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A hydrochemical investigation and socioeconomic assessment in Rio Zapomeca river basin focusing on arsenic contamination

by

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Abstract

The awareness of problems concerning arsenic contaminated drinking water sources has during recent years increased. WHO (World Health Organization) decided in 1993 to lower the recommended limit of arsenic in drinking water from 50 µg/l to 10 µg/l, mainly due to observations of its carcinogenicity. New places where the WHO limit for arsenic is exceeded are constantly discovered all over the world. Several areas in Nicaragua in Central America have since 1996 been discovered to have arsenic concentrations above the recommendations.

This Minor Field Study aims to investigate the origin and triggers of the arsenic that is contaminating the drinking water sources in the river basin of Rio Zapomeca located in central Nicaragua. The study also evaluates different drinking water distribution methods and assesses the need of arsenic filters, so called Kanchan filters, by doing an analysis according to the principles of cost-benefit-analysis.

Nicaragua is located close to a subduction zone resulting in tectonically active geology including earthquakes, active volcanoes and geothermal activity. The river basin of Rio Zapomeca is no exception with both hot springs and strong faulting. The geology in the river basin is dominated by two Tertiary groups named Matagalpa and Coyol. This study includes hydrochemical measurements of pH, temperature, salinity, conductivity and total dissolved solids. Arsenic analysis of drinking water sources and collected rock samples were also carried out. Furthermore, resistivity surveys and groundwater level measurements were done.

The arsenic analysis showed that 15 of the 20 analysed drinking water samples had an arsenic concentration above the WHO limit (10 µg/l). The highest value of 104 µg/l was found in Los Negritos. The results of the investigations showed that the correlation between arsenic and the hydrochemical parameters pH, temperature, salinity and total dissolved solids is weak. The correlation with conductivity the highest showing an R^2-value of 0.47. The decrease of arsenic in relation to increase of elevation shows a clear trend in the project area but the reason is unclear, perhaps the increased elevation results in shorter retention time due to higher hydraulic gradient and thereby less time to dissolve arsenic. The clearest connection found is that elevated values of arsenic, both in the rock samples and in the water, occur along the contact zone between the rock type groups Coyol and Matagalpa in the southern to south-western part of the Zapomeca basin. The geothermal activity does probably affect the arsenic concentration in the groundwater, since the solubility of arsenic in water increases with temperature. However, to conclude the geothermal involvement concerning the arsenic contamination in the river basin of Rio Zapomeca further studies are needed.

The decrease in life expectancy for persons living in the river basin of Rio Zapomeca due to drinking the arsenic contaminated water was calculated using two different methods. The first method which included calculations regarding the percentage of life reduced resulted in an average decreased life expectancy of 3.2 years. The second method was calculated with the relative risk methodology that 26% of the deaths in the river basin can be linked to arsenic contaminated drinking water. Assuming that each person that dies of arsenic contaminated drinking water loses 15 years of lifetime makes the life expectancy decreases with 3.9 years. The value of statistical life (VSL) of a Nicaraguan was estimated to a value of $260 000. By using the VSL it was proven that it is economically valid to invest in Kanchan filters for the population living in the Rio Zapomeca river basin. The payback for each dollar invested varies depending on which discount rate that is used. Calculating conservatively and with a high but reasonable discount rate the payback per invested dollar is at least $2.6 thus making it a sound investment.

Resumen

En los últimos años ha surgido un gran interés de estudiar los problemas relacionados a la contaminación natural de arsénico en fuentes de agua para consumo. En 1993, la Organización Mundial de la Salud (OMS), decidió disminuir el límite recomendado de arsénico en el agua potable desde 50 µg/l a 10 µg/l, debido a sus efectos negativos de producir carcinogenicidad en los seres humanos. Nuevos lugares donde se supera el límite de arsénico de la OMS son constantemente descubiertos en todo el mundo. Desde 1996, varias zonas en Nicaragua (Centroamérica) han sido estudiadas y se han encontrado niveles de arsénico por encima de los limites recomendados.

El presente estudio tiene como objetivo investigar los mecanismos y el origen de la contaminación de arsénico en fuentes de agua potable en la cuenca del Río Zapomeca, la cual, se localiza en el centro de Nicaragua. En esta investigación también se evalúa los diferentes métodos de distribución de agua potable y determina la necesidad de utilizar filtros de arsénico, también llamados filtros Kanchan, al hacer un análisis de costo-beneficio.

Nicaragua se encuentra en una zona tectónicamente activa debido a la proximidad de la zona de subducción, la cual, es la causa principal de la actividad sísmica, volcánica y geotérmica en el país. La cuenca del Río Zapomeca no es una excepción, presenta fuentes termales y un intenso fallamiento. La geología de la zona está caracterizada por los grupos Matagalpa y Coyol de edad Terciaria. En este estudio se incluye mediciones hidrogeológicas tales como; pH, temperatura, salinidad, conductividad y sólidos disueltos totales. También se realizaron análisis de arsénico en fuentes de agua potable y se obtuvieron muestras de rocas en el campo. Por otra parte, también se hicieron mediciones de resistividad eléctrica y de los niveles de agua subterránea.

El análisis de arsénico en agua mostró que trece de las veinte muestras tenían una concentración de arsénico por encima del límite de la OMS. El valor más alto fue de 104 µg/l y se encontró en la localidad Los Negritos. Los resultados de las investigaciones también demuestran que la correlación entre el arsénico y los parámetros hidrogeológicos (pH, temperatura, salinidad y sólidos disueltos totales) es baja. La correlación con la conductividad es mayor y presenta un valor R^2 de 0.47. La disminución del arsénico en relación al aumento de la elevación muestra una clara tendencia en el área de estudio, pero la razón no está clara. Tal vez el aumento de la elevación resulta en un tiempo de retención más corto y un mayor gradiente hidráulico y por lo tanto menos tiempo para disolver el arsénico. La relación más clara encontrada es que los valores elevados de arsénico, tanto en las muestras de roca y agua, se producen a lo largo de la zona de contacto entre los grupos Coyol y Matagalpa, y esta se localiza en la parte Suroeste y Sur de la cuenca Zapomeca. La actividad geotérmica probablemente afecta la concentración de arsénico en el agua subterránea, ya que la solubilidad del arsénico en el agua aumenta con la temperatura. Sin embargo, no es posible concluir la relación entre la actividad geotérmica con la contaminación de arsénico de la cuenca del Río Zapomeca en este estudio y son necesarias más investigaciones.

La disminución de la esperanza de vida para las personas que viven en la cuenca del Río Zapomeca se debe al consumo de agua contaminada con arsénico, la cual, se estimó utilizando dos diferentes metodologías. En el primer método se calculó el porcentaje de reducción en la esperanza de vida, y resultó un promedio de 3.2 años. El segunda metódo utilizó la técnica de riesgo relativo y se obtuvó que el 26% de las muertes en la cuenca del río puede estar relacionada con la contaminacion del agua potable por arsénico. Suponiendo que cada persona muere por el consumo de agua contamina y pierde 15 años de vida, esto hace que la disminución de la esperanza de vida sea de 3.9 años. El valor estadistico de la vida (VSL) de un nicaragüense se estimó en $ 260 000. Al utilizar el VSL se comprobó que es económicamente razonable invertir en los filtros Kanchan para las comunidades que encuentran en la cuenca del Río Zapomeca. La recuperación de la inversión por cada dólar varía en función de la tasa de descuento que se utiliza. El cálculo con una alta tasa de descuento razonable y la recuperación de la inversión por cada dólar es por lo menos $ 2.6 por lo que se hace una buena inversión.

Table of Contents

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2 Abbreviations and explanations

As	Arsenic
Caldera structure	A formation that is formed when a volcano collapses after its magma chamber has been depleted.
CIGEO	Centro de Investigaciones Geocientíficas
Coyol	Geological group abundant in Rio Zapomeca river basin.
ERT	Electrical Resistivity Tomography
IP	Induced Polarization
Kriging method	Interpolation method
Matagalpa	Geological group abundant in Rio Zapomeca river basin.
PAF	Population Attributable Fraction
RTK-GPS	Real Time Kinematic-Global Positioning System
TDS	Total Dissolved Solids
UNAN	Universidad Nacional Autónoma de Nicaragua
VSL	Value of Statistical Life
WHO	World Health Organization
XRF spectrometry	X-Ray Fluorescence spectrometry

3 Introduction

Nicaragua is the poorest country in Central America and has during the last half of the 20th century suffered from both civil war and devastating natural disasters (CIA, 2015a). Both the economy and the infrastructure were and are still heavily affected by the hurricane Mitch that hit the country in 1998 and a massive earthquake in 1972 that left the capital, Managua, in ruins with two thirds of the buildings in rubble (CIA, 2015a) (Rojahn, 1973).

Overall, Nicaragua has gone through many positive changes during the last two decades. Examples of these are that the number of children born per woman has decreased from 6 in 1980 to 1.99 in 2014 and the economic activity of the country is growing while the inflation is decreasing, allowing the government to change focus from crisis control to making long term decisions instead (CIA, 2015a) (The World Bank, 2014). The poverty is decreasing in Nicaragua but the income is unevenly distributed with 80% of the poor people living in rural areas (The World Bank, 2014).

The life expectancy at birth in Nicaragua is 74.5 years, 71.5 for men and 77.6 for women. The most common causes of death are cancer, cardiovascular deceases, cerebrovascular diseases, diabetes and chronic renal insufficiency (Pan American Health Organization , 2012).

There have been several projects carried out in order to enhance the waste water treatment in Nicaragua during the latest decades (Central America Data, 2015). For example, the German government has subsidised a water treatment plant in Managua to improve the poor environmental conditions in Lake Managua. The focus lately has also been to improve the accessibility to potable water especially in urban areas. Approximately 97.6 % of the population living in the urban areas had access to an improved drinking water source, compared to 67.8 % in the rural parts (CIA, 2015a). An improved drinking water source is defined as: piped water into home, yard, or plot; public tap or standpipe; tubewell or borehole; protected dug well; protected spring; or rainwater collection. Unimproved drinking water means use of any of the following sources: unprotected dug well; unprotected spring; cart with small tank or drum; tanker truck; surface water, which includes rivers, dams, lakes, ponds, streams, canals or irrigation channels; or bottled water (CIA, 2015b). The improvement concerning water related issues in Nicaragua has been rapid and during recent years has the Nicaraguan government decided that they no longer need foreign assistance when it comes to water resource management related issues. The UN has therefore withdrawn its financial aid to this field (Bigot, 2015). However, there are still water related issues which need to be solved in Nicaragua. Arsenic is a poisonous component contaminating drinking water at places all over the world. Nicaragua is one of these countries where arsenic concentrations above the WHO limit of 10µg/l have been found in drinking water. Arsenic concentration above this limit can be considered a risk source. Arsenic in drinking water is known to cause skin, bladder, kidney and lung cancer as well as cardiovascular disease, have development effects, neurotoxicity and diabetes (Flanagan & Zheng, 2011). The most common effects are skin cancer and lesions. In USA the average years lost from all kinds of cancer was 15.4 years in 2006 while skin cancer decreased life with 18 years and bladder cancer 11.2 years (National Cancer Institute, 2006). The healthcare in the USA is significantly better than in Nicaragua, (WHO, 2000). Hence, it can be considered a conservative assumption that the average years of life lost due to these diseases is equal to 15 years.

When treating a risk source there are two different approaches, elimination or mitigation of the hazard. Water is a necessity for the population meaning that the consumption cannot be affected. Filtration does not remove all arsenic and therefore transportation from a safe water source is the only alternative for complete risk elimination. Mitigation of arsenic includes various filter methods or projects for identifying and prospecting of wells with low concentrations.

4 Background

The focus of this study is the river basin of Rio Zapomeca close to the city of Teustepe which is approximately 70 kilometres east of Managua in the western region of Nicaragua, see Figure 1. Teustepe is a small town with around 4000 inhabitants and a somewhat increasing tourism thanks to the hot springs, Agua Caliente, just west of the town. The municipality of Teustepe had a total of 26 265 inhabitants in 2008 and 85 % of the people were living in rural areas (CATIE, 2008).

The land use in the municipality of Teustepe is dominated by crops and especially maize and beans are cultivated. The area is also to a large extent grazed by cattle (CATIE, 2008). Deforestation is becoming a problem due to agricultural overexploitation (MARENA & INETER, 2003).

The general level of development is improving in the municipal of Teustepe, however, out of a total of 5955 houses in Teustepe municipality 3708 still had no access to improved drinking water sources and 2903 houses did not have access to electricity in 2008 (CATIE, 2008).

Figure 1 Nicaragua and the study area. The study area is located within the red circle seen in the picture named Rio Zapomeca river basin.

4.1 Background of study

Sequeira (2008) did a hydrochemical study in the area around Rio Zapomeca, data from this study is found in Appendix 7. Sequeira discovered that the levels of arsenic were higher than the, by WHO (2012), recommended 10 µg/l at three different drinking water sources within the catchment of Rio Zapomeca. Also, a fourth place, the hot springs named Agua Caliente, with raised arsenic concentration was found just outside the catchment. According to Sequeira's research, the concentration of arsenic around the village of Asiento Viejo was 39 µg/litre. Other hazardous compounds such as lead were also found in the river basin. However, this Minor Field Study (MFS) is limited to the investigation of arsenic within the Rio Zapomeca river basin.

The report consists of two different fields of engineering, water resource management focusing on engineering geology and risk management. This gives the report an understanding of both the hydrogeological problem concerning the arsenic contamination and solutions to associated risks.

4.2 Purpose of study

Previous studies, (Sequeira, 2008), show arsenic contaminated drinking water sources within Rio Zapomeca river basin. Rio Zapomeca river basin can be seen in Figure 2. This condition made up the main motive of this study. The expectation is that this study can improve the understanding of the arsenic situation concerning drinking water in Rio Zapomeca river basin. The information gathered in this study will be undertaken by the host university UNAN-Managua and the local authorities in Teustepe.

4.2.1 Main Objectives

- Collect information concerning location and properties, including groundwater depth, borehole protocols and number of users, of wells within the river basin of Rio Zapomeca.
- Investigate the source of arsenic in Rio Zapomeca river basin by means of arsenic analysis of the drinking water, hydrochemical characteristics of the groundwater, resistivity surveys and knowledge concerning the local geology.
- Assess the socioeconomic impact of the arsenic contamination to determine if it is economically justifiable to take measures to provide drinking water with arsenic concentrations below the WHO's limit of 10µg/l.

The project is associated with large uncertainties and assumptions that will be presented in the report. These need to be taken into consideration and treated in a manner so that they will not undermine the credibility of the report. The expectation is that this study can improve the understanding of the arsenic situation concerning drinking water in Rio Zapomeca river basin.

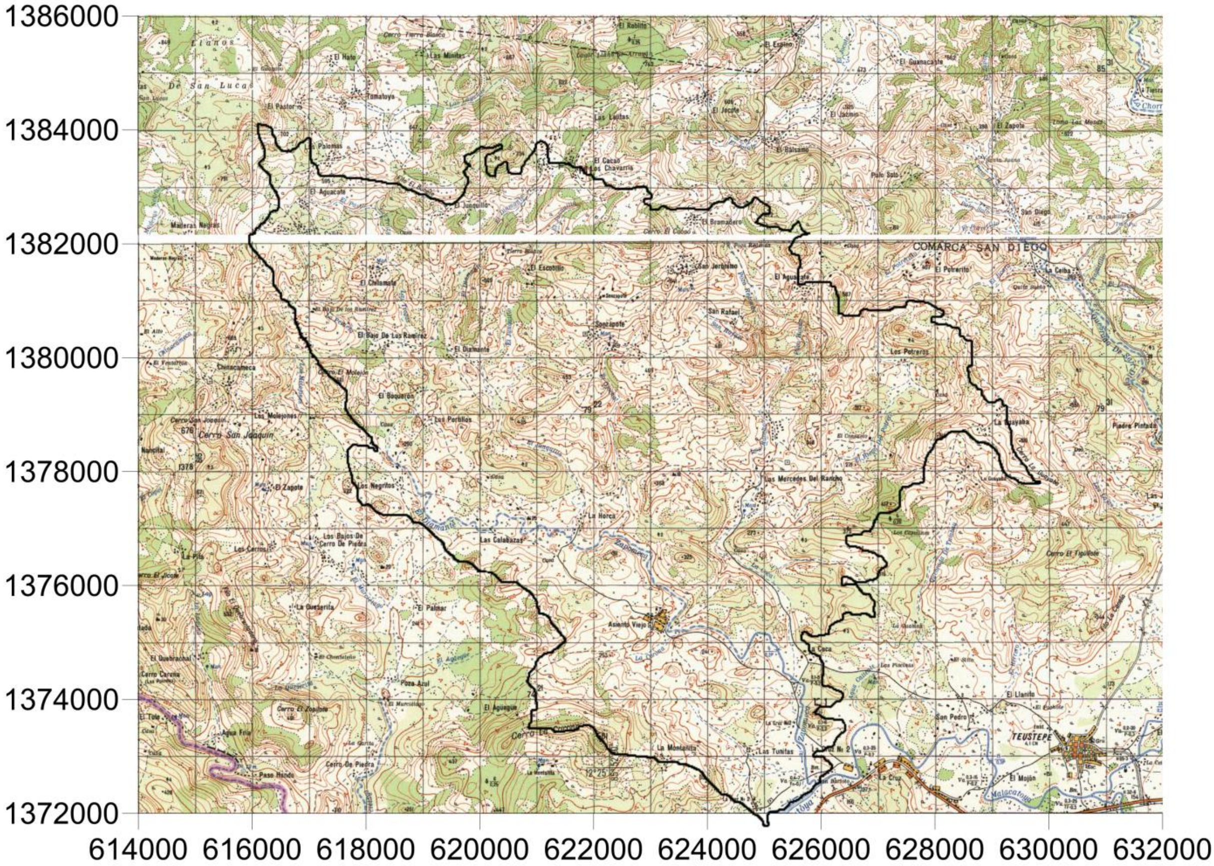

Figure 2 The black line indicates the Rio Zapomeca river basin (Sequeira, 2015) Map adapted from (INETER, 1988).

4.3 Project limitations

The field work done in this study was limited to eight weeks and includes investigations of pH, conductivity, temperature, salinity, Total Dissolved Solids (TDS), arsenic concentration and resistivity surveys. Furthermore, the language barrier was an issue and in many situations interpreters were required. Due to broken equipment at the host university in Managua there were no IP-measurements, induced polarization (geophysical investigation method), done. IP-measurements could have given a more detailed interpretation of the geology. Other limiting factors are time and resources. The limitation of time and resources also reflects back on the risk assessment since there were wells and springs that not were investigated in Rio Zapomeca river basin. This lack of data will most likely affect the assessment.

4.4 Previous studies in the area

There have been two previous MFS projects carried out in the nearby area a few years ago;

Andler and Petersson (2008) made an inventory of the groundwater situation in northern Rio Malacatoya river basin, situated nearby the Rio Zapomeca river basin. The report discusses recharge zones and different groundwater types and their abundance and creates a conceptual model of the hydrogeological situation.

Karlsson and Retamal (2007) did an inventory of the drinking water sources in Teustepe valley and made a chemical characterisation of the different types of groundwater. Also, data concerning the characteristics of the aquifers around Teustepe were gathered.

Ehrenborg (1999) made a geological map of the western Nicaraguan highland including the study area.

INETER (Instituto Nicaragüense de Estudios Territoriales) (1998) made a hydrogeological map of the area around Managua where different groundwater types and their chemical properties are presented. The project was financed by COSUDE (Swiss Agency for Development and Cooperation).

MARENA and INETER (Ministry of the Environment and Natural Resources in Nicaragua) (2003) made a map of the land use and municipal management for the municipality of Teustepe.

A geological report made by Ehrenborg and Alvarez (1988) where they presented coverage of the study area with geological maps and categorised the local geology.

A hydrochemical report made by Sequeira (2008), shows raised arsenic levels in drinking water sources within Rio Zapomeca river basin.

4.5 Geology of Nicaragua

Nicaragua together with the neighbouring countries in Central America are located in the western part of the Caribbean tectonic plate close to the border to the Cocos plate, see Figure 3. The Cocos plate is subducted, meaning that it moves in beneath the Caribbean plate, thus resulting in a volcanic arc that follows the southeast/northwest direction of the border between the two plates in the western part of the Nicaraguan main land. The subduction also results in numerous earthquakes, volcanoes and several areas with geothermal activities that can result in hydrothermal springs (Nyström, et al., 1987).

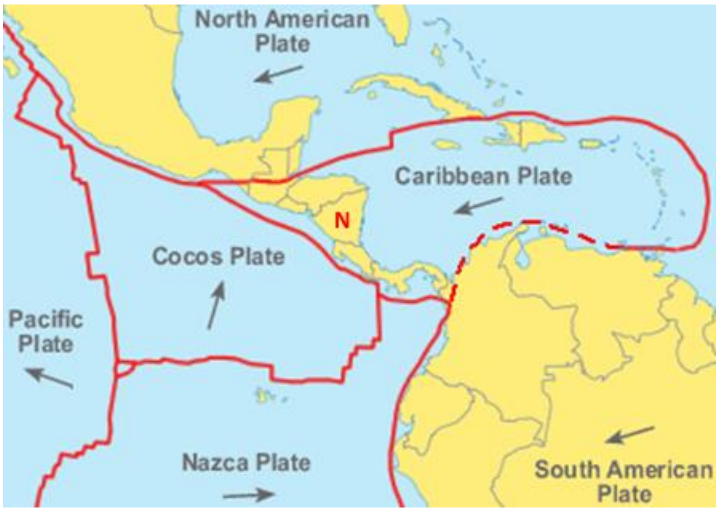

Figure 3 Nicaragua is marked with a red "N" (CAVA, 2012).

The westernmost part of Nicaragua is an approximately 75 kilometres wide stretch called the pacific coastal plains which is limited by an arc of volcanoes according to Figure 4. The volcanoes are located within a long and narrow stretch which is often referred to as the Nicaraguan depression, see Figure 5. Further east stretches the Nicaraguan highland with altitude increasing towards the northwest where it occasionally reaches altitudes of up to 2000 m.a.s.l. The altitude decreases closer to the Atlantic coast and in the southern parts of Nicaragua (Google Maps, 2015).

The crust in Nicaragua is generally thinner than the crust in the neighbouring countries. It is around 30 km thick compared to 30-45 km in El Salvador/Guatemala and 30-40 km in Costa Rica (Nyström, et al., 1987).

The geology in Nicaragua is mainly of volcanic origin. The central highlands of Nicaragua are dominated by Tertiary volcanic rocks (1.83-65 million years B.P) whereas the pacific coastal plains consist of Tertiary marine sedimentary rocks and Pliocene-Pleistocene volcanic rocks (0.01-5.3 million years B.P (Walker, et al., 2012)). The border between the western lowlands and the central highlands, the Nicaraguan Depression, see Figure 5, is characterised by more recent volcanic rocks from volcanoes which are still active today. The eastern parts of Nicaragua mainly consist of Tertiary marine sedimentary rocks or alluvial deposits (Nyström, et al., 1987).

Figure 4 The volcanic arc of today. Active volcanoes indicated with red triangles (Simkin & Siebert, 1994).

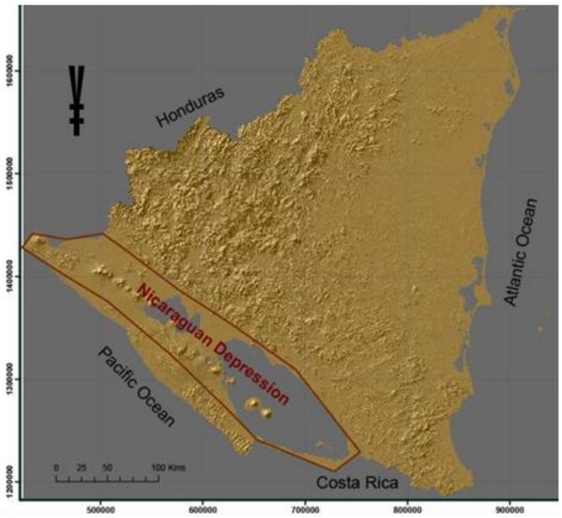

Figure 5 The Nicaraguan depression (Komuro, 2011).

4.5.1 Geology in the study area

The study area is the catchment area of a river named Rio Zapomeca, located where the depression meets the central Nicaraguan highlands and is therefore characterised by plains that turn into hillocks. The area is hydrothermally active with springs reaching temperatures of 46ºC (INETER, 1998). Old minor volcanic centres occur within the catchment area and there are larger Coyol caldera structures 15-20 km outside the catchment area of Rio Zapomeca, mainly to the south, north and east (Ehrenborg, 1999). The volcanic centres and the calderas cut through the older Matagalpa Group which implies that the geothermal activity outside and within the Rio Zapomeca catchment area is of Coyol age rather than the older Matagalpa. The geothermal areas are concentrated to the southern and central parts of the catchment. Furthermore, faults are common in the area generally striking in a NW-SE direction (Sequeira, 2015)

There has most likely not been any volcanic activity in the project area since the formation of the Coyol group, meaning that that there has not been any active volcanism in the area for at least five million years (Ehrenborg, 2015).

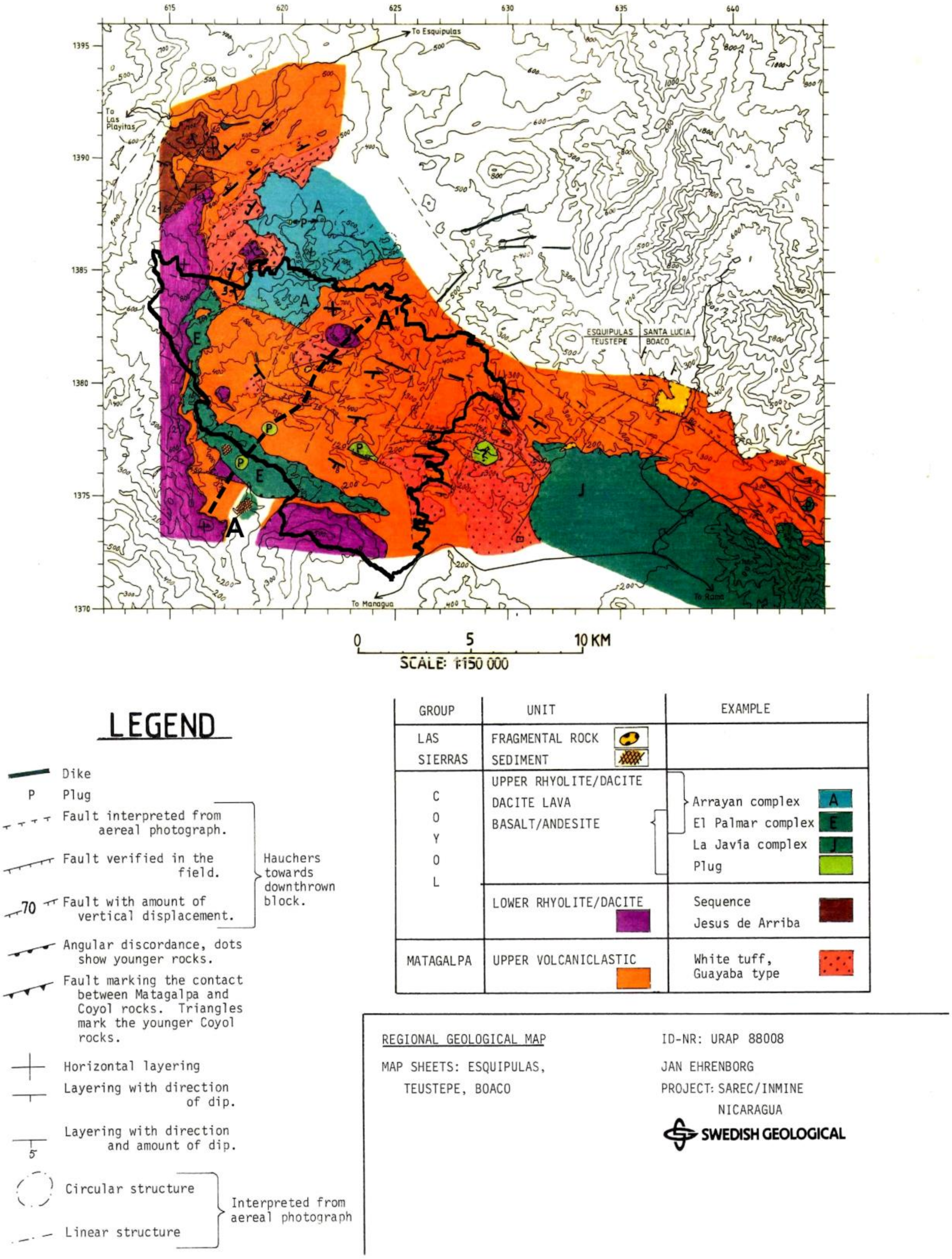

Figure 6 Rio Zapomeca river basin indicated with a solid black line. Cross-section found in Figure 7 is drawn from A-A' see dashed black line. Adapted from (Ehrenborg & Alvarez, 1988).

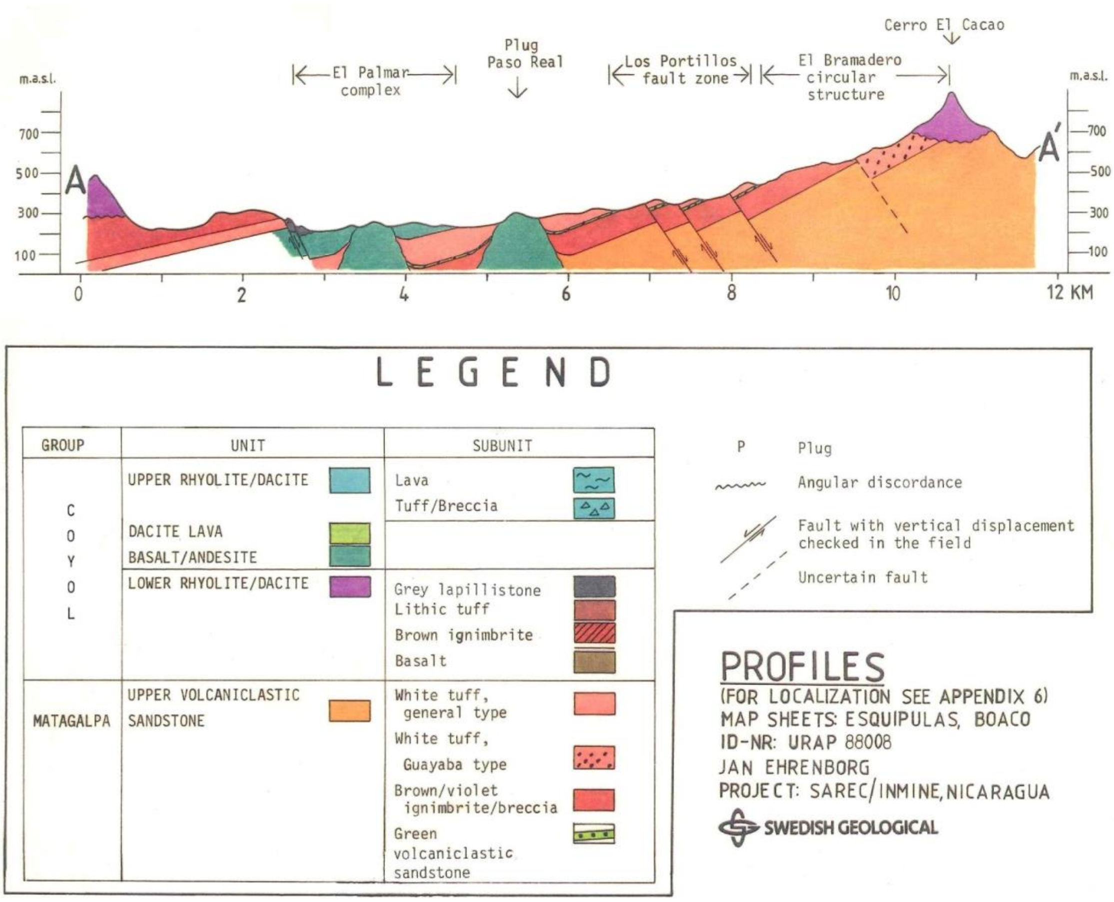

Figure 7 Cross-section A-A' of Rio Zapomeca river basin from southeast to northeast. See orientation in Figure 6 Adapted from (Ehrenborg & Alvarez, 1988)

The Tertiary volcanic rocks in the study area are divided into two main volcanic periods named the Matagalpa group (~35-45 million years B.P) and the Coyol group (~5-23 million years B.P.). Numerous fractures and faults in the highland are connected to the Matagalpa and Coyol volcanisms. A characteristic for the Matagalpa group is that it is generally tilting 2-10 degrees to the southwest. There are also examples of higher tilting of 15-30 degrees within the Matagalpa group when there is stronger faulting nearby. Hence, higher tilting than 10 degrees in the Matagalpa group implies faulting in the vicinity (Ehrenborg & Alvarez, 1988) (Ehrenborg, 1996).

Uncommon minerals such as stilbite and levyne have both been found within the study area and are geological indicators of stronger faulting and also of a more hydrothermally active area compared to the surroundings (Ehrenborg & Alvarez, 1988).

The geology is characterised by rhyolitic-dacitic ignimbrites e.g. brown or violet ignimbrite-breccia and air-fall deposits from volcanic eruptions from the Matagalpa group and rhyolitic-dacitic ignimbrites/tuffs to volcanic breccia and andesitic to basaltic lavas from the Coyol group (Ehrenborg, 2015).

The Coyol and Matagalpa group are divided into units corresponding to periods of time when the volcanic eruptions were more frequent. In between these periods of time the intensiveness and frequency of the eruptions were not as prominent. Examples of Coyol units are Santa Lucia (~3-15 million years B.P), La Libertad and Las Maderas (~14-18 millions years B.P). Examples of Matagalpa units are Juigalpa (~20-25 millions years B.P), Cerro Oluma (~2-20 million years B.P) and Cuapa (~25-30 million years B.P) (Ehrenborg & Alvarez, 1988) (Ehrenborg, 1999).

The general stratigraphy in the study area is from north-east consisting of Matagalpa guayaba white tuff on top and further south Matagalpa ignimbrite/breccias and general white tuff, see Figure 7. The SW part of the area consists of Coyol basalt/andesite on top of the Matagalpa white tuff. The Coyol rocks make up a rather homogeneous basalt/andesite terrain making the slope more difficult to generalise. The direction and slope of different basalt/andesite layers within the Coyol rocks are possibly similar to the orientation of the Matagalpa sequence but this cannot be taken for granted. The Matagalpa white tuff is homogeneous and could be made up from one specific volcanic event and does therefore most likely lack stratification. However, both Matagalpa and Coyol basalt/andesite are heterogeneous units originating from several volcanic events. This difference in heterogeneity and homogeneity does most probably explain the different weathering of the different layers since it opens the possibility for different layers being exposed to weathering for different amounts of time. Also, different porosity and rock type of the rock layers and different exposure to stress reflects the appearance of the layer sequence and the permeability. Differences in weathering could be expected especially in the heterogeneous layered Matagalpa ignimbrite/breccia and the Coyol basalt/andesite units and possibly less in the homogeneous none-layered Matagalpa white tuff unit (Ehrenborg, 2015) (Ehrenborg & Alvarez, 1988).

Within the river basin of Rio Zapomeca the Coyol group is dominated by basalt and andesite whereas the Matagalpa group is dominated by ignimbrites/breccias and white tuffs. To simplify the geology, by means of rock species, the geological features in this report will from now on only differ between the "Coyol group" and the "Matagalpa group". Subunits such as Coyol basalt/andesite or Matagalpa ignimbrite/breccias will not be used.

The Matagalpa rocks found within the study area are generally light coloured and do to a large extent consist of quartz and feldspar which make them more resistible to weathering compared to the darker, less feldspar- and quartz-rich Coyol rocks (Johansson, 2015) (Svensson, 2015).

4.6 Hydrology and Climate

Nicaragua is located in the tropics, meaning that the temperature is varies slightly over the year, with mean temperature varying between 25^{o}C-27^{o}C in the lowlands and 21^{o}C-25^{o}C in the highlands. The climate in Nicaragua varies geographically, especially from east to west. There are two distinct seasons in Nicaragua, the wet season and the dry season. The wet season lasts from May to November and the dry season from December to April. The eastern, Atlantic side of Nicaragua has a more humid climate and receives 250-500 mm of rainfall per month during the wet season whereas the western side receives around 150-250 mm of rainfall per month during wet season. During the dry season the eastern, Atlantic side receives approximately 100-200 mm of rainfall per month and the western, Pacific side around 100 mm of rainfall per month or less. The wet season is mitigated from the second half of July to the first half of August when the precipitation decreases. This phenomenon is called Canícular (McSweeney, et al., 2010) (CIA, 2015a).

Nicaragua is prone to hurricanes, especially during the hurricane season which lasts from July-November. Hurricanes are more frequent on the eastern side as well as floods, whereas the western side is more susceptible to droughts (McSweeney, et al., 2010).

The climate is changing in Nicaragua and the mean annual precipitation has decreased with approximately 5-6% per decade since 1960. The temperature is increasing and has since 1960 increased with 0.9 ^{o}C (McSweeney, et al., 2010).

The central part of Nicaragua has an annual mean precipitation between 750-1250 mm/year. The mean annual precipitation in Teustepe is 1173 mm and the mean annual temperature is 25.8 ^{o}C, see

Figure 8. The central parts of Nicaragua belong to the driest parts of the country (World Trade Press, 2015). The climate in the study area is classified as tropical-dry and does suffer from shortage of water, particularly during the end of the dry season. Since around 90 % of the precipitation falls during the wet season, the study area is highly dependent on the rains during this period (Andler & Petersson, 2008). The inhabitants in the village Los Postillos in the western part of Rio Zapomeca river basin have been forced to emigrate due to shortage of water, according to locals.

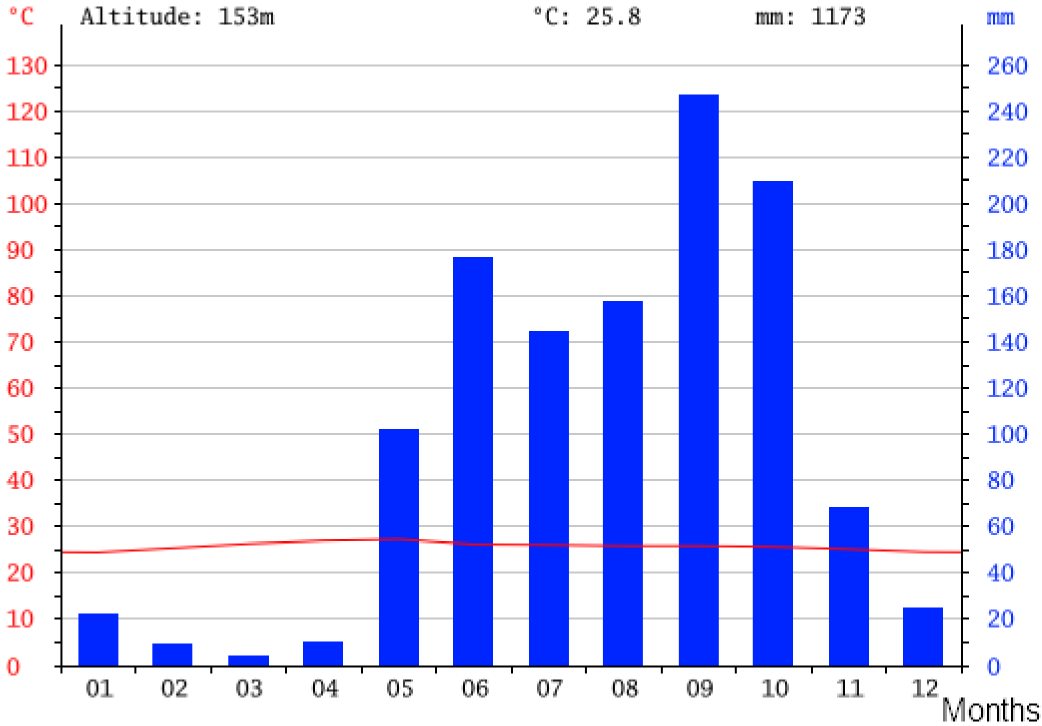

Figure 8 Temperature and precipitation distribution in Teustepe over the year (Climate Data, 2015)

4.7 Hydrogeology and hydrochemistry in the study area

The general pattern of the groundwater flow in Rio Zapomeca river basin follow the topography as can be seen in Figure 9. The cross-section stretches from SW to the NE. The Matagalpa group is the dominating geological group whereas the Coyol group only exists in the south-western parts. Springs emerge along the path down to Rio Zapomeca, especially north of the river in the Matagalpa group. Deeper groundwater flows are presumed in the parts just north of Rio Zapomeca since the groundwater temperature here is raised. As can be seen in Figure 9, Rio Zapomeca is located in between the Coyol and the Matagalpa group.

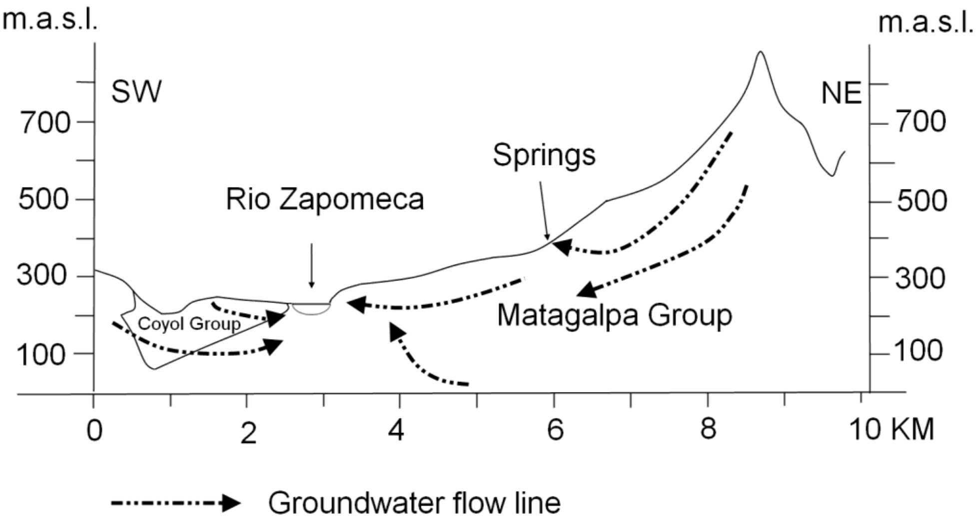

Figure 9 Conceptual groundwater flow model of Rio Zapomeca river basin.

The broad picture of the hydrochemistry in the river basin of Rio Zapomeca is presented in Figure 10. Within the river basin there might be differences not visible on this map. The dominating water types in the river basin of Rio Zapomeca are HCO_3-Ca and/or HCO_3-Na-Mg and SO_4-Na but also HCO_3-Ca-Na and/or HCO_3-Na-Ca in the easternmost parts of the river basin. There is a hydrothermal spring with a water temperature of 46^{o}C just east of the river basin, see Figure 10, and an increasing amount of total dissolved solids, nitrate and chlorine southwest of the river basin, close to Teustepe.

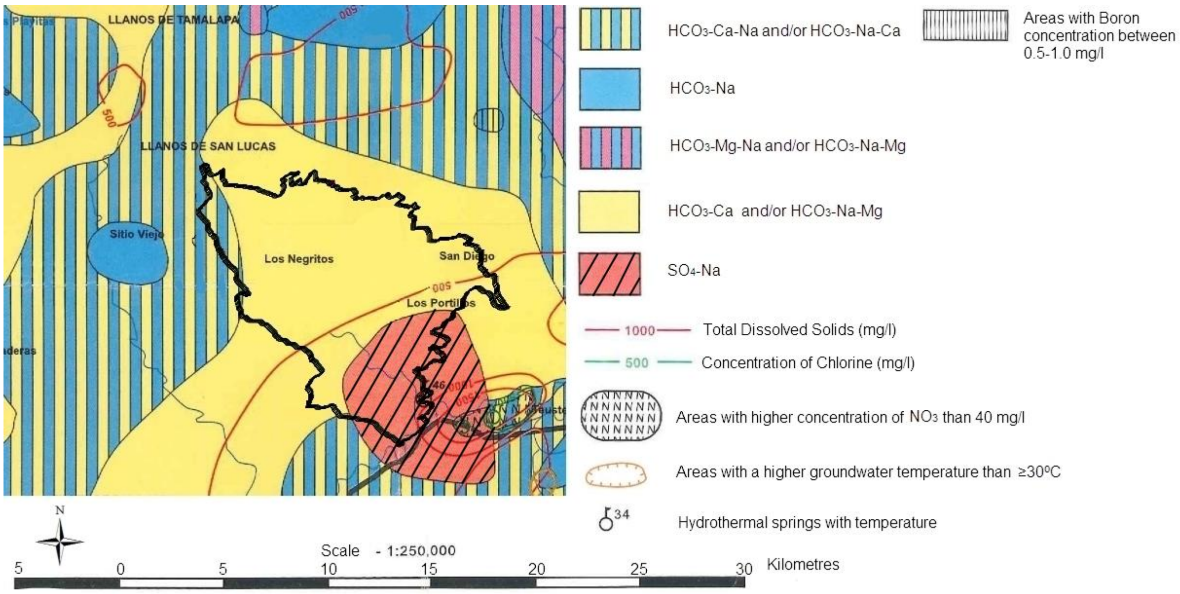

Figure 10 Hydrochemical map of Rio Zapomeca river basin. River basin borders indicated with solid black line. The dominating ions indicated in the legend are at least 50 meq %. Adapted from (INETER, 1998).

Springs are commonly used as drinking water supply in the river basin of Rio Zapomeca. The hydrogeological mechanisms creating the springs are various. Two examples of types of springs can be seen in Figure 11, these two types are likely to be found within the river basin of Rio Zapomeca. In the fault spring in Figure 11, a confining layer, which in this case is a shale layer, prevents the water from continuing in its expected direction and is forced upwards resulting in springs. The fracture spring is dependent on the fracture zone shown in Figure 11, in which the water can flow much easier thus changing the direction of the groundwater flow.

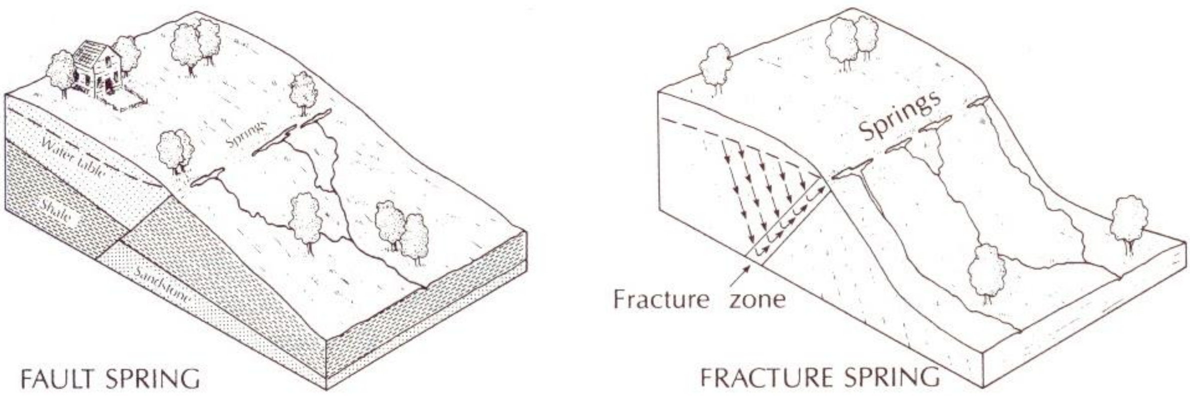

Figure 11 Types of springs believed to be found in the study area (Fetter, 1994).

5 Theory

Arsenic is a toxic compound abundant in the river basin of Rio Zapomeca. Physical and chemical properties of arsenic in natural waters and problems with arsenic in drinking water are discussed in this section. Furthermore, a brief theory of how resistivity surveys are used as a geophysical tool for investigating subterranean properties is presented.

5.1 Arsenic

Arsenic (As) is a semimetal element which is naturally abundant in the earth crust and has a molar mass of 74,92 g/mole (Lindeskog, 2009) (Sharma & Sohn, 2009). It is the 20th most frequently occurring element in nature and its three most common oxidation states are –III (arsine), III (arsenite) and V (arsenate), the elemental state 0 (arsenic) is less common. As (III) and As (V) are both soluble in the pH and Eh range of most natural waters and exist worldwide (Duker, et al., 2005) (WHO, 2012). As(V) is the dominating ion in oxidising environments whereas As(III) is more common in reducing environments and in anaerobic conditions (Duker, et al., 2005). The oxidation of As(III) to As(V) is a relatively slow process, implying that As(III) also can be present in more oxidising environments for some time before it is converted to As(V) (Bundschuh & Maity, 2015). As(III) is harder to remove with available treatment methods which is why many treatment methods include an oxidation step to transform it to the more easily removable As(V) (Socialstyrelsen, 2006) (Litter, et al., 2010).Normal concentrations of total arsenic in natural waters are around 1-2 µg/l. There are few analytical instruments available for analysing the different forms separately, therefore most investigations present results as total arsenic (WHO, 2008).

Arsenic can exist in inorganic as well as organic compounds and both inorganically and organically bound arsenic have been found in water. For a long time arsenic has been considered a poison and has an approximate toxicity four times as high as mercury (Socialstyrelsen, 2006). Arsenic is toxic for animals and plants and generally, inorganic compounds containing As (III) are seen as the most dangerous form of arsenic to humans (Sharma & Sohn, 2009). As (III) is approximately sixty times more toxic than As (V) (Socialstyrelsen, 2006). As (0) is on the other hand not taken up well by the human body and is not as toxic as the other oxidation states (Duker, et al., 2005).

During the last decades the awareness of problems related to arsenic contaminations in drinking water has increased. In 1993 the WHO decided to lower the recommended limit of arsenic in drinking water from 50 µg/l to 10 µg/l, mainly due to observations of its carcinogenicity (WHO, 2008). More places with arsenic contaminated drinking water are continuously discovered around the world. In many of them the arsenic originates from natural sources, but there are also places where it comes from human activities such as tailings from mining industry. An estimated 130 million people worldwide are exposed to arsenic concentrations above 10 µg/l in the drinking water (UNICEF, 2008, pp. 1-2).

5.2 Arsenic and Geochemistry

Arsenic exists in more than 245 different minerals where some of the more common ones are orpiment ($As_2^{III}S_3$), realgar (AsS) and arsenopyrite (FeAs S) (Lindeskog, 2009) (Lopez, et al., 2012). However, it appears that even if there is arsenic present in the ground, it does not necessarily dissolve into the ground- or surface water (UNICEF, 2008). Some of the most arsenic polluted aquifers are not associated with minerals with an unusually high arsenic content. There has to be a "trigger" that makes the arsenic dissolve. In Figure 12 normal arsenic concentrations in various rock types are presented.

Rock/sediment type	As concentration average and/ or range (mg kg^{-1})	No of analyses	Reference
Igneous rocks			
Ultrabasic rocks (peridotite, dunite, kimberlite etc)	1.5 (0.03–15.8)	40	
Basic rocks (basalt)	2.3 (0.18–113)	78	
Basic rocks (gabbro, dolerite)	1.5 (0.06–28)	112	Onishi and Sandell (1955);
Intermediate (andesite, trachyte, latite)	2.7 (0.5–5.8)	30	Baur and Onishi (1969);
Intermediate (diorite, granodiorite, syenite)	1.0 (0.09–13.4)	39	Boyle and Jonasson (1973);
Acidic rocks (rhyolite)	4.3 (3.2–5.4)	2	Ure and Berrow (1982);
Acidic rocks (granite, aplite)	1.3 (0.2–15)	116	Riedel and Eikmann (1986)
Acidic rocks (pitchstone)	1.7 (0.5–3.3)		
Volcanic glasses	5.9 (2.2–12.2)	12	
Metamorphic rocks			
Quartzite	5.5 (2.2–7.6)	4	
Hornfels	5.5 (0.7–11)	2	
Phyllite/slate	18 (0.5–143)	75	Boyle and Jonasson (1973)
Schist/gneiss	1.1 (<0.1–18.5)	16	
Amphibolite and greenstone	6.3 (0.4–45)	45	
Sedimentary rocks			
Marine shale/mudstone	3–15 (up to 490)		
Shale (Mid-Atlantic Ridge)	174 (48–361)		
Non-marine shale/mudstone	3.0–12		
Sandstone	4.1 (0.6–120)	15	Onishi and Sandell (1955);
Limestone/dolomite	2.6 (0.1–20.1)	40	Baur and Onishi (1969);
Phosphorite	21 (0.4–188)	205	Boyle and Jonasson (1973);
Iron formations and Fe-rich sediment	1–2900	45	Cronan (1972); Riedel and
Evaporites (gypsum/anhydrite)	3.5 (0.1–10)	5	Eikmann (1986); Welch et al.
Coals	0.3–35,000		(1988); Belkin et al. (2000)
Bituminous shale (Kupferschiefer, Germany)	100–900		
Unconsolidated sediments			
Various	3 (0.6–50)		Azcue and Nriagu (1995)
Alluvial sand (Bangladesh)	2.9 (1.0–6.2)	13	BGS and DPHE (2001)
Alluvial mud/clay (Bangladesh)	6.5 (2.7–14.7)	23	BGS and DPHE (2001)
River bed sediments (Bangladesh)	1.2–5.9		Datta and Subramanian (1997)
Lake sediments, Lake Superior	2.0 (0.5–8.0)		Allan and Ball (1990)
Lake sediments, British Colombia	5.5 (0.9–44)	119	Cook et al. (1995)
Glacial till, British Colombia	9.2 (1.9–170)		Cook et al. (1995)
World average river sediments	5		Martin and Whitfield (1983)
Stream and lake silt (Canada)	6 (<1–72)	310	Boyle and Jonasson (1973)
Loess silts, Argentina	5.4–18		Arribére et al. (1997); Smedley et al. (2002)
Continental margin sediments (argillaceous, some anoxic)	2.3–8.2		Legeleux et al. (1994)

Figure 12 Examples of arsenious rocks (Smedley & Kinniburgh, 2001)

5.2.1 Triggers of arsenic contamination

There are in total four common arsenic triggers, which will be presented in this section. The two most important triggers are high pH (>8.5) during oxidizing conditions in arid conditions and reducing environments at neutral pH (Smedley & Kinniburgh, 2001). However, there are two other common triggers that are increasing the solubility of arsenic: sulphide oxidation and geothermal activities (UNICEF, 2008). A combination of triggers is plausible, in such case the arsenic occurrence and mobilisation is harder to predict. Areas where both reducing and oxidising environments coexist are found for example in California, USA (Smedley & Kinniburgh, 2001).

5.2.1.1 Sulphate oxidation

Sulphate oxidation often occurs in waters with high concentration of SO_4^{2-} and oxic conditions. These environments are commonly very acidic and are often linked with unusual metals such as gold. Sulphate oxidation does usually only affect the arsenic concentration on a local level. (UNICEF, 2008).

5.2.1.2 High pH in arid conditions

Environments with a pH above 8.5 can together with arid conditions cause As and other elements to form anions. The increased presence of anions cause the As anions either to desorb from surfaces or decrease the possibilities of being adsorbed, thus increasing the As concentration. As is mainly desorbed from mineral oxides such as arsenolite ($As_2^{III}O_3$) or scorodite $FeAs^{V}O_4 \bullet 2H_2O$ (Dove & Rimstidt, 1985) (Smedley & Kinniburgh, 2001).

5.2.1.3 Reducing environments

Strong reducing environments at pH-values near 7, leads to As dissolving from mineral oxides. Higher concentrations of chemical species such as HCO_3^-, Si and PO_4^{3-} , which are present during reducing conditions, might also facilitate the liberation of As since their presence increase the competition for adsorption sites (Smedley & Kinniburgh, 2001) (Svensson, 2011). Typical reducing environments with higher As concentrations include lower concentrations of SO_4^{2-} (<1 mg/l), a pH around 7 and higher concentrations of NO_3^- , Fe-ions, Mn-ions, HCO_3^- and NH_4^+. This type of arsenic rich reducing environment usually occurs in river deltas in sediments from Holocene (<12 000 years B.P) in for example Bangladesh, Hungary and India (UNICEF, 2008).

5.2.1.4 Geothermal waters

Geothermal waters are present in volcanically active areas and close to borders of tectonic plates. The arsenic dissolving in geothermal waters is dependent on factors such as rock composition, temperature, pressure, redox-potential, presence of gases (especially H_2S and CO_2) and microbiological activity. The arsenic solubility increases with higher temperature and experiments where hot water was applied on andesite show that the concentration of As can reach 1300 µg/kg in the leachate. Andesite typically contains arsenic within the range of 0.5-5.8 mg/kg (Bundschuh & Maity, 2015).

The water is heated up as it approaches warmer regions during the descent into the crust and temperatures may reach several hundred ^{o}C. As the water reaches higher temperature, its density decreases and it will consequently start to ascend towards the surface of the earth again. Arsenic becomes more mobile at higher temperatures, thus higher temperatures imply higher arsenic concentration in the water (Webster & Nordstrom, 2003) (Espinoza & Bundschuh, 2005).

The way geothermal water approaches the surface from the deeper reservoirs affects the presence of arsenic. When the transport from the deeper water reservoirs is quick, there is a higher probability of higher arsenic content in the water. This is due to a number of factors including little time for oxidization. The hydrochemical composition also affects the arsenic content as it keeps a similar composition as the water deeper down with high TDS-, NaCl- and sulphur-content. This way of transport is common in faulted bedrocks.

If the geothermal water on the other hand approaches the surface slower, the chances are bigger that it mixes with meteoric water and that As(III) is oxidised into As(V). Also, mineralisation or precipitation of arsenic are more likely if the concentration becomes high enough (Smedley &

Kinniburgh, 2001). However, the possibilities of arsenic precipitation are low since most geothermal waters are unsaturated with arsenic rather than saturated (Webster & Nordstrom, 2003).

The most common forms of arsenic in geothermal waters are oxyanions or neutral species such as $H_2AsO_4^{2-}$ or H_3AsO_3 (Arsenious acid). In geothermal waters with higher concentration of sulphur As might appear as thioarsenites or thioarsenates (Planer-Friedrich, et al., 2007) (Bundschuh & Maity, 2015). Arsenious acid ($H_3As^{III}O_3$) is a neutral species abundant in geothermal waters, it originates from both Arsenic oxide (As_4^{III} O_6) and orpiment. The solubility of orpiment is growing with temperature leastways up to 300 ^{o}C. Also, high pH increases solubility of orpiment whereas more acidic or neutral conditions or high concentrations of SO_4^{2-} do not (Webster & Nordstrom, 2003). Arsenopyrite seems not to be a mineral contributing to the arsenic contamination in geothermal waters, but it seems that its participation increases with temperature. Arsenopyrite seems to release more arsenic at temperatures above 250 ^{o}C, whereas at temperatures between 150-250 ^{o}C, As-rich pyrite is the mineral that releases more arsenic (Lopez, et al., 2012).

Microbial activity in geothermal waters

Microbial activity plays an important role when it comes to arsenic mobilisation especially in deeper aquifers with anaerobic/anoxic conditions and temperatures below 70 ^{o}C (Lopez, et al., 2012) and several types of bacteria can liberate As from arsenic-rich minerals. Also, some heterotrophic prokaryotes thrive on oxidising As(III) to As(V), although other sources of energy and organic matter is necessary. (Stolz, et al., 2006).

5.2.2 Arsenic and organic content

As(III) and As(V) do only react to a very little extent with organic material and clay particles. The sorption of Arsenic is instead predominated by hydroxides and ferrous (III)-hydroxides in particular. For arsenic to be abundant during oxic conditions, only lower amounts of arsenic can be tolerated to make the arsenic stay dissolved in the water (Smedley & Kinniburgh, 2001)

5.2.3 Arsenic in Rio Zapomeca river basin

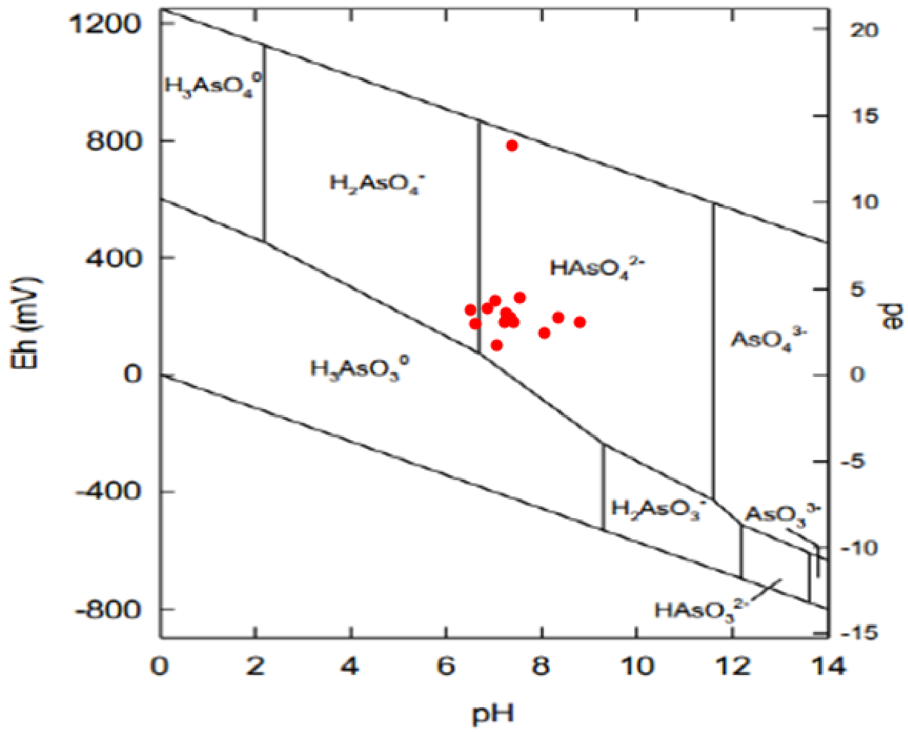

Figure 13 Distribution of arsenic species coupled to pH and Eh. Red dots represent results from investigation made by Sequeira (2008) in Zapomeca River basin. Figure modified from (Parajuli, 2013).

The arsenic species are affected by the pH and the redox-potential in the water. With higher pH the $HAsO_4^{2-}$ is dominant while $H_2AsO_4^-$ dominates with lower pH, as seen in Figure 13 (Parajuli, 2013). According to hydrochemical analyses performed by Sequeira (2008), in Figure 13 marked with red dots, the groundwater in the region is mainly favouring $HAsO_4^{2-}$. The groundwater in Rio Zapomeca river basin has a pH between 7.17-8.82, based on measurements on seven different locations (Sequeira, 2008) see Appendix 7. The trivalent species of arsenic, As(III) is more common under reduced conditions but according to Figure 13 the water that has been investigated has a redox-potential on the upper half of what is normal and therefore likely contains low amounts of As (III) species.

5.2.4 Arsenic in Nicaragua

The first reports of arsenic contaminated groundwater in Nicaragua emerged in 1996. These concerned an area named the Sébaco valley situated in the central parts of Nicaragua, about 50 kilometres north of the study area in this report. Levels as high as 1320 µg/l were found in a drinking water well in El Zapote village and the inhabitants drinking this water suffered from acute arsenicosis. Investigations made in Sébaco valley show that the Tertiary volcanic rocks are the source of the arsenic contamination. The dominating Tertiary volcanic rocks in the Sébaco valley are from the Coyol group. Hydrothermal alteration and severely fractured bedrock enhance the weathering of the Coyol rocks (Espinoza & Bundschuh, 2005).

Espinoza & Bundschuh (2005) made a study that among other things aimed at finding the trigger and source of arsenic in Sébaco valley. However, it turned out to be impossible to determine the exact trigger and source since more information about the geochemistry and the unsaturated zone is needed.

5.2.5 The risks of arsenic in drinking water

There are various methods for elimination and mitigation of arsenic. A number of different alternatives presented with reasoning concerning the possibility of implementation is presented below.

5.2.5.1 Alternatives for treating the arsenic hazard

- Pipeline – Within the project area there is a pipeline implemented between a village with low availability of water and a natural spring four kilometres uphill. A problem throughout the project area is the scarcity of water. Some villages have been abandoned when the wells have run dry. The monetary costs and the availability of water from these wells in combination with arsenic analyses can show the possibility of utilising this method and should be studied further.
- Transportation of water by truck – Water could be imported to the villages with polluted wells from areas with low or no arsenic contamination. Depending on availability of wells without arsenic this method could result in elimination of the risk. The population in the project area is poor and transporting water by truck to each affected village is an expensive and logistically difficult method. From a socioeconomic point of view it is not a recommended method for authorities to implement.
- Collect rainwater – Rainwater is not affected by arsenic pollutions in the ground which is why the utilisation can be considered hazard elimination. Nicaragua has a rainy season and a dry season during which very little precipitation can be expected. Harvesting rainwater is often connected with the need for sedimentation or filtration for sufficient quality. This means that collecting rainwater cannot solely provide drinking water for the population. During the rainy season it is a good technique to limit the stress on other sources such as wells or transportation.
- New wells – Prospecting of new wells could be a measure to mitigate or entirely eliminate arsenic from the drinking water. Investigations and drilling is expensive and it is unclear if all villages can be provided unpolluted water at a reasonable walking distance since there might not be wells with sufficient water in near vicinity. This method will also require time to investigate and develop for such a large quantity of villages.
- Filters – A filter cannot normally eliminate the arsenic but rather mitigate the concentration. There are all kinds of filters at different price ranges. Many filters demand advanced equipment and education and therefore not suitable in the project area that struggles with electrical supply. There are a few kinds of filters that are used in rural areas in developing countries. The Kanchan filter stands out among these with its low price and user friendliness.

The inexpensive Kanchan filter, developed by MIT (Massachusetts Institute for Technology), will be explained and investigated below as an alternative for treating the arsenic hazard in this report. It has been used in areas with similar issues, mainly in Bangladesh but also in Nicaragua with satisfying results (Ngai, et al., 2005) (UNI, 2009). This method is used in the village Asiento Viejo within the project area where one hundred families purify their drinking water using this method. Results from these filters are good with a decrease from the initial concentrations of 24 – 49µg/l to values below the WHO limit. The removal rate of the Kanchan filters in these studies was 80-100%. Investigations in other parts of Nicaragua show even better results with removal rates of 97-99% (UNI, 2009).

5.2.6 Kanchan arsenic filter

The Kanchan filter is a simple and inexpensive filter with good capacity of precipitating, thus removing arsenic from drinking water. Except for arsenic it can also reduce the amount of pathogens, the iron content, odour and the turbidity of the water. The filter, see Figure 14, consists of a plastic container which contains a sand filter with the addition of iron nails that precipitate the arsenic by hydroxide adsorption.

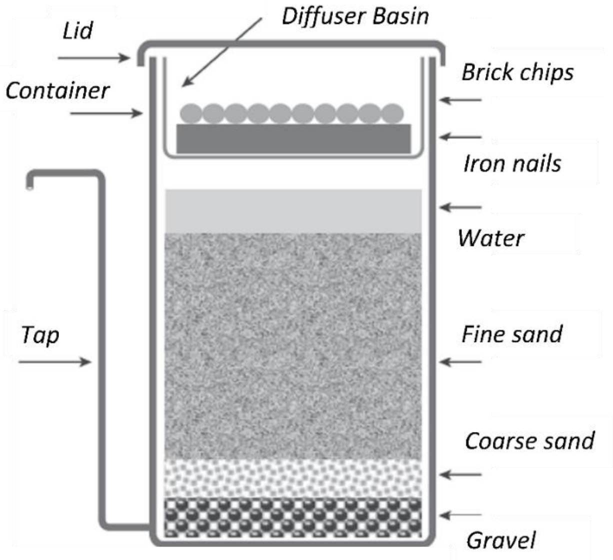

Figure 14 The principle of the Kanchan filter. (Ngai, et al., 2005)

On top is a layer of brick chips which weighs down the iron nails and prevents them from being moved when water is poured into the filter. Above the sand filter a 5 cm layer of water should be present to provide sufficient moist and oxygen to the biological layer in the sand filter. It is important to use the filter every day to prevent the anoxic conditions in the sand filter, thus killing the microbes (Ngai, et al., 2005).

The principle for arsenic mitigation is based on the basin containing iron nails, when exposed to air and moist they will rust rapidly thus producing ferric hydroxide which arsenic particles will effectively adsorb to. The water, now containing rust particles with arsenic is flushed to the lower layer with the sand filter where the particles are effectively trapped in the top centimetres as a result of filtration through the small pores (Ngai, et al., 2005).

Normally ground water does not contain pathogens but sometimes, often due to poor hygiene a well can be contaminated. The Kanchan filter does reduce pathogens by physical straining, meaning that large microorganisms get trapped in the sand filters. Small amount of organic particles from the water will result in the formation of a biological film with predatory organisms that will consume smaller bacteria and viruses. The filter is efficient but does not reach the international standard of no colony forming E. Coli per 100 ml of water. In case of pathogen contamination an additional filter designed for this purpose is required. The filter is also efficient at removing dissolved iron by oxidation and turbidity by filtering the small dust particles (Ngai, et al., 2005).

Maintenance of the filter is needed every one to six months depending on the water, especially the amount of organic particles. Need of maintenance is self-explanatory since the flow through the filter reduces as the biological layer becomes thicker. Maintenance is done by removing sludge that is created in the top of the sand filter by stirring the sand and removing the turbid water with a cup (Ngai, et al., 2005).

The sludge produced contains high concentrations of arsenic, up to 7 kg per m^3, and should therefore be disposed correctly. One good option is to dispose the arsenic rich sludge in a hole together with cow dung. The nutrients in the dung allow growth of arsenic reducing bacteria which metabolise the arsenic to a volatile form that is released to the atmosphere. With this method it is important to have a good dung to arsenic ratio (Rahman, et al., 2014). Another method is to stabilise the sludge by mixing the sludge with up to 40% of volume when making cement or concrete. This method does not reduce the arsenic content but instead stabilises it by fixating it in building material. The arsenic leaching has proven to be limited so that it meets Indian governmental standards (Ras, 2014).

5.3 Socioeconomic assessment

The societal validity of the implementation of Kanchan filter in the project area will be evaluated by comparing the total costs of measures compared to the positive outcome, the benefits. This is done according to the principle of a so called cost-benefit-analysis where the total benefits are divided by the total costs of the project. An example of this methodology could be to compare the building of a road with the vaccination of measles. The total projecting and construction of a certain road amounts to $ 10 million while the sum of the benefits of faster transportation, fewer deaths due to safer roads and better job matching corresponds to $ 20 million. The alternative, to invest in vaccinating the population against measles, would cost $ 15 million and would have health effects resulting in decreased mortality and disease corresponding to $ 35 million.

A quota of the benefits divided by the costs resulting in a value higher than one shows that the measures are economically valid. All countries have a limited economy and therefore have to prioritise between various projects. The quota of the road construction is 2 and the quota of the vaccination is 2.3. Both alternatives have a positive quota but a project that has a positive quota can still be economically correct to postpone if the quota is compared to that of other projects with higher quotas. Projects can be ranked with cost-benefit-quotas and thus the value can be used to prioritise projects (David, et al., 2013). In this example it would be sound, from a societal point of view to prioritise the vaccination if the economy can allow it.

There are several benefits of implementing Kanchan filters including avoiding various diseases and effects on development of fetuses and children. Because of simplifications this study focuses solely on decrease of premature mortality thus excluding other positive effects of arsenic mitigation.

There are different types of methods of valuing life. In many western countries a common tool for valuing life is using Value Statistical Life (VSL). There are different methods of calculating the VSL but a common method is to use a county’s willingness to pay. This value is affected by the wealth of a certain country, in a rich country the population has more spare money to spend on safety equipment and measures. This means that the Swedish VSL of $2.6 million is not applicable for the rural population in Nicaragua (Trafikverket, 2014).

5.4 Resistivity

Resistivity measurement is a geophysical method widely used as a tool for forming an image of the subsurface. There are several ways of performing this, but the general concept of the resistivity method is to determine the resistivity, unit in Ωm, of the subsurface by transmitting a current into the ground via a pair of electrodes. Examples of resistivities in various substances and geological units are presented in Figure 16. Through another pair of electrodes the equipment then measures the voltage drop caused by the subsurface. The resistivity equipment measures the average value in measured volume in a form of a half sphere between a pair of electrodes. The current distribution is affected by the resistivity distribution of the ground and the result form one measurement will be a weighted mean of the resistivities of the materials within the investigated volume. An example of the principle of a resistivity survey is presented in Figure 15.

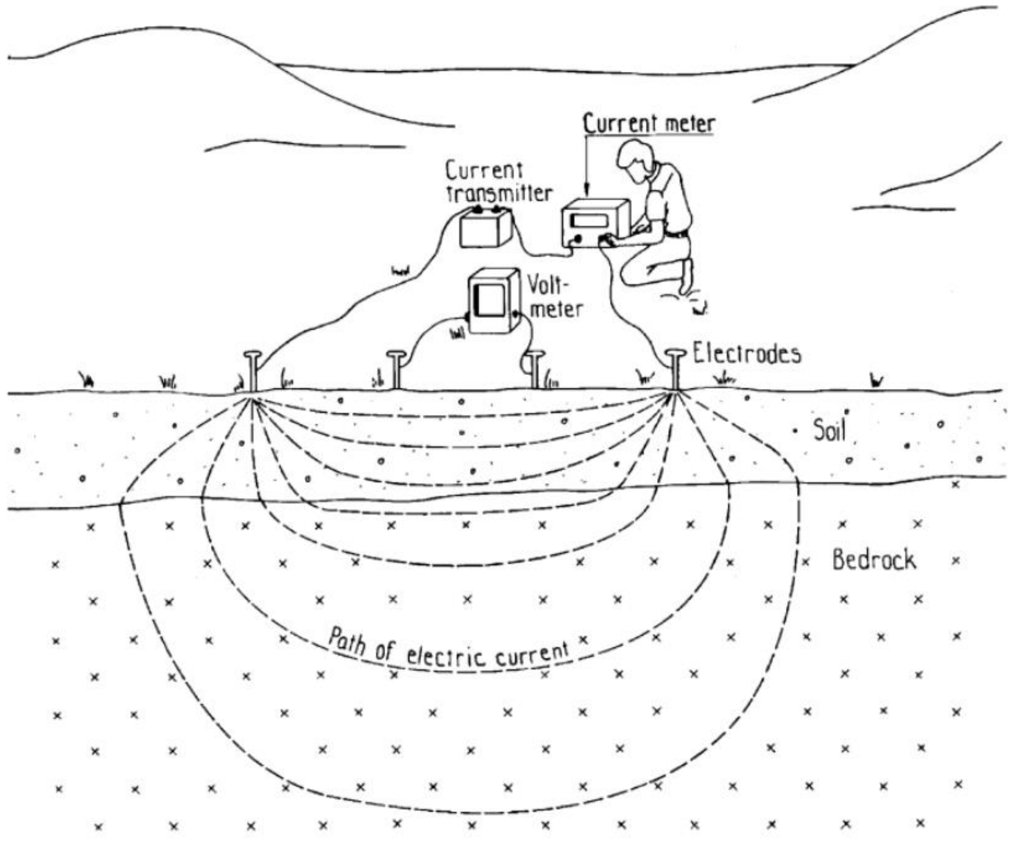

Figure 15 Example of configuration of a resistivity survey. C1 &C2 are transmitting electrodes and P1 & P2 are measuring the voltage drop (Dahlin, 2001).

The depth penetration of the measurement is dependent on the spacing in between the electrodes, a longer spacing means deeper penetration. However, longer spacing between the electrodes also means poorer resolution. By systematically measuring with different electrode separations the resistivity variation with depth can be estimated. By doing measurements with different electrode separations along a line or over a surface it is possible to estimate the resistivity distribution in two or three dimensions (2D or 3D). With modern resistivity equipment it is possible to acquire such data sets in a time and cost efficient manner in order to create 2D or 3D models of the subsurface, which is called electrical resistivity tomography (ERT). The result from an ERT survey is often presented as a vertical section where different colours are indicating the model resistivities (Milsom & Eriksen, 2013).

The further down in the ERT section, the poorer resolution since the number of measuring points here are lower compared to the upper parts. An ERT section will have the greatest depth penetration in the middle of the profile and will be shallower towards the ends. The number of measuring points will be more in the middle part of the resistivity line since the number of electrode combinations are higher. Towards the ends it will not be possible to have as great depth penetration as in the middle since the current cannot penetrate as deep (Milsom & Eriksen, 2013).

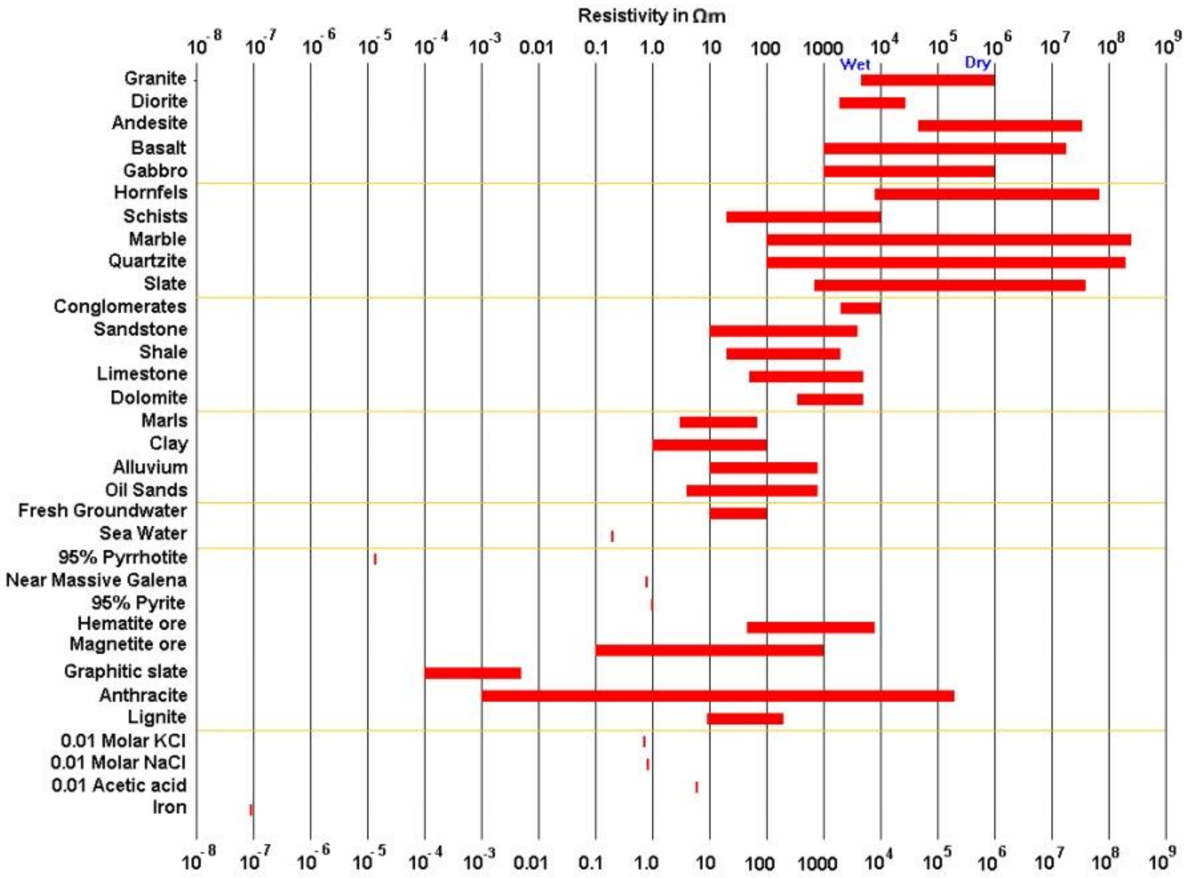

Figure 16 Resistivity of rock, soils and minerals (Loke, 2001).

It is important to stress that the resistivity models cannot in themselves separate between different geological units, but only zones with different resistivity. Since different geological units can have the same resistivity, see Figure 16, resistivity measurements need some sort of reference investigation such as a drilling core from the vicinity of where the resistivity survey was executed that can validate the interpretation of the measurements. One should also bear in mind that the resistivity in a geological unit can also change from day to day due to variations in for example temperature (Hayley, et al., 2007) (Milsom & Eriksen, 2013).

One way of measuring ERT is called multiple-gradient-array surveying, which was used in this study. By interpreting the data using an inversion software, RES2DINV, models of the resistivity distribution of the ground were created. In the inversion a number of iterations are made to decrease the difference between the measurements and the model data to create a 2D profile through the subsurface that matches the measured data (Dahlin & Zhou, 2006). The results from a resistivity survey are often presented as a profile where different colours are indicating the measured resistivities.

Water gets a certain resistivity depending on its properties, it can be obtained by inverting the conductivity that can be measured with a conductivity meter. In some cases the water has a higher resistivity than the rock material in a resistivity profile. This is because water is not the only conductive factor, ions also contribute to increased conductivity. Conductivity is the same as inverted resistivity which means that the resistivity of the water of the well can be calculated from the conductivity measurement. The resistivity is obtained by dividing 10 000 with the conductivity (adjusting for conversion of units), see Table 3 (Reynolds, 2011).

6 Methodology

The field work was divided into two field campaigns, each with a total of eight days of work spread over two weeks. During the first two week-long field campaign the aim was to investigate hydrochemical properties including pH, conductivity, Total Dissolved Solids (TDS), salinity and temperature throughout the area. The locations where the measurements were taken are shown in Figure 18.

6.1 Hydrochemical sampling points

The measurements were performed using an Orion 115 A+ meter for measuring conductivity, salinity and TDS whereas for pH and temperature a Thermo Orion 4 Star meter was utilised. The first week was spent getting acquainted with the area and trying to find as many drinking water places i.e. wells or springs as possible and measure the hydrochemical parameters. If several drinking water sources were found in a smaller area, e.g. in a village, a maximum of three were chosen in order to not spend too much time in certain villages due to time shortage. The spots where the hydrochemical measurements were taken were chosen so that the river basin of Rio Zapomeca was covered spatially to as large extent as possible. Factors such as road conditions and lack of time partly limited this attempt. The number of people using the drinking water source was also taken into account. The drinking water sources used by most people were prioritised and if several sources were found in a village the most used source/s were chosen for measurements. In Figure 17 a typical hand pumped well can be seen.

Figure 17 Typical hand pumped well in the village El Llanito.

Before the hydrochemical measurements were carried out the wells were pumped for a number of minutes either by hand or with electrical pump if installed. This was done in order to assure that water came fresh from the soil and had not been stored in the well, thus being affected by the atmosphere or conditions in the well. The wells were most often used frequently by the inhabitants and at many places there was shortage of drinking water so during the withdrawal of water the inhabitants were asked to fill their water containers in order to minimise the spill. At a few places the inhabitants were not very content of the water withdrawal from their drinking water sources due to drought conditions. Additional hydrochemical measurements were made during the second week on the wells of interest after 30 minutes of pumping to ensure water directly from the aquifer. Hydrochemical measurements done in springs were performed without withdrawal of water since this flowed continuously from underneath and thus, was not affected by atmospheric conditions. The analysed water was collected in a half litre bottle which was filled and then emptied three times in the sampling water before the sample was taken. The electrode was then put into the water and the results read from the equipment.

6.2 Arsenic sampling

During the second week of the first field campaign, arsenic samples were taken. The factors determining which spots that were chosen for sample-taking were water temperature above 30 ^{o}C and geographic position. Higher water temperatures are thought to increase the probabilities of having raised concentrations of arsenic in ground water and according to a previous, unpublished study made by Dr. Lener Sequeira at UNAN, this is likely for this area as well. The geographic position was taken into account since the aim was to spread the arsenic samples evenly over the study area and time and budget limited the number of samples.

The procedure during the arsenic sampling was to first pump the well during 30 minutes with an electrical pump brought from the university that had a capacity of 15 l/min meaning a total of 450 litres being withdrawn from each well. The depth and diameter of the wells were not always possible to measure since some of the openings of wells were closed. However, according to well drilling protocols of drillings made in the area, a common depth of the wells in the area is 61 metres (200 feet) and a common diameter is 38 centimetres (15 inches). This corresponds to a total volume of 1.12 m^3. After the pumping a one litre bottle was filled and emptied three times in the sampling water before the sample was taken, 2 ml of nitric acid (HNO_3) was then added to the sample and the lid was closed. The bottle was finally placed in a cool box filled with ice and stored until it was analysed in the laboratory in Managua.

The arsenic concentrations together with the GPS coordinates were then used to create a contour map in the computer software *Surfer 11*. The method chosen for the making of the contour map was the kriging method which is an interpolation method.

6.2.1 Laboratory arsenic analysing method

The water samples taken in the project area were analysed at *Centro para la Investigación en Recursos Acuáticos de Nicaragua*, CIRA, which is a laboratory within the UNAN University. To analyse the total arsenic concentration in the samples atomic absorption spectrophotometry was used. This method allows detection of concentrations down to 0.99 µg/l. The general methodology of atomic absorption spectrophotometry is explained below with information from Picado (2015).

To analyse a water sample, a volume of 100 ml is taken and concentrated in a chloride acid medium at 60 ^{o}C to a volume of 25 ml. This is done in order to digest any organic content present in the sample. Arsenic can bind to the organic content and make the analysis less precise since arsenic bound to organic content results in a value with lower arsenic concentration. The sample is then cooled down to room temperature and diluted with deionised water to a volume of 100 ml. This method analyses total arsenic and therefore a reduction of all As (V) to As (III) is necessary. This is done by adding 10 ml of potassium iodide and allowing the sample to react for an hour in a dark room. To complete the reaction, vapour generation assembly is used, which includes having the sample passing through an acid channel with 10 molar of hydrochloric acid and then through a reduction channel with sodium borohydride. At this point all arsenic has been reduced to AsH_3. This molecule is ultimately exposed to an acetylene flame that produces free arsenic atoms which can be analysed by the atomic absorption spectrophotometer (Picado, 2015).

6.3 Resistivity measurements

During the first week of the second field campaign resistivity measurements were done. A Terrameter SAS 4000 and Electrode Selector ES10-64 manufactured by the Swedish funded company ABEM was used. Each cable used was 200 metres long with an electrode spacing of 10 metres. Seven different layouts at five different locations were done. Each layout had a total length of 800 metres except for the resistivity line going from south to north in Las Mercedes del Rancho which was 1000 metres long and in La Horca where the terrain limited the survey resulting in a slightly shorter layout. The main reasons for choosing the localities for resistivity measurements were:

- The concentration of arsenic in the well(s) or springs. The wells with highest concentration of arsenic had the highest priority.
- Presence of faults. Were these were found the resistivity lines were laid out perpendicularly to them.
- Geological features such as contact zones between different geological units or volcanic plugs which like the faults also were crossed perpendicularly with the resistivity line.
- The presence of roads which facilitated the layout of the resistivity line.

The resistivity lines were drawn as close as possible to the arsenic polluted wells. Due to houses, fences and other obstacles the distance sometimes had to be longer than anticipated. Laying the resistivity line on roads makes the work easier and roads were therefore followed if they were considered straight enough.

The Terrameter SAS 4000 equipment produces a file with the file format *.s4k*. This file needs to be inverted in order to be able to interpret the measurements. The first measure is to convert the file into a text file with the format *.dat* using the program *SAS 4000 Utilities*. When this is done it can be read and modified in RES2DINV and excel and measurements with no data or faulty data can be modified. When electrodes had to be excluded these excluded electrodes resulted in these bad measurements.

The next step was to process the file in an inversion program called RES2DINV. For the data from this survey three inversion steps have been used. In the first step the anomalies in the project area were elongated mainly horizontally, which was the reason for setting the vertical/horizontal ratio to 0.75. In project areas with more vertical elongations the ratio can be set to higher values, for example 2, in order to force the program to produce vertical models (Geotomo Software, 2010). In Candelaria the structures were more vertical than in the other locations and therefore the ratio was set to neutral, 1.0. To get best possible resolution the finest grid was chosen and robust constraint inversion gives distinct differences between different materials. Data with an error larger than 40% was removed and furthermore error was decreased by performing a number of iterations where a number of iterations were made to adapt the model to the model data to decrease their differences. For the resistivity lines seven iterations have been used to reach sufficient levels of mathematical error.

The topography is included in the model by distorting the grid according to topography from earlier obtained elevation for the area combined with GPS locations along the resistivity line. In the last inversion step the software creates additional imaginary data points, instead of the ten metre spacing that was made in the field, the software creates an imaginary spacing of 5 metres. This allows the image to have softer boundaries between layers and a result that is easier to interpret.

6.4 Groundwater table measurements using RTK-GPS

RTK-GPS was used to determine the exact altitude of wells. The depth to the ground water table was measured in 16 wells using a plastic measuring tape with a probe that has an electrode that transmits electricity. When the electrode gets in contact with water the circuit is closed and thus the water level can be sensed. These 16 wells were chosen so that an area, as large as possible, could be covered. The method needs one RTK-GPS instrument to be the so called base station. The base station had the same position during the measurements since it was used as a reference point to other RTK-GPS instruments. The range that a RTK-GPS can position itself within, in relation to the base station, is mostly dependent of the number of satellites it is able to make contact with, but time is also an important factor since the establishing of contact itself takes time. The position of the base station was La Horca, marked L.H. in Figure 18. La Horca was chosen since it is located in the middle of the geographical centre of the wells which were being measured. The other RTK-GPS instruments where moved around and placed in the vicinity of the wells/springs where the altitude was to be measured and did then measure its position in relation to the base station. The measured altitudes are therefore only true relative to the base station, it is not the exact altitude above sea level at the spot measured. But for this investigation only the relative altitude was needed since only the groundwater flow direction and hydraulic gradient were of interest.

In order to measure the groundwater levels a measuring tape was lowered into the well until the probe came in contact with water, the equipment then made beeping sounds and the depth down to the groundwater table could be read from the measuring tape. In some wells it was not possible to measure the groundwater depth due to not being able to lower measuring tape into the well. In these locations RTK-GPS has not been used, instead a handheld GPS has been used and will therefore have less exact value of elevation.

6.5 Arsenic analysis of rock samples using XRF-spectrometry

XRF stands for X-Ray Fluorescence and is used for determining the chemical composition of many different types of materials. The concepts of XRF-spectrometry are that an X-ray source irradiates X-rays on the object being analysed for a certain time. The object will absorb some of the X-rays and then emit it back as fluorescent X-ray radiation which can be detected by the instrument. Each element has its own unique energy of the radiation it emits back and by determining this energy, it is possible to distinguish different elements from each other. By measuring the intensity of the radiation emitted it is possible to determine the concentration of an element in a sample. A typical resulting curve after an XRF analysis has intensity on its y-axis and energy on its x-axis. Each element will result in a peak in this curve and the area of the peak corresponds to the concentration of the element in the sample. Hence, both the element and its concentration in the sample can be measured using XRF. Depending on which energy it is in the X-rays emitted from the instrument it is possible to have different sensitivity at different types of elements. For example, a certain type of X-ray can be suited for measuring lighter elements and other X-rays for heavier elements. The X-ray used in this analysis cannot analyse elements as light as sodium and had problems analysing magnesium.

The samples analysed have been collected by Jan Ehrenborg in 1988 and have been analysed earlier, the results of these analyses are available in “Semi-regional mapping within the Esquipulas, Teustepe and Boaco map sheets, Nicaragua” a report by Jan Ehrenborg (Ehrenborg & Alvarez, 1988). Both a chemical and X-ray analysis have been performed on these samples but not for arsenic.

A total of 18 samples from both within and outside the study area were analysed using a handheld x-ray instrument, XRF Thermo XRF Niton XL 3T GOLDD at the Geological Department of Lund University. A thin section had been made earlier from the 18 samples, therefore there was a flat area on all of the samples on which the XRF-analysis was made on. 11 of the 18 samples were chosen as interesting for the study, since they were collected in the vicinity of where the arsenic sampling had been performed. These 11 samples were therefore analysed 2 times and the other 7 only once in order to save time. Three standards named 2709a by Thermo Scientific Niton XRF Analyzers with an arsenic concentration of 10.5 ppm were used to investigate the sensitivity of arsenic. The instrument turned out to show too high concentrations of arsenic and the results had therefore to be adjusted. This was done by extrapolating the results from the standards linearly.

6.6 Valuing life

The benefit of providing pure drinking water is simplified to the reduced premature mortality of the population in the villages with polluted wells. The monetary benefit can be derived from the average statistical life value for the Nicaraguan population. For many countries including Nicaragua there is no determined Value of Statistical Life (VSL) and therefore Miller (2000) has attempted a regression model for all countries. The VSL increases almost linearly with countries GDP but Miller (2000) still argues that the regression model might not be valid when stretched beyond the GDP lower limit of $2000 per capita. Despite this, Miller (2000) attempted to derive VSL for a few countries with lower GDP, including Jamaica which is close to Nicaragua both geographically and economically. GDP per capita in Jamaica 1995 was $ 2357 while Nicaragua's GDP per capita 2014 was $ 1914 (The World Bank, 2015a). When comparing GDP of countries the purchasing power parity (PPP) should be included since countries with lower income often also have lower prices, PPP compensates for this. The GDP per capita including PPP for Jamaica 1995 was $ 6302 and Nicaragua 2014 had $ 4794 per capita (The World Bank, 2015b). The calculated VSL for Jamaica 1995 was $ 340 000, by dividing that value with the GDP(PPP) for Jamaica 1995 and multiplying with Nicaragua's GDP(PPP) from 2014 the interpolated VSL of $260 000 is obtained from the linear regression.

The VSL represents the value of an average individual of a population, it is therefore logic to assume that this value decreases with age. The US Environmental Protection Agency (EPA) suggested a 37 % discount for seniors. This controversial "senior death discount" has been questioned, and is therefore normally not used, but it is used here as a conservative measure (Viscusi & Aldy, 2006). With this discount, the VSL for a person dying from arsenic polluted water in Teustepe corresponds to $ 163 200, in accordance with equation 1.

$$259\,000 \times (1-0.37) = 163200 \qquad (1)$$

Preventing premature mortality due to consumption of arsenic polluted water will have health effects in the far future. For new born children this will have effects approximately 60 years into the future. For economic calculations a discount rate is normally used to compensate for the fact that money is worth more today than in the future. In business a discount rate is normally in the magnitude of 10 %. However, a lower discount rate should be used for health benefits, some health policy studies suggest that health benefits measures should not be discounted at all. Others recommend a discount rate of one to three percent for long term investments (Murray, 1994). In Table 1 different discount rates have been presented. The calculation of discounted VSL is made using equation 2.

The number of people that will die as a consequence of drinking polluted water will decrease as soon as the source is removed but a "normal" risk of developing cancer or cardiovascular disease cannot be achieved unless polluted water is avoided throughout life. This is why the number of discount years is chosen to 60 years, this can also be considered to be a conservative assumption. In reality the exchange of polluted water would have significant health effects and might prevent the development of cancer sooner, thus giving better health effects than according to the calculations.

Table 1 Value of statistical life (VSL) with different discount rates.

Discount rate	Discounted VSL ($)
0%	163200
1%	89800
3%	27700
5%	8740
10%	540

$$\boldsymbol{PV} = \boldsymbol{VSL} \times (\boldsymbol{1} + \boldsymbol{i})^{-\boldsymbol{n}} \tag{2}$$

$$PV = Present\ Value$$
$$VSL = \ Value\ Statistical\ Life$$
$$i = Discount\ rate$$
$$n = Years$$

6.7 Kanchan Arsenic Filter Calculations

The material cost of a Kanchan filter in Nicaragua is $ 21, where the main cost is iron nails (UNI, 2009). Adding to this is labour, profit for production, transportation and education of the families. In Table 2 is an estimation of the total cost per filter.

Table 2 Costs for production and implementation of Kanchan filter in Nicaragua.

Cost object	Calculated costs ($)	Calculated costs with filter from AMEC ($)
Material	21 (2009)	
Labour	2	
Profit 20%	4.6	
Tot production	27,6	70
Education	2	2
Transportation	1	1
total	30.6	73

Assuming that the material costs have increased since 2009 an approximate cost of $35 dollars per filter is used for calculations. AMEC, a workshop that produces filters in Managua, Nicaragua charges $ 70 for such a filter if bought individually without negotiations. Ngai, et al. (2005) calculated a production cost including transportation of $20 for Kanchan filters in Nepal.

6.8 Computer Software

Surfer 11&12
Were used to create the Rio Zapomeca river basin border, (Golden Software, 2015).

ArcGIS
Was used to produce figures where the vector layer Rio Zapomeca is included, (ESRI, 2015).

Paint.net
Was used to process pictures and figures, (Paint.net, 2015).

7 Results and interpretation

Results from arsenic analysis, hydrochemical measurements and resistivity and GPS investigations will be presented in this stated order. The locations of the measurements done in the arsenic analysis, hydrochemical measurements and collected rock samples are presented in Figure 18 on a geological map made by Ehrenborg (1988).

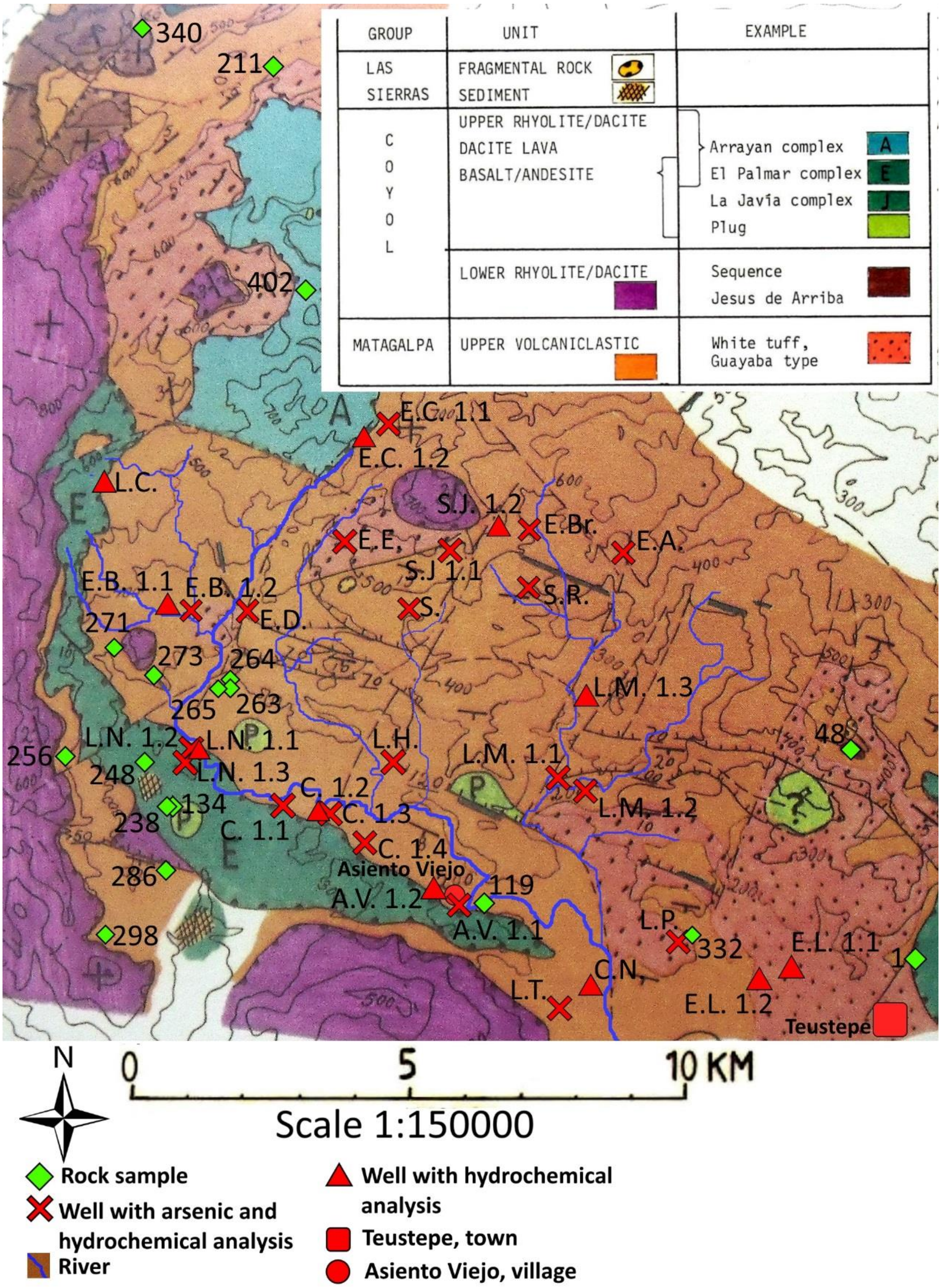

Figure 18 Geological map with investigated drinking water sources and locations for the rock samples. Details from hydrochemical measurements are shown in Table 3.

7.1 Hydrochemical measurements

The results from the hydrochemical measurements and arsenic analysis are shown in Table 3. The arsenic analysis result is presented in Figure 19, with each arsenic value presented at its location. The interpolation between these points was made with the Kriging method.

Table 3 Sampling points of hydrochemical measurements. Sample number location can be found in Figure 18.

Sample number	As (µg/l)	Well /spring	Name	pH	Conduct. (µs/cm)	Resist. (Ωm)	Salinity (‰)	TDS (mg/l)	Temp. (ºC)	Elev. (m)
C. 1.4	33.9	Well	Asiento Viejo	6.9	950	10.5	0.4	403	30.7	214
L.C.		Well	Las Cañitas	7	694	14.4	0.3	310	28.4	550
E.L. 1.1		Well	El Llanito	6.9	662	15.1	0.3	285	30.1	166
E.L. 1.2		Well	El Llanito	6.5	702	14.2	0.3	296	31.2	152
L.P.	26.3	Spring	La Piscina	7.9	1500	6.7	0.6	556	38.6	164
A.V. 1.1	41.5	Well	Asiento Viejo	7.3	1185	8.4	0.5	524	29.4	185
A.V. 1.2		Well	Asiento Viejo	7.0	761	13.1	0.3	337	28.7	190
C. 1.3		Well	Candelaria	6.7	726	13.8	0.3	315	29.7	232
C. 1.1	15.9	Well	Candelaria	7.3	901	11.1	0.4	391	29.3	243
E.D.	3.3	Well	El Diamante	6.9	903	11.1	0.4	397	29.3	365
E.B. 1.2	10.8	Well	El Bajo de los Ramirez	6.9	715	14.0	0.3	312	29.2	305
E.B. 1.1		Well	El Bajo de los Ramirez	6.7	694	14.4	0.3	307	28.6	313
C.N.		Well	Cruz nr 2	6.9	1370	7.3	0.6	591	30.4	147
L.T.	23.1	Well	Las Tunitas	7.1	842	11.9	0.4	367	29.4	164
E.A.	14.6	Well	El Aguacate	6.9	774	12.9	0.4	354	27.5	446
S.J. 1.2		Well	San Jeronimo	7.3	182	54.9	0.1	80	28.1	600
S.J. 1.1	5.3	Well	San Jeronimo	7.2	738	13.6	0.3	335	26.4	580
E.Br.	15.2	Well	El Bramadero	7.1	719	13.9	0.3	295	30	475
S.R.	10.0	Well	San Rafael	7.0	856	11.7	0.4	373	29.4	412
L.H.	21.6	Well	La Horca	7.1	660	15.2	0.3	266	33.3	264
S	18.7	Well	Sonzapote	7.3	880	11.4	0.4	403	27.4	435
E.E.	3.1	Spring	El Escobillo	7.1	697	14.3	0.3	326	26.4	503
E.C. 1.1		Spring	El Cacao	7.2	475	21.1	0.2	225	25.4	615
E.C. 1.2	5.0	Spring	El Cacao	7.1	472	21.2	0.2	225	25.8	640
L.M. 1.1	29.9	Well	Las Mercedes del Rancho	7.1	1015	9.9	0.4	441	29.8	185
L.M. 1.3		Well	Las Mercedes del Rancho	7.2	868	11.5	0.4	379	29.6	214
L.M. 1.2	22.3	Spring	Las Mercedes del Rancho	7.2	834	12.0	0.3	340	33.0	177
L.N. 1.2	104.3	Well	Los Negritos	7.4	1463	6.8	0.7	649	29.0	245
L.N. 1.1		Well	Los Negritos	7.0	736	13.6	0.3	324	29.2	259
L.N. 1.3	36.5	Well	Los Negritos	7.0	695	14.4	0.3	307	28.9	246
C. 1.2	10.4	Well	La Candelaria	7.2	805	12.4	0.4	345	30.4	237

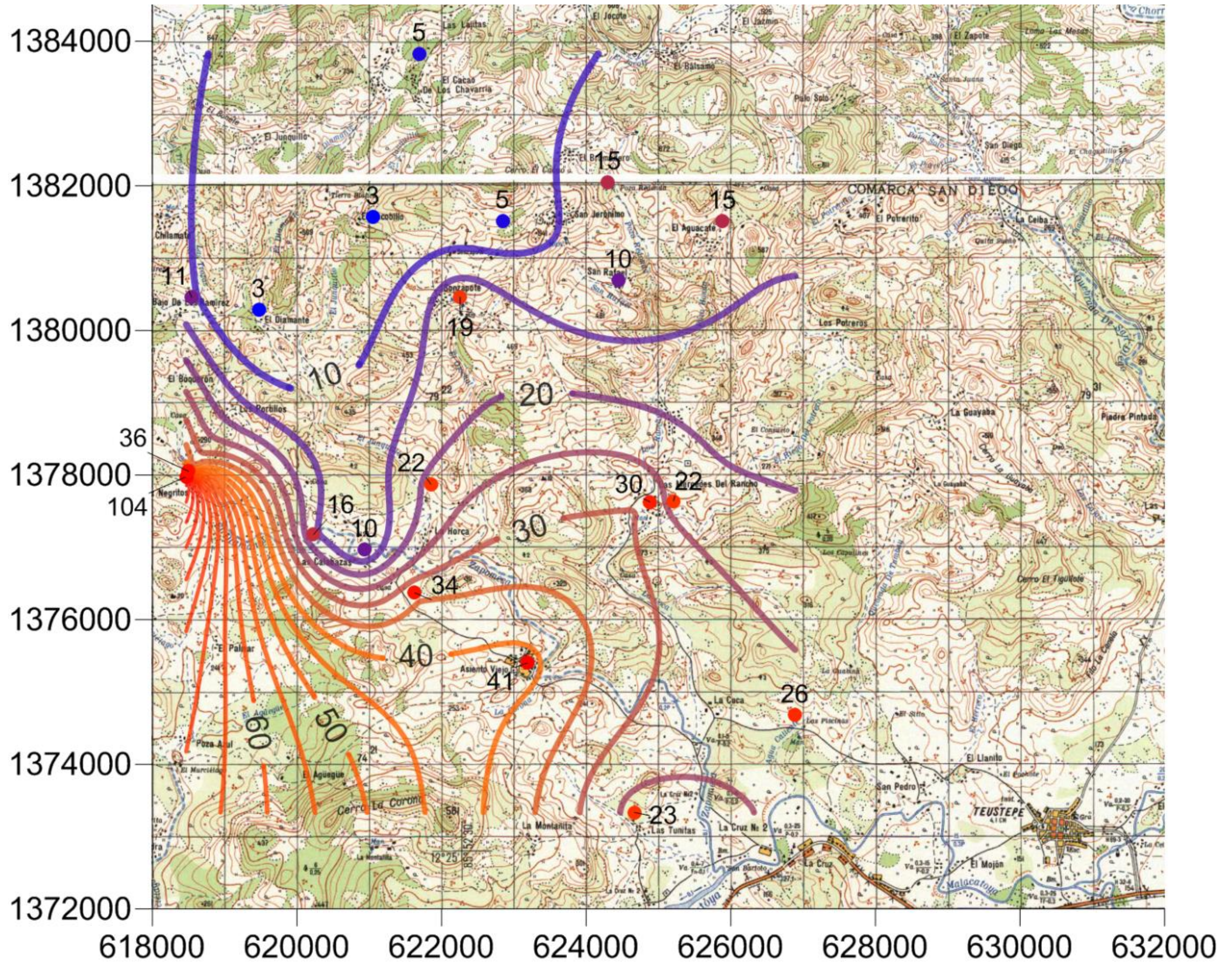

Figure 19 Arsenic concentrations shown in µg/l in the river basin of Rio Zapomeca. The arsenic concentration is presented with numbers and colours ranging from blue (lower arsenic concentration) to red (higher arsenic concentration).Map adapted from (INETER, 1988).

7.2 Correlations

During the first field campaign the temperature, elevation and hydro chemical properties were measured. At Lund University, Sweden, rock samples were analysed with x-ray analysis for various species content. Selected interesting correlations are presented in Figure 20 to Figure 23.

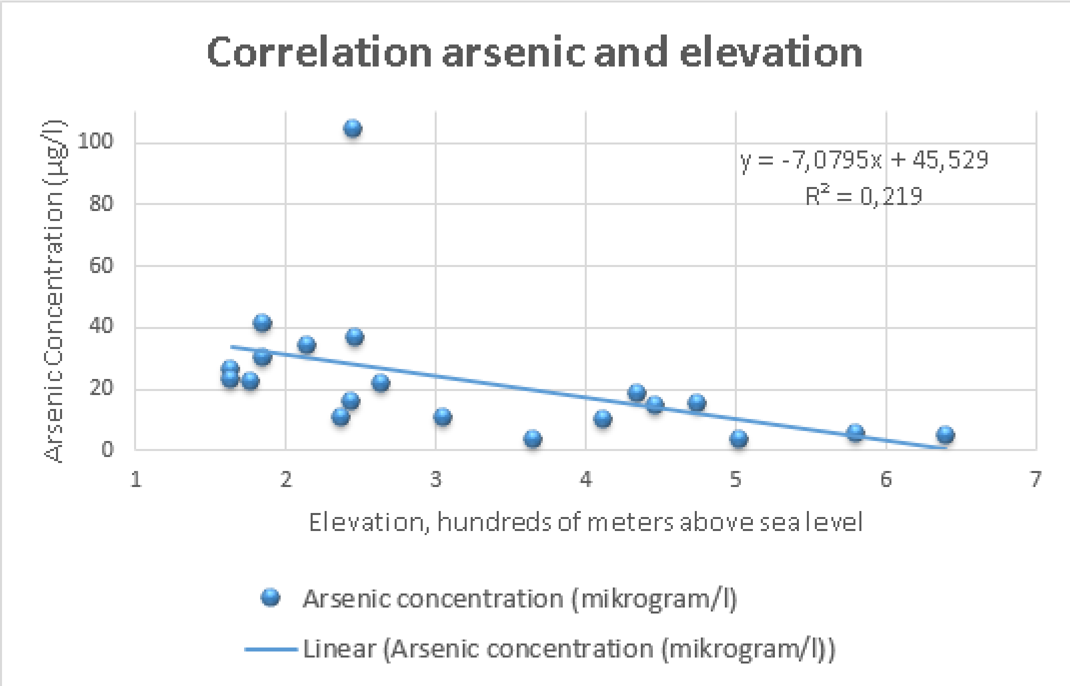

Figure 20 Correlation between arsenic concentration and elevation in hundreds of metres. From the data obtained the arsenic concentration decreases with seven micrograms per litre for each hundred metres.

Temperature and pH is known to affect the solubility of arsenic. Values of different physical and chemical factors are plotted to determine possible correlations. The most notable correlations were a negative correlation to elevation, see Figure 20, meaning that the arsenic levels were systematically higher in the valley than further up on the hills. The R^2-value, which indicates how well the curve fit suites the data, is only 0.2 (20% of the values can be explained by the curve). If the value with 104µg/l, which is considered an outlier, is excluded the R^2 value increases to 0.5 while the decrease of arsenic concentration decreases to -5.5 µg/l per 100 metres.

The correlation between arsenic and conductivity, how well the water conducts electricity, shows a positive trend with increasing conductivity, R^2 value 0.47 according to Figure 21. If the highest arsenic value is excluded for this plot both the R^2 value and the regression gradient decreases. The other correlation plots, including temperature, TDS, pH and salinity are presented in Appendix 2 - Appendix 5.

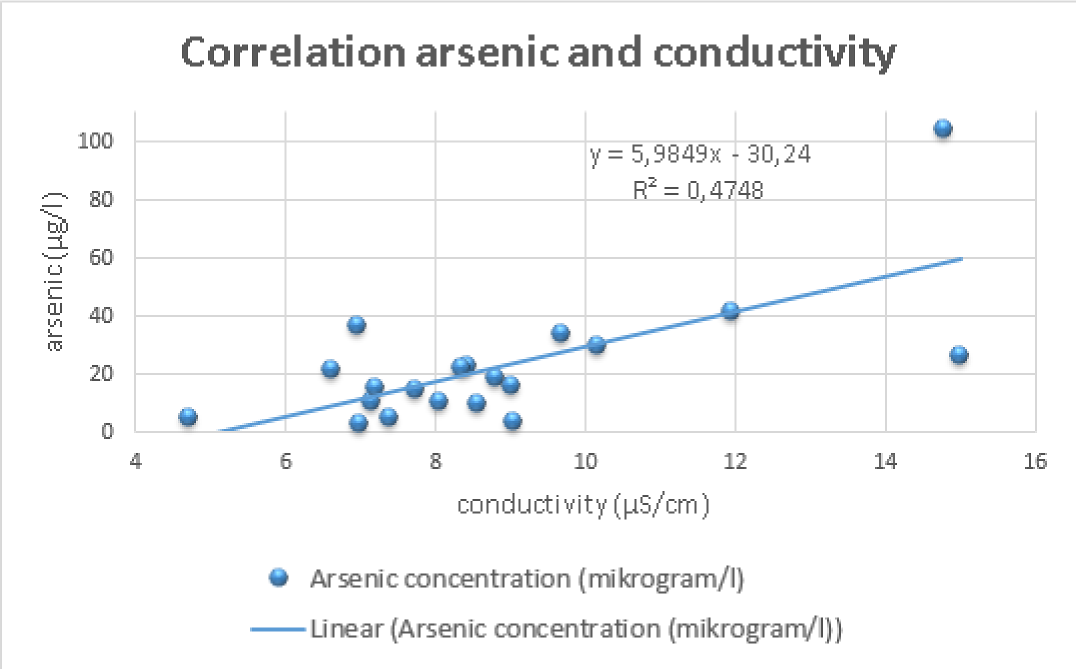

Figure 21 The correlation between arsenic and conductivity shows that the arsenic increases with 6 micrograms per litre for each hundred units of conductivity (µS/cm).

7.2.1 Correlation of rock sample analysis

Arsenic is normally bound to minerals together with sulphur and iron minerals such as realgar (AsS) and arsenopyrite (FeAsS). Therefore one could expect the content of these substances to correlate (O'Day, et al., 2004). Neither plot, Figure 22 nor Figure 23, show a clear trend for arsenic in relation to iron and sulphur respectively.

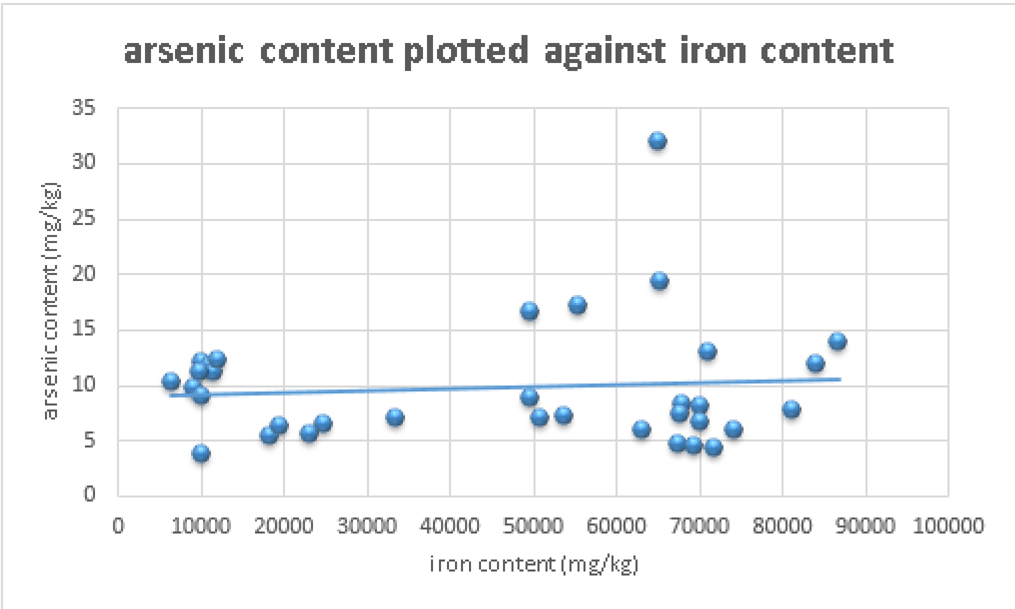

Figure 22 The correlation between iron content and arsenic content in rocks from the region close to Rio Zapomeca.

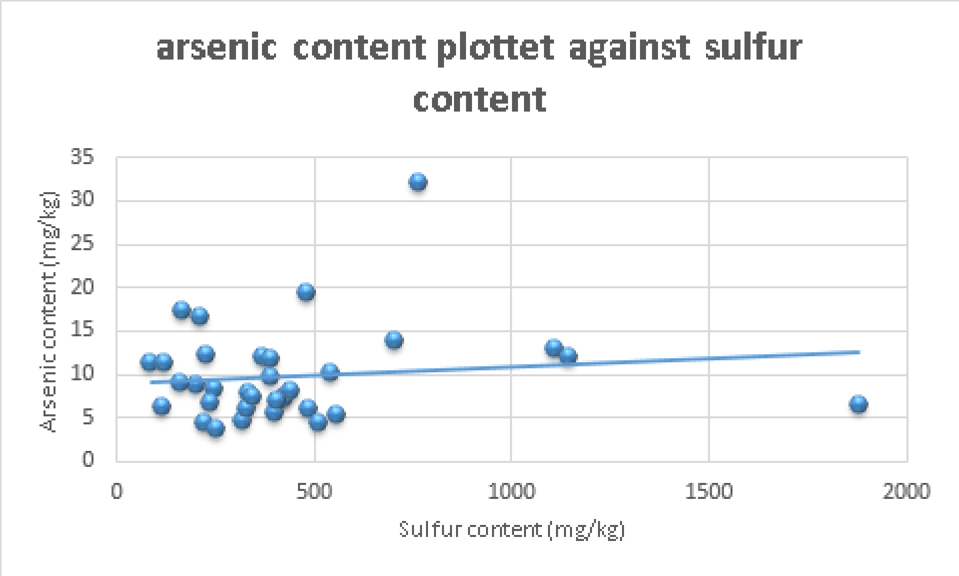

Figure 23 The correlation between sulphur content and arsenic content in rocks from the region close to Rio Zapomeca.

All rock analyses with high arsenic concentrations, exceeding 10 mg/kg were obtained in the vicinity of the border between Coyol and Matagalpa in the south-western part of the catchment area. These rocks are presented in Table 4 and the location for the samples can be found in Figure 18. A table with a selection of the results from the rock sample analysis can be found in Appendix 1. There is no obvious connection between high arsenic content and a specific rock type. Notable is also that it is not possible from these analyses to determine which rock type that arsenic more easily dissolves from. Generally darker rock types, in this case Coyol, are more easily weathered (Svensson, 2015).

Table 4 The seven rock sample analysis with arsenic content exceeding 10 mg/kg in order after highest arsenic content. The rock type groups are marked with X and additional information tells the rock type more specifically. For more information chemical properties and rock type, see *Appendix 1* and in the report *Semi-regional mapping within the Esquipulas, Teustepe and Boaco map sheets, Nicaragua* by Jan Ehrenborg (1988).

Rock sample	Arsenic content (mg/kg)	Coyol	Matagalpa
271	26		**X**
238	17	**X**	
119	13	**X**	
264	12		**X**
265	11		**X**
256	11	**X**	
263	10		**X**

7.3 Resistivity

Resistivity surveys were made to increase the understanding of the hydrogeology in the vicinity of the wells. Resistivity profiles can give an idea of which hydrogeological layers that are acting as aquifers and aquitards. By acquiring this knowledge the search for the relevant geological units, concerning arsenic pollution, can be narrowed down. It is not possible to identify an arsenic releasing unit but units with low resistivity, roughly below 10Ωm, transmits water poorly. Units with medium resistivity are generally better aquifers and can therefore be expected to contain and transmit arsenic to the drinking water sources.

The locations of the resistivity lines are shown on a geological map in Figure 24. According to the geological map by Jan Ehrenborg (1988) the rock types that can be expected where the resistivity lines have been drawn are from both the Coyol group and the Matagalpa group. In La Horca and Las Mercedes del Rancho which are located one to a few kilometres north of Rio Zapomeca, only the Matagalpa group is to be expected.

In La Horca and Las Mercedes Del Rancho the water temperature was higher than anywhere else in the Rio Zapomeca basin. The resistivity values in the profiles are presented as different colours. There is no definite value of resistivity for each colour, instead the relation between colour and resistivity varies between every location for the resistivity surveys. Low resistivity units are presented with blue to green colour, medium with green to yellow colour and high resistivity units with yellow to red coloured areas in the profiles. The definite resistivity values for each profile are presented in a resistivity legend presented with each profile. Fine grained rocks, high water content and especially water with a high conductivity generally generates low resistivities whereas low porosity, dry rock and coarse grained rocks generally results in higher resistivities. When it comes to resistivities below 10 Ωm it is likely that it is a clayey material with high water content or salinity/ions, causing these low resistivities.

The geological maps used are as always generalised and areas dominated by the Matagalpa group also contains smaller areas with rocks from the Coyol group either as cutting volcanic plugs or as overlaying covers. Likewise small areas of the Matagalpa group can occur in areas dominated by the Coyol group.

The 4 profiles south of Rio Zapomeca, Asiento Viejo, Candelaria, Los Negritos road and Los Negritos field cuts across the rocks of the Coyol group in the south and ends in the rocks of the Matagalpa group in the north. Due to depth penetration of the resistivity survey, it is very unlikely that the Matagalpa group occurs even in the deepest part of the Los Negritos profiles.

The 3 profiles north of Rio Zapomeca, La Horca, Las Mercedes del Rancho SW-NE and Las Mercedes del Rancho WNW-ESE are situated in rocks of the Matagalpa Group along their entire length and the rocks of the Coyol Group occur along these profiles.

Each specific spot has both a result-part and an analysis-part. The result-part consists of observations made in the field and results from the resistivity survey, hydrochemical analysis and arsenic analysis. No interpretations of the results are made and the presentation is aimed to be objective and based on facts. In the analysis-part subjective thoughts and ideas are brought up and discussed.

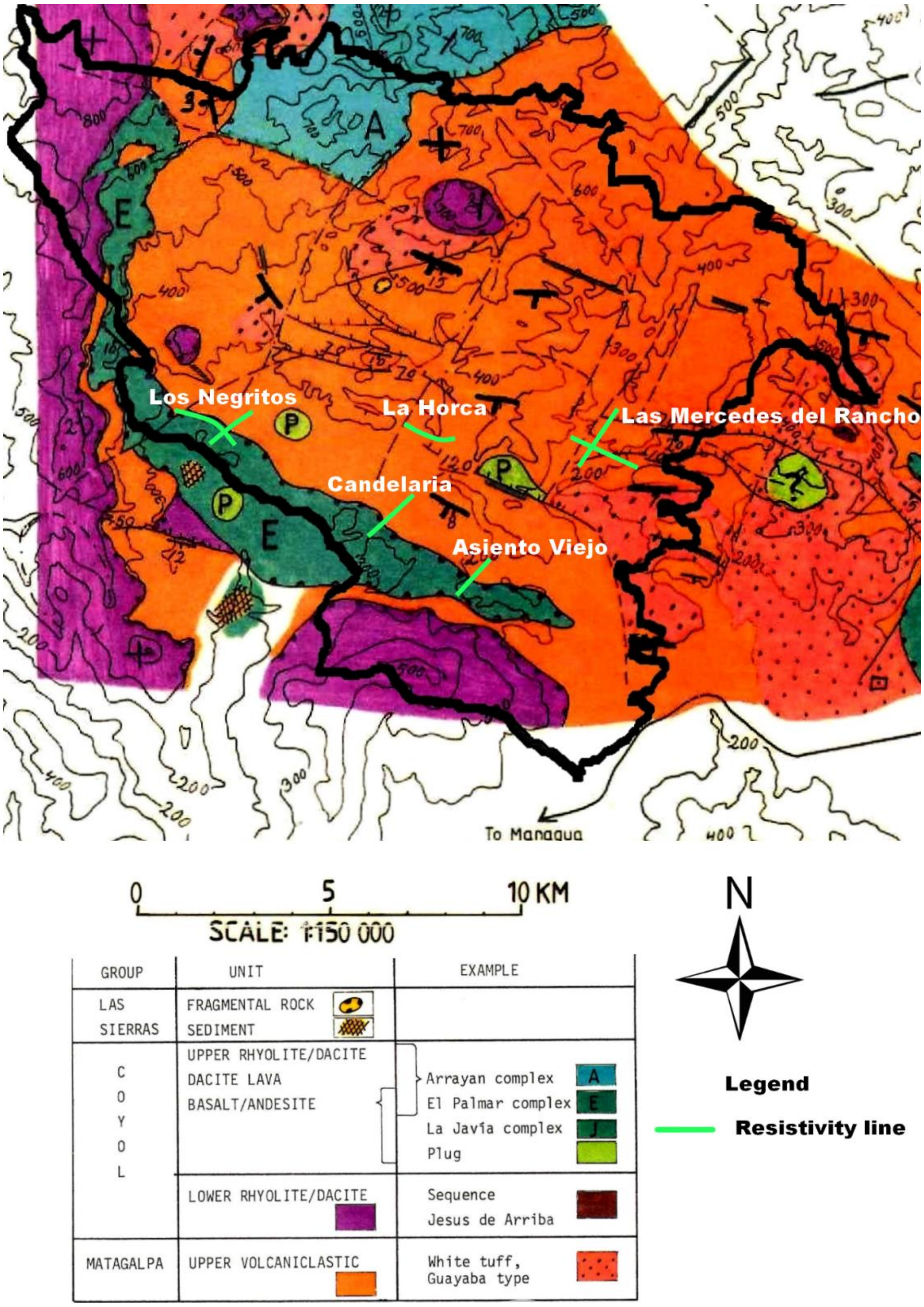

Figure 24 Location of resistivity lines. Resistivity lines indicated with light green colour.

The wells are marked

in the resistivity profiles

7.3.1 Asiento Viejo results

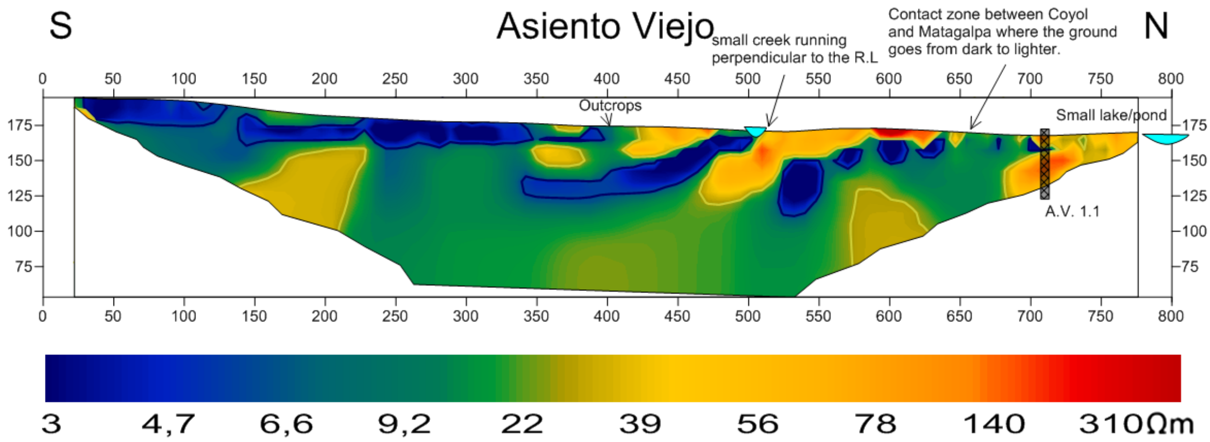

Figure 25 Resistivity profile from Asiento Viejo.

Table 5 Values for the well in Asiento Viejo.

Arsenic concentration (µg/l)	41.45
Water temperature (^{0}C)	29.4
Altitude (m.a.s.l.)	176
Groundwater level (metres below ground surface)	3.3
Resistivity in well water (Ωm)	10.5

The general structure of the resistivity profile in Figure 25 are layers with a trend of positively inclined layers towards north, low and high resistivity units alternately. These resistivity layers are approximately 15 metres thick and have a gradient of up to 1:4. The units in the southern half of the profile have low resistivity while the areas further to the north have units of high resistivity material. In the middle part of the profile outcrops occur and the northern part where there are higher resistivity units these outcrops are common resulting in a rocky ground. At 500 metres there is a low point in the terrain, including a rather dry creek. Between the distance of 600 and 700 metres the ground colour changed from dark to lighter. The resistivity line passed the well in Asiento Viejo at a distance of 15 metres. The well is bored into a material of high resistivity. The resistivity line ends by the side of a large pond situated in the high resistivity material. White fracture/breccias material in basaltic rock in the creek, see Figure 26, indicates likely hydrothermal alteration, (Ehrenborg, 2015).

Figure 26 Creek bottom referred to in Figure 25. Hydrothermally affected basaltic rock (Ehrenborg, 2015).

7.3.2 Asiento Viejo interpretation

The low resistivity areas are probably more weathered with a clayey character and thereby can hold more water and ions, resulting in units with low resistivity. Units with such low resistivity generally have low hydraulic conductivity, and are therefore not considered aquifers. In the northern parts of the profile the water might be able to flow throughout the medium resistivity area. This means that the water that ultimately ends up in the well close to the resistivity line at 710 metres, could be transported from other areas and from greater depths and thereby be the source of arsenic. On the other hand there is no evidence of raised groundwater temperature. The well temperature was 29.4 ^{0}C, which according to Lener Sequeira (2015) is a normal groundwater temperature in the area.

650 metres into the profile the ground colour changes from a darker to a lighter material which is an indication of having passed the contact zone between the darker Coyol and the lighter Matagalpa. The general direction of the slope of the resistivity layers seen in Figure 25 is changing around 250-350 metres. It is also worth noticing that the very abrupt change in the resistivity anomaly pattern at 350 metres seems to be so sharp that it very likely might indicate a fault or an intrusive contact.

The lake in the end of the resistivity line is located on outcrops with high resistivity material. This material will probably not allow water to infiltrate thus the creation of a pond.

No clear ground water level can be identified in the resistivity profile but the groundwater level in the well is located 3,3m below surface and close to the well is a large pond. There is also an almost dry creek 200 metres from the well. All these indicators show that the ground water level is close to the surface.

7.3.3 Los Negritos Road results

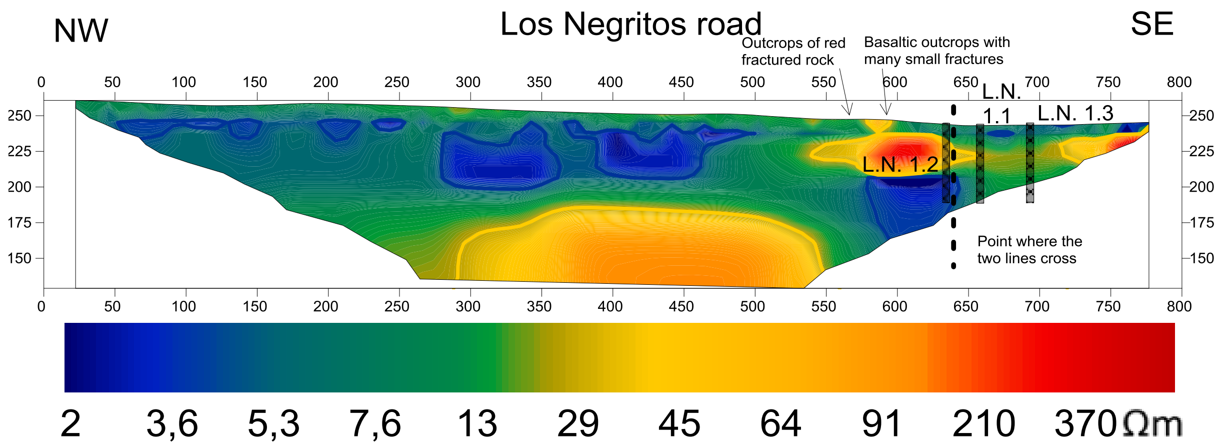

Figure 27 Resistivity profile for Los Negritos, where the line follows the road. Unit for resistivity is ohm metres (Ωm).

Table 6 Values for wells in Los Negritos.

Arsenic concentration well L.N. 1.2 (µg/l)	36.5
Arsenic concentration well L.N. 1.3 (µg/l)	104.3
Water temperature L.N. 1.2(°C)	28.9
Water temperature L.N. 1.3(°C)	29.0
Altitude L.N. 1.1(m.a.s.l.)	250
Altitude L.N. 1.2 (m.a.s.l.)	251
Altitude L.N. 1.3 (m.a.s.l.)	251
Ground water level L.N. 1.1 (metres below ground)	7.9
Ground water level L.N. 1.2 (metres below ground)	7.3
Ground water level L.N. 1.3 (metres below ground)	6.5
Resistivity in well water L.N.1.1(Ωm)	13.6
Resistivity in well water L.N.1.2(Ωm)	6.8
Resistivity in well water L.N.1.3(Ωm)	14.4

In Los Negritos two resistivity lines were made that crossed each other, the crossing can be seen as a dashed line in Figure 27 and Figure 30. A fence diagram showing this intersection can be seen in Figure 31 and Figure 32. The resistivity line follows a road that passes the three wells in the village. The rock units are rather homogeneous throughout the major part of the resistivity line with a layer of 60-70 metres with low resistivity. At greater depth a unit of medium resistivity can be observed. 550 metres into the profile units of higher resistivity are seen and are also present in the form of outcrops at the surface. At distance 560-570 metres these outcrops have the colour red while at distance 600 metres they have a darker grey colour, see Figure 28 and Figure 29. These outcrops are full of fractures and are as a consequence of this and the weathering very brittle. Beneath the high resistivity layer there is a unit of low resistivity.

Figure 28 Reddish outcrops from the Coyol group at the distance 560-570 metres.

Figure 29 Grey outcrops from the Coyol group at the distance 600 metres.

According to the drilling protocol made by AbacusDrilling (2014) when drilling the well L.N. 1.2 the groundwater was found at 15 feet (=4.6 m). The materials discovered during the drilling were: 3 metres of gravel and 3-61 metres of rocks of the Coyol group (basaltic rock), see Appendix 6. In conjunction with the resistivity investigations the present groundwater level was measured to be 6.5 – 7.9 metres below ground surface in the three wells.

7.3.4 Los Negritos field results

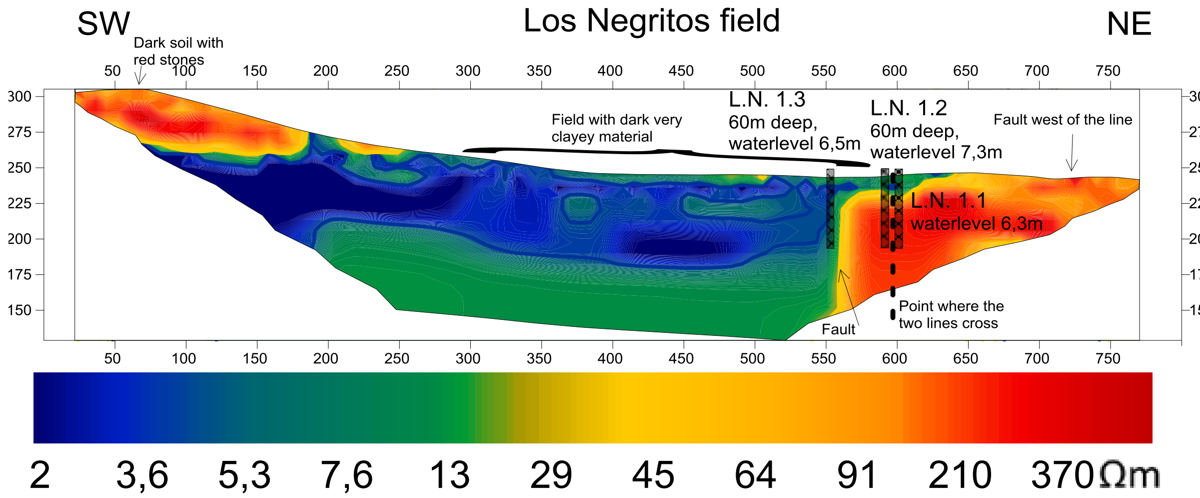

Figure 30 Resistivity profile over Los Negritos field from the hill southwest of the village.

The first 200 metres in south-western is a steep hill with high resistivity. The ground surface in this area consists of dark rock sprinkled with red stones. The middle part of the profile is characterised by rocks from the Coyol group and has low resistivity throughout. The resistivity increases from low to medium at 65 metres depth. At the distance of 550 metres a possible fault occurs just by well L.N. 1.3. After this point the resistivity is high. To get a better understanding of the three dimensional resistivity properties in the area a fence diagram was made, see Figure 31 and Figure 32.

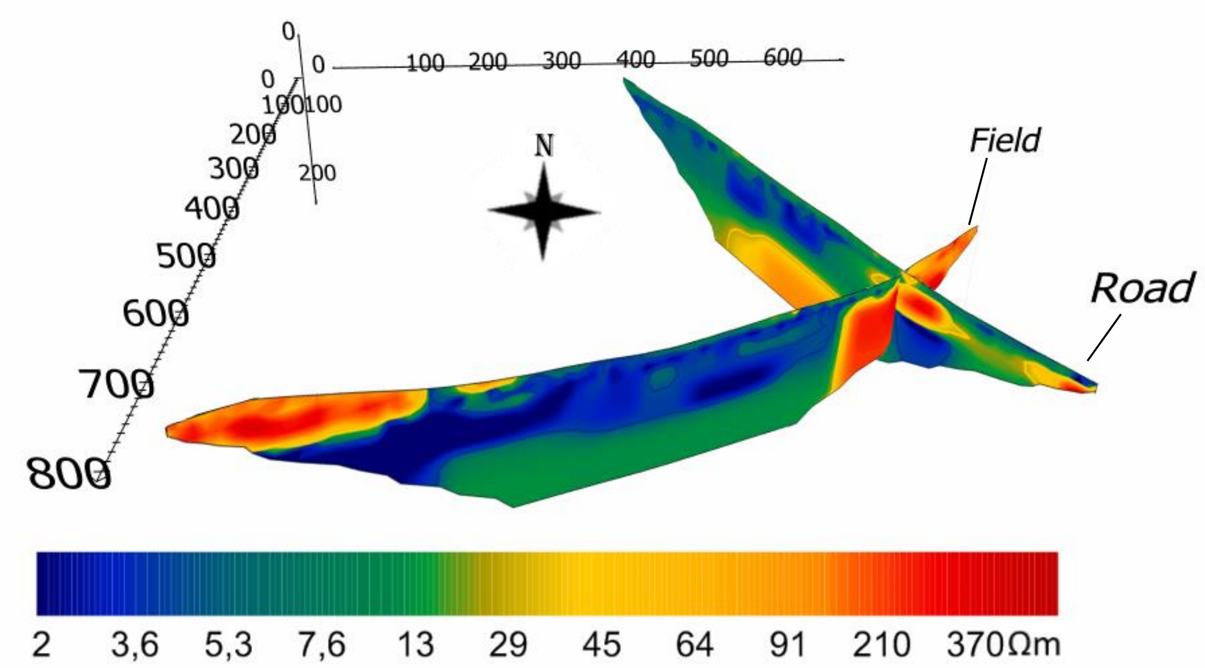

Figure 31 Fence diagram of the intersection of the two resistivity lines in Los Negritos.

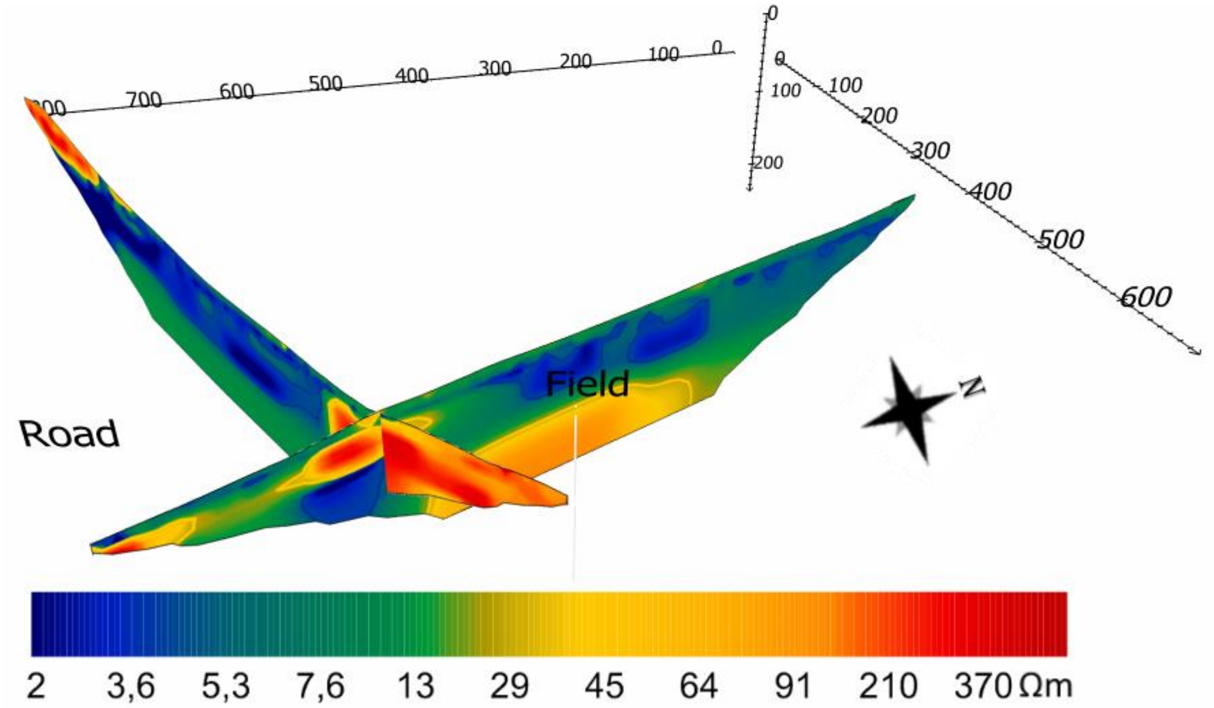

Figure 32 Fence diagram of the intersection of the two resistivity lines in Los Negritos.

7.3.5 Los Negritos road interpretation

The first 60 metres in the well L.N. 1.2 consists of basaltic rock according to boring protocols from AbacusDrilling (2014). This well was drilled into different resistivity units and still all are basaltic rock. This means that the different units most likely are basaltic rock with different levels of weathering and fracturing. In the profile a clear horizontal band of low resistivity occurs on approximately 10 metres depth throughout the major parts of the profile. The ground water level in the wells occurs at approximately 7 metres depth. This means that the low resistant horizon could be groundwater level. This horizontal band could work as an aquitard preventing the groundwater from percolating further down.

7.3.6 Los Negritos field interpretation

The well L.N. 1.3 is located at the limit of a sub vertical fault, the limit between the high resistivity unit and the low resistivity clayey unit can have cracks in which water can be transported. The low resistivity unit, which probably has low hydraulic conductivity, ending at 550 metres, can cause the groundwater flowing from northeast to flow vertically. This means that groundwater originating from deeper aquifers can be forced upwards by this unit. Since groundwater originating from greater depths are more likely to contain more total dissolved solids they are thereby more likely to contribute to the high concentrations of arsenic in the well. Outcrops found in the area shows evidence of extensive fracturing and weathering but there are two separate areas of high resistivity material. This indicates that the area in between might have been affected by stress, allowing water to infiltrate and weather the bedrock.

7.3.7 La Horca results

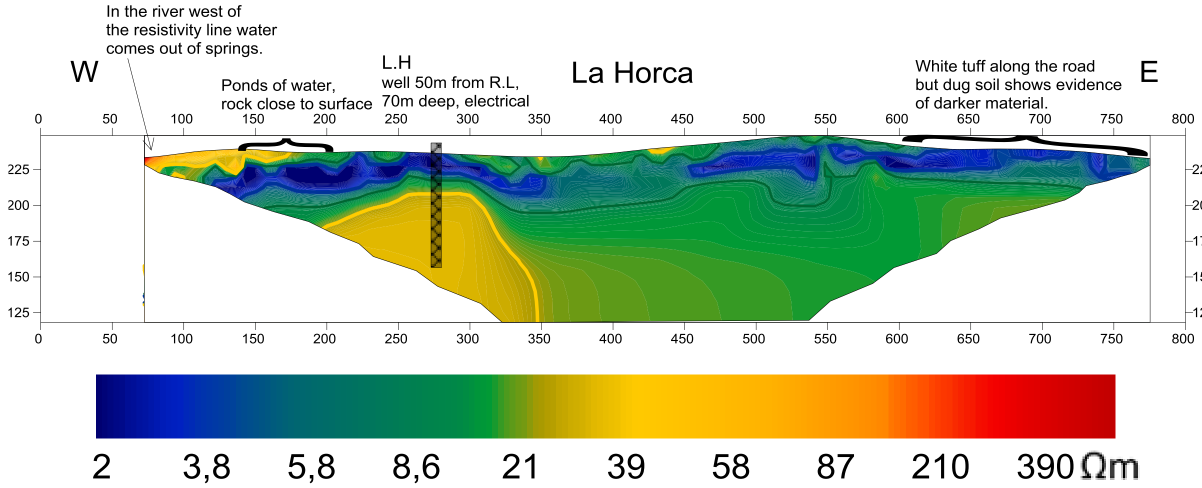

Figure 33 Resistivity profile of La Horca. R.L. in figure is short for Resistivity Line and L.H. for La Horca.

Table 7 Values for the well in La Horca.

Arsenic concentration (µg/l)	21.58
Water temperature (°C)	33.4
Altitude (m.a.s.l.)	243
Groundwater level (metres below ground)	-
Resistivity in well water L.H(Ωm)	15.2

The resistivity line in La Horca was drawn along a road stretching in a W-E direction. The well was not possible to open and therefore no groundwater level could be measured. The five westernmost electrodes were discarded in La Horca since the ground consisted of outcrops which were not possible to penetrate with electrodes. The profile is therefore shorter than a normal 800 m layout is. The profile has several low resistive units close to the surface and medium units appear on an approximate depth of 30 metres. In the western parts of the line there are units of higher resistivity. Approximately 50 metres west of the first electrode of the resistivity line there is a river running in a north-south direction, in which there are springs coming up from fractures in the outcrops, one spring can be seen in Figure 35. In Figure 36 between 140-210 metres there is an area with small, shallow ponds in which the water does not infiltrate. Approximately 70 metres south of the resistivity line at around 120-200 metres there was a hillock with of a maximum height of 290 m.a.s.l. which is 50 metres higher than the resistivity line (INETER, 1988). The well at 243 metres, where the arsenic sample was taken, is situated 50 metres north of the resistivity line.

Figure 34 Contact zone between darker and underlying lighter material at 600 metres.

Along the western 200 metres of the line, there are multiple outcrops of white rock along the road. The contact zone between the lighter and darker material was visible north of the resistivity line at 600 metres, see Figure 34, but the resistivity line does not cross the contact zone.

The water temperature in the well in La Horca was 33.3 ^{o}C making it slightly warmer than normal groundwater temperature for the region. According to the geological cross sectional maps there might be two different subunits of the Matagalpa group in this area, see Figure 7 as an example of the layering of the Matagalpa group (Ehrenborg, 1999).

Figure 35 Spring in the river west of La Horca.

Figure 36 Ponds indicating that the bedrock is close to the surface.

7.3.8 La Horca interpretation

The interpretation of the long, low resistivity area which stretches over the whole profile, might be that it is a clayey unit that holds more water than the surrounding materials. The southward slope of this layer coincides with the layering of the Matagalpa group. It is possible that the medium resistant units below the low resistant area have a higher hydraulic transmissivity, thus being more beneficial for water extraction. The well that seems to be drilled into such a unit provides major parts of the village with water which means that the availability of water is fairly good. The springs 50 metres west of the resistivity line could have their origin from a contact zone between a low resistant unit and a unit with higher resistivity and hydraulic conductivity. The low resistivity unit, with its low hydraulic conductivity, might force water to the surface thus making water trickle through the outcrops in the stream. The high resistivity outcrops seem to continue west of the resistivity line and on the other side of the stream there is a hilly region which could feed the stream with water. The water flows up through cracks in the outcrops resembling of a fracture spring. However, there is a major fault situated in the vicinity of the river, which suggests that it affects the occurrence of fault springs. The springs are perhaps a combination of the two spring types.

Since the groundwater temperature is higher than normal in La Horca, one could expect that the aquifer of the well is in contact with deeper, warmer hydrogeological layers. The unit where the well is located has higher resistivity, which could allow water from beneath to percolate closer to the surface.

7.3.9 Candelaria results

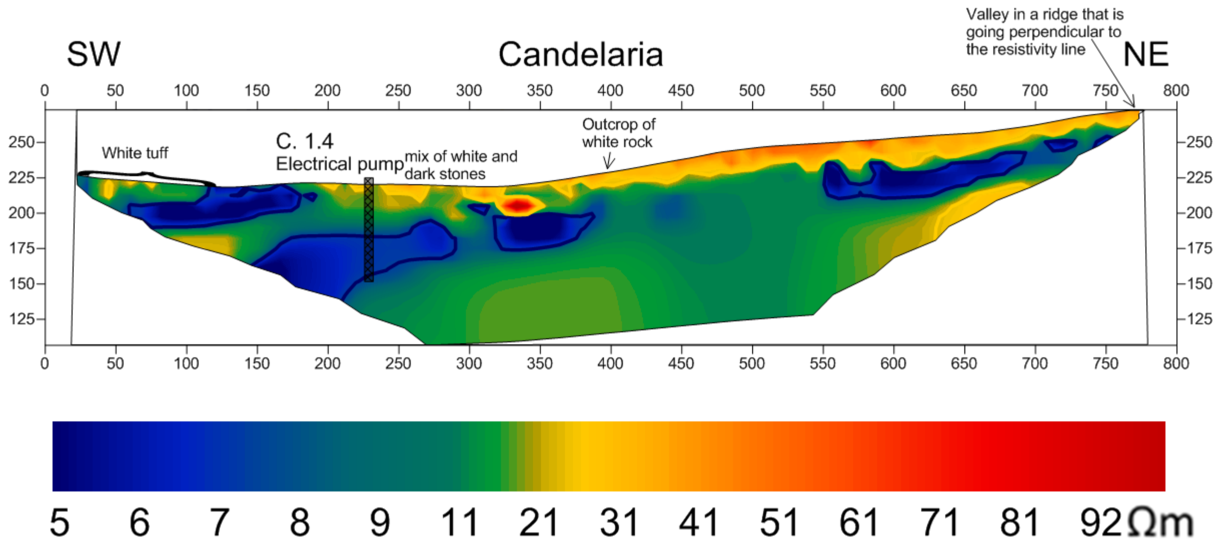

Figure 37 Resistivity profile of Candelaria

Table 8 Values for the well in Candelaria.

Arsenic concentration (µg/l)	33.9
Water temperature (^{0}C)	30.7
Altitude (m.a.s.l.)	214
Ground water level(metres below ground)	-
Resistivity in well water C.1.4(Ωm)	10.5

The first 120 metres are characterised by white material in the surface layer, this layer has medium resistivity. Under this layer is a layer of low resistivity, which has contact with the surface 120 metres into the resistivity line. At this point the surface material turns darker. The electrically pumped well is located 230 metres along the line and is bored through a layer of medium resistivity into a low resistant unit.

Figure 38 Boulders in both darker and lighter color on dark soil.

The ground northeast of the well has a mixture of light and dark boulders, see Figure 38, and further along the line outcrops of the lighter material are present. This area has a top layer of medium to high resistivity at 10-20 metres depth under which the material has medium to low resistivity. The last 200 metres show indications of having a low resistant layer of 25 metres thickness beneath the top layer of high resistivity before an additional layer can be seen with increasing resistivity. The last electrode of the resistivity line is located in a valley on a ridge, which is perpendicular to the resistivity line, seen in Figure 39. Both the unit of low resistivity and the one with higher follow an inclined pattern of up to 15%. This direction of the slope of the resistivity layers corresponds to the general slope of the layering in the Matagalpa group.

Figure 39 Valley following a possible fault. Picture taken at the NE end of the resistivity line in Candelaria.

7.3.10 Candelaria interpretation

125 metres into the resistivity line there could be the contact zone between a layer of rocks from the Matagalpa group and the darker rocks from the Coyol group. It was observed that the ground with rocks from the Matagalpa group rocks were dryer than the darker rocks from the Coyol group which had a more clayey character. There are similar low resistivity units throughout the resistivity line which could be the same type of material but it could also be two different materials with the same resistivity. The depth of the well is unknown as a result of it being an electrically driven, thus blocked, but from looking at the resistivity profile it seems like the best depth for water extraction are the first 40 metres. The low resistivity layer could act as a confining layer and thereby increase the flow in the unit of higher resistivity. The resistivity line was drawn 8 metres from the well and the well was providing reasonable amounts of water, enough for the major parts of the village of Asiento Viejo with its 550 inhabitants.

Water is more likely to percolate through the cracks and fractures present in material that have been affected by stress. Therefore it could be expected that the valley shown in Figure 39 might be the recharge zone in this area, since it might be a fault.

7.3.11 Las Mercedes del Rancho south-north results

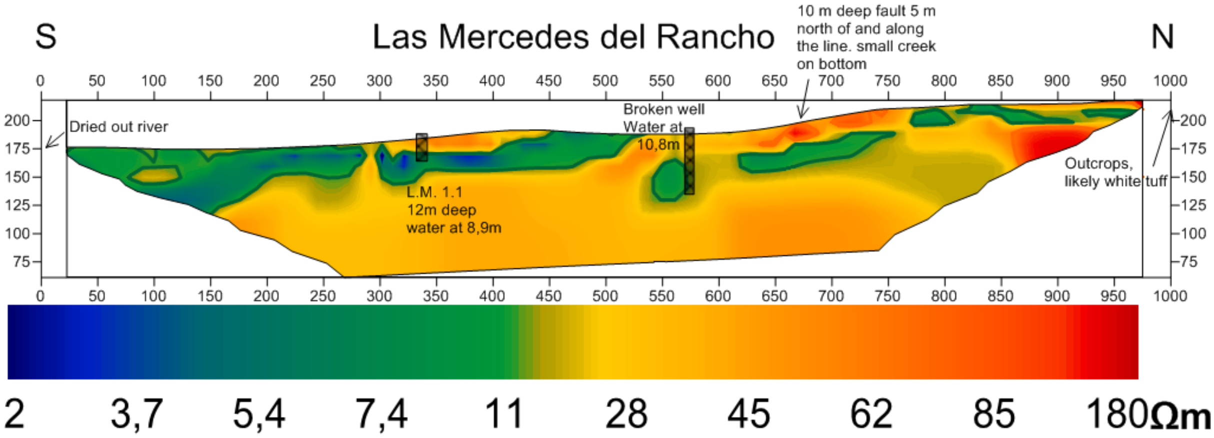

Figure 40 S-N Resistivity profile in Las Mercedes del Rancho.

Table 9 Values for wells in Las Mercedes del Rancho

Arsenic concentration spring L.M. 1.2 (µg/l)	22.29
Arsenic concentration well L.M. 1.1 (µg/l)	29.85
Water temperature L.M. 1.2 spring (^{o}C)	33
Water temperature well L.M. 1.1 (^{o}C)	29,7
Altitude spring L.M. 1.2 (m.a.s.l.)	183.8
Altitude well L.M. 1.1 (m.a.s.l.)	186.4
Altitude broken well (m.a.s.l.)	192.5
Groundwater level spring L.M. 1.2 (metres below ground)	0
Groundwater level well L.M. 1.1 (metres below ground)	8.9
Groundwater level broken well (metres below ground)	10.8

In the southernmost part of the S-N resistivity profile, Figure 40, there is a dried out river running perpendicular to the line. This creek is filling a larger river which in the southernmost parts runt along the S-N resistivity line. The S-N profile is to a large extent consisting of medium resistive materials with thinner low resistive areas closer to the ground surface. The low resistivity areas are more frequent closer to the upper parts of the profile and the southern part of the S-N profile is dominated by low resistivity areas. A fault stretching in a S-N direction is situated approximately 5 metres west of the resistivity line at 650-670 metres in Figure 40, south and north of that stretch the fault runs further away from the resistivity line. This fault is situated at 650-675 metres in Figure 42 where a creek runs in this fault west of the resistivity line. Since the fault and the steep scarp only are 5 metres away from the resistivity line it might affect the resistivity measurements. Air is a high resistive media and will affect the results giving a higher resistivity. In the area around 650-675 metres there are outcrops. The circular green area at 550 metres and approximately 20 metres depth is continuing in an E-W direction as can be seen in Figure 42, where it stretches between 50-375 metres. It is visible in the fence diagrams, Figure 45 and Figure 46, where this area can be found at the intersection of the two profiles. Just at the northern end of the resistivity profile, there are outcrops of a reddish tuff seen in Figure 41. According to a geological map, Ehrenborg & Alvarez (1988) there is a fault, stretching perpendicularly to the resistivity line at 810 metres. The faults in Las Mercedes del Rancho are normal faults with the northern side of the fault down faulted relative the southern side Both the high and the low resistivity layers are sloping from the north to the south approximately 1:7. The resistivity layers have a steeper slopes than the general slopes of the topography which has an approximate slope of 1:20.

Figure 41 Reddish tuff at the northern end of the S-N resistivity line

7.3.12 Las Mercedes del Rancho west-east results

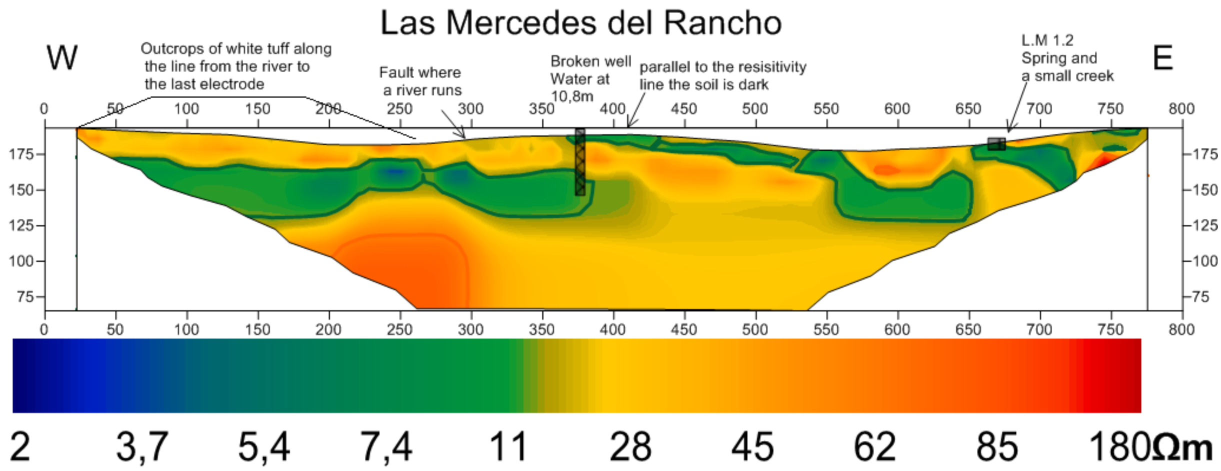

Figure 42 W-E resistivity profile in Las Mercedes del Rancho

The W-E resistivity profile is similar looking to the S-N profile with a large, medium/high resistivity area covering the bottom parts of the profile and lower resistivity areas in the topmost parts of the W-E profile. Outcrops of White Tuff occur the first 260 metres of the W-E profile along the resistivity line. Just before 300 metres there is a river, running along a fault crossing the resistivity line perpendicularly. The well at 360 metres is located 7 metres north of the resistivity line. The well was closed at the time of the investigation and therefore no information of its capacity is known. East of the well and parallel to the W-E resistivity line there is an area larger than 250 m^2 which is prominently darker than the surrounding soil. There is a creek running perpendicularly to the W-E resistivity line at ~660-670 metres and at 670 metres there is a spring, located in the low resistivity part of the W-E profile flowing up through the outcrops. The water temperature in the spring at 670 metres is 33 ^{o}C which is above normal groundwater temperature in the project area. The spring is flowing up from cracks in outcrops, see Figure 43. The high and low resistive layers are sloping from the west to the east with a dip of around 1:5, whereas the topography broadly speaking is flat over the profile.

Figure 43 Spring at 660 metres flowing up from cracks in the outcrop in Las Mercedes del Rancho.

Figure 44 Picture taken at 50 metres. Outcrops along the road where the resistivity line was drawn in Las Mercedes del Rancho.

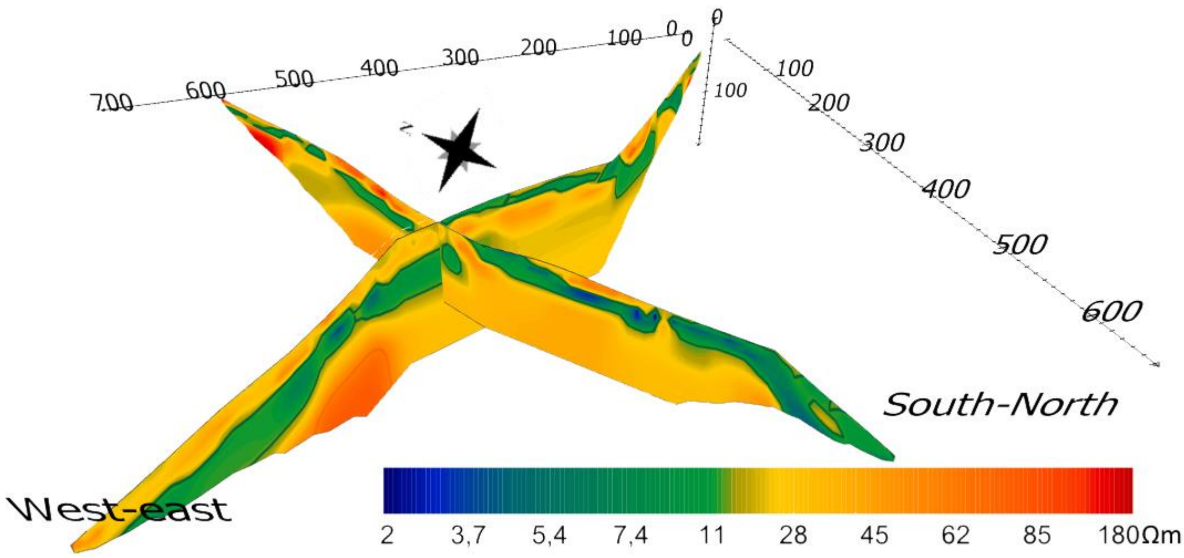

Figure 45 Fence diagram over the two resistivity lines in Las Mercedes del Rancho

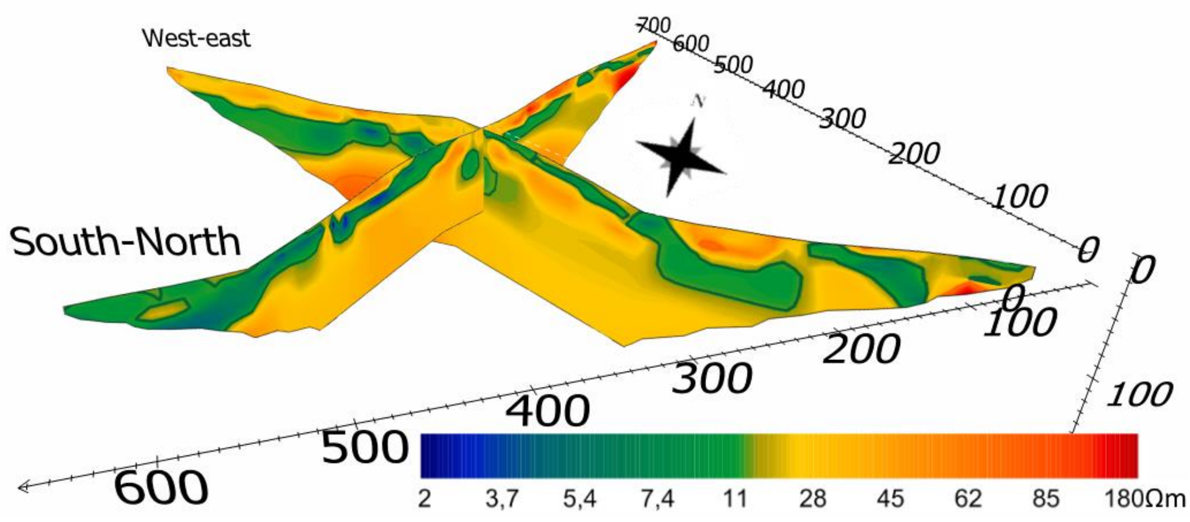

Figure 46 Fence diagram over the two resistivity lines in Las Mercedes del Rancho

7.3.13 Las Mercedes del Rancho south-north interpretation

The lower resistivity area close to the surface stretching from 0 to around 530 metres might be either a clayey unit or a unit with high total dissolved solids. Since there is water at 8.9 m in the well at 325 m and since the resistivity line was drawn 7 m from the well, this indicates that the unit/units situated in the vicinity of the well carries water. The aquifer of the well was therefore visible in Figure 40. Attempting to determine which resistivity layer is the aquifer, by examining Figure 40, becomes speculative, since it could be the low resistive layer as well as the high or a combination. It is also plausible that the water is hindered from percolating further down by the low resistive layer meaning it works as a confining layer of the aquifer. In this case it would mean that it would be the high resistivity area on top of the low resistivity area that is the aquifer.

Since there is a creek running along the line, in the fault with a 10 metres deep scarp this implies that the low resistivity area below the fault at 650-700 metres could be a material with higher water content than the surrounding material.

The bottom of the well at 560 metres is situated in the round, low resistive area. The low resistivity implies that the material here is less permeable and plausibly that it is less likely to transmit water. The resistivity line was drawn 12 metres from the well, meaning that it might not be possible to see its aquifer in Figure 40, the resistivity of the well water is unknown. However, looking at the profile and taking into account that the groundwater level in the well is at 10.8 metres depth, it is more likely that the aquifer of the well not is located in the low resistivity zone, but in the medium resistivity zone. The medium resistivity area is more likely to transmit water and is also more than 10.8 metres thick, which means that the aquifer could be situated in this area.

At ~810 m there is a fault, which might be what is seen in the lower parts of the profile at 850 m with a straighter cut on its left side of the high resistivity area. But it could also be the cut seen just below the surface at 820 m in the low resistive area.

7.3.14 Las Mercedes del Rancho west-east interpretation

The low resistivity areas occurring from west to east all along the profile might be layers with higher clay content since the resistivity only is around 10 Ωm or less. The spring located at 660 metres is situated along the border between a lower resistivity area and higher resistivity area. Since there is water flowing constantly from a spring it needs to be in contact with a water supply from below. The most plausible way for the water to be transported is probably the contact zone between the low resistive area below and the high resistive area on top. The low resistive layer is more likely to be clayey and the high resistive layer is more likely to be better at transmitting and transporting water. One theory is that the water is flowing on top of the low resistive layer since it may be hard to percolate through, whereas the high resistive layer probably is more permeable. The water temperature in the spring is raised, 33 ^{o}C implying contact with deeper, warmer hydrogeological layers. The water in the spring is flowing up through cracks in the outcrop implying that the spring is a fracture spring but the low resistivity layer underneath the spring most likely affects the spring characteristics as well.

The well at 360 metres has a groundwater level at 10.8 metres below the ground surface. In the resistivity profile it looks like the medium resistive area in the top parts of the well could be an unconfined aquifer. Furthermore, the low resistive area in the lower parts of the well could serve as a confining layer preventing the water to percolate downwards.

7.3.15 Interpretation of fence diagrams

The fence diagrams, Figure 45 and Figure 46, show that both in the S-N and the E-W profiles a pattern can be seen in how the high resistivity and low resistivity layers are sloping. The layers in the S-N profile seem to be sloping towards the south and the layers in the W-E profile are sloping towards the east. Neither of these direction are of course true, but extrapolating these 2D-profiles into a 3D-model there are good reasons of supposing that the general direction of the slope of the resistivity layers is towards SE. The Matagalpa group has a general sloping direction towards the SSW of around 1:6. The Matagalpa group present in the area around Las Mercedes del Rancho is generally thicker than the penetration depth of the resistivity profile. A tentative way of analysing the resistivity profiles is that the layers of high and low resistivity in the profiles could be different geological layers, all part of the Matagalpa group, but perhaps from different eruptions. The different geological layers have been exposed to weathering for different amount of time and they probably have different chemical and physical properties making them differently sensitive to weathering and that is why they show different resistivities.

7.4 Resistivity analysis summary

The general orientation of rock layers in the study area seems to be reflected by the slope of both low and high resistivity layers towards SW-S-SE in profiles Asiento Viejo, Candelaria, Las Mercedes del Rancho S-N and Las Mercedes del Rancho W-E. Rock layering could be responsible for the layering of high and low resistivities in profiles Los Negritos road, Los Negritos field and La Horca. However, recent weathering affecting the topmost layer must also be taken into account. Weathering affects the topmost layer so that the resistivity decreases since the weathering crumbles the rock and makes it much finer grained thus increasing its capacity of holding water but decreasing the transmissivity.

7.5 Cost-benefit-analysis

The concentrations found in the project area vary between values below WHO's limit of 10µg/l up to a value of 104 µg/l. To focus on the people with the most acute need of actions only values exceeding 20 µg/l have been used. The highest value was obtained from a well with water that was not used for consumption purposes, therefore this sample has been excluded from the calculations. The arsenic concentrations found in Rio Zapomeca river basin are not high enough to give acute arsenic poisoning. However, the concentrations give long term effects, therefore this study will focus on studying premature mortality.

Despite clear evidence of the health effects of arsenic, it is hard to make quantitative assessments. Some studies have attempted to investigate if arsenic is related to specific types of cancer, various diseases and brain development but few have analysed the risk of all health effects combined (Maddison, et al., 2005). The dose response relation is rather linear for low concentrations of arsenic. At the content of 0.05 mg/L of arsenic, the lifetime risk of dying from cancer of liver, lungs, kidney, or bladder(not including skin cancer, cardiovascular decease) from drinking 1lt/day can be as high as 13.4 per 1000 persons (Samadder, 2010). This means that In Asiento Viejo with arsenic concentrations of close to 40 µg/l the corresponding number of deaths would be 10.7 / 1000. If the relationship is assumed to be linear this means that 24 persons per 1000 can be expected to die from these diseases if the, by the European Food Safety Authority(2010), two liters for women and 2.5 litres for men of consumed water per day is used. Drinking water consumption has been found to be higher in the rural areas of Bangladesh and West Bengal than in more economically developed countries such as USA and Taiwan. If this fact is valid also for the hot rural project area, where most people work physically with agriculture, it could mean that the health effects in Nicaragua are more severe than in the developed countries (Flanagan & Zheng, 2011).

There are several different methods for calculating the cost of premature mortality. This type of calculation is associated with many uncertainties and therefore two different approaches are chosen with different approaches of determining the dangers of drinking arsenic polluted water. This is to see if different methods give significantly different outcomes or if the results support each other. The first method, *percentage of life reduced* is based on Samadder's (2010) article which determines different percentages shorter lifetime expectancy based on various levels of arsenic contamination in the wells in West Bengal, India. The second method, *Population Attributable Fraction* by Flanagan and Zheng (2011) for UNICEF*,* is a study from Bangladesh which is based on relative risk in relation to drinking water with arsenic concentrations below 10µg/l. Risk assessments concerning arsenic polluted drinking water has been more thoroughly investigated in Bangladesh, West Bengal and Taiwan than in Nicaragua and therefore a great part of data and reports are from these countries.

The two separate approaches for calculating the premature mortality is used to get two different results which can be compared to determine if the result is reasonable. The two methods were chosen because they have been used in similar conditions in Bangladesh and West Bengal.

7.6 Percentage of life reduced

By analysing data for contaminated wells in West Bengal, Samadder (2010) came to the conclusion that arsenic, at a concentration of 50-100 µg/l the total reduced life expectancy is 12.99% including all causes of death by arsenic consumptions. Assuming that the interval is evenly distributed, 75 µg/l will be used for calculations.

Table 10 Percentage shorter life expectancy at birth and increased relative risk depending on arsenic concentration in drinking water.

Micrograms arsenic per litre of water	Percent shorter life	Increased risk of drinking
10	0%	1
20	2%	1,17
30	4%	1,34
40	6%	1,51
50	8%	1,68
75 µg/l (50-100µg/l)	12,99%	

The average arsenic concentration in the water consumed in the villages investigated is just over 30 µg/l resulting in a 4.2% shorter life expectancy in accordance with Table 10. Life expectancy at birth in Nicaragua is 75 years. Meaning that a premature mortality of 3.2 years can be expected on average using the *percentage of life reduced* method.

7.7 Population Attributable Fraction (PAF)

Arsenic has been found to have increasing mortality rates at all concentrations of arsenic indicating a linear trend rather than a poison with a threshold value. The trend at low concentrations is rather linear. It was found that well water with an arsenic concentration of between 10 and 50µg/l increases the all-cause mortality rate with 34%, with a 95% confidence interval of between -1% to 82% increased mortality, compared to a population with drinking water containing arsenic levels below the WHO guideline value. (Samadder, 2010) (Flanagan & Zheng, 2011).

PAF is used to determine the contribution of a risk factor, in this case arsenic, to a disease or death. Therefore the *PAF* value is equal to the reduction of disease or mortality if the arsenic source would be removed. The value of relative risk that is used is for increased mortality compared to those exposed to arsenic concentrations below 10µg/l (Flanagan & Zheng, 2011). Equation 3 is used to calculate the *PAF* value using values from Table 11.

Table 11 Input values for equation 3 for six villages with a total of 8 wells with the highest investigated arsenic concentrations excluding the salt polluted well in Los Negritos because that water was not used for drinking.

nr	Village	Inhabitants	P_i	Arsenic in wells (µg/l)	Average consumption in village	RRi
1	Asiento Viejo	550	39%	33.9 and 41.5	2/3×33.9 + 1/3×41.5 = 36.4	1.45
2	Los Negritos	200	14%	36.5	36,5	1.45
3	Las Mercedes del Rancho	260	18%	22.3 and 29.9	0.15×22.3 + 0.85×29.9 = 28.8	1.32
4	Las Tunitas	50	4%	23.1	23.1	1.22
5	La Horca	300	21%	21.6	21.6	1.2
6	Las Piscinas	50	4%	26.3	26.3	1.28
	Total	1410				

$$\sum_{i=1}^{n} P_i \left(\frac{RR_i - 1}{RR_i}\right) \quad (3)$$

$$P_i = Proportion\ of\ population\ at\ exposure\ level\ i.$$
$$RR_i = Relative\ Risk\ at\ exposure\ level\ i.$$
$$n = Number\ of\ exposure\ levels.$$

The relative risk value is interpolated by assuming no increased mortality for arsenic concentrations below 10µg/l, the reference value of 1 is therefore set at this concentration. According to Flanagan & Zheng (2011) the increased risk in the interval between 10-50µg/l is 1.34. Assuming that the relative risk increases linearly in the interval the relative risk value of 1.34 is set to arsenic concentrations of 30µg/l. The interpolation results in a relative risk interval between 1 and 1.68 for the concentration interval, presented in Table 10. All values used are well into the limits of the interval.

The resulting *PAF* value, is 0.26, meaning that 26% of the mortality in these villages can be connected to arsenic. The national crude death rate in Nicaragua is 5 per 1000 persons resulting in 1.8 persons dying from arsenic in the villages each year according to calculations from equation 4 (Unicef, 2015).

$$\frac{5}{1000} \times 1410 \times 0.26 = 1.8 \quad (4)$$

The total value of the 1.8 persons dying in the project area per year, using VSL is presented in Table 12.

Table 12 Total value of the people dying prematurely due to arsenic consumption in the investigated villages

Discount rate	Total value premature mortality ($)
0%	293800
1%	161600
3%	49900
5%	15700
10%	970

There are roughly 260 families depending on the investigated wells in the project area, thus the same number of filters are desirable. As seen in Table 13, it is socioeconomically valid to invest in filters as long as the discount rate is below 3%. With a discount rate of 5% it is valid only when the price of a filter is $35 but if the high cost of filters is used the investment could be recouped within two years instead of one. Additional maintenance costs are the addition of new iron nails to replace the ones that get depleted. The first set of iron nails has been reported to last for at least 3 years why an addition of 1 kg of iron nails is suggested each year, at the cost of less than $ 2 per year (Ngai, et al., 2005).

Table 13 Number of filters that can be afforded with the decreased mortality during one year 60 years from now, depending on filter price and discount rate.

Discount rate	Number of filters with the price per filter: $35	Number of filters with the price per filter: $73
0%	8390	4020
1%	4620	2210
3%	1430	680
5%	450	220
10%	30	13

The strength of a cost-benefit-analysis is that it can be evaluated and compared to other lifesaving projects in a society. Table 14 presents payback per invested dollar depending on discount rate and price of the filter. These values can be used to evaluate and decide which project should be allocated money according to what is socioeconomically correct. All values of >1 are socioeconomically correct but there might be projects with higher payback rates meaning that these should have higher priority. Observe that the payback of the more expensive filter does not exceed one if the discount rate is set to five percent. It is important to remember that Table 14 only includes the VSL from one year's death in the project area, those of the 1,8 lives saved in 60 years' time. When integrating, thus including the lives saved until the year in 60 years' time and those lives saved after that point, the positive result of the cost-benefit-analysis will be strengthened.

Table 14 Payback per invested dollar depending on discount rate and price of the filter.

Discount rate	Payback per invested $ with filter price $35	Payback per invested dollar with filter price $73
Discount rate 0%	32,3	15,5
Discount rate 1%	17,8	8,5
Discount rate 3%	5,5	2,6
Discount rate 5%	1,7	0,8

8 Discussion

Both the field study and the risk analysis have major assumptions, uncertainties and sources of error which are presented and discussed in the following chapter. Working with something as essential as water there a number of ethical dilemmas occur, the dilemmas identified in this study are also presented. Some theories of the origin of the arsenic in the well water are given.

8.1 Uncertainties

The methodology and calculations for the risk assessment is based on various assumptions and uncertainties. These have consequently been made conservatively and thus the socioeconomic outcome can therefore also be considered conservative.

The WHO limit for arsenic is set to 10 µg/l, but there is no known threshold value for arsenic toxicity. The WHO limit is chosen with consideration of difficulties in treatment and measuring of arsenic (WHO, 2012). For the calculations this limit has been used as a reference value for safe drinking water. This means that the results for drinking water with concentrations just above this value will be conservative and might be underestimated. Values below 10 µg/l are widely considered safe in relevant literature because a limit to work towards is needed.

In a study of filter efficiency in an area in Nicaragua with similar arsenic concentrations the average removal rate was 90% but all filters reached effluent concentrations below WHO´s limit of 10µg/l. In the case of water with higher concentrations the Kanchan filter has proven to produce sufficient drinking water of water with concentrations up to 2500µg/l, meaning that the treatment rate increases with concentration (Ras, 2014). Even though the arsenic mitigation results in water with concentrations below the limit, the concentrations in the effluent water does increase with higher influent concentrations. This means that there is a limit of influent arsenic concentration that the Kanchan filter can remove to sufficient levels. According to previous research this limit is probably way above the arsenic concentrations within the study area.

8.2 Sources of error

When taking water samples from wells it is important to get water that has not been in contact with the atmosphere since the air affects the groundwater properties. This is done by withdrawing at least twice the total well volume. The volume of the wells was often hard or impossible to determine since the opening to the well often was locked. Instead a pumping time of 30 minutes was used. This does not guarantee that the wells were emptied sufficiently.

The topography data used to resistivity profiles does not correspond to the map coordinates. This affects the topography throughout all the resistivity profiles but is most significant in the resistivity profiles in Las Mercedes del Rancho. A more convenient method would have been to use differential GPS to determine the exact position and elevation but because of lack of time and old equipment this was not a good solution for the project. With faulty topography data the resistivity profiles are slightly distorted.

During the resistivity measurements one electrode take-out in one of cables was malfunctioning. This take-out had therefore to be excluded from the measurements. This gives a lower resolution in that part of the resistivity profile.

The equipment used for the hydrochemical measurements, an Orion 115 A+ meter was used for measuring conductivity, salinity and TDS and a Thermo Orion 4 Star meter, for pH and temperature, has been stored for several years before this study. The Thermo Orion 4 Star meter was compared with another device measuring the same parameters and showed no sign of malfunction. However, the other device had also been stored for several months without usage. This results in the electrode getting dry and thereby loses precision, but increased its precision after being submerged in an electrolyte.

The XRF-analysis of the rock samples does only give a hint of the arsenic content and only in very small parts of the sample. The rock samples analysed were remains from thin sections made in 1988. Some of these samples were smaller than needed according to Johansson (2015). To get a more representative value, larger rocks and more measurements would have been needed. The rock samples were not homogenised which also could have given a more representative value for the sample itself.

Since the method used for analysing the arsenic concentration in the drinking water cannot differ between As(III) and As(V) it is hard to tell how poisonous the arsenic in the river basin of Rio Zapomeca is.

When investigating the groundwater depth in the wells it is preferable that the groundwater table is unaffected by pumping by the inhabitants. It is not ensured that the wells were not utilised just before the measurement. On the other hand the preparation of the measuring probe did take some time during which the well was not used. This means that the well had time to recover water. It is not crucial with centimetre precision for the result when it comes to the ground water table measurement since the topographical variations makes the main difference of up to hundreds of metres within the catchment area. The groundwater table does also change with time giving different results on different days.

8.3 General discussion

According to the XRF-spectrometry, the rocks close to the high arsenic values also have a high arsenic content. An example is the rock sample 271, a rock from the Matagalpa group, located northwest of Los Negritos which has an arsenic content of 26 mg/kg. This is the highest of all rock samples and the nearby well L.N. 1.2 has the highest measured arsenic concentration of 104 µg/l, see Figure 18. However, this coupling cannot be made for all wells since the arsenic concentration in the wells does not appear to be solely dependent on neither the arsenic content of the rocks nor the geological group i.e. Matagalpa or Coyol.

The highest arsenic values in wells are found in or close to the Coyol group rocks in the south-western part of the river basin, see Figure 19. Since the Coyol rocks here are darker, thus having lower content of feldspar and quartz these Coyol rocks are probably more sensitive to weathering. Rocks more sensitive to weathering do most likely yield higher concentrations of total dissolved solids in the groundwater, which in many cases is coupled to higher arsenic concentration. In this study a weak connection between high concentrations of total dissolved solids and inclined arsenic concentrations, see Appendix 3.

The retention time of the groundwater plays an important role when it comes to the dissolving of arsenic. The drinking water sources with the highest arsenic concentrations are located closer to Rio Zapomeca rather than in the mountainous northern part of the river basin. The groundwater retention time is most probably longer closer to Rio Zapomeca compared to the mountainous northern parts, since the landscape is flatter and the topography less dramatic. This gives more time for the arsenic to dissolve and yields higher concentrations. When arsenic is plotted against elevation a decrease of 7 µg/l was found per 100 metres of elevation, though the coefficient of determination is 0.22, meaning that 22% of the values can be explained by that regression, see Figure 20. If the highest value, of 104 µg/l is excluded the decrease of arsenic per 100 metres is 5.5 µg/l while the coefficient of determination is 0.52. This shows that there is a connection between altitude and arsenic content in water in the project area. This connection might also be related to other factors such as geology. However, in order to evaluate how strong the connection is further investigations are needed.

According to Altamirano Espinoza & Bundschuh (2005) the main source of the arsenic in Sébaco valley is the Tertiary rocks with geothermal alteration working as the arsenic trigger. It seems that this theory is applicable in Rio Zapomeca as well. The rocks in Rio Zapomeca river basin are Tertiary and do contain arsenic. The geothermal influence in the area does possibly affect the arsenic concentration, but no clear correlation between the groundwater temperature and arsenic concentration could be found in this study. However, deeper and warmer hydrogeological layers could have contact with the groundwater closer to ground surface. The groundwater closer to ground surface could still show normal temperatures if the ascending of the water of deeper origin is slow and the mixing with meteoric water is significant. Areas with lots of fractures and faults are more likely to have contact with deeper groundwater aquifers since these make groundwater transport easier.

Two different methods, *percentage of life reduced* and *PAF*, are used to calculate the premature mortality in the project area. The two results do not differ significantly. The first approach, calculating with percentage decreased life expectancy, gave a shorter average life of 3.2 years. Using the relative risk methodology it was calculated that 26% of the deaths in the area can be linked to arsenic polluted drinking water. Assuming that each person that dies of that reason loses 15 years of lifetime the average life lost corresponds to 3.9 years. Considering assumptions and uncertainties it can be concluded that these two methods support each other.

The symptoms from drinking arsenic polluted water of the levels in the project area do not occur for many years. This can lead the inhabitants to believe that the water is not dangerous, since they have not experienced any problems. It might therefore be problematic to introduce the additional work of filtration. Therefore continuous education and information is needed, for example by placing information signs at the location of arsenic polluted wells.

When performing a resistivity survey in the village Asiento Viejo, a village within the project area that has been provided with Kanchan filters, it was discovered that at least one family in the village did not use the filter. The reason was that the father of the family worked in a location nearby with another well which they thought, incorrectly, was free from arsenic. When introducing filters in the region it is important to inform the population that it is not safe to drink water from any well that has not been analysed for arsenic within the project area. It is also important to have a long term project with repeated education and additional filters to ensure that younger generations and families that moves into the villages are reached. Internet is a good tool for spreading information and a forum for questions and answers that arise after the initial education and demonstration should be established. Smartphones are rather common in this rural area and to avoid insecurity from the population such a solution is both efficient and inexpensive.

The maintenance for the Kanchan filter is close to self-explanatory. The iron nails rust and thus eventually reduce in volume. As the mass of iron nails reduces they need to be filled up. It is also advised to wash the nails annually to expose new surface area to encourage oxidation. Depending on the composition of the influent water the filter will eventually clog. When this happens, every one to three months, the sand filter needs to be cleaned. The need for cleaning is self-explanatory since the clogging makes the filtration slow. A text messaging service with additional information and reminders when filter maintenance can be expected is advised, especially initially before the filter maintenance has become routine. Without maintenance the filters won't work and might thereby result in the population consuming untreated water. This is not a problem that has been reported from where the Kanchan filter has been used earlier, but it is an issue that should be addressed during the implementation instruction meetings.

All arsenic concentrations used for the calculations are well within the interval between 10-50 µg/l. For interpolation it is therefore most relevant to use the percentage of reduced life expectancy and relative risk for this interval. According to Flanagan & Zheng (2011) the relative risk is higher for arsenic concentrations between 10-50µg/l than for concentrations between 50-150µg/l. This fact is probably due to sources of error in their report but doesn't affect the result for this report since no values are in that latter interval.

For simplifications the Asiento Viejo, which is a village that already has Kanchan filters, has been included in the calculations. This is due to having a greater population to do the calculations for and the conclusions will still be valid for the project area and similar areas elsewhere in Nicaragua.

Both the methodology for calculating the cost of health effects, premature mortality, and the Kanchan filter is developed for Bangladesh where a lot of studies concerning arsenic have been conducted. Methodology and data specifically made and produced for Nicaragua would be preferable but many of the most substantiated arsenic pollution studies have been conducted in Bangladesh, often including data from the US. In Bangladesh there are a lot of wells with concentrations of arsenic greatly exceeding the concentrations in the Nicaraguan project area. Despite this fact the societal cost of arsenic polluted drinking water for the project area is higher than that of Bangladesh according to Flanagan & Zheng (2011). This is because they calculated the cost for the whole country of Bangladesh including unpolluted wells while this investigation was made solely including polluted wells of the region, with arsenic concentrations of above 20 µg/l.

The villages with wells containing low concentrations of arsenic were not included in the cost-benefit-analysis. This is because the study concentrated only on the villages that suffer the most from arsenic polluted water. From this report's results it is recommended to measure arsenic content in wells that are suspected to contain arsenic before providing filters. This is due to not worrying the population, not to give the families additional work and due to the fact that an arsenic laboratory test cost less than providing the population with filters. Laboratory testing of arsenic costs 36 dollars per sample but with an arsenator, field arsenic measuring equipment the approximate cost is 6.6 dollars per sample (George, et al., 2012).

The limit of 20 µg/l, to be included in the cost-benefit-analysis, is chosen as a consequence of two factors. Firstly the value for relative risk was calculated by interpolating between the relative risk for the interval between 10 and 50 µg/l. For calculation purposes it was best to exclude values far from the central value since a value close to 10 µg/l would mathematically imply that water with that concentration is safe to drink. This is not true, no safe threshold for arsenic has been found. Instead, one could argue that the interpolations should have been done from 0 to 50 µg/l but the input data for relative risk was not presented in a manner that would allow such measures (Flanagan & Zheng, 2011). This is because concentrations below the WHO's limit normally are considered safe in similar calculations. Secondly, there is a discussion in Nicaragua of allowing drinking water with concentrations below 20 µg/l. Sergio Gamez, a professor at UNI, Universidad Nacional de Ingeniería, argues that with Nicaragua's economic limitations, focus should primarily be on handling wells with high arsenic concentrations. He also argues that the harmful effects at low concentrations are not severe enough to take acute actions, such as closing wells, since such measures will have negative effects. Examples of these effects are economical and health effects that could overshadow the arsenic issue (UNI, 2009).

In order to be able to compare various projects concerning reduced premature mortality, using the cost-benefit quota, guidelines for standardisations of development of analyses is needed. The quota derived in this report shows that, even with systematically conservative assumptions, the investment in arsenic mitigating filters is socioeconomically valid. On the other hand, since the result is conservative there might be other projects that will prove to be more socioeconomically profitable. In some cases this could be because these reports have not been made with as conservative assumptions and calculations. Therefore the report would benefit from being updated after comparing to the calculations of similar projects.

8.4 Ethical aspects

After sampling and in field water analysis the local inhabitants normally asked whether the water had sufficient quality or not. During the first field campaign analyses only included hydrochemical measurements of the water and during the second field campaign water samples were brought from the project area to a laboratory in the capital of Nicaragua, Managua. When doing the sampling it was not possible to say anything about the quality and therefore we told them at each spot that the water seemed normal. This was not to worry them without knowing for sure. When we now have some information regarding polluted wells it would be preferable to share this information with the local authorities, at least if this means that something can be done for the population.

In West Bengal the local government was advised to mark arsenic polluted wells red to warn inhabitants. That is a cost efficient measure to give information to the population. Problems occurred when the communist local government stopped the painting due to not wanting the red party colour to be coupled with dangerous drinking water (Cervenka & Lindblom, 2013). This example shows that unexpected difficulties can occur, therefore it is important to follow up measures taken. For families that do not have the opportunity to access an unpolluted drinking water source, due to for example long distance or poverty, drinking from a marked well can be shameful. For this reason the work with marking the wells can be counteracted by the actual people that the markings are meant to help. For these people, informing them of the danger of the drinking water without providing a practically feasible solution might result making the situation worse. Sergio Gamez (2015) argues that wells with concentrations below 20 µg/l initially should be considered safe, since the worse polluted should be the primary focus. Gamez also means that banning slightly polluted wells will cause more problems than it solves considering factors presented here.

To ensure that the water used for analysis had not been exposed to the atmosphere each well was pumped for a while, thus extracting a vast amount of water. A few families got upset over water wastage since the project area is a dry area where some wells lack enough water to support the population. To avoid this and to utilise the water it is preferable to inform the locals that water needs to be extracted and encourage them to take the opportunity to fill up water containers for the day's usage. If possible it is preferable to inform the population prior to the pumping to ensure that they have containers prepared and so that they haven't already filled all containers for the day.

When calculating the societal validity, using the principles of cost-benefit-analysis of treating the water the statistical value of a Nicaraguan life is used. Valuing human life in money can be considered unethical, especially since a Nicaraguan life, according to the calculations, is worth approximately a tenth of the monetary value of a Swedish statistical life. The VSL's are partly based on a population's willingness to pay, not directly on the economic wealth. This means that, statistically, this value represents what the Nicaraguan population is willing to pay to prevent one statistical death. It also means that the same population would chose to spend the money on other societal measures if the cost of saving one life exceeds the VSL, according to the theoretical principles of a cost-benefit-analysis. This has unethical aspects but is rational for a country with limited resources. One should also remember that it is important to take actions to prevent long term arsenic poisoning but, since it is a long term exposure, it could be more economically correct to invest in other more acute projects. Furthermore, using the methodology from this report for calculating VSL it is possible to redo the calculations using alternative values if required. When a nationally accepted value is developed or a sensitivity analysis needs to be made, this value should be used to update the results of this report.

9 Conclusion

It is hard to conclude the reason for arsenic in the water in the region. A combination of presence of an arsenic source, a trigger for dissolution and the rate of weathering of the arsenic containing material all play a role in polluting the drinking water. Presence of arsenic has been confirmed from rock sample analysis in which the content of arsenic exceeds what is normal for the rock types but no clear differentiation was found between different rock groups. Which mineral(s) or rocks type that contain the arsenic is not possible to tell from this study. Anthropogenic origin of the arsenic cannot be excluded but the rock sample analysis shows that natural occurrence is likely and in combination with no identified industry or mining in the area the conclusion is that the arsenic most likely has natural origin.

The hydrochemical properties of 31 wells and springs were investigated, among these were 20 analysed for arsenic. 15 of the 20 analysed samples had an arsenic concentration above the WHO limit (10 µg/l).Studies of correlation between arsenic and other factors have shown a weak connection between arsenic and other factors some relationship to, for example, conductivity of the water and concentration of iron, which normally have clearer connection. The decrease of arsenic in relation to increase of elevation shows a clear trend in the project area but the reason is unclear, perhaps the increased elevation results in shorter retention time due to higher hydraulic gradient and thereby less time to dissolve arsenic. The clearest connection found is that elevated values of arsenic, both in the rock samples and in the water, occur along the contact zone between the rock type groups Coyol and Matagalpa in the south to south-western part of the Zapomeca basin.

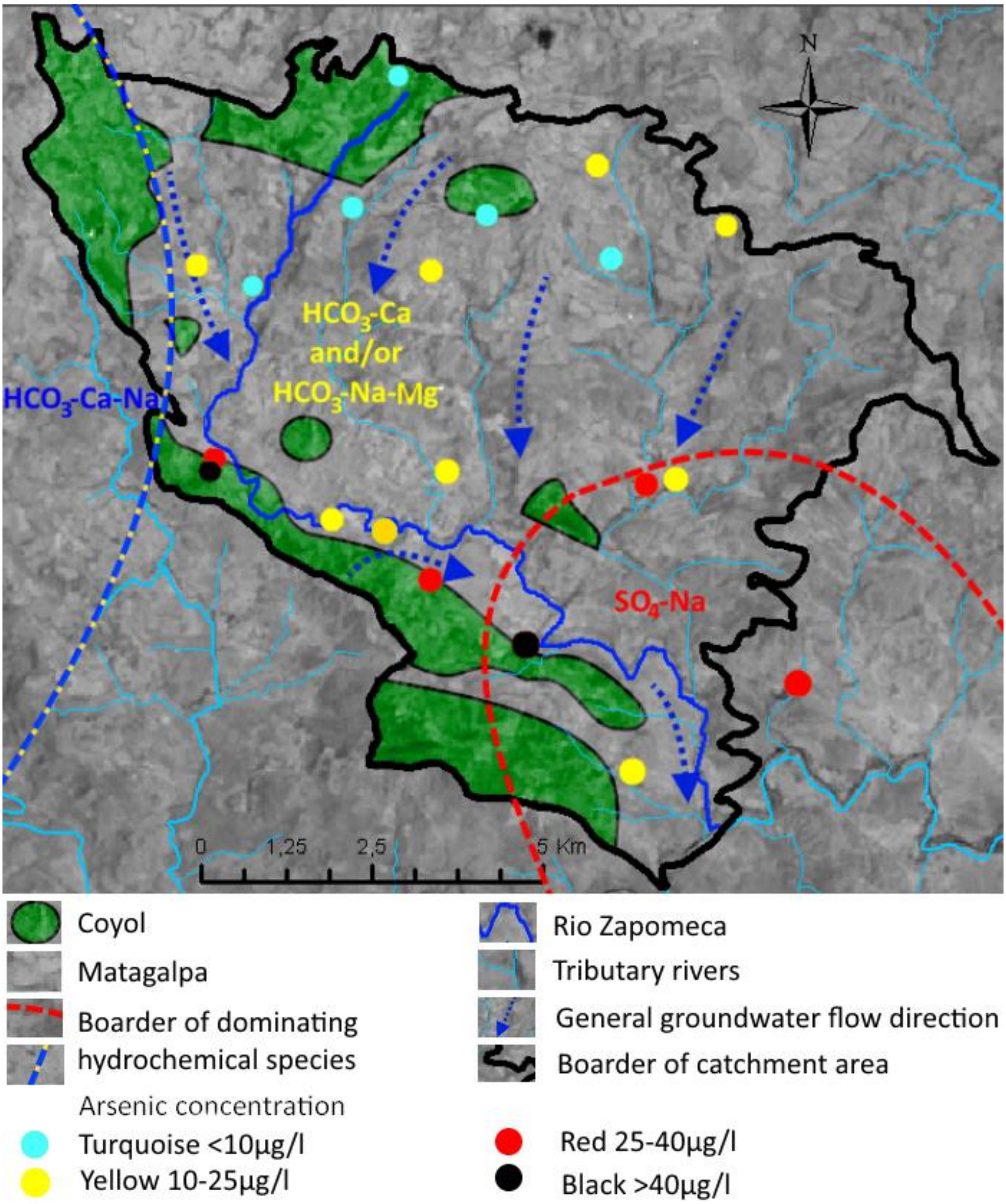

Figure 47 Conceptual model with the information collected throughout the project is presented. Concerning hydrochemistry, observe that the composition of Calcium (Ca) and Sodium (Na) can vary within the area furthest to the west. Adapted from (Ehrenborg & Alvarez, 1988) and (INETER, 1998).

Figure 47 presents a conceptual model of the study area, with the information obtained from literature and field studies. The black line is the border of the catchment area which consists mainly of rock types from the Matagalpa group. The green areas are dominated by the younger rock type group, Coyol, close to the surface. The hydrochemistry in the area is characterised by bicarbonate (HCO_3) which is the most common ion and therefore it is presented first in order. The composition of the other ions varies. In the south-eastern part of the catchment area the main ion is sulphate (SO_4). The arsenic concentrations and ground water levels were measured during field campaigns for the project, noticeable is that the southern parts have higher arsenic concentrations than further north. The general direction of groundwater flow follows the declination of topography towards Rio Zapomeca which in turn is a tributary river to Rio Malacatoya.

The arsenic concentrations found, do in many cases exceed the limit of 10 µg/l, which is the limit set for drinking water by WHO. A number of villages with wells containing high levels of arsenic were chosen for the cost-benefit-analysis, the total population in these villages was estimated to 1410 persons. There are different approaches which include exchanging the polluted water or arsenic mitigation including filters, for example so called Kanchan filters. An investigation of the socioeconomic effects of premature mortality due to drinking the arsenic polluted water from the project area was made. The years lost due to drinking polluted water was calculated and by using the value of statistical life (VSL), which was calculated to a value of $260 000, it is proven that it is economically valid to invest in Kanchan filters for the population with polluted wells. The payback for each dollar invested varies depending on the discount rate but calculating conservatively and with a high but reasonable rate the payback per invested dollar is at least $2.6 thus making it a sound investment. This report shows the need for further investigation and preparation for decision making.

Throughout the socioeconomic assessment, uncertainties have been treated conservatively resulting in a conservative cost-benefit-quota meaning that the actual payback per dollar will likely be higher than indicated by the report.

10 Future studies and recommendations

If there were more time and resources a more thorough investigation of the origin and cause of the arsenic contamination could be done. Suggested objects of investigation in the future concerning the arsenic origin are the correlation between arsenic content in the rock samples and the closest drinking water source, the arsenic content in soil, more arsenic analyses of drinking water sources. Also, plotting the hydraulic gradient in the Rio Zapomeca river basin with the arsenic concentration could be of interest. It is likely that the retention time of the groundwater has a great impact on the levels of dissolved solids and thereby perhaps the arsenic concentration as well.

More information regarding the unsaturated zone, geochemistry and groundwater flow could also be of interest. This could provide information of which rocks and/or minerals(s) that are releasing arsenic and how.

An alternative to Kanchan filter for the project area is to build pipelines from the hillier parts of the project area to the villages with arsenic polluted wells. The arsenic concentrations have proven to be lower in the parts of the river basin with higher elevation. The project area has a natural declination towards the south-southwest why pipelines could transport water with low arsenic concentrations by gravity. This cannot be considered hazard elimination since no tested well had arsenic concentrations below the level of detection but several water sources were found that had concentrations below the WHO’s limit. Slug tests of the possible wells are of interest for further studies and should therefore be studied further.

The calculations of benefits from arsenic mitigation only include people, 60 years from now, that not would be affected by drinking arsenic polluted water. This is a simplification that makes the calculations conservative by not including the decrease in premature mortality during the coming 60 years. If assumed that the decrease in premature mortality follows a linear pattern depending on consumption of polluted water half as many persons, 0.9 persons, would die from the water 30 years from the introduction of filters. These avoided deaths will give the cost-benefit-analysis a stronger outcome but become especially important for the result if a high discount rate is chosen. This is because lives are valued higher, monetary, in 30 years’ time than in 60 years’ time. The simplification is done because of time limitations but is recommended for further studies.

The results from the *PAF* calculations include data from a few villages with polluted wells and demonstrate the effects of arsenic on premature mortality. All data used for the calculations are not valid for the limited area of the rural villages in this survey. The national crude death rate is valid only for the nation as a whole and the relative risk originates from an investigation in Bangladesh. Local values would have been preferable but is not available, further investigations are needed for more accurate results.

There are a number of assumptions and uncertainties, including the amount of water consumed and the relation between As(III) and As(V), within the calculations of the cost-benefit-analysis. It is recommended to perform a sensitivity analysis to conclude which factors could affect the outcome the most. From this analysis a conclusion of what factors play the most important role can be made and thereby help with decision making concerning focus on further studies.

Various crops are grown in the study area, these are irrigated with arsenic contaminated water. For future studies it would be of interest to determine the concentrations and health impacts of the consumption of these crops.

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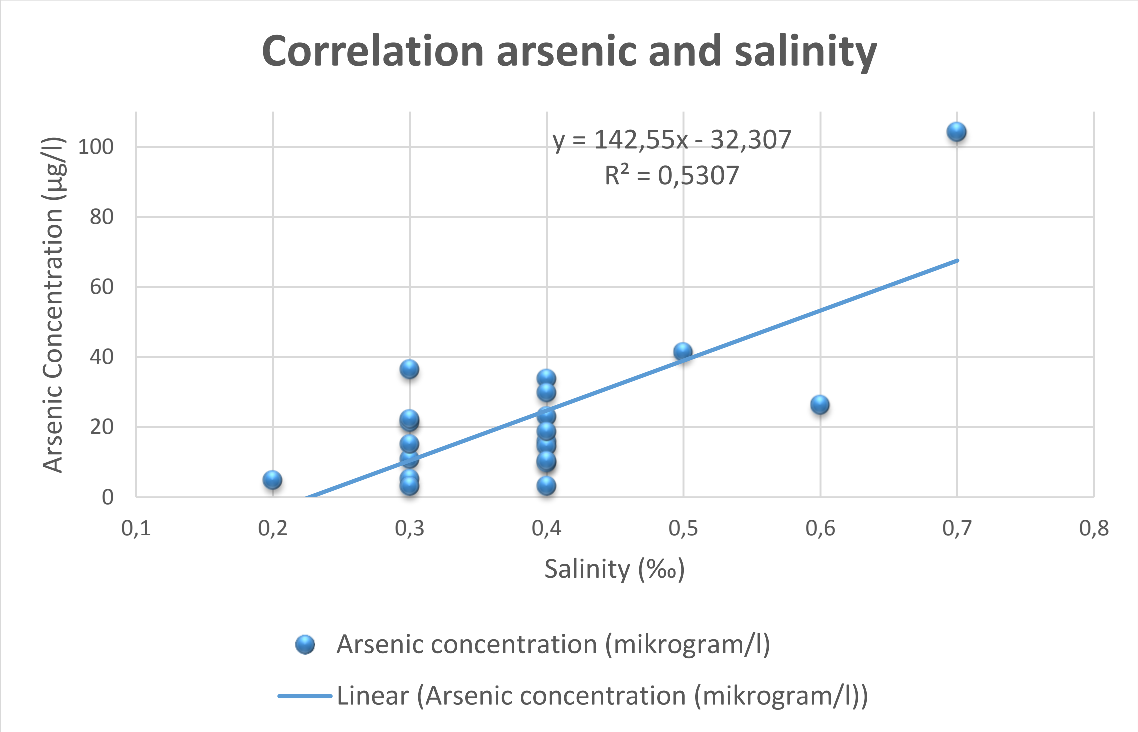
12 Appendices

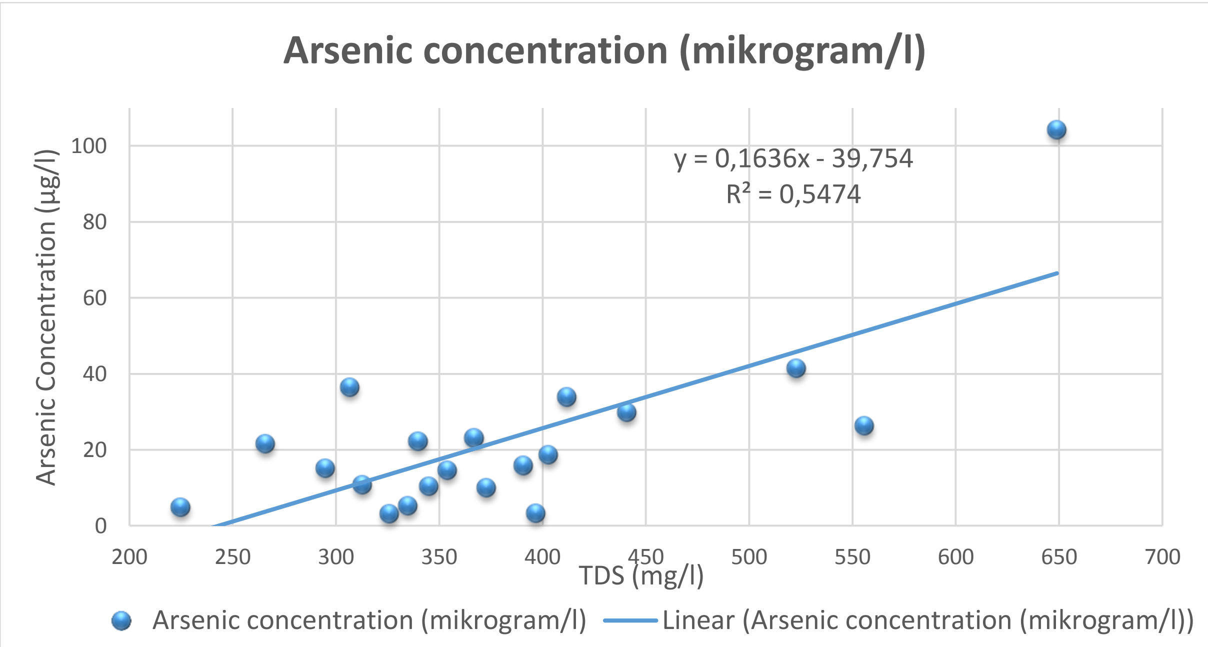
The four appendices include rock sample analysis, correlations, drillings protocol and the investigation data from Lener Sequeira.

Appendix 1 A selection of species which were analysed during the rock sample analysis. The unit is ppm (mg/kg) and the suffix b or c indicates several analysis of one rock sample. <LOD means lower than limit of detection.

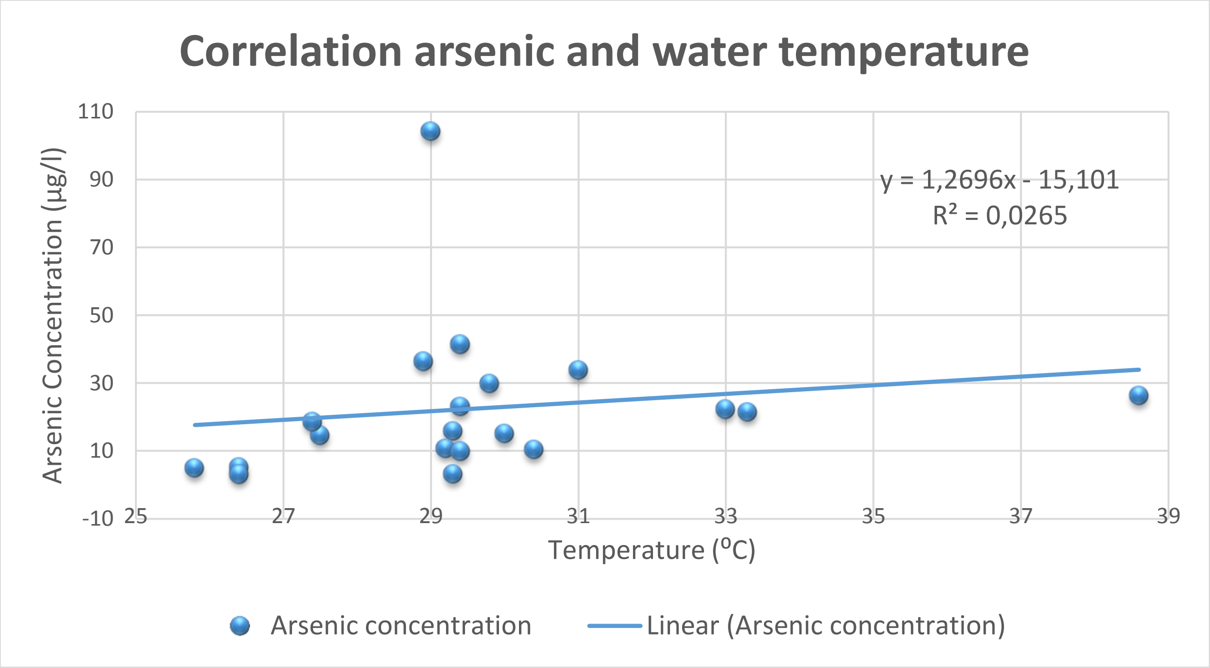
SAMPLE	As	S	Fe	Mn	Mg	Ca	K	P	Cu	Zn
s-265	12	371	10102	415	< LOD	5030	27356	2437	< LOD	7
s-265b	10	540	6466	< LOD	< LOD	14258	21929	359	< LOD	< LOD
s-284	7	419	50811	1456	18637	50858	12639	651	113	51
s-284b	9	202	49579	1305	15954	53028	12639	908	114	48
s-284c	7	425	53664	1481	22600	46433	13954	409	132	60
s-263	10	391	9192	72	4098	2310	51683	< LOD	21	22
s-263b	9	160	10116	< LOD	< LOD	1738	51839	< LOD	< LOD	16
s-263c	12	388	11084	< LOD	5480	2229	51135	< LOD	19	19
s-286	5	319	67518	1313	24252	59268	6235	2142	92	64
s-286b	4	225	69319	1235	29772	58029	5885	2092	103	66
s-286c	8	249	67950	1276	28914	57998	6192	2069	90	65
s-211	6	1879	24690	125	6466	12972	15331	480	18	42
s-211b	6	398	23154	121	4354	11840	15857	1007	< LOD	28
s-211c	5	556	18345	76	7284	12668	14805	754	< LOD	27
s-256	8	441	70140	1875	23765	60683	6752	1167	118	72
s-256b	13	1110	71090	3291	26145	61029	7076	1278	127	88
s-048	6	486	63125	980	17620	56573	11211	2687	64	70
s-298	6	327	74282	1201	31037	64008	6263	1091	125	66
s-340	8	334	81098	1461	20657	48798	15898	2423	352	92
s-264	11	88	11528	201	3903	5256	31011	< LOD	16	18
s-264b	12	227	12123	< LOD	< LOD	7915	31892	< LOD	15	22
s-264c	11	120	9775	< LOD	< LOD	6794	32059	< LOD	< LOD	19
s-001	4	513	71647	1090	25513	64625	5324	763	121	85
s-402	7	402	33439	885	9369	27490	14272	1664	< LOD	45
s-271	32	765	65069	1438	29237	61815	7395	1036	91	62
s-271b	19	479	65313	1393	33316	62304	7212	1118	67	59
s-273	4	184	10922	80	7961	3380	51837	311	17	25
s-273b	4	254	9995	< LOD	4634	3110	53190	560	21	17
s-332	6	116	19438	624	< LOD	8924	20048	507	< LOD	53
s-238	17	166	55481	452	10966	31705	18554	559	89	61
s-238b	17	213	49532	330	12455	36285	16768	673	84	59
s-134	7	239	70109	1249	22827	58461	8245	400	144	76
s-134b	7	345	67699	1228	28886	56752	8653	578	142	76
s-119	12	1144	83966	993	21577	62950	5511	719	224	132
s-119b	14	706	86720	1075	20087	63604	5110	496	195	126



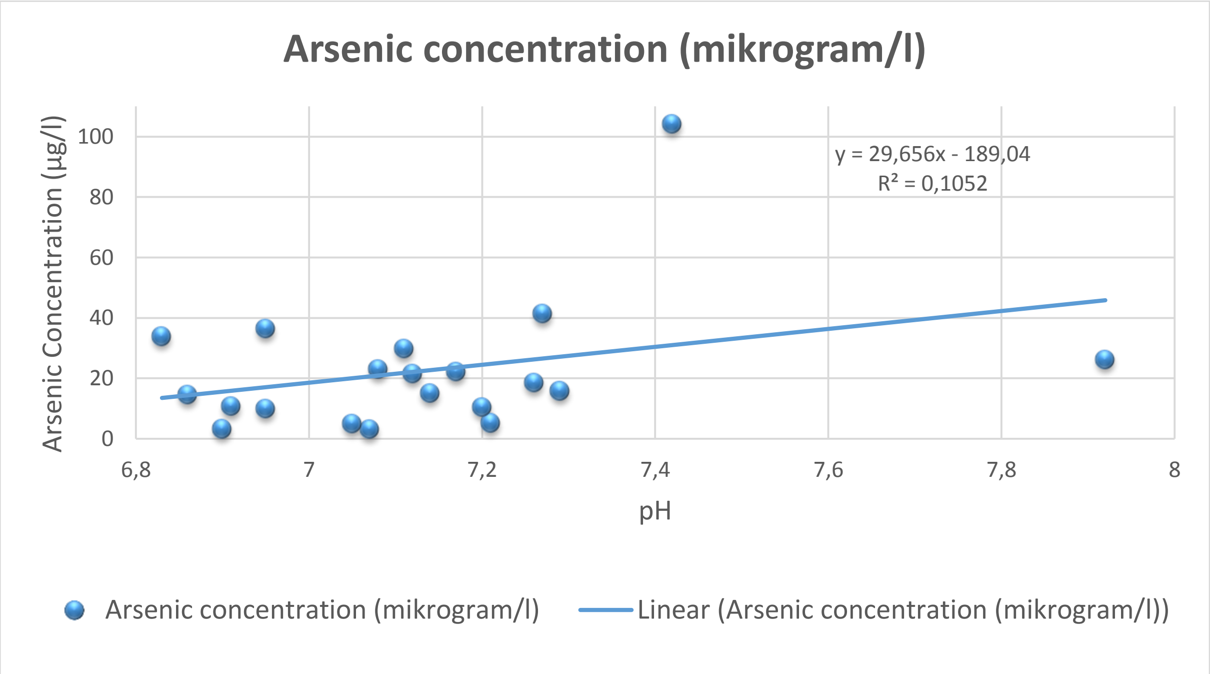
Appendix 2 Correlation between arsenic concentration and salinity in per mille. From the data obtained the arsenic concentration increases with increase of salinity.



Appendix 3 Correlation between arsenic concentration and total dissolved solids, TDS, in mg/l. From the data obtained the arsenic concentration increases with increase of TDS.



Appendix 4 Correlation between arsenic concentration and temperature in ºC. From the data obtained the arsenic concentration increases with increase of temperature.



Appendix 5 Correlation between arsenic concentration and pH. From the data obtained the arsenic concentration increases with increase of pH.

Abacus Drilling

Código: WA14011 (Pozo # 1)

Propietario: ALCALDIA MUNICIPAL DE TEUSTEPE
Dirección: Comunidad El Negrito, Municipio de Teustepe, Departamento de Boaco
Localización del pozo: Com. El Negrito, Municipio de Teustepe, Dpto. de Boaco
Perforador: Sr. Jorge Luis Nicaragua Castillo (T011).
Ubicación GPS: lat 12.42150 -85.79922
Fecha Finalización: Sábado, 08 de Marzo de 2014

Propósito del pozo:

Domestico		Industrial		Municipal	X
Irrigation		Prueba del pozo		Otros	

Tipo de Pozo:

Nuevo	X	Excavado	
Profundizar		Percusion	
Recondicionar		Rotacion	X

Dimension:

Diametro	6" Pulgadas
Pies Perforado	200' Pies
Profundidad Completa del Pozo	200' Pies

Detalles de la Perforación:
Instalación de : PVC SDR26 DE 4"
Hierro: N/A Plástico: PVC
100' Pies Tubería Ranurada PVC SDR26 de 4"
103' Pies Tubería Ciega PVC SDR26 de 4"
01 Mts3 Empaque de Grava de ¼" a ½"

Cedazo: N/A
Tipo:__N/A__Modelo:__N/A___
Diámetro: __N/A__ Tamaño:__N/A___

Superficie sellada:
20 Pies de Sello Sanitario
02 Tapones Hembra Liso de 4"

Nivel del Agua:
Estática del nivel del agua: 15'

Prueba de capacidad del Pozo: 30 GPM

Distancia Hoja de Registro
Casing

Desde	Hasta	Material	Desde	Hasta
0'	10'	Cascajo		
10'	200'	Roca Basalto		

Continuar atrás si es necesario

Planes de Altamira, Casa #198 Managua, Nicaragua 505-2278-0924
www.abacusdrilling.com info@abacusdrilling.com

Appendix 6 AbacusDrilling protocol from Los Negritos (AbacusDrilling, 2014)

Appendix 7 Data adapted from Lener Sequeira (2008).

Village	pH	Well/spring	Fe (µg/l)	As (µg/l)
Las Cañitas	8,83	Well	165,51	5,03
Cacao	7,17	Well	197,12	1,88
Asiento Viejo	7,50	Well	234,03	38,83
Agua caliente	8,06	Spring	290,75	23,89
Cacao	7,34	Spring	139,22	3,55
Sonzapote	8,19	Spring	211,10	32,15
Las Mercedes	7,18	Spring	204,21	15,61