As(III) to As(V), making several removal technologies more efficient (Bundschuh et al., 2010). The SORAS (solar oxidation and removal of arsenic) model is one method that has been used in Bangladesh and India with removal efficiencies of between 50% and 70% (Bundschuh et al., 2010), as well as in Argentina (Garcia et al., 2004), where it has shown to be effective, although with the author noting the complexities in arsenic chemistry that make the efficiency unpredictable. In other areas where this method has been tested, results were better. In Chile, removal efficiencies of nearly 95% were achieved (Lara et al., 2006). The system works by adding water to a transparent PET bottle with the addition of lemon juice and Fe(III) if not naturally present in the water, and left in the sun in the vertical position to allow the precipitate to be removed (Bundschuh et al., 2010).

In Peru, a low-cost arsenic removal system was developed for households using the product ALUFLOC, which is a mixture of oxidant, activated clays, and coagulant (Litter et al., 2010). At a concentration of arsenic in the raw water of 1000 μg/L, this technology can achieve 98% efficiency

(Bundschuh et al., 2010). Another home-scale method was developed in Argentina using an activated alumina hydroxide hydrogel (Bundschuh et al., 2010). The hydrogel can be applied directly to the water, and testing has shown it to be able to remove arsenic to levels below 10 µg/L (Litter et al., 2010). The hydrogel was estimated to be financially suitable if produced for 30,000 residents, but in smaller applications it may not be affordable (Bundschuh et al., 2010). An adsorbent called goethite was used in Mexico and showed the potential to lower arsenic concentrations below 10 µg/L, although some results were higher (Bundschuh et al., 2010). It is not clear whether this is more suitable for a household or for a treatment plant. Another application suitable for the community level but likely too expensive for individual households is polymer-supported Fe(III) oxide particles used as a sorbent material (Bundschuh et al., 2010).

Another feasible home-scale solution for people in low income or remote areas is the use of natural soils and sediments as adsorbent materials. The primary benefit of such solutions is the cost; however, if the soils of the area are polluted as well with arsenic, this is not an effective method (Bundschuh et al., 2010). In Mexico (Romero et al., 2004) removal efficiencies of 90% were achieved; however, removal efficiencies have been highly variable depending on the soil and water conditions (Mellano and Ramirez, 2004).

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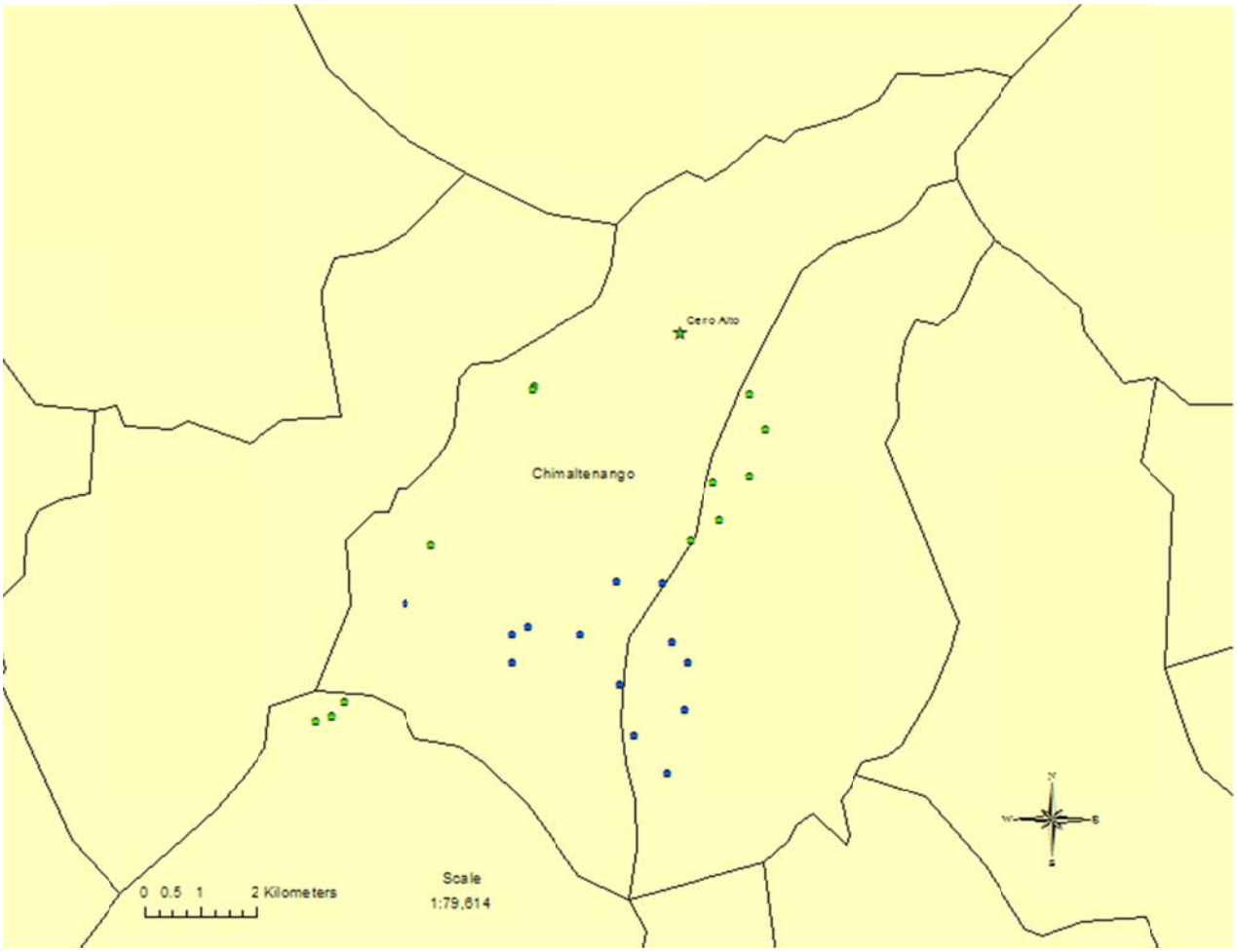
APPENDICES

APPENDIX A

Map of Sampling Sites



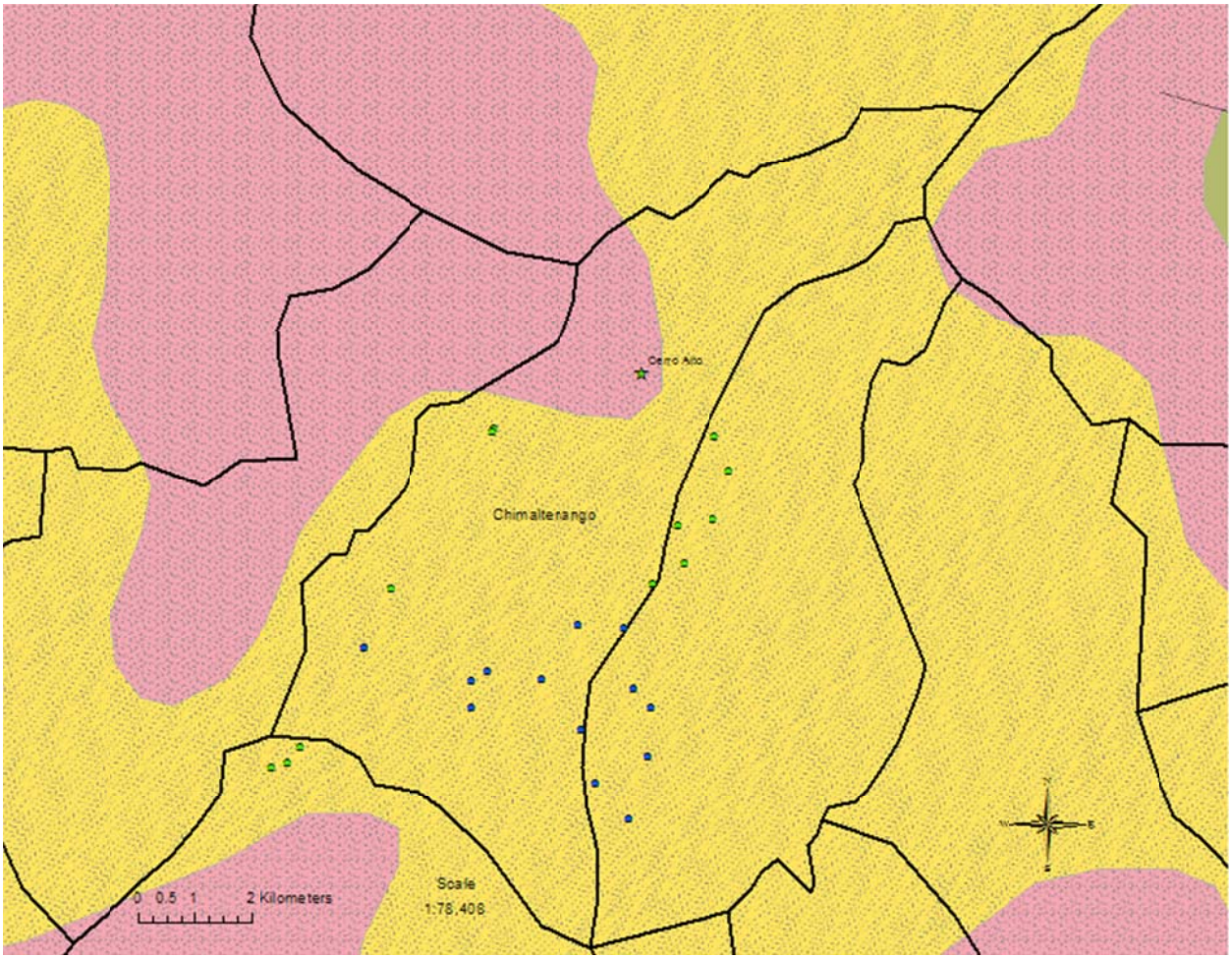
Urban Sites

Rural Sites

Figure 2: Map of Sampling Sites

APPENDIX B

Map of Sampling Sites with Geologic Overlay



Urban Sites

Rural Sites

Tertiary Volcanic Rock

Quaternary Pumice Fills and Pyroclastic Mantles

Figure 3: Map of Sampling Sites with Geologic Overlay

APPENDIX C

Risk Assessment Exposure Parameters

Concentration: In the risk calculations for Cerro Alto, since there is only one site of sampling results, the average concentration of arsenic found in the community, 0.0475 mg/L, was used for both RME and CTE conditions. In calculations for the rest of the municipality, the 95% upper confidence limit on the mean, 9.4209E-04, was used for RME conditions, and the average concentration, 7.7E-04, was used for CTE conditions. The 95% upper confidence limit on the mean was calculated using the EPA's ProUCL software.

Ingestion Rate: While there is some published data (Makkes et al., 2010) indicating Guatemala has lower ingestion rates than in the United States, values used were taken from the *Exposure Factors Handbook* as they represent a more conservative estimate and are consistent with other risk assessments. For RME conditions the 95th percentile values were used, and for CTE conditions the mean values were used. Where age groups in the *Exposure Factors Handbook* did not match designated age groups for the risk assessment, a weighted average of the values for the different groups was used.

Exposure Frequency: Exposure frequency was assumed to be 350 days per year.

Exposure Duration: The exposure duration was equal to the amount of years of the exposed age group (e.g. 11–16 years = 5 years)

Body Weight: Multiple studies (Kuzaka et al., 2012; Smith et al., 2003) provide data on body weight in Guatemala. These values are less than US body weights and thus more conservative, however the values from the *Exposures Factors Handbook* were used to be consistent with risk assessment guidelines. The mean values were used for both RME and CTE.

Averaging Time: For noncarcinogenic effects, the averaging time is equal to the duration of the exposed age group in days (e.g. AT (for 11–16 years) = 5 years*365 days/year = 1825 days). For carcinogenic effects, the averaging time is equal to 70 years expressed in days (25550 days).

APPENDIX C (continued)

TABLE VI

INGESTION RATE AND BODY WEIGHT EXPOSURE PARAMETERS

	0–1 year		1–2 years		2–11 years		11–16 years		16–21 years		21–70 years	
	RME	CTE	RME	CTE	RME	CTE	RME	CTE	RME	CTE	RME	CTE
IR (L/day)	1.011	0.324	0.837	0.271	1.148	0.374	1.821	0.520	2.134	0.638	2.935	1.043
BW (kg)	7.83333		11.4		25.4		56.8		71.6		80	

APPENDIX D

Dose Calculations for Risk Assessment

TABLE VII

DOSE CALCULATIONS FOR RME

Age	0–1 year		1–2 years		2–11 years		11–16 years		16–21 years		21–70 years	
Population	CA	Chimal	CA	Chimal	CA	Chimal	CA	Chimal	CA	Chimal	CA	Chimal
ADD (mg/kg-d)	5.88E-03	1.17E-04	3.34E-03	6.63E-05	2.06E-03	4.08E-05	1.46E-03	2.90E-05	1.36E-03	2.69E-05	1.67E-03	3.31E-05
LADD (mg/kg-d)	8.40E-05	1.67E-06	4.78E-05	9.48E-07	2.65E-04	5.25E-06	1.04E-04	2.07E-06	9.70E-05	1.92E-06	1.17E-03	2.32E-05

TABLE VIII

DOSE CALCULATIONS FOR CTE

Age	0–1 year		1–2 years		2–11 years		11–16 years		16–21 years		21–70 years	
Population	CA	Chimal	CA	Chimal	CA	Chimal	CA	Chimal	CA	Chimal	CA	Chimal
ADD (mg/kg-d)	1.88E-03	3.05E-05	1.08E-03	1.76E-05	6.71E-04	1.09E-05	4.17E-04	6.76E-06	4.06E-04	6.58E-06	5.94E-04	9.63E-06
LADD (mg/kg-d)	2.69E-05	4.36E-07	1.55E-05	2.51E-07	8.63E-05	1.40E-06	2.98E-05	4.83E-07	2.90E-05	4.70E-07	4.16E-04	6.74E-06

APPENDIX E

Complete Results of Well Information

TABLE IX

WELL SYSTEM CHARACTERISTICS

Site Name	Urban/Rural	System Type	Well Depth	Well Diameter	Flow Rate	Pump Schedule			Elevation	Well Elevation
			m	m	L/min	h/d	d/wk	h/wk	m	m
El Rosario	Rural	Mechanical	400	—	606	24	7	168	1775.119	1375.119
Cienaga Grande	Rural	Mechanical	183	0.3048	—	10	6	60	1782.302	1599.302
El Durazno	Rural	Mechanical	132	0.3048	102	8	5	40	1765.874	1633.874
Santa Isabel	Rural	Artesian	7	1	—	24	7	168	1715.354	1708.354
Santa Isabel second well	Rural	Mechanical	—	—	—	12	7	84	1772.863	—
Bosques del Porvenir	Rural	Mechanical	91	0.3048	—	3	7	21	1742.041	1651.041
Leonidas Mencos	Urban	Mechanical	150	0.3048	—	16	7	112	1839.809	1689.809
Bodega Municipal	Urban	Mechanical	200	0.3048	—	24	7	168	1798.785	1598.785
Hospital Nacional	Urban	Mechanical	72	0.2540	—	24	7	168	1778.144	1706.144
Monte Cristo (instituto)	Rural	Artesian	96	1	—	3	7	21	1810.346	1714.346
Monte Cristo	Rural	Spring	—	—	26	—	—	—	—[a]	—
El Refugio	Rural	Mechanical	335	0.3048	235	3	7	21	1894.22	1559.220
Agua Viva Puerto Rico[b]	Rural	Artesian/Mech.	30.5, 30.5, 75	0.9, 0.9, 0.3	—	—	—	—	2055.87, 2040.099, 2041.532	2025.37, 2009.599, 1966.532
Puerto Rico	Rural	Spring	—	—	122	—	—	—	—[a]	—
Fundación El Castillo	Rural	Mechanical	27	—	—	12	7	84	2043.413	2016.413
Hierba Buena	Rural	Spring	—	—	—	—	—	—	—[a]	—

APPENDIX E (continued)

WELL SYSTEM CHARACTERISTICS

Site Name	Urban/Rural	System Type	Well Depth m	Well Diameter m	Flow Rate L/min	Pump Schedule h/d	Pump Schedule d/wk	Pump Schedule h/wk	Elevation m	Well Elevation m
La Pedrera Municipal	Urban	Mechanical	96	0.3048	—	24	7	168	1867.816	1771.816
Residenciales La Cañada	Urban	Mechanical	—	—	—	3	7	21	1832.621	—
Residenciales Las Margaritas	Urban	Mechanical	—	—	—	12	7	84	1816.38	—
El Esfuerzo	Urban	Mechanical	183	0.3048	1760	6	7	42	1771.479	1588.479
Alameda B 1 T. Concreto	Urban	Artesian	61	—	265	7	7	49	1765.62	1704.620
San Rafael 1	Urban	Mechanical	137	0.2032	1060	6	7	42	1786.269	1649.269
San José Bethania	Urban	Mechanical	450	0.3048	284	10	7	70	1777.339	1327.339
Santa Ana Cooperativa	Urban	Mechanical	30	0.3048	—	17	7	119	1774.832	1744.832
Las Victorias	Urban	Mechanical	160	0.3048	—	10	7	70	1770.954	1610.954
Alameda A	Urban	Artesian	55	0.9144	—	7.5	7	52.5	1770.435	1715.435
Cerro Alto	Rural	Mechanical	244	0.2032	256	—[c]	—[c]	—[c]	1788.014	1544.014

[a] Springs located away from communities they feed. Could not take GPS coordinates.

[b] Three wells (2 artesian, 1 mechanical) mix together in storage tank.

[c] Inconsistent operating schedule.

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