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A review of two decades of experience

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Arsenic contamination of rural community wells in Nicaragua: A review of two decades of experience

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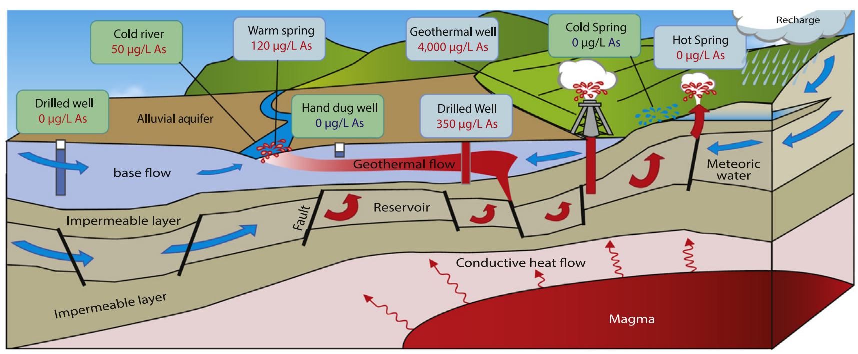
HIGHLIGHTS

- The As contamination in drinking water sources is probably of volcanic origin.
- As-rich groundwater sources exceeding 10 μg/L has been detected in 34 municipalities.
- The concern about the presence of As in groundwater was first recognized in 1996.

GRAPHICAL ABSTRACT



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ABSTRACT

Several surveys have been conducted in Nicaragua between 1996 and 2015 confirming the presence of high levels of arsenic (>10 μg/L). In this paper, these peer-reviewed ($n = 2$) and non-peer reviewed sources ($n = 14$) have been combined to provide an extensive overview of the arsenic contamination of drinking water sources in Nicaragua. So far, arsenic contamination has been detected in over 80 rural communities located in 34 municipalities of the country and arsenic poisoning has been identified in at least six of those communities. The source of arsenic contamination in Nicaragua is probably volcanic in origin, both from volcanic rocks and geothermal fluids which are distributed across the country. Arsenic may have directly entered into the groundwater by geothermally-influenced water bodies, or indirectly by reductive dissolution or alkali desorption, depending on the local geochemical conditions.

1. Introduction

In Latin America (from Argentina to Mexico) As occurrence has been reported in 14 out of 20 countries and it is estimated that around 14 million people regularly ingest water with As concentrations exceeding 10 μg/L (Bundschuh et al., 2008; Bundschuh et al., 2012). The first documented case of natural As-contaminated water, including the impact on human health, was reported in the beginning of the 20th century in Argentina (Bundschuh et al., 2008; Bundschuh et al., 2012; Goyenechea, 1917). With an estimated number of inhabitants of 4 million (around 9% of the total population) consuming As-contaminated water (Villaamil Lepori[1], 2015), Argentina is nowadays considered to have the largest population affected by the consumption of water with high concentrations of As in Latin America (Bundschuh et al., 2012). Between 1950 and 1970 water sources in Mexico and Chile were identified as being contaminated with As (Bundschuh et al., 2008; Bundschuh et al., 2012). During the last two decades, cases of As contamination

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have been reported in various countries in Central America (Bundschuh et al., 2008; Bundschuh et al., 2012).

In Nicaragua, the first documented case of arsenic poisoning was reported in 1996 in a rural community located in the northern part of the country (Gomez, 2002). Since then, several assessments confirmed the presence of high levels of arsenic in drinking water sources located in different geological environments (Altamirano Espinoza and Bundschuh, 2008; Barragne, 2004; CARE, 2002; CISTA, 2012; ENACAL et al., 2005; González et al., 1997; INAA, 1996; Morales et al., 2008; OPS/OMS and Nuevas-Esperanzas, 2011; OPS/OMS and UNICEF, 2005; PIDMA-UNI, 2001; PIDMA-UNI and UNICEF, 2002; PIDMA-UNI and USAID, 2001). The source of arsenic contamination in Nicaragua is probably volcanic in origin, both from volcanic rocks and geothermal fluids which are distributed across the country (Altamirano Espinoza and Bundschuh, 2008; Bundschuh et al., 2012; González et al., 1997; Morales et al., 2008; OPS/OMS and Nuevas-Esperanzas, 2011). In Nicaragua, the provisional guideline of the World Health Organization (WHO, 2003) has been adopted as national guideline (10 μg/L).

Nicaragua is situated on the isthmus of Central America, with both Caribbean and Pacific coasts. The Central American volcanic front extends from Mexico to Costa Rica and is formed by subduction of the Cocos Plate beneath the Caribbean Plate. Nicaragua forms part of the Chortis Block, one of the major structural units which make up the Caribbean Plate (Weinberg, 1992). Most Central American volcanoes occur along a volcanic front that trends parallel to the strike of the subducting Cocos Plate (Carr et al., 2003). Three major volcanic events have occurred in Nicaragua since middle Tertiary time, from shield volcanism which produced ignimbrites in the Highlands, though basaltic and andesitic magmas along the Pacific coast, to arc volcanism which created the modern volcanic chain (Ehrenborg, 1996). Nicaragua is composed of five geomorphologic regions (Fig. 1). These are: (1) the Paleozoic and Mesozoic platform, with the oldest rock formations of the country; (2) the Tertiary volcanic region (central area); (3) The Central Depression or graben, a new geologic area in which Quaternary volcanism is concentrated; (4) the sedimentary basin of the Atlantic coast; and (5) the sedimentary basin of the Pacific coast which consists of Tertiary marine sediments, partly overlain by Quaternary deposits (Hodgson, 1998; McBirney and Williams, 1965).

The majority of recent knowledge (2010–2015) on arsenic contamination in Nicaragua cannot be found in international publications, but as non–peer reviewed reports and dispersed raw data held by particular organizations within the country (e.g., Nuevas Esperanzas, CISTA – UNAN LEON). Therefore, the objective of this paper is to present an overview of the current state of knowledge of arsenic occurrence and mobilization mechanisms in Nicaragua, based on existing literature, as well as the interpretation of unpublished research reports and data files. These studies related to arsenic contamination of groundwater processed during the past two decades have been obtained from Nicaraguan research organizations, government institutes and non-governmental organizations.

2. Methods

2.1. Data collection and mapping of As occurrence

This study is based on a review of research literature related to As contamination of water in Nicaragua produced between 1996 and 2015, including two peer-reviewed paper and 14 non-peer reviewed reports. Most of the non–peer reviewed reports were published in Spanish.

Table 1 shows a list of the peer reviewed and non-peer reviewed reports, and data files obtained from different organizations in Nicaragua. Additionally,

Table 1 shows a classification of the studies based on their geologic settings and their research areas. The research areas correspond to

Fig. 1. Map of Nicaragua showing the geological settings of the country (Hodgson, 1998).

Table 1
Overview of published and unpublished reports related to arsenic occurrence in Nicaragua produced from 1996 to 2015.

Reference of study	Type of research literature	Number of water supply points tested (*)	Number of water supply points exceeding the national norm (10 μg/L)	Percentage of water supply points exceeding the national guideline (10 μg/L)	Maximum As concentration (μg/L)	Geological settings	Research area
INAA. (1996)	Non-peer reviewed reports	25	11	44%	289 μg/L	Tertiary Volcanic-region	Alluvial aquifer of the Sebaco valley and surrounding areas
GONZALEZ,M. et al. (1997)	Non-peer reviewed reports	46	12	26%	50 μg/L	Tertiary Volcanic-region	Alluvial aquifer of the Sebaco valley and surrounding areas
PIDMA - UNI. (2001)	Non-peer reviewed reports	20	6	30%	69 μg/L	Tertiary Volcanic-region	Alluvial aquifer of the Sebaco valley and surrounding areas
PIDMA-UNI-USAID (2001)	Non-peer reviewed reports	124	6	5%	23 μg/L	Tertiary volcanic region, Paleozoic and Mesozoic platform & depression or graben	Central Region of Nicaragua & North-west region
CARE International. (2002)	Non-peer reviewed reports	11	2	18%	16 μg/L	Tertiary volcanic-region	Alluvial aquifer of the Sebaco valley and surrounding areas
PIDMA -UNI. (2002)	Non-peer reviewed reports	106	6	5.7%	88 μg/L	Tertiary volcanic-region & depression or graben	Hydrothermal mineral deposit areas
Barragne-Bigot (2004)	Non-peer reviewed reports	77	22	28.6%	108 μg/L	Tertiary volcanic-region & depression or graben	Hydrothermal mineral deposit areas
ENACAL. (2005)	Non-peer reviewed reports	44	41	93%	1200 μg/L	Tertiary volcanic region	Central region of Nicaragua
L. Morales et al.	Peer reviewed reports	12	3	25%	115.00 μg/L	Tertiary volcanic-region & depression or graben	Hydrothermal mineral deposit areas
González, R.M. (2004)	Non-peer reviewed reports	11	2	18%	10 μg/L	Tertiary volcanic-region	Alluvial aquifer of the Sebaco valley and surrounding areas
PAHO/WHO/UNICEF. (2005)	Non-peer reviewed reports	1488	50	3%	161 μg/L	Tertiary volcanic-region, Paleozoic and Mesozoic platform Depression or Graben	Alluvial aquifer of Sebaco valley and surrounding areas Central region of Nicaragua & North-west region Hydrothermal mineral deposit areas
Altamirano E.M. et al. (2009)	Peer reviewed reports	57	24	42%	122 μg/L	Tertiary volcanic-region	Alluvial aquifer of the Sebaco valley and surrounding areas
Longley, A.J. (2010)	Non-peer reviewed reports	59	20	34%	235 μg/L	Depression or graben	North-west region
OPS - OMS/Nicaragua - Nuevas Esperanzas. (2011)	Non-peer reviewed reports	183	45	25%	325 μg/L	Depression or graben	North-west region
CISTA UNAN LEON (2012)	Non-peer reviewed reports	141	13	9%	57 μg/l	Depression or graben	North-west region
Longley, A.J. (2015).	Raw data files	369	95	26%	1050 μg/L	Tertiary volcanic-region, Paleozoic and Mesozoic platform & Depression or Graben	Central region of Nicaragua & North-west region

(*) Public piped water supplies (urban areas); community water systems; boreholes/tubewells and protected wells.

municipalities grouped according to their geographic proximity. The data extracted from the studies mentioned in.

Table 1 were used for the preparation of maps showing municipalities and water supply points affected by As contamination. Of the total number of samples cited, 40% were georeferenced.

2.2. Detailed analysis of four research areas

Four different highly As-affected areas were identified within the existing data sets to provide new insights into arsenic mobilization mechanisms in Nicaragua. These research areas are:

(1) *Alluvial aquifer of the Sebaco valley and surrounding areas*: one of the main alluvial aquifers in the country (Meza, 2004; Plata Berdmar, 1988), located in the Tertiary volcanic province; the surface area of the catchment extends approximately 652.79 km^2.
(2) *Central region of Nicaragua*: subdivided into two distinct geologic areas: the northern area which belongs to the Paleozoic and Mesozoic platform, and the central northern area belonging to the central geologic province, comprising groups of Tertiary volcanic rocks (Hodgson, 1998; McBirney and Williams, 1965)
(3) *Hydrothermal mineral deposit areas*: parallel to the graben, a series of mineralized geologic structures are found which

area associated with gold and arsenic minerals (Barragne, 2004; Estrada, 2003).

(4) *North-western region*: belonging to the depression or graben; a volcanic chain is formed by 19 volcanos (active and inactive) which are part of the Pacific ring of fire (McBirney and Williams, 1965).

2.3. Pearson correlation of co-occurring compounds

Co-occurrence of As with other physicochemical parameters (e.g. temperature, trace elements, major ions) may provide a better understanding of the As mobilization mechanisms. The Pearson correlation coefficient (r) was determined, which is a measure of the linear relationship between two quantitative aleatory variables (Currell and Dowman, 2009), with absolute values oscillating between 0 and 1. The closer r is to 1, the stronger the correlation (Currell and Dowman, 2009). To determine the level of significance of the calculated correlation, the p value was calculated. When the p value was below 0.001, the correlation was considered to be meaningful.

3. Results

3.1. Occurrence of arsenic in Nicaragua

3.1.1. History of reported arsenic contamination

In Nicaragua, the presence of As in water bodies was reported for the first time in surface water (a lake of volcanic origin) in the early 1990s (Lacayo et al., 1992). This study observed As contamination (ranging between 10 and 30 μg/L) in Xolotlán Lake and Tipitapa's hot springs (≈200 μg/L). Concern in Nicaragua about the presence of As in groundwater, the principal source of potable water for rural and urban populations, and its influence on human health, started in 1996. In that year, the first documented case of As poisoning was reported in a rural community (El Zapote) in the north of the country. From 1994 to 1996, this community was supplied by a well that extracted water from the alluvial aquifer of the Sebaco Valley, with an As concentration of 1320 μg/L (Gomez, 2002).

The Zapote incident led to the beginning of research related to As contamination in Nicaraguan groundwater resources. New studies, conducted between 1996 and 2015, resulted in the discovery of more As-contaminated drinking water sources exceeding 10 μg/L in scattered rural communities distributed in 34 municipalities (Altamirano Espinoza and Bundschuh, 2008; Barragne, 2004; Bundschuh et al., 2008; Bundschuh et al., 2012; CARE, 2002; CISTA, 2012; Estrada, 2003; González et al., 1997; INAA, 1996; Longley, 2010; Longley, 2015; OPS/OMS and UNICEF, 2005; PIDMA-UNI, 2001; PIDMA-UNI and UNICEF, 2002; PIDMA-UNI and USAID, 2001) (Fig. 2). As concentrations exceeding the national guideline in water samples taken from public piped supply systems in the main urban areas have not been reported.

While most of the research over the last two decades has focused on identifying water sources contaminated by As, several studies have also related the presence of As in drinking water to As poisoning of rural communities based on dermatologic and epidemiologic studies (Gomez, 2002; OPS/OMS and Nuevas-Esperanzas, 2011) as well as the use of biomarkers (OPS/OMS and Nuevas-Esperanzas, 2011). These studies considered the impact of historic as well as current As exposure and concluded that As poisoning was responsible for a wide range of skin and pulmonary diseases in at least six rural communities.

3.1.2. Distribution of exposed rural communities

This study has identified the presence of high arsenic concentrations in the drinking water sources of >80 rural communities (Fig. 3). These rural communities are distributed over 34 municipalities, belonging to the Central and Pacific regions of the country. In 23 of these affected communities it was estimated that around 5000 inhabitants were exposed to high As concentrations in drinking water sources (Bundschuh et al., 2012; ENACAL et al., 2005; Gomez, 2002; OPS/OMS and Nuevas-Esperanzas, 2011). In 2004 it was estimated that approximately 56,000 people were ingesting water contaminated by As (Barragne, 2004). Most of those people lived in scattered, small rural communities or were semi-concentrated in municipal and small towns (Barragne, 2004). In urban and rural areas, when potential water sources are found to be contaminated by arsenic, the corresponding authorities proceed to close such sources and look for alternative ones. In some cases, despite of the fact that the authorities have prohibited the consumption of water of the wells affected by As, the population still uses them because of the lack of alternative water sources. In one case, in Telica, a “dual water” system was devised which provides warm, As-contaminated water to two communities with a combined population of approximately 900 for non-potable use, while a second distribution system provides potable water from an uncontaminated spring source 4 Km away. The spring source was insufficient to meet the total domestic demand but is sufficient to meet drinking water needs (Nuevas-Esperanzas, 2013).

Throughout Latin America several As removal technologies have been assessed (Cardoso et al., 2010; Hoyos et al., 2013; Litter et al., 2010). In Nicaragua the experiences with arsenic removal systems is scarce. Few arsenic mitigation programs have been carried out. In 2009, the Minister of Health and OPS gave 39 Kanchan filters to the community of Muy Muy after discovering arsenic concentrations of up to 30 to 40 μg/L. Half of the community had stopped using the filter within the first eight months. Because of a lack of funding, the project was stopped after one year (Admiraal et al., 2015). In 2012, a Kanchan filter pilot project was conducted by the NGO Nuevas Esperanzas in a community located in the municipality of Telica. Eight Kanchan filters were given to this community, but after six months the filters already had a very poor removal and the pilot project was stopped (Admiraal et al., 2015).

In the alluvial aquifer of the Sebaco Valley and surrounding areas, 54 (31.6%) out of 170 investigated drinking water sources contained As concentrations ranging from 10 to 289 μg/L (Altamirano Espinoza and Bundschuh, 2008; CARE, 2002; González et al., 1997; González, 2004; INAA, 1996; PIDMA-UNI, 2001). The contaminated water sources are distributed over 19 rural communities.

In the central region of Nicaragua, 42 rural communities have been found to be affected by the presence of high concentrations of As in drinking water sources. In this area, 95 (16.3%) out of 583 drinking water sources tested exceeded the provisional guideline of the World Health Organization (ranging between 11 μg/L to 1196 μg/L) (ENACAL et al., 2005; OPS/OMS and UNICEF, 2005; PIDMA-UNI and USAID, 2001).

In the hydrothermal mineral deposit area 270 drinking water sources have been analyzed. Of these sampling points, 36 (13.3%) were reported to have an As concentration ranging between 11 and 161 μg/L (Barragne, 2004; Morales et al., 2008). The affected water sources are located in nine rural communities within the study area.

Studies conducted more recently in the north-western region resulted in the identification of around 20 rural communities with As contaminated drinking water sources, exceeding the national regulatory limit (CISTA, 2012; Longley, 2010; Longley, 2015; OPS/OMS and Nuevas-Esperanzas, 2011). From a total of 510 sampled water sources, 108 (21%) contained As concentrations higher than 10 μg/L. The arsenic concentration in the samples ranged from 10 μg/L to 1050 μg/L.

The studies referenced have mainly focused on the rural areas belonging to the Central and Pacific region of the country. To date, no arsenic contamination studies have been carried out in the Atlantic coast region.

3.1.3. Arsenic concentrations

Fig. 4 shows a map based on the georeferenced samples (40% of the total samples) with the distribution of the As concentrations in Nicaragua. The reported As concentrations range from below 10 μg/L to 1320 μg/L. The majority of As concentrations are below 10 μg/L

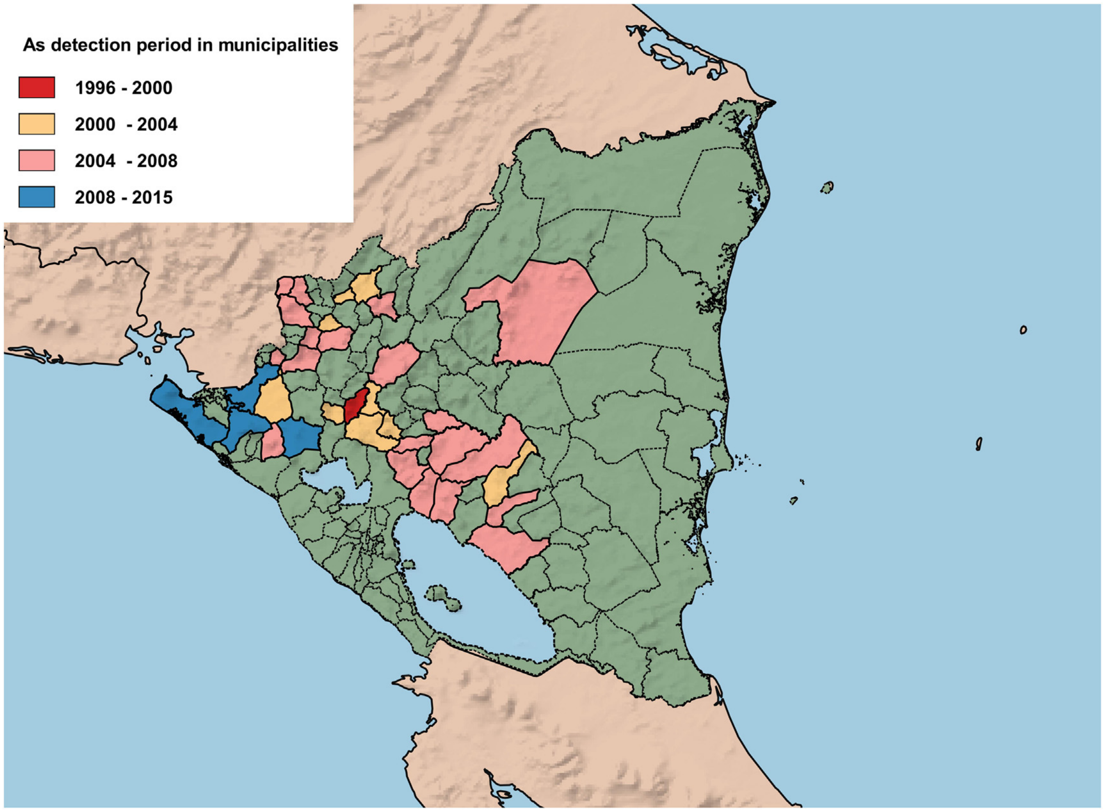

Fig. 2. Nicaraguan municipalities containing at least one drinking water source with an arsenic concentration exceeding the 10 μg/L, classified by the year in which arsenic was first detected (Altamirano Espinoza and Bundschuh, 2008; Barragne, 2004; Bundschuh et al., 2008; Bundschuh et al., 2012; CARE, 2002; CISTA, 2012; Estrada, 2003; González et al., 1997; Longley, 2010; Longley, 2015; OPS/OMS and Nuevas-Esperanzas, 2011; PIDMA-UNI, 2001; PIDMA-UNI and UNICEF, 2002; PIDMA-UNI and USAID, 2001).

(88.7%), less frequent are the As concentrations in the range of 10 and 100 μg/L (10.06%) and rarely concentrations over 100 μg/L (1.28%) were found.

3.2. Detailed analysis of four arsenic-affected areas

3.2.1. Alluvial aquifer of the Sebaco Valley and surrounding areas

Several reports (CARE, 2002; González, 2004; PIDMA-UNI, 2001) mentioned water sources with relatively high temperatures (ranging between 30.5 °C to 32.7 °C where the average temperature of other sources was around 27 °C) and As contamination on the western half of the Sebaco valley (Table 2). These relatively high temperatures were interpreted to be caused by geothermal influence (CARE, 2002). The existence of a residual hydrothermal influence on the western half of the Sebaco valley, has been reported previously (Plata Berdmar, 1988). In this area the water reaches temperatures of up to 35 °C, which has been related to the occurrence of saline water and elevated silicate (SiO_2) concentrations, found in the same part of the aquifer (Plata Berdmar, 1988).

The study conducted by Altamirano Espinoza and Bundschuh (2008) focuses on the southwestern part of Sebaco valley (El Zapote area), which is located in the contact zone between the alluvial valley with Tertiary volcanic rocks. This area is far from the residual hydrothermal focus (Plata Berdmar, 1988), and the water temperatures are equal to or below 28 °C. This investigation states that the dissolution of minerals from the extensive hydrothermally altered Tertiary volcanic rocks aid As release into groundwater by reductive dissolution or alkali desorption (Altamirano Espinoza and Bundschuh, 2008). Similar As contamination processes have been identified in the municipality of Mixco in Guatemala (Bundschuh et al., 2012; Cardoso et al., 2010). From the data (Table 2) obtained from Altamirano Espinoza and Bundschuh (2008) a high (positive) and significant correlation ($r = 0.88$, $\rho < 0.001$) has been observed between As and potassium (K^+) concentration, which could be a consequence of hydrolysis of K-feldspar (Kouras et al., 2007). No other high correlation between As and other physicochemical parameters (e.g. pH, EC, TDS and major ions) have been found.

3.2.2. Central region of Nicaragua

Among the studies conducted in the central region of Nicaragua, only PIDMA-UNI and USAID (2001) have included water quality parameters that can be used to elucidate the mechanism of arsenic mobilization. In the area studied by PIDMA-UNI and USAID (2001) the As-contaminated water sources have been characterized by temperatures between 23 °C to 30 °C with a pH that varied from slightly acid to alkaline (6.3–11.2). Oxidized species such as SO_4^{2-} (0.2–180 mg/L) and NO_3^- (0.2–14 mg/L) were present in low and medium concentrations. Another feature of the water quality is the low levels of Fe (0.04–1 mg/L) and Mn (<1 mg/L). The HCO_3^- concentration varied from 63 mg/L to 370 mg/L. With the available data it was not possible to find a correlation (Pearson) between arsenic and other physicochemical parameters. However, based on the characteristics of the drinking water sources (both oxic and anoxic waters), mentioned above, it seems that reductive dissolution and alkali desorption could play a role in the As mobilization mechanism in this area.

3.2.3. Hydrothermal mineral deposit areas

Barragne (2004) has pointed out two areas of interest, each with a different As mobilization mechanism. The first area corresponds to drinking water sources belonging to the municipality of Santa Rosa del Peñon (western region of Nicaragua). In this area the water sources have a relatively high temperature (up to 32.2 °C) and commonly As concentrations (ranging between 11 and 95

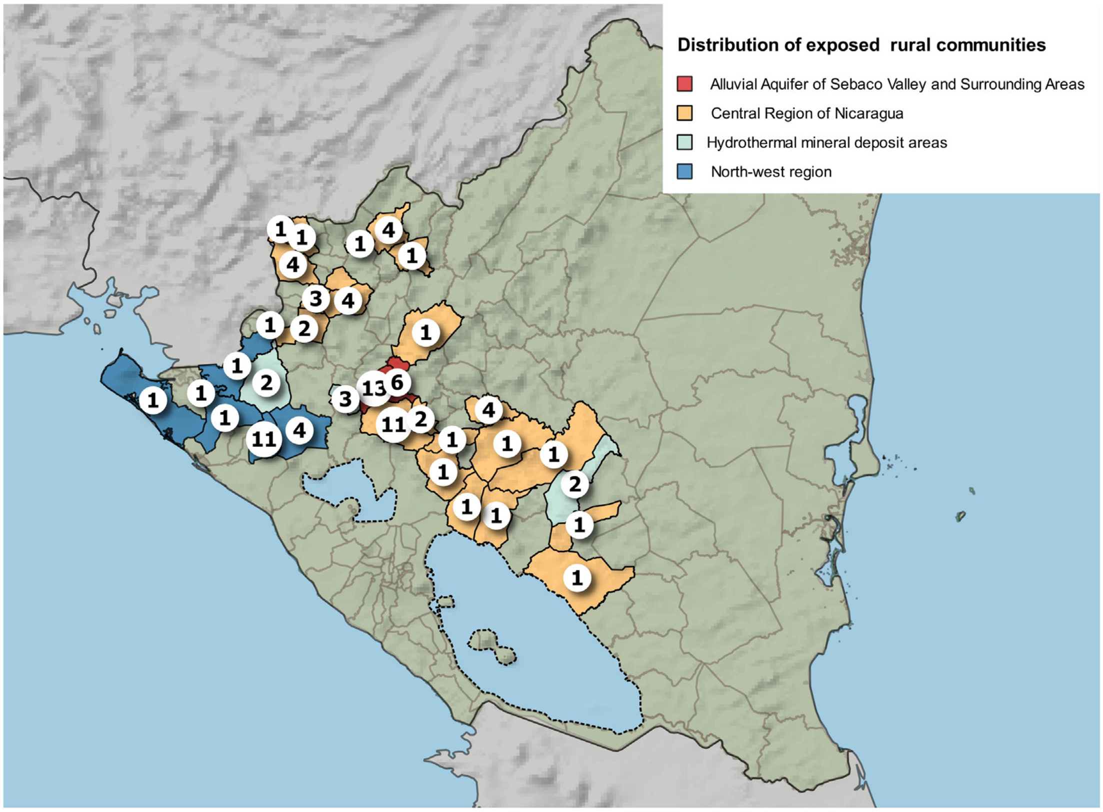

Fig. 3. Distribution of exposed rural communities in arsenic affected areas. The numbers enclosed in circles indicate the number of rural communities affected by arsenic-rich drinking water sources (Altamirano Espinoza and Bundschuh, 2008; Barragne, 2004; CARE, 2002; CISTA, 2012; Estrada, 2003; González et al., 1997; INAA, 1996; Longley, 2010; Longley, 2015; OPS/OMS and Nuevas-Esperanzas, 2011; PIDMA-UNI, 2001; PIDMA-UNI and UNICEF, 2002; PIDMA-UNI and USAID, 2001).

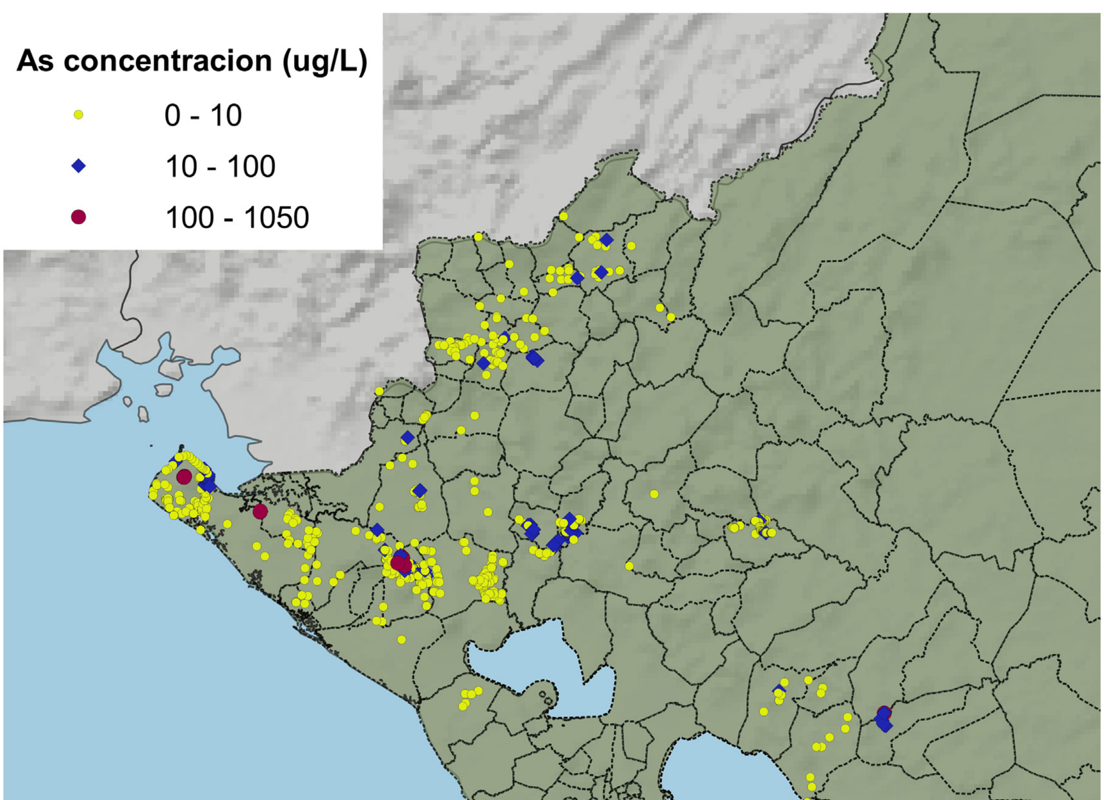

Fig. 4. Measured arsenic concentrations across in Nicaragua – this map was based on 40% of the total samples (Altamirano Espinoza and Bundschuh, 2008; Barragne, 2004; CISTA, 2012; Estrada, 2003; Morales et al., 2008; Longley, 2015; PIDMA-UNI and USAID, 2001).

Table 2
Water matrix composition for some communities located in alluvial aquifer of the Sebaco Valley and surrounding areas.

Parameter	Unit	Altamirano Espinoza and Bundschuh (2008) Range	González (2004) Range	PIDMA-UNI (2001) Range
As	μg/L	0–122	2–11	1–69
Turbidity	NTU	0.15–203	0.24–26	NM
pH	–	6.3–8.3	6.4–7.4	6.5–7.7
Conductivity	μs/cm	121–764	386–1148	159–1291
Temperature	°C	23–28	26–32	25–31
Eh	mV	166–636	NM	NM
Ca^{2+}	mg/L	10–115	38–99	NM
Mg^{2+}	mg/L	3–19	6–22	NM
Na^{+}	mg/L	8–96	3–189	NM
K^{+}	mg/L	0.5–18	1–5	NM
Cl^{-}	mg/L	4–26	7–141	NM
NO_3^{-}	mg/L	0–32	1.5–20	NM
SO_4^{2-}	mg/L	1–24	10–184	NM
HCO_3^{-}	mg/L	57–435	120–509	NM
Si	mg/L	31–98	34–94	NM
Fe	mg/L	0.02–14	0.04–1.4	NM
F	mg/L	0.1–0.6	0.2–0.9	0.1–0.9
B	mg/L	NM	0.09–0.25	NM

NM = not measured

μg/L) exceed maximum allowable levels (10 μg/L) with pH ranging between 6.2 and 8, and Eh values ranging between +40–+260 mV. The authors proposed that the dominant As species was the oxidized form of arsenate (As(V)). The high As concentrations and the relatively high temperature found in the water sources of Santa Rosa del Peñon have been attributed to the influence of geothermal fluids (Barragne, 2004). Geothermally influenced As-water has been reported along the Pacific region of Latin America (López et al., 2012) The second area, mentioned by Barragne (2004), is located in the municipality of La Libertad (southeast region). The maximum temperature in the As-contaminated water sources (ranging between 10 and 110 μg/L) did not exceed 28.7 °C. The

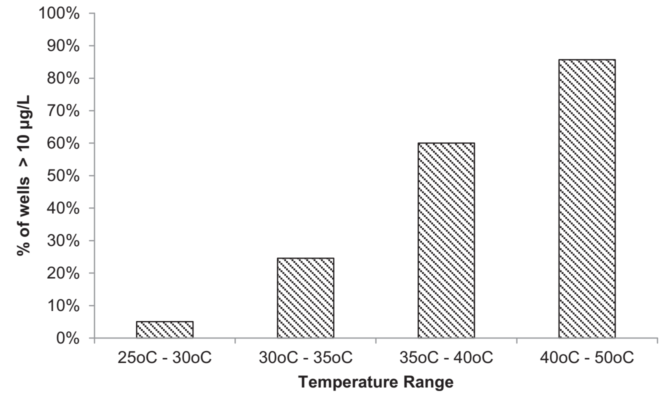

Fig. 6. Percentage of As – contaminated wells in the municipality of Telica for different ranges of temperature (OPS/OMS and Nuevas-Esperanzas, 2011).

pH varied from 6.8 to 7.5, and the Eh values were between +89 to +188 mV. The dominant species in the area was the reduced form of arsenite (As(III)). This underlines that it is likely that reductive dissolution plays an important role in the As contamination in the area of La Libertad. Reductive dissolution as an As mobilization mechanisms have been identified in Asian countries such as Bangladesh, India (Nickson et al., 2000) and Nepal (Gurung et al., 2005).

Morales et al. (2008) studied groundwater sources in the municipality of San Juan de Limay (northwestern region). The pH varied from neutral (7) to alkaline (10.3) and the As-contamination ranging between 10 and 115 μg/L. The dominant As species in the tested wells was As(V). This study suggested that the volcanic ash layer could be the main source of As contamination in this area. This research noted that the wells with higher As concentration also have higher pH values. The relationship between high pH and high As concentration has also been observed in earlier research conducted in La Pampa, Argentina (Smedley et al., 2002). Morales et al. (2008) proposed that dissolution of carbonate and dissolution of silicates in volcanic glass may explain the mentioned relationship.

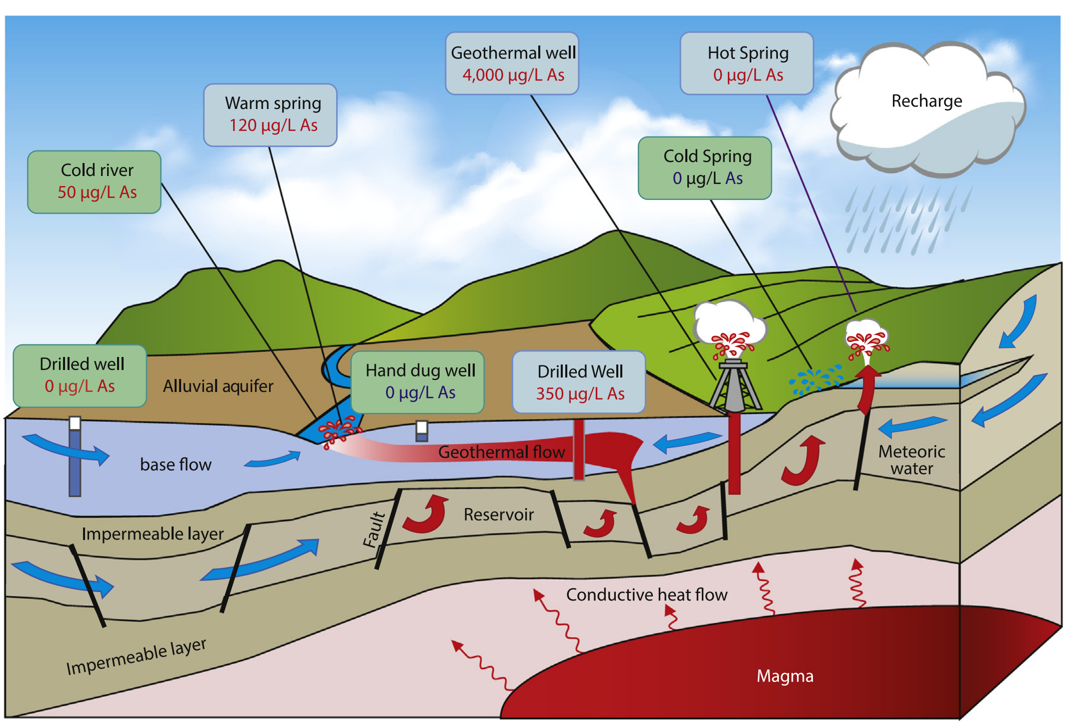

Fig. 5. Representation of As geothermal influence in Telica municipality (OPS/OMS and Nuevas-Esperanzas, 2011).

Table 3
Water matrix composition for some communities located in Telica (OPS/OMS and Nuevas-Esperanzas, 2011).

Parameter	Units	Range
As	μg/L	0–325
Temperature	°C	30–49
Ca^{2+}	mg/L	37–118
Mg^{2+}	mg/L	21,367.0
Na^{+}	mg/L	28–320
K^{+}	mg/L	3–26
Cl^{-}	mg/L	26–252
SO_4^{2-}	mg/L	25–369
HCO_3^{-}	mg/L	58–494

3.2.4. North-west region

The authors (OPS/OMS and Nuevas-Esperanzas, 2011) who conducted the research in the Municipality of Telica have identified two distinctive study areas with different potential As mobilization mechanisms. In the first area, the authors have suggested that the reductive dissolution As mobilization mechanism influences arsenic contamination in this region. The average temperature in this area was 29 °C, and the As concentration varied between 10 and 50 μg/l. For the second area, however, the shallow alluvial aquifer is influenced by the hot fluids associated with active geothermal fields located in the volcanic chain of "Los Maribios" (OPS/OMS and Nuevas-Esperanzas, 2011) (Fig. 5). The drinking water sources in this area tend to be dominated by high temperature (average of 33.8 °C), and elevated As concentrations, above 50 μg/l (up to 325 μg/l). This explanation is aligned with other As-contaminated geothermal waters found throughout Latin American, which have been related with the active geothermal fields associated with the volcanic chain of the Pacific Ring of Fire (López et al., 2012). For example the influences of geothermal arsenic in drinking water sources have also been recognized in Los Altos de Jalisco, Mexico (Hurtado-Jiménez and Gardea-Torresdey, 2008). In this area the drinking water is mainly extracted from aquifers located in the Transmexican Volcanic Belt. The temperature varies from 22.2 to 45.2 °C and the As concentration varies from 0.5 to 263 μg/l. The mentioned study also found that the higher the temperature is the higher the As concentration in the aquifers. A similar trend can be observed in Telica, where the percentage of As-contaminated wells (above 10 μg/L) (Fig. 6) and the As concentration increases as temperature increases. Table 3 presents a summary of the water composition for some of the rural communities located in Telica.

The raw data provided by CISTA (2012) (Table 4) show that As-contaminated drinking water sources have a pH ranging from neutral to alkaline (7 to 8.2) and HCO_3^- concentrations varying from 50 mg/L to 600 mg/L. Furthermore, these waters are characterized by the low content of Fe (<0.1 mg/L) and Mn (<0.15 mg/L). On the other hand, oxidized species such as SO_4^{2-} (0.6 mg/L to 90 mg/L) and NO_3^- (1.5 mg/L to 400 mg/L) are present, although it is likely that the high content of NO_3^- is caused by anthropogenic influences (e.g. agriculture). Temperature, Eh, and dissolved oxygen concentration measurements were missing in the CISTA-UNAN report (CISTA, 2012). From the data obtained from the mentioned study a positive, high, and moderate correlation was found between As and some trace elements such as Se ($r = 0.46$, $\rho < 0.001$), Mo ($r = 0.48$, $\rho < 0.001$), B ($r = 0.59$, $\rho < 0.001$) and V ($r = 0.82$, $\rho < 0.001$). Altogether this water type suggests As mobilization through alkali desorption (Bhattacharya et al., 2006; Robertson, 1989; Smedley and Kinniburgh, 2002). However, the co-occurrence of As with V (Vanadium) and the other trace elements reported by CISTA-UNAN (CISTA, 2012) has also been observed by (Smedley and Kinniburgh, 2002) in arid oxidizing environments like The Chaco-Pampean Plain of Central Argentina.

Table 4
Summary of the water matrix composition provided by (CISTA, 2012).

Parameter	Units	Range
As	μg/L	0.3–57
TDS	mg/L	2–612
Conductivity	μS/cm	127–1225
pH	–	7–8.2
Na^{+}	mg/L	5–57
Ca^{2+}	mg/L	4–85
Mg^{2+}	mg/L	0–39
HCO_3^{-}	mg/L	49–615
SO_4^{2-}	mg/L	0.6–90
Cl^{-}	mg/L	5–148
NO_3^{-}	mg/L	1.5–400
Fe	mg/L	~0.1
Mn	mg/L	~0.15
B	μg/L	0–330
V	μg/L	1–240
Se	μg/L	0.7–2.1
Mo	μg/L	0.02–20

4. Conclusion

Natural As contamination in groundwater, exceeding the provisional guideline of the World Health Organization of 10 μg/L, has been detected in drinking water sources in >80 rural communities distributed in 34 municipalities in Nicaragua between 1996 until 2015. It is likely that more contaminated drinking water sources will be detected with the increase in monitoring campaigns, since As monitoring has so far only been conducted in 23.5% of municipalities.

The source of arsenic contamination in Nicaragua is probably of volcanic origin, both from volcanic rocks and geothermal fluids, resulting in widespread occurrence across the country. As may enter into the groundwater directly, from geothermally influenced water bodies, or indirectly, by reductive dissolution or alkali desorption, depending on local geochemical conditions.

In order to understand the full extent of As contamination in Nicaragua and to be able to reliably map As distribution, a more extensive sampling campaign is recommended. A good understanding of regional arsenic mobilization mechanisms will aid in the selection of appropriate technologies for arsenic removal or alternative mitigation strategies.

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