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Analysis of dry and wet season water quality in the municipality of La Gomera, Guatemala

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ABSTRACT

There is a need for access to clean potable water worldwide. However, almost every source of surface water in Guatemala is contaminated. This study assesses the potential exposure to water contaminants in proximity to Medecins Sans Frontieres's (MSF) chronic kidney disease clinic population in La Gomera, Guatemala during wet and dry seasons. Five municipal wells and four artisanal wells (servicing approximately 18.9% of La Gomera) were selected for their proximity to MSF La Gomera clinic to determine the presence of coliforms, physicochemical parameters, heavy metals, and pesticide residues. Water samples were collected over 3 consecutive days during La Gomera's wet season and again during the dry season. *Wet season 2022*: Total coliforms and *Escherichia coli* exceeded the acceptable limits for several artisanal wells but were not detected in municipal wells. Mercury and arsenic were detected in all wells during at least one sampling period. *Dry season 2023*: Total coliforms exceeded the acceptable limits for all wells and *E. coli* was detected in all four artisanal wells. Lead and arsenic were detected in all wells. Our results suggest that water from artisanal wells does not meet COGUANOR or WHO microbiological criteria for human consumption.

Key words: coliforms, Guatemala, heavy metal, pesticides, water quality

HIGHLIGHTS

- No information on water quality in La Gomera, Guatemala.
- Comprehensive assessment of water quality in region.
- Assess public and private water sources.
- Relationship between water quality and health.
- Timeseries of water quality.

INTRODUCTION

There is a critical need worldwide for access to safe potable water (Brown *et al.* 2010), as approximately 2.2 billion people currently lack access to clean drinking water (UNICEF and WHO 2019). In several countries, consistent mismanagement of water resources has deteriorated distribution systems, which in turn, has negatively impacted health outcomes and economic activities. In an effort to highlight the severity of the world's water crisis, the United Nations has designated Sustainable Development Goal 6 (SDG), 'Ensure availability and sustainable management of water and sanitation for all', to focus on the improvement of water quality control (United Nations Department of Economic and Affairs 2022).

Exposure to contaminated water is associated with several chronic health conditions (Fu & Wang 2011) including cardiovascular disorders, neuropathy, renal injuries, cancers, and diabetes. Fecal and non-fecal coliforms are known to be a leading cause of gastroenteritis and toxin-mediated food poisoning (Halkman & Halkman 2014). Heavy metals from contaminated water are known to bioaccumulate in the body and can displace metabolic functions when they reach high enough concentrations. For example, lead, zinc, and cadmium can replace calcium and affect the regulation of proteinkinase C, affecting nerve function and memory (Flora *et al.* 2008). Metalloids such as arsenic are considered carcinogenic due to their ability to produce free-radicals and cause oxidative stress. This not only causes direct damage to proteins and DNA over time, but it promotes the activation of redox-sensitive transcription factors which interfere with the process of DNA repair (Genestra 2007). Contaminated water containing herbicides, like glyphosate, have been theorized to work synergistically with other toxic exposures to cause harm by acting as an amino acid analog of glycine, which could potentially interfere with mechanisms that protect against other toxic chemical exposures (Gunatilake *et al.* 2019). Glyphosate's compounding health effects when combined with other pollutants, in particular paraquat (Gramoxone) could result in substantial renal damage (Abdul *et al.* 2021).

Ensuring safe potable water is a critical public health priority in Guatemala, one of the most populous countries in Central America with over 17 million residents (National Institute of Statistics (Guatemala) 2018). Guatemala's unique combination of geographic location and booming agricultural industry potentially expose citizens to contaminated water containing high concentrations of pesticides, heavy metals, and bacteria. Studies have demonstrated that almost every surface water source in Guatemala is somewhat contaminated (Programa de las Naciones Unidas para el Desarrollo 2016). Upper aquifers in major urban areas are contaminated from a variety of sources and only deep wells are safe from biological and chemical contamination (Gallardo *et al.* 2013). Seasonality affects water quality in Guatemala, particularly in agricultural areas during dry seasons when water resources are stressed due to increasing demand. Heavy rainfall during wet seasons is known to contribute to increases in agricultural runoff, such as fecal coliforms, from both human and animal sources caused by direct domestic wastewater discharges and runoff usually associated with the beginning of the rainy season (Gil-Rodas *et al.* 2021). While there are many different kinds of water contaminants found in Guatemalan water sources, to date the majority of peer-reviewed water quality studies in Guatemala have focused on arsenic contamination (Morales-Simfors *et al.* 2020), pesticide use (Grandia 2022), or have focused on microbial risks such as exposure to coliforms (Luby *et al.* 2008; Lacey *et al.* 2011). Very few studies focus on exposure to heavy metals other than arsenic or on contaminants such as per- and polyfluoroalkyl substances (PFAS) (Redmon *et al.* 2022).

Despite widespread contamination, proper watershed management in Guatemala is lacking. Water resources are stressed by increasing demand and non-heterogeneous population distribution where the most densely populated regions suffer from the greatest lack of water. Guatemala's water supply is managed by several government agencies at the local and federal levels (Spillman *et al.* 2000). However, even though 91% of Guatemalans have access to improved drinking water (World Bank 2018), government management of municipal water operates with little or no coordination between agencies. This often creates inefficient use of resources as watershed management plans that focus on improving water quality are poorly managed between agencies.

As a potential consequence of improper watershed management, cases of chronic kidney disease (CKD) in Guatemala could be elevated, particularly within Guatemala's agricultural sector. Water containing high concentrations of heavy metals, particularly arsenic, has been associated with high rates of CKD in Central America and Mexico (Laws *et al.* 2016; Bustamante-Montes *et al.* 2018). Additionally, a wide variety of CKD factors, such as poor water quality, strenuous physical labor, dehydration, diet, and occupational exposure to pesticides and pollutants, are common among Guatemalan farmers (Johnson *et al.* 2019; Krisher *et al.* 2021). As a result, Guatemala has high rates of CKD, with 14.7 cases per 100,000 individuals, of which 39% of cases occur in individuals less than 60 years of age, putting CKD among the top 15 causes of death in Guatemala (Garcia *et al.* 2020). Currently, much research is focused on the epidemic of CKD that affects agricultural workers in Guatemala (Butler-Dawson *et al.* 2019; Dally *et al.* 2020). However, there is currently a paucity of research investigating water quality in the rural and agricultural communities of Guatemala.

The aim of this study was to measure the potential exposure to water containing arsenic, Cadmium, Mercury, Lead, Pesticide residues, and coliform bacteria from potable sources of drinking water in proximity to Medecins Sans Frontieres's (MSF) clinic population in La Gomera, Guatemala during the wet and dry seasons. The results of this study will promote the improvement of planetary health in Guatemala by providing actionable information about water contamination. Additionally, results obtained from this study could be compared to the results of other water quality studies conducted by other researchers.

CLIMATE, GROUNDWATER, AND WATER RESOURCES IN GUATEMALA

Climate and weather patterns

The tropical climate of Guatemala typically varies according to the country's topography, with temperate highlands, humid coastal areas, the northern Petén region jungles, and dry scrub in the eastern dry corridor. Annual average temperatures vary from 25 to 30 °C in coastal regions to 15 °C at higher altitudes in inland mountains. In general, two seasons exist in Guatemala: a dry season from November to April and a rainy season from May to October. The rainy season includes a 5- to 15-day break with little or no rain in July or August called the canícula. Average annual rainfall varies between 600 mm in the eastern dry zone and 5,000 mm in coastal areas, with the majority of the country receiving around 1,100 mm. Weather patterns for the departmental region of Escuintla, Guatemala, where this study's catchment area of La Gomera is, are similar to weather patterns for Guatemala's Pacific coastal region. Temperatures are considered to be hot throughout the year, with temperatures ranging from 25° to 33 °C. Rainy seasons typically last 8–9 months, from March to December, with an average of 1.3 cm of rain per day. However, the peak of the rainy season is typically around September with approximately 21 cm of precipitation per day during this period (WeatherSpark 2024).

Groundwater and water resources

Guatemala is considered to be rich in water resources; however, water resources are distributed unevenly throughout the country during the dry season, which results in sporadic water shortages throughout the year. Surface water is the main water source for rural and urban areas and is a major source of potable water for agricultural and domestic use. However, surface water quality is poor throughout the country, and virtually every source of surface water Guatemala is considered to be contaminated to some degree due to poor wastewater treatment and lack of regulation for wastewater discharge (Spillman *et al.* 2000). Ground water is generally plentiful from sedimentary aquifers throughout the plains, valleys, and lowlands of the country. Water from deep wells supplies approximately 30% of the portable water for urban areas. Guatemala's water basins are divided into three primary sections. The Caribbean Sea water basin encompasses approximately 31% of Guatemala's land area, contains 10 watersheds, and annual surface runoff of 31.9 km^3. The Gulf of Mexico water basin covers approximately 47% of Guatemala's land area, has a surface runoff of approximately 43.3 km^3, and also contains 10 watersheds. The Pacific Ocean water basin, which covers the catchment area of this study in La Gomera, covers 22% of Guatemala's land area and contains 18 watersheds. The annual surface runoff is approximately 25.5 km^3. Surface water sources in the Pacific Ocean water basin contain volcanic sediments that have the potential to contaminate water sources with heavy metals and contribute to flooding due to the blockage of tidal marshes (FAO 2016).

MATERIALS AND METHODS

Study location and well selection

La Gomera is a municipality of 46,500 inhabitants, located in southern Guatemala (National Institute of Statistics 2018). Water is supplied for public consumption by means of 18 municipal wells, each with a depth between 1,000 and 1,500 feet, and several household artisanal wells, each approximately 35–50 feet deep that provide water for individual use and are not part of the public water supply. Five municipal wells and 4 artisanal wells in proximity to Medecins Sans Frontieres (MSF) CKD clinic population in La Gomera were selected to assess microbiologic, physicochemical, heavy metal (lead, arsenic, cadmium, and mercury), and pesticide characteristics.

Sample collection and transportation

Water samples were collected in accordance with the International Organization for Standardization for drinking water and the World Health Organization guidelines for drinking water quality (WHO 2022). Samples were collected once each day for 3 consecutive days in 2022 during La Gomera's wet season (October 25, 26, 27) and then again using the same methodology during La Gomera's dry season (April 17, 18, 19) in 2023. Samples collected from municipal sites were collected using sampling ports which were heated with a flame before microbiologic samples were collected, while samples collected from artisanal wells were collected directly from the well source. Samples were collected in sterile sampler bags (100 mL) and kept at 8 °C for microbiologic analysis, plastic containers for physicochemical analysis (1 L), plastic PET containers for metal analysis (2 L), and glass containers for pesticide residues (3.8 L). All samples were transported at 4–8 °C within 24 h after collection for testing at the University of San Carlos in Guatemala City.

Sample analysis

Microbiological analysis of water samples for total coliforms and *Escherichia coli* (*E. coli*) were performed using the most probable number technique (Williams & Busta 1999). Briefly, the most probable number technique for assessing *E. coli* uses serial dilution of a sample that is inoculated into media and after an incubation period, the resulting bacterial count is referenced against an index to determine the count of bacteria in the sample (Williams & Busta 1999). Physical parameters include: color, conductivity, salinity, total dissolved solids, pH, turbidity, hardness, and odor. Chemical parameters included metals such as iron, calcium, magnesium, aluminum, copper, manganese, zinc, nitrates, nitrites, chlorides, and sulfates. The presence of mercury, lead, cadmium, and arsenic was investigated using an AAS Perkin Elmer AAnalyst 700atomic absorption spectrophotometry machine. Cold vapor method of detection was used for the analysis of mercury samples. Lead and cadmium samples were analyzed using graphite furnace methodology, while arsenic samples were analyzed using metalloid flow injection. The presence of glyphosate and 430 pesticide residues (see Supplementary material, Appendix A) was determined using mass-associated liquid chromatography LC/MS and gas chromatography GC/PFD. Pesticide residues were analyzed after an organic extraction was performed using ethyl acetate and dichloromethane. The solvent was evaporated and taken to 4 mL with petroleum ether. One mL was taken in a vial to inject into the gas chromatograph. Another milliliter was evaporated and rebuilt with acetonitrile grade LC/MS. Multiresidue analysis of pesticides was performed in a liquid chromatograph coupled to a triple quadrupole and by means of GC, coupled to a photometric flame detector and Agilent 7890 gas chromatograph, coupled to an electron capture detector. Guidelines for determining acceptable limits of contaminants originate from the Comisión Guatemalteca de Normas (COGUANOR) (Comisión Guatemalteca de Normas (COGUANOR) 2013) and the World Health Organization Guideline for Drinking Water Quality (World Health Organization 2017) (Table 1).

RESULTS

Wet season

Total coliforms and *E. coli*

Total coliforms exceeded the acceptable limits set by COGUANOR and the WHO for all artisanal wells (wells 1, 5, 7, and 9). Total coliforms exceeded acceptable limits for wells 5, 7, and 9 consistently for each sampling day, while total coliforms for well 1 exceeded acceptable limits only on the first day of sampling. Wells 5 and 7 presented approximately 9 times the number of total coliforms than wells 1 and 9. The presence of total coliforms was not detected in any of the municipal wells. The presence of *Escherichia coli* was detected in artisanal wells 5 and 7 consistently on each sampling day. The presence of total coliforms and *E. coli* was not detected in any of the municipal wells (Table 2).

Physical characteristics

Water from three artisanal wells exceeded the maximum acceptable limit of 180 mg/L of $CaCO_3$ set by COGUANOR standards, and was subsequently classified as being 'very hard'. Artisanal well 1 and municipal well 6 presented average iron values higher than the maximum permissible limit (0.3 mg/L), while all wells except for artisanal well 9 and municipal wells 4 and 8 had higher manganese than the maximum permissible limit (0.4 mg/L). However, iron and manganese are not considered harmful to human health in these concentrations according to WHO standards. All wells contained copper concentrations above the maximum acceptable limit of 0.05 mg/L but below the maximum permissible limit of 1.5 mg/L. The pH at all sampling sites was slightly alkaline. The range of pH in artisanal wells was between 7.33 and 7.67, while the range in municipal wells was between 7.52 and 7.92. All pH values were within the permissible range. Ion parameters such as sulfates, chlorides, and nitrates were found in all sites well below the maximum acceptable and permissible limits of the COGUANOR standard for drinking water (Table 3).

Table 1 | COGUANOR and WHO water quality guidelines to study contaminants based on health considerations

Contaminants	CONGUANOR guidelines (acceptable limit)	CONGUANOR guidelines (permissible limit)	WHO guidelines
Coliforms			
Escherichia coli	Not detectable in 100 mL	0 CFU in 100 mL	0 CFU in 100 mL
Total coliforms	Not detectable in 100 mL	0 CFU in 100 mL	0 CFU in 100 mL
Physical chemical parameters			
Conductivity (μS/cm)	750	1,500	400
Salinity	NA	NA	NA
Total dissolved solids (mg/L)	500	1,000.0	300
Turbidity	5.0 UNT	15 UNT	5 NTU
pH	7.0–7.5	6.5–8.5	6.5–8.5
Hardness (mg/L)	100.0	500.0	500.0
Nitrates (mg/L)	NA	50.0	50.0
Nitrites (mg/L)	NA	3.0	3.0
Chlorides (mg/L)	100.0	250.0	NA
Sulfates (mg/L)	100.0	0.4	NA
Iron (mg/L)	0.3	0.3	0.3
Calcium (mg/L)	75.0	150.0	500
Magnesium (mg/L)	50.0	100.0	50.0
Manganese (mg/L)	0.1	0.4	0.08
Aluminum (mg/L)	0.05	0.1	0.1
Zinc (mg/L)	3.0	70.0	3.0
Copper (mg/L)	0.05	1,500	2.0
Heavy metals			
Lead (mg/L)	NA	0.010	0.010
Cadmium (mg/L)	NA	0.003	0.003
Mercury (mg/L)	NA	0.001	0.001
Arsenic (mg/L)	NA	0.010	0.010
Pesticides			
Glyphosate	NA	NA	NA

NA, limits are not established.

Heavy metals

Mercury and arsenic were detected in all wells during at least one sampling period. Lead and cadmium were not detected in any of the wells sampled. Artisanal wells 5 and 7, along with municipal wells 6 and 2 had at least 1 day of sampling where mercury levels were equal to or exceeded the maximum permissible limit for drinking water (0.001 mg/L). Only artisanal well 5 had arsenic levels that reached the maximum permissible limit (0.01 mg/L) (Table 4).

Samples taken during dry season

Escherichia coli

Apart from well 6, total coliforms exceeded the acceptable limits set by COGUANOR and the WHO for all artisanal and municipal wells during at least 2 consecutive sampling days. The presence of *E. coli* was only detected in artisanal well 1 and was consistently detected on each sampling day (Table 5).

Physical characteristics

Turbidity values varied widely, between 0.55 mg/L for well 5 and 16.40 mg/L for well 1. The average hardness ranged between 100.67 mg/L in well 9 and 249.13 mg/L in well 7 and all wells exceeded the acceptable limit

Table 2 | The presence of *Escherichia coli* and total coliforms among municipal and artisanal wells during the wet season

	Oct 25		Oct 26		Oct 27	
No. of well[a]	**Total coliforms (MPN/100 mL)**	***E. coli***	**Total coliforms (MPN/100 mL)**	***E. coli***	**Total coliforms (MPN/100 mL)**	***E. coli***
1	387.3	ND[b]	ND	ND	ND	ND
2[a]	ND	ND	ND	ND	ND	ND
3[a]	ND	ND	ND	ND	ND	ND
4[a]	ND	ND	ND	ND	ND	ND
5	2,419.6	1,986.3	1,299.7	73.7	1,732.9	192.7
6[a]	ND	ND	ND	ND	ND	ND
7	14,670.0	125.9	2,419.6	46.4	686.7	16.9
8[a]	ND	ND	ND	ND	ND	ND
9	178.9	ND	517.2	ND	365.4	ND

[a]Municipal well.
ND, not detectable in 100 mL.

Table 3 | Average physical characteristics of water derived from municipal and artisanal wells during the wet season

No. of well[a]	**1**	**2[a]**	**3[a]**	**4[a]**	**5**	**6[a]**	**7**	**8[a]**	**9**
Conductivity (μS/cm)	556.4	302.4	327.4	241	430.9	320.3	942	305.3	146.0
Salinity (mg/L)	0.32	0.196	0.207	0.166	0.259	0.204	0.519	0.197	0.124
Total dissolved solids (mg/L)	273	148.3	160.8	118.6	211.7	157.1	483.3	150.1	72.0
Turbidity	9.8 UNT	0.75 UNT	0.98 UNT	0.63 UNT	0.23 UNT	0.96 UNT	0.47 UNT	0.67 UNT	0.52 UNT
pH	7.55	7.74	7.81	7.79	7.6	7.58	7.55	7.78	7.42
Hardness (mg/L)	250	121.7	136.9	94.2	182.6	123.2	324.6	105.0	67.4
Nitrates (mg/L)	7.3	2.7	4.5	2.3	9.4	5.8	4.2	2.1	1.7
Nitrites (mg/L)	0.071	0.027	0.036	0.024	0.022	0.211	0.027	0.022	0.24
Chlorides (mg/L)	45	60	20	20	25	22	45	35.0	25
Sulfates (mg/L)	8.5	0.5	0	0	29	2	65	4	5.0
Iron (mg/L)	1.13	0.29	0.25	0.45	0.05	1.25	0.1	0.26	0.05
Calcium (mg/L)	46.75	31.6	29.1	19.6	41.8	22.7	70.3	28.4	18.1
Magnesium (mg/L)	32.35	10.18	16.05	11.74	17.6	15.72	36.1	8.30	5.44
Manganese (mg/L)	2.11	0.58	0.72	0.31	0.11	0.67	0.49	0.32	0.12
Aluminum (mg/L)	0.022	0.0037	0.035	0.044	0.041	0.037	0.037	0.084	0.067
Zinc (mg/L)	0.04	0.06	0.045	0.045	0.04	0.04	0.07	0.02	0.04
Copper (mg/L)	0.12	0.95	0.135	0.16	0.05	0.1	0.08	0.06	0.06

[a]Municipal well.

of the COGUANOR. However, none of the sampled wells exceeded the maximum permissible limit of 500 mg/L. Aluminum was found in concentrations higher than the maximum acceptable limit (0.05 mg/L) in wells 7 and 8, with well 8 exceeding the maximum permissible limit of 0.100 mg/L (Table 6).

Heavy metals

Lead and arsenic were detected in all wells at least once during the dry season. No wells contained detectable levels of mercury and Cadmium was only detected in well 1 during one sampling period (Table 7). While lead and arsenic were detected in all wells, lead levels were lower than the maximum permissible limits.

Residual pesticides (wet and dry seasons)

None of the wells were found to have traces of pesticides or glyphosate during both the wet and dry seasons.

Table 4 | Lead, cadmium, mercury, and arsenic derived from municipal and artisanal wells during the wet season

	Oct 25				Oct 26				Oct 27			
No. of well[a]	Lead (mg/L)	Cadmium (mg/L)	Mercury (mg/L)	Arsenic (mg/L)	Lead (mg/L)	Cadmium (mg/L)	Mercury (mg/L)	Arsenic (mg/L)	Lead (mg/L)	Cadmium (mg/L)	Mercury (mg/L)	Arsenic (mg/L)
1	NA	NA	0.0003	0.0008	NA	NA	0.0002	0.0004	NA	NA	0.001	0.0005
2[a]	NA	NA	0.0002	0.002	NA	NA	0.001	0.004	NA	NA	0.001	0.005
3[a]	NA	NA	0.0003	0.004	NA	NA	0.002	0.004	NA	NA	0.0009	0.005
4[a]	NA	NA	0.0009	0.003	NA	NA	0.0009	0.004	NA	NA	0.002	0.004
5	NA	NA	NA	0.001	NA	NA	0.001	0.001	NA	NA	0.0009	0.001
6[a]	NA	NA	0.001	0.003	NA	NA	0.0009	0.004	NA	NA	0.001	0.004
7	NA	NA	NA	0.004	NA	NA	0.001	0.005	NA	NA	0.001	0.006
8[a]	NA	NA	0.0006	0.003	NA	NA	NA	0.004	NA	NA	0.001	0.004
9	NA	NA	NA	0.0004	NA	NA	0.0007	0.0004	NA	NA	0.001	0.0003

[a]Municipal well.

Table 5 | The presence of *Escherichia coli* and total coliforms among municipal and artisanal wells during the dry season

	April 17		April 18		April 19	
No. of well[a]	Total coliforms	*E. coli*	Total coliforms	*E. coli*	Total coliforms	*E. coli*
1	98.5	9.6	52.0	4.1	1,710.0	2
2[a]	ND	ND	133.3	ND	27.5	ND
3[a]	ND	ND	6.3	ND	2.0	ND
4[a]	ND	ND	3.1	ND	3.1	ND
5	3.1	ND	436.6	76.8	500.0	80
6[a]	ND	ND	ND	ND	6.0	ND
7	3.0	ND	816.4	1.0	500.0	16.9
8[a]	2.0	ND	100.0	ND	2.0	ND
9	461.0	ND	160.0	44.8	1,550.0	ND

[a]Municipal well.
ND, not detectable in 100 mL.

Table 6 | Average physical characteristics of water derived from municipal and artisanal wells during the dry season

No. of well[a]	1	2[a]	3[a]	4[a]	5	6[a]	7	8[a]	9
Conductivity (μS/cm)	273.3	303.6	320.7	247.5	398.5	322.2	729.3	307	155.6
Salinity (mg/L)	0.18	0.2	0.2	0.17	0.24	0.2	0.4	0.2	0.12
Total dissolved solids (mg/L)	134.4	149.3	157.6	121.8	195.8	157.9	357.9	150.9	76.72
Turbidity	16.4 UNT	1.02 UNT	0.76 UNT	0.88 UNT	0.55 UNT	2.9 UNT	1.88 UNT	1.5 UNT	2.76 UNT
pH	7.79	7.76	7.7	7.81	7.71	7.75	7.71	7.79	7.85
Hardness (mg/L)	115.4	132	116.7	11.07	157.3	134.3	249.1	125.5	100.7
Nitrates (mg/L)	6.93	2.63	3.83	2.13	8.2	6.13	6.47	3.7	5.63
Nitrites (mg/L)	0.02	0.02	0.03	0.02	0.02	0.09	0.41	0.25	0.03
Chlorides (mg/L)	18.33	18.33	20	20	20	21.67	48.33	20	15
Sulfates (mg/L)	2.33	NA	NA	NA	20.33	1.33	42.33	0.67	4
Iron (mg/L)	1.27	0.74	1.34	0.71	0.13	1.07	1.11	0.53	0.19
Calcium (mg/L)	27.87	27.13	29.6	27.57	43.31	29.7	62.67	28.43	22.97
Magnesium (mg/L)	11.1	15.57	10.4	10.27	12.17	14.63	22.53	13.27	10.5
Manganese (mg/L)	1.14	0.6	1.26	0.44	0.13	0.72	0.67	0.39	0.11
Aluminum (mg/L)	0.02	0.03	0.02	0.01	0.01	0.02	0.09	0.15	0.03
Zinc (mg/L)	0	0	0.02	0.17	0.05	0.03	0.05	0.03	0.06
Copper (mg/L)	0	0.01	0.03	0	0	0.01	0.01	0	0.04

[a]Municipal well.

DISCUSSION

Access to clean water is a basic human right (Scientific and Cultural Organization United Nations Educational 2019) and while over 90% of rural Guatemalans have access to improved water sources, the majority of community water sources are contaminated to some degree. Improving Guatemala's access to clean water and sanitation will help Guatemala reach its target for UN SDG 6 (United Nations General Assembly 2015), 'Ensuring the availability and sustainable management of water and sanitation for all'; goal 6.1 'Safe and affordable drinking water', and goal 6.6 'Improving water quality, wastewater treatment and safe reuse'. Water samples were taken from both artisanal and municipal wells to capture water quality differences between private and public sources of water. Additionally, water samples were collected during the 'wet' and 'dry' seasons, which correspond to different

Table 7 | Lead, cadmium, mercury, and arsenic derived from municipal and artisanal wells during the wet season

	April 17				April 18				April 19			
No. of well[a]	Lead (mg/L)	Cadmium (mg/L)	Mercury (mg/L)	Arsenic (mg/L)	Lead (mg/L)	Cadmium (mg/L)	Mercury (mg/L)	Arsenic (mg/L)	Lead (mg/L)	Cadmium (mg/L)	Mercury (mg/L)	Arsenic (mg/L)
1	0.0021	0.0017	NA	0.0007	0.0009	NA	NA	0.0006	0.0012	NA	NA	0.0006
2[a]	0.0019	NA	NA	0.0034	0.0011	NA	NA	0.0034	0.0012	NA	NA	0.0035
3[a]	0.0016	NA	NA	0.0034	0.0009	NA	NA	0.0035	0.001	NA	NA	0.0037
4[a]	0.0013	NA	NA	0.003	0.0007	NA	NA	0.0031	0.0009	NA	NA	0.0028
5	0.0011	NA	NA	0.0005	0.0008	NA	NA	0.0005	0.0006	NA	NA	0.0004
6[a]	0.0012	NA	NA	0.0031	0.001	NA	NA	0.0029	0.0013	NA	NA	0.0029
7	0.0007	NA	NA	0.0041	0.0007	NA	NA	0.0039	0.0004	NA	NA	0.0039
8[a]	0.0015	NA	NA	0.0032	0.0012	NA	NA	0.0033	0.0009	NA	NA	0.0033
9	0.0009	NA	NA	NA	0.0012	NA	NA	NA	0.0009	NA	NA	NA

[a]Municipal well.

agricultural periods. As a result, our study represents water that is potentially accessed by 18% of the La Gomera population throughout the year.

Our results suggest that water from artisanal wells is not suitable for human consumption during both dry and rainy seasons. Municipal well water met the COGUANOR and WHO microbiological criteria for consumption during the rainy season, while several wells were not compliant during the dry season. The detection of total coliforms suggests that water samples contain fecal contamination, and while the presence of coliforms are not always harmful, coliforms are used as an indicator for other harmful fecal bacteria, such as *E. coli* which was found in several artisanal wells and is a more specific indicator of fecal contamination (Bari & Inatsu 2014). It is possible the presence of microbiological contamination could exacerbate the high rate of CKD in La Gomera as studies have found that CKD patients are more likely to experience urinary tract infections and diarrheic diseases, both of which are linked to microbiological contamination (Bradshaw *et al.* 2018; Scherberich *et al.* 2021). The presence of coliforms suggests a potential problem could exist with treatment systems, water sources, or breaches in distribution systems that could introduce coliform contamination. For example, our results found that chloride levels were lower during the dry season, which might be caused by suboptimal chlorination. This could cause an increase in bacterial growth, facilitated by a reduction in water during the dry season. Conversely, the higher presence of coliforms during wet seasons compared to dry seasons has been well-documented, particularly in rural settings (Kostyla *et al.* 2015). Studies have shown that rising water tables and the leaching of contaminants due to rainfall have resulted in higher coliform counts (Elisante & Muzuka 2016). Additionally, artisanal wells with poor coverage, improper casing, and antiquated pumping systems (i.e. buckets and pulley systems) were likely to harbor excessive coliforms (Chuah & Ziegler 2018). In addition to wastewater caused by excessive rainfall, excessive agrochemicals found in water sources contribute to algae blooms resulting in the degradation of flora and fauna. Guatemala's wastewater treatment infrastructure is limited and as of 2018, Guatemala had a total of 320 waste water treatment facilities in only 134 of the 340 municipalities (SEGEPLAN 2018). It is believed that only approximately 5% of all waste water is treated before being released into the environment, with the remaining 95% of waste water being released into the environment without any treatment at all (Kurth *et al.* 2021).

Heavy metal (lead, cadmium, mercury) and metalloid (arsenic) levels from all wells were within maximum permissible limits, except for mercury levels sampled from municipal well 3 on October 26 during the dry season. Mercury levels for municipal well 3 during this sampling period were twice the maximum limit (max limit: 0.001 mg/L). Lead was observed in all municipal and artisanal wells during the dry season, although in values lower than the maximum established limit. Interestingly, lead was detected in all wells during the dry season but not during the wet season. Conversely, mercury was not detected during the dry season but was detected in the majority of wells during the wet season. It is possible that seasonal variations of heavy metal concentrations in groundwater could be caused by fluctuating water tables during seasonal rainfalls (Guo *et al.* 2022). While rainfall during the wet season was found to be responsible for increases in heavy metal concentrations in some studies, other studies have found similar results to our study where lead concentrations were the highest during the dry seasons (Guo *et al.* 2022). This could suggest that naturally occurring lead is what our study detected during the dry season sampling period. Mercury and arsenic are found naturally in Guatemalan water sources because of high volcanic activity. These metals are released naturally into the environment and are transported up to hundreds of kilometers away from their source via atmospheric winds or water flows where humans and livestock are exposed to them through drinking water or contaminated food (Bundschuh *et al.* 2021). It is possible that naturally occurring lead and mercury were released from sources outside of La Gomera and were transported to the sampled wells via increased seasonal rainfall. While it is possible the heavy metals detected in this study are naturally occurring, they still have the potential to affect CKD rates in La Gomera. Studies have shown that CKD patients excrete metals through urine at a lower rate than non-CKD patients, which could result in the bioaccumulation of metals due to the inability of the kidney to excrete them (Rango *et al.* 2015). This bioaccumulation of heavy metals could result in chronic kidney damage, where chronic exposure to mercury can result in tubular dysfunction with elevated urinary excretion of albumin, transferrin, retinol-binding protein, and β-galactosidase (Zalups 2000) while chronic exposure to lead could result in increased urate secretion, vasoconstriction, and consequent glomerulosclerosis, hypertension and interstitial fibrosis (Patrick 2006).

Only a few artisanal and municipal wells had physicochemical parameters exceeding the maximum acceptable limits, notably manganese in the rainy season and iron in the dry season. While nitrates and nitrites were found in both artisanal and municipal wells, the amounts did not exceed the maximum permissible limits. Nitrates and nitrites are common groundwater pollutants due to their water solubility and difficulty in binding to soil (Abascal *et al.* 2022). Although nitrates and nitrites are naturally found in the environment, modern nitrate and nitrite pollution is often caused by nitrogen-rich fertilizers used for agricultural purposes, industrial waste, and livestock feces. Given that the economy of La Gomera is highly dependent on agriculture, it is likely that the high concentration of nitrates is associated with agricultural runoff.

Macro level water contamination pathways in La Gomera are fairly well known. The Pacific Ocean water basin, the water basin for La Gomera, is fed into by several rivers and tributaries, including the Rio Motagua, the Rio Villalobos, the Rio Michatoya, the Rio Las Vacas, the Rio Samala, and the Rio Guacalate (Spillman *et al.* 2000). Each of these rivers are known to be contaminated with domestic wastewater and agricultural runoff. Specifically, regarding Escuintla, the Department of La Gomera, the Rio Guacalate and the other minor streams that run through the Department are severely contaminated by biological waste and large amounts of chlorides and sulfates that originate from volcanic activity in the area. Wastewater treatment is minimal in Escuintla because while wastewater treatment exists, only a few plants are functioning at an acceptable capacity (FAO 2016). As a result, surface water is laden with sewage, particularly in heavily populated areas, and much of it is not usable for water supply.

Ultimately, this study has highlighted the need for greater efforts to ensure the quality of water in La Gomera. Ideally, public health activities focused on microorganism control targeting artisanal wells (i.e. boiling water before use, chlorination, filtration, etc.) would be initiated by local NGO's or municipal authorities. Such activities would establish an improvement plan for the protection of artisanal wells along with establishing plans of action regarding microbiological and physicochemical monitoring.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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