Groundwater arsenic in Chimaltenango, Guatemala

Jason T. Lotter, Steven E. Lacey, Ramon Lopez, Genaro Socoy Set,
Amid P. Khodadoust and Serap Erdal

ABSTRACT

In the Municipality of Chimaltenango, Guatemala, we sampled groundwater for total inorganic arsenic. In total, 42 samples were collected from 27 (43.5%) of the 62 wells in the municipality, with sites chosen to achieve spatial representation throughout the municipality. Samples were collected from household faucets used for drinking water, and sent to the USA for analysis. The only site found to have a concentration above the 10 μg/L World Health Organization provisional guideline for arsenic in drinking water was Cerro Alto, where the average concentration was 47.5 μg/L. A health risk assessment based on the arsenic levels found in Cerro Alto showed an increase in noncarcinogenic and carcinogenic risks for residents as a result of consuming groundwater as their primary drinking water source. Using data from the US Geological Survey and our global positioning system data of the sample locations, we found Cerro Alto to be the only site sampled within the tertiary volcanic rock layer, a known source of naturally occurring arsenic. Recommendations were made to reduce the levels of arsenic found in the community's drinking water so that the health risks can be managed.

Key words | arsenic, groundwater, Guatemala, risk assessment

Jason T. Lotter
Serap Erdal
School of Public Health,
Environmental and Occupational Health Sciences Division,
University of Illinois at Chicago,
2121 W Taylor Street,
Chicago,
IL 60612,
USA

Steven E. Lacey (corresponding author)
Ramon Lopez
Fairbanks School of Public Health,
Department of Environmental Health Science,
Indiana University, 714 N Senate Avenue,
Indianapolis, IN 46202,
USA
E-mail: *selacey@iu.edu*

Genaro Socoy Set
Chimaltenango Health Management Sector (Dirección Área de Salud de Chimaltenango),
Ministry of Health and Social Assistance (Ministerio de Salud y Asistencia Social),
6a Avenida la Alameda,
Zona 1, Chimaltenango, Chimaltenango,
Guatemala

Amid P. Khodadoust
Department of Civil & Materials Engineering,
University of Illinois at Chicago,
842 W Taylor Street, Chicago,
IL 60607,
USA

INTRODUCTION

Arsenic is a naturally occurring element present in the air, water and land. Ingestion of inorganic arsenic has been shown to cause noncarcinogenic adverse health effects – including skin lesions, high blood pressure, circulatory problems, decrements in lung function, gastrointestinal symptoms, and neurological and reproductive effects – as well as cancers, primarily of the skin, bladder and lung (Agency for Toxic Substances and Disease Registry (ATSDR) 2007). Over 140 million people in at least 70 countries have been exposed to arsenic concentrations above the World Health Organization (WHO) provisional guideline of 10 μg/L as a result of naturally contaminated groundwater or surface water (Ravenscroft 2007). With increasing use of groundwater globally (Shah 2005), and the fact that the arsenic presence in many parts of the world is yet to be fully characterized, estimates of the populations exposed will likely grow. In Guatemala, the first published findings of elevated groundwater arsenic levels were reported in 2007 from a well water source in the municipality of Mixco with an arsenic concentration of approximately 15 μg/L (Garrido Hoyos *et al.* 2007; Cardoso *et al.* 2011; Bundschuh *et al.* 2012). Other studies in Guatemala have found arsenic in surface waters as a result of mining activities (Basu & Hu 2010; E-Tech International 2010), and in soils used to produce ceramic pot drinking water filters (Archer *et al.* 2011). McClintock *et al.* (2012) noted that the number of persons in Guatemala potentially exposed to elevated arsenic concentrations is not yet known.

doi: 10.2166/wh.2013.100

The Municipality of Chimaltenango, Guatemala is a 212 km^2 area with a population of 74,077 according to the 2002 census (Instituto Nacional de Estadística (INE) 2002). Projections from the Guatemalan National Institute of Statistics (Instituto Nacional de Estadística) estimated the population to be approximately 125,000 in 2012, and to increase in the years that follow (INE 2003). The city of Chimaltenango is the main urban center within the municipality, and Cerro Alto is one of several small rural communities surrounding the city. Unpublished data from the Cerro Alto community in 2009 estimated the population to be 1,283.

The impetus for this current study came from a drinking water metals analysis performed in the community of Cerro Alto in 2009 as part of a university service-learning project. Results showed total inorganic arsenic concentrations in the community's two wells of 48.97 and 55.15 μg/L, respectively. Since these levels were approximately five times in excess of the WHO provisional guideline for arsenic in drinking water (WHO 2011), the results and their potential health implications were discussed both with the community and with officials in the Ministry of Health and Public Assistance in Chimaltenango. It was agreed that further testing of other wells in the area would be performed to determine regional concentrations of arsenic in drinking water and to estimate health risks for those exposed.

The objectives of this study were to characterize the presence of arsenic in groundwater drinking sources in the Municipality of Chimaltenango, Guatemala, and to estimate the risks for carcinogenic and noncarcinogenic health outcomes for residents consuming that water.

METHODS

Sample collection

Groundwater samples of 950 mL were collected throughout the Municipality of Chimaltenango over a 3-day period in January 2012. In total, 55 samples were collected at sites in an effort to achieve spatial representation; sites were chosen in part due to convenience (e.g., well accessibility, road conditions, and time constraints). The majority of the wells ($N = 38$) were located within the city of Chimaltenango, while the remaining ($N = 24$) were in rural communities outside of the city. Samples were collected at 13 (34.2%) of the 38 urban wells and 14 (58.3%) of the 24 rural wells. In all, 27 (43.5%) of the 62 wells in the municipality were sampled (see Figure 1).

To accurately determine individual exposure to arsenic in drinking water, samples were collected from a nearby household faucet used as a source of drinking water; all samples were collected prior to intermediate household storage, if present. Duplicate samples were taken at the majority ($N = 20/27$) of the sites, and blank samples ($N = 8$) were prepared in the field and stored and shipped alongside the other field samples. Global positioning system (GPS) coordinates were taken at all sites using a handheld GPS device (Trimble®, Sunnyvale, CA).

Sample analysis

Analysis for total inorganic arsenic was performed by an American Industrial Hygiene Association accredited

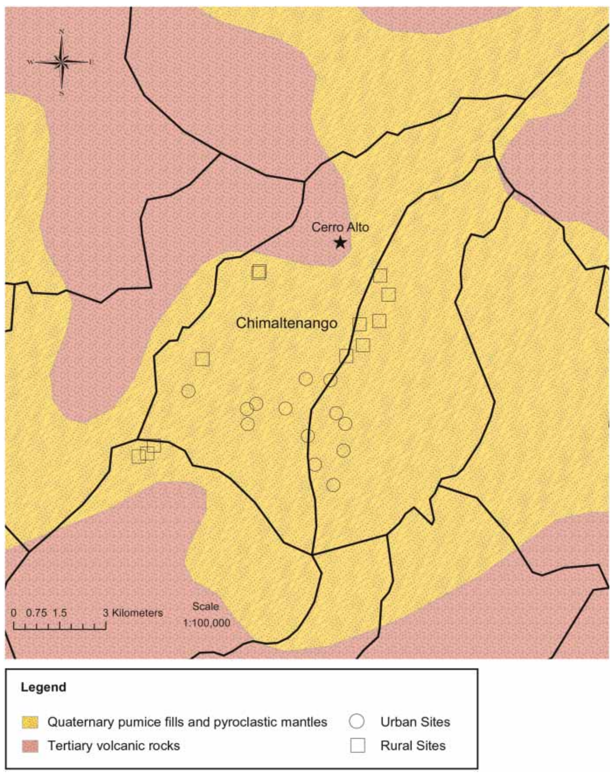

Figure 1 | Map of sampling sites with geologic overlay. *Source of geologic map:* French & Schenk (2003).

laboratory using modified US Environmental Protection Agency (USEPA) Method 200.8 *Determination of Trace Elements in Waters and Wastes by Inductively Coupled Plasma-Mass Spectrometry* (USEPA 1994), with a method reporting limit (MRL) of 0.40 μg/L. In-field preservation of samples was not performed due to anticipated logistical difficulties in sample transportation; however, samples were shipped to the USA and, per USEPA Method 200.8 recommendations, received for analysis within 2 weeks of collection.

Risk assessment model

The model developed by the National Academy of Sciences (NAS 1983), and commonly used by the USEPA for environmental decision-making and establishment of standards (USEPA 1989, 1995), was used to determine the potential for adverse health effects for residents of Chimaltenango as a result of consuming groundwater as their drinking water source. Health risk estimates were made for both carcinogenic and noncarcinogenic effects as a result of exposures occurring at multiple life stages (0 to <2 years old, 2 to <16 years old, and 16 to <70 years old), as well as cumulative lifetime exposure. Risks were calculated separately for Cerro Alto and the rest of the municipality based on the arsenic concentrations found in these two distinct areas.

The USEPA's Integrated Risk Information System's (IRIS) toxicity values were used to inform risk estimates (USEPA 2003). The oral reference dose (RfD_O), 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 RfD_O established by the USEPA under IRIS for inorganic arsenic is 3×10^{-4} milligrams per kilogram per day (mg/kg-d), which is based on a no observed adverse effect level of 8×10^{-4} mg/kg-d and uncertainty and modifying factors of three and one, respectively. The oral cancer slope factor (CSF_O) for inorganic arsenic is 1.5 (mg/kg-d)$^{-1}$, and is the toxicity value used to estimate the excess cancer risk (ECR) associated with exposure to arsenic in drinking water. Per USEPA's *Supplemental Guidance for Assessing Susceptibility from Early-Life Exposure to Carcinogens* (USEPA 2005), the CSF_O was multiplied by a factor of 10 for exposures occurring in the first 2 years, and multiplied by a factor of three for exposures occurring between the ages of two and 16. These multiplicative factors adjust for the generally higher cancer risks from early-life exposures than from similar exposures later in life.

The average oral daily dose (ADD_O), used for noncarcinogenic effects, and the lifetime average oral daily dose [$L(ADD)_O$] used for carcinogenic effects, for the ingestion of drinking water were calculated using the following equation (USEPA 1992):

$$L(ADD)_O/ADD_O = \frac{C_w \times IR \times EF \times ED}{BW \times AT}$$

where $L(ADD)_O/ADD_O$ is the estimated daily oral intake of arsenic (mg/kg-d); C_w is the concentration of arsenic in water (milligrams per liter); IR is the water ingestion rate (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 hazard quotient (HQ) is an indicator of risks associated with health effects other than cancer, and the ECR is the incremental probability of an exposed person developing cancer over a lifetime. Hazard quotients are scaling factors and are not statistically based the greater the value of the HQ above unity, the greater the level of concern for potential adverse systemic health effects in the exposed individuals (USEPA 1989). The USEPA's acceptable criterion for carcinogenic risks is based on public policy as described in the National Contingency Plan and is the exposure concentration that represents an ECR in the range of 10^{-4} to 10^{-6} , (i.e., 1 in 10,000 to 1 in 1,000,000 excess cancer cases) (USEPA 1990). The oral hazard quotient (HQ_O) and oral excess cancer risk (ECR_O) were calculated using the following equations (USEPA 1989).

Non-cancer risk:

$$\text{Hazard quotient } (HQ_O) = \frac{ADD_O}{RfD_O}$$

Excess cancer risk:

$$ECR_O = L\,(ADD)_O \times CSF_O$$

Two values for each exposure parameter were used to calculate the ADD_O and the $L(ADD)_O$; one value to represent an average or central tendency exposure (CTE) and another value for a worst-case or reasonable maximum exposure (RME) (see Table 1). Appropriate exposure parameters for ingestion rate (*IR*) and body weight (*BW*) in support of risk calculations were selected, in part, based on the USEPA's *Exposure Factors Handbook* (USEPA 2011). Although published literature indicate that both water ingestion rates and body weights are, on average, lower for Guatemalans than US population-based values (Smith *et al.* 2003; Campos *et al.* 2009; Montenegro-Bethancourt *et al.* 2009; Kuzawa *et al.* 2012), the *Exposure Factors Handbook* was utilized due to a lack of complete data for all age groups for Guatemalan populations.

RESULTS

Groundwater arsenic concentrations

Arsenic concentrations for each site are reported in Table 2. The concentrations ranged from below the MRL (0.40 μg/L) to 49.0 μg/L. Seven of the eight blank samples had non-detectable arsenic concentrations, with one having a value of 0.43 μg/L, slightly above the MRL. Among the samples with detectable amounts, all but one site were below the 10 μg/L WHO provisional guideline value for arsenic. Cerro Alto was the only site with notably elevated arsenic levels (mean: 47.5 μg/L), which were consistent with our initial 2009 findings.

Risk assessment

The calculated values for the ADD_O and $[L(ADD)_O]$ are presented in Table 3, and the values for the oral hazard quotients (HQ_Os) and oral excess cancer risk (ECR_Os) are presented in Table 4 for each age group in both Cerro Alto and the rest of the Municipality of Chimaltenango. Values in bold represent a risk likely to be associated with adverse health effects. For ECR, the age groups represent the contribution of exposures that occur during that age range to the overall lifetime excess cancer risk. Under RME conditions, the HQ_Os and ECR_Os are elevated for all age groups in Cerro Alto. Using CTE exposure parameters resulted in elevated HQ_Os in Cerro Alto for the birth to less than 2 years age group; ECR_Os were elevated in all age groups in Cerro Alto under CTE conditions.

The hazard index (*HI*) is the summation of the HQ_Os for each age group to give the lifetime noncarcinogenic risk. Similar to the hazard index, the summation of the age group-specific ECR_Os gives the total lifetime excess cancer

Table 1 | Health risk assessment exposure parameters

Exposure parameter	Age group (years)	CTE	RME
C_w (mg/L)	All age groups (Chimaltenango)[a]	7.70×10^{-4}	9.43×10^{-4}
	All age groups (Cerro Alto)	0.049	0.049
IR (L/day)	0 to <2	0.297	0.924
	2 to <16	0.426	1.389
	16 to <70	1.006	2.861
EF (day/year)	All age groups	175	350
ED (years)	0 to <2	2	2
	2 to <16	14	14
	16 to <70	54	54
BW (kg)	0 to <2	9.62	9.62
	2 to <16	36.6	36.6
	16 to <70	70	70
AT (days)	0 to <2 (noncarcinogenic)	730	730
	2 to <16 (noncarcinogenic)	5110	5110
	16 to <70 (noncarcinogenic)	19,710	19,710
	All age groups (carcinogenic)	25,550	25,550

[a]Values represent the mean and the 95% upper confidence limit (UCL) on the mean, normal distribution (USEPA 2013), for all locations outside of Cerro Alto.

Table 2 | Groundwater arsenic concentrations in Chimaltenango, Guatemala

Sampling site location	Arsenic concentration (μg/L) Sample 1	Sample 2	Average
Monte Cristo	MRL[a]	MRL	MRL
Agua Viva Puerto Rico	MRL	MRL	MRL
Puerto Rico	MRL	MRL	MRL
Fundación El Castillo	MRL	MRL	MRL
Hierba Buena	MRL	MRL	MRL
Residenciales Las Margaritas	MRL	–	MRL
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**

[a]Method reporting limit (MRL), 0.40 μg/L.

risk at 70 years of age (see Table 5). The hazard indices for Cerro Alto were 4.5 and 27 for CTE and RME conditions, respectively. The lifetime ECR_Os in Cerro Alto of 9.5×10^{-4} and 5.8×10^{-3} exceed the 10^{-4} to 10^{-6} range deemed acceptable by the USEPA (USEPA 1990). Groundwater arsenic concentrations found in the rest of the municipality did not result in an unacceptable HQ_O or ECR_O for any age range using either CTE or RME conditions under the USEPA criteria described above.

DISCUSSION

Location and potential sources of contamination

Only a single site, Cerro Alto, was found to have a groundwater arsenic concentration greater than the WHO provisional guideline for arsenic in drinking water of 10 μg/L. The average concentration found in Cerro Alto in this study (47.5 μg/L) was similar to our initial findings in 2009. All other sampling locations in the Municipality of Chimaltenango had levels well below the WHO provisional guideline.

The common anthropogenic sources of arsenic pollution, such as smelting operations and mining, are not present in the study area, and arsenical pesticides or other agricultural sources would likely be minor and more widely distributed given the low-scale farming present in the region. Recent studies have examined arsenical compounds used in poultry feed and their potential to contaminate groundwater drinking sources (Denver *et al.* 2004; Fisher *et al.* 2011). Fisher *et al.* (2011) noted that arsenical compounds may be used in chicken feed to prevent disease, improve growth, and improve pigmentation. Their recent review of published studies concluded that arsenic from animal waste has little, if any, effect on groundwater concentration levels, even in shallow aquifers (Fisher *et al.* 2011). The availability of studies on this subject is limited, however, and it cannot be ruled out as a possible source of groundwater contamination. Since a large-scale poultry

Table 3 | Estimates of daily oral intake of arsenic (mg/kg-d)

	Age group (years) Population	0 to <2 Chimaltenango	Cerro Alto	2 to <16 Chimaltenango	Cerro Alto	16 to <70 Chimaltenango	Cerro Alto
CTE	ADD_O	1.1×10^{-5}	7.3×10^{-4}	4.3×10^{-6}	2.7×10^{-4}	5.3×10^{-6}	3.4×10^{-4}
	$L(ADD)_O$	3.3×10^{-7}	2.1×10^{-5}	8.6×10^{-7}	5.5×10^{-5}	4.1×10^{-6}	2.6×10^{-4}
RME	ADD_O	8.7×10^{-5}	4.5×10^{-3}	3.4×10^{-5}	1.8×10^{-3}	3.7×10^{-5}	1.9×10^{-3}
	$L(ADD)_O$	2.5×10^{-6}	1.3×10^{-4}	6.9×10^{-6}	3.6×10^{-4}	2.9×10^{-5}	1.5×10^{-3}

Table 4 | Age-specific health risk estimates for carcinogenic and noncarcinogenic effects

	Age group (years) Population	0 to <2 Chimaltenango	Cerro Alto	2 to <16 Chimaltenango	Cerro Alto	16 to <70 Chimaltenango	Cerro Alto
CTE	HQ_O	0.038	**2.4**	0.014	0.91	0.018	1.1
	ECR_O	4.9×10^{-6}	$\mathbf{3.1\times10^{-4}}$	3.9×10^{-6}	$\mathbf{2.5\times10^{-4}}$	6.1×10^{-6}	$\mathbf{3.9\times10^{-4}}$
RME	HQ_O	0.29	**15**	0.11	**5.9**	0.12	**6.4**
	ECR_O	3.7×10^{-5}	$\mathbf{1.9\times10^{-3}}$	3.1×10^{-5}	$\mathbf{1.6\times10^{-3}}$	4.3×10^{-5}	$\mathbf{2.2\times10^{-3}}$

Table 5 | Lifetime health risk estimates for carcinogenic and noncarcinogenic effects

Age group (years) Population	CTE 0 to <70 Chimaltenango	Cerro Alto	RME 0 to <70 Chimaltenango	Cerro Alto
HI_O	0.070	**4.5**	0.53	**27**
ECR_O	1.5×10^{-5}	$\mathbf{9.5\times10^{-4}}$	1.1×10^{-4}	$\mathbf{5.8\times10^{-3}}$

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 tertiary volcanic rocks, and all other sites sampled are located outside of this geological zone, as shown in Figure 1. It has been recognized that volcanic rocks can contribute to elevated arsenic levels in water, including in many areas of Central America (Bundschuh *et al.* 2012; López *et al.* 2012). In geothermal fields in Guatemala, well water samples have revealed arsenic concentrations as high as 12.34 mg/L (López *et al.* 2012).

Significance of health risk assessment

In reviewing the outcomes of the health risk assessment, there is no potential concern with the levels of arsenic causing either carcinogenic or noncarcinogenic adverse health outcomes in the study region, outside of Cerro Alto; all HQ_O and ECR_O estimates are below the values deemed unacceptable. Within Cerro Alto, however, our health risk estimates indicate that there is a likelihood of increased risk of both noncarcinogenic and carcinogenic effects. The hazard indices for both exposure scenarios are well in excess of one, and the potential lifetime excess cancer risks in Cerro Alto of 9.5×10^{-4} and 5.8×10^{-3} signify that conservative estimates for cancer development amongst residents in Cerro Alto range from approximately one to six out of 1000 individuals exposed. Under both exposure scenarios the contribution of exposures occurring during the first 2 years results in greater than 50 percent of the lifetime noncarcinogenic risk, and greater than 30 percent of the lifetime carcinogenic risk.

Studies of inorganic arsenic exposure in humans have indicated that the development of skin lesions as a result of exposure to arsenic is typically associated with doses greater than 0.02 mg/kg-d; although, some studies have reported increased incidence of skin lesions at doses as low as 0.0012 mg/kg-d (ATSDR 2007). Other arsenic-related health effects have been reported at slightly higher doses, including cardiovascular effects (0.014–0.065 mg/kg-d), respiratory effects (0.03–0.05 mg/kg-d), gastrointestinal effects (0.01 mg/kg-d), and neurological effects (0.03–0.1 mg/kg-d) (ATSDR 2007).

Health risk assessments provide estimates of the potential for the development of adverse human health effects. The reliability of these estimates depends on the accuracy and applicability of the exposure parameters used in their calculation. The selection in this study of non-Guatemalan-based values for ingestion rate and body weight likely do not reflect the true values for the population of this study, which literature has shown to be lower on average, particularly in children (Smith *et al.* 2003; Campos *et al.* 2009; Montenegro-Bethancourt *et al.* 2009; Kuzawa *et al.* 2012). Due to a lack of completeness in the data for these parameters for all age groups, standard values and those provided in the *Exposures Factor Handbook* (USEPA 2011) were used. While a lower ingestion rate would decrease an individual's dose, a lower body weight would increase dose estimates. In 2010, the USEPA's IRIS program released a draft *Toxicological Review of Inorganic Arsenic* (USEPA 2010), where they developed a cancer slope factor of 25.7 $(mg/kg\text{-}d)^{-1}$, a roughly seven-fold increase from the current 1.5 $(mg/kg\text{-}d)^{-1}$. The quality review of the draft report is yet to be finalized; however, use of this newly developed cancer slope factor would significantly increase carcinogenic risk estimates in Cerro Alto. 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 concentrations can be brought down to safe levels.

Study limitations

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. Additionally, prior to sample collection, no data on well locations were available in order to design a more informed sampling strategy. The site nearest to Cerro Alto, Bola de Oro, was also not sampled and may have similarly elevated arsenic levels.

Results of our risk assessment indicate an increased risk of arsenic-related carcinogenic and noncarcinogenic health outcomes for residents of Cerro Alto. However, no data on the prevalence of such outcomes (e.g., skin lesions) are available for the Cerro Alto community, nor was biological monitoring (e.g., hair or nail samples) conducted. Such information, were it available, would help confirm the health risk estimates developed, and contribute to a more precise characterization of the extent of arsenic exposure.

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 advantage of not having to maintain or pay for treatment processes, although both capital and operating costs would still be involved. Acquiring access to another water source for the residents of Cerro Alto may not be feasible due mainly to the financial constraints and geographical isolation of the community. In certain parts of the world with groundwater arsenic contamination, concentrations have been found to vary depending on well depth (Ravenscroft 2007; Becker *et al.* 2010); in some instances deeper wells have produced water with arsenic levels below 10 μg/L, where shallower wells in the same area have produced water with concentrations in excess of 50 μg/L (Kinniburgh & Smedley 2001). At the time of our study in 2012, residents of Cerro Alto were utilizing only one of the two wells in the community. During initial sampling in 2009, the current well (depth: 244 m) and a shallower well (depth: 28 m) were in operation. According to results from the 2009 study, the shallower well had a lower arsenic concentration (48.97 μg/L) than the deeper well (55.15 μg/L); although, both were well in excess of the 10 μg/L standard. Without further testing it is unclear whether modifying the well depth would sufficiently reduce arsenic concentrations.

Several low-scale treatment strategies have been developed that may be appropriate in this context, on either the household or communal level, to reduce arsenic concentrations below 10 μg/L. These include the use of zerovalent (metallic) iron or other organic or natural adsorbents such as iron oxide-bearing soils, which remove arsenic through a process of adsorption, co-precipitation and ion exchange (Bundschuh *et al.* 2010). The advantages of such options are the low cost and availability of adsorbent materials, yet like all potential treatment strategies they must be tailored to the specific water conditions in order to have maximum effectiveness. To increase arsenic removal efficiencies, the use of zerovalent iron is often coupled with solar radiation technologies (Bundschuh *et al.* 2010). An in-depth evaluation of arsenic remediation options is beyond the scope of this study; however, prior to any remediation steps being implemented, additional information on water characteristics (e.g., pH, dissolved organic matter, presence of other ions), arsenic species present (i.e. arsenite/arsenate ratio), availability of treatment materials, associated capital and operating costs, acceptability of the proposed solution by residents, and its sustainability must be thoroughly analyzed.

It would also be advisable to take samples to the north of Cerro Alto and in surrounding regions in the same geologic zone to provide additional evidence to our hypothesis of a naturally present arsenic geologic source and help identify the extent of the contamination. The likelihood that the nearby poultry farm is the source of the contamination in Cerro Alto is uncertain; given the large size of the farm, further investigation regarding use of arsenical compounds in feed should be gathered to assess the likelihood of this source contributing to the observed high arsenic concentrations in Cerro Alto drinking water. If this source is a contributing factor, product substitution by using a different feed free of arsenic should be implemented.

Biomarkers for arsenic exposure such as hair or nail samples would contribute to a greater understanding of the level of individual exposures. Such information would also help inform potential health-based interventions. As noted, arsenic exposures occurring between birth and 2 years of age contribute a significant proportion of both the carcinogenic and noncarcinogenic lifetime exposures. Potential intervention strategies should first focus on reducing or eliminating exposures in newborns and infants, as this would significantly reduce the overall exposure risk. To more fully characterize arsenic exposure, other routes of exposure should be incorporated into the health risk assessment. McClintock *et al.* (2012) reported that in some areas of Latin America, food contributes up to 50 percent of total arsenic intake. Future data collection should also focus on assessing appropriate exposure parameters (e.g., water ingestion rate, body weight) of the Guatemalan populations under study.

CONCLUSIONS

This study contributes to the limited available data on groundwater arsenic in Guatemala and to the potential number of individuals exposed to elevated concentrations of arsenic in drinking water. Our measurements confirmed elevated arsenic levels in Cerro Alto drinking water; although, we did not find any other location in the Municipality of Chimaltenango that exceeded the WHO provisional guideline of 10 μg/L. Evidence to date suggests that the presence of volcanic rock in Cerro Alto is the source of the high arsenic concentrations 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; for this reason, further sampling should be conducted in these neighboring areas to assess the validity of this hypothesis. Risk estimates showed that at the level of arsenic found in the drinking water of Cerro Alto (47.5 μg/L), both excess cancer and non-cancer indices are above the USEPA's acceptable risk criteria, posing a likelihood of potential adverse health effects in community residents. Immediate measures need to be taken to reduce or eliminate the arsenic levels in the water of Cerro Alto. Several low-cost, small-scale remediation options have been developed which may be effective treatment options. Prior to any intervention, an in-depth analysis of potential solutions should be performed, with emphasis put on their effectiveness and sustainability.

REFERENCES

Archer, A., Elmore, A., Bell, E. & Rozycki, C. 2011 Field investigation of arsenic in ceramic pot filter-treated drinking water. *Water Sci. Technol.* **63** (10), 2193–2198.

ATSDR (Agency for Toxic Substances and Disease Registry) 2007 *Toxicological Profile for Arsenic*. ATSDR, Division of Toxicology and Environmental Medicine/Applied Toxicology Branch, Atlanta, GA.

Basu, N. & Hu, H. 2010 Toxic Metals and Indigenous Peoples near the Marlin Mine in Western Guatemala. Report prepared for Physicians for Human Rights.

Becker, C. J., Smith, S. J., Greer, J. R. & Smith, K. A. 2010 Arsenic-Related Water Quality with Depth and Water Quality of Well-Head Samples from Production Wells, Oklahoma, 2008. Report prepared for US Geological Survey, Reston, VA.

Bundschuh, J., Litter, M., Ciminelli, V. S., Morgada, M. E., Cornejo, L., Hoyos, S. G., Hoinkis, J., Alarcón-Herrera, M. T. & Bhattarcharya, P. 2010 Emerging mitigation needs and sustainable options for solving the arsenic problems of rural and isolated urban areas in Latin America – A critical analysis. *Water Res.* **44** (19), 5828–5845.

Bundschuh, J., Litter, M. I., Parvez, F., Román-Ross, G., Nicolli, H. B., Jean, J. S., Liu, C. W., López, D., Armienta, M. A., Guilherme, L. R., Cuevas, A. G., Cornejo, L., Cumbal, L. &

Toujaguez, R. 2012 One century of arsenic exposure in Latin America: A review of history and occurrence from 14 countries. *Sci. Total Environ.* **429**, 2–35.

Campos, R., Montenegro-Bethancourt, G., Vossenaar, M., Doak, C. & Solomons, N. W. 2009 Volume, frequency and participation in plain drinking water consumption by third- and fourth-grade schoolchildren in Quetzaltenango, Guatemala. *Asia Pac. J. Clin. Nutr.* **18** (2), 164–170.

Cardoso, S., Grajeda, C., Argueta, S. & Garrido, S. E. 2011 Experiencia satisfactoria para la remoción de arsénico en Condado Naranjo, Mixco, Guatemala. In: *Tecnologías económicas para el abatimiento de arsénico en aguas* (M. I. Litter, A. M. Sancha & A. M. Ingallinella, eds). IBEROARSEN, Argentina.

Denver, J. M., Ator, S. W., Debrewer, L. M., Ferrari, M. J., Barbaro, J. R., Hancock, T. C., Brayton, M. J. & Nardi, M. R. 2004 Water Quality in the Delmarva Peninsula, Delaware, Maryland, and Virginia, 1999–2001. US Geological Survey Circular 1228. US Geological Survey, Reston, VA.

E-Tech International 2010 Evaluation of Predicted and Actual Water Quality Conditions at the Marlin Mine, Guatemala. Report prepared for E-Tech International, Santa Fe, NM.

Fisher, D., Yonkos, L. & Staver, K. 2011 The Environmental Concerns of Arsenic Additives in Poultry Litter: Literature Review. Report prepared for Harry R Hughes Center for Agro-Ecology.

French, C. D. & Schenk, C. J. 2003 *Surface Geology of the Caribbean Region (geo6bg)*. US Geological Survey Central Energy Resources Team, Denver, CO. Available at http://certmapper.cr.usgs.gov/pubs/servlet/PubBroker?issue=ofr97470k&path=/graphic/data.html. Accessed 31 August 2012.

Garrido Hoyos, S. E., Avilés Flores, M., Rivera Huerta, M. L. & Nájera Flores, M. C. 2007 Diagnóstico de la presencia de arsénico en agua de pozo, Mixco, Guatemala. Report prepared for Instituto Mexicano de Technología del Agua, Morelos, Mexico.

INE (Instituto Nacional de Estadística) 2002 *XI Censo nacional de población y VI de habitación*. INE, Guatemala.

INE (Instituto Nacional de Estadística) 2003 *Proyección de población por municipio 2008–2020*. INE, Guatemala. Available at http://www.ine.gob.gt/np/poblacion/index.htm. Accessed 20 September 2013.

Kinniburgh, D. G. & Smedley, P. L. (eds) 2001 *Arsenic Contamination of Groundwater in Bangladesh, Vol 1: Summary*. Report prepared for British Geologic Survey, BGS Technical Report WC/00/19. BGS, Keyworth.

Kuzawa, C. W., Hallal, P. C., Adair, L., Bhargava, S. K., Fall, C. H., Lee, N., Norris, S. A., Osmond, C., Ramirez-Zea, M., Sachdev, H. S., Stein, A. D., Victoria, C. G. & COHORTS Group 2012 Birth weight, postnatal weight gain, and adult body composition in five low and middle income countries. *Am. J. Hum. Biol.* **24** (1), 5–13.

López, D. L., Bundschuh, J., Birkle, P., Armienta, M. A., Cumbal, L., Sracek, O., Cornejo, L. & Ormachea, M. 2012 Arsenic in volcanic geothermal fluids of Latin America. *Sci. Total Environ.* **429**, 57–75.

McClintock, T. R., Chen, Y., Bundschuh, J., Oliver, J. T., Navoni, J., Olmos, V., Villaamil Lepori, E., Ahsan, H. & Parvez, F. 2012 Arsenic exposure in Latin America: Biomarkers, risk assessments and related health effects. *Sci. Total Environ.* **429**, 76–91.

Montenegro-Bethancourt, G., Vossenaar, M., Doak, C. M. & Solomons, N. W. 2009 Total daily water intake in Guatemalan children. *Food Nutr. Bull.* **30** (4), 340–350.

NAS (National Academy of Sciences) 1983 *Risk Assessment in the Federal Government: Managing the Process*. National Academy Press, Washington, DC.

Ravenscroft, P. 2007 Predicting the Global Extent of Arsenic Pollution of Groundwater and its Potential Impact on Human Health. Report prepared for UNICEF, New York.

Shah, T. 2005 Groundwater and human development: challenges and opportunities in livelihoods and environment. *Water Sci. Technol.* **51** (8), 27–37.

Smith, P. K., Bogin, B., Varela-Silva, M. I. & Loucky, J. 2003 Economic and anthropological assessments of the health of children in Maya immigrant families in the US. *Econ. Hum. Biol.* **1** (2), 145–160.

USEPA (US Environmental Protection Agency) 1989 *Risk Assessment Guidance for Superfund, Volume I: Human Health Evaluation Manual (Part A) (Interim Final)*. Publication EPA/540/1-89002, USEPA Office of Emergency and Remedial Response, Washington, DC.

USEPA (US Environmental Protection Agency) 1990 *National Oil and Hazardous Substances Pollution Contingency Plan*. Fed. Reg. 40 CFR Part 300, USEPA, Washington, DC.

USEPA (US Environmental Protection Agency) 1992 *Guidelines for Exposure Assessment*. Publication EPA/600/Z-92/001, Fed. Reg. 57:228878–22938, USEPA Risk Assessment Forum, Washington, DC.

USEPA (US Environmental Protection Agency) 1994 *Method 200.8: Determination of Trace Elements in Waters and Wastes by Inductively Coupled Plasma and Mass Spectrometry: Revision 5.4*. USEPA Office of Research and Development, Cincinnati, OH.

USEPA (US Environmental Protection Agency) 1995 *Guidance for Risk Characterization*. USEPA Science Policy Council, Washington, DC.

USEPA (US Environmental Protection Agency) 2003 *Arsenic, Organic*. USEPA Integrated Risk Information System (IRIS), National Center for Environmental Assessment, Washington, DC. Available at http://www.epa.gov/iris/subst/0278.htm. Accessed 1 February 2012.

USEPA (US Environmental Protection Agency) 2005 *Supplemental Guidance for Assessing Susceptibility from Early-Life Exposure to Carcinogens*. Publication EPA/630/R-03/003F, USEPA Risk Assessment Forum, Washington, DC.

USEPA (US Environmental Protection Agency) 2010 *Toxicological Review of Inorganic Arsenic: In Support of Summary*

Information on the Integrated Risk Information System (IRIS). Publication EPA/635/R-10/001, USEPA, Washington, DC.
USEPA (US Environmental Protection Agency) 2011 *Exposure Factors Handbook 2011 edition (Final)*. Publication EPA/600/R-09/052F, USEPA Office of Research and Development, Washington, DC.
USEPA (US Environmental Protection Agency) 2013 *ProUCL version 5.0.00: Statistical Software for Environmental Applications for Data Sets with and without Nondetect Observations*. USEPA Office of Research and Development, Washington, DC.
WHO (World Health Organization) 2011 *Guidelines for Drinking-Water Quality*, 4th edn. WHO, Geneva.

First received 13 May 2013; accepted in revised form 3 December 2013. Available online 26 December 2013