Chapter 4
Water Quality and Access in Isabela: Results from a Household Water Survey

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Abstract Contaminated water represents one of the major health threats for the inhabitants of Puerto Villamil, Isla Isabela, Galápagos. Water supply on this island depends on brackish groundwater as the main drinking water source. Historically, drinking water quality has been one of the main concerns of the population. This has encouraged the habit of using bottled water as a drinking source and even a cooking water source for most people. In July 2019, an observational pilot study was conducted, focused on analyses of survey data and physicochemical and microbial (total coliforms and *Escherichia coli*) water samples from 35 households spread across town and from the municipal desalination water treatment plant. Two samples were taken at each household, one from tap water and a second from the main drinking water source. In situ parameters such as pH, conductivity, dissolved oxygen, temperature, and salinity were recorded at each sampling point. Results show minimal treatment by the municipal desalination plant with testimonial evidence that current infrastructure is insufficient to meet the water demands of Puerto

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Villamil. All households had total coliforms confirmed in the tap or drinking water source (n = 35), indicating environmental contamination. Ten households exceeded national and international guidelines for *E. coli* coliforms in drinking water, but most tap and drinking water samples tested positive for *E. coli* at concentrations <10 MPN per 100 mL. Physicochemical measurements indicated high salinity, conductivity, and pH in tap water piped to households was similar to that of high levels of water at the treatment plant, although within international guidelines. This pilot study provides comparisons of the water environment on Isabela to that of other islands in the Galápagos and insights on future actions that authorities and inhabitants can take to improve water security.

Keywords Water security · Water quality · Heavy metals · Salinity · Household survey

4.1 Introduction

Inadequate supply of clean water is a major contributor to health disparities worldwide and is of particular concern in tropical island settings that have limited freshwater resources. Water is a foundational component of life, crucial for many hygiene and health-related activities. The health risks associated with contaminated water are well-established and have been linked to gastrointestinal and diarrheal diseases (Cairncross et al. 2010; Fewtrell et al. 2005; Wolf et al. 2014), childhood stunting (Checkley et al. 2008; Danaei et al. 2016), maternal mortality (Benova et al. 2014), and psychological well-being (Bisung and Elliott 2017; Hirve et al. 2015; Wutich and Ragsdale 2008). Water security, here defined as "the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water," is recognized as a global priority as part of the United Nations Sustainable Development Goals (United Nations 2015).

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Islands, particularly those located in tropical and subtropical regions, have unique climatic and physical conditions that often lack sustainable freshwater resources. Small volcanic islands, including the Galápagos islands located nearly 1000 km west of mainland Ecuador, are particularly vulnerable to water scarcity (Reyes et al. 2016). Research in the Galápagos has mainly focused on the rich biodiversity adapted to the arid island climate and isolation, with little attention given to the growing human population on the islands, especially the residential population. The Galápagos have had widespread issues related to water and health for decades (Gerhard et al. 2017; Liu and D'Ozouville 2013; Ochoa-Herrera et al. 2014; Reyes et al. 2016; Walsh et al. 2010). San Cristóbal is the only island with available surface freshwater sources in the highlands, El Cerro Gato and La Toma, which are treated by two drinking water treatment plants, Las Palmeras and El Progreso, respectively (Gerhard et al. 2017; Grube et al. 2020). A recent study demonstrated that high-quality drinking water is generally produced in San Cristobal's municipal treatment plants, but *E. coli* was detected in 2–30% of post-treatment samples, suggesting contamination or re-growth during distribution and storage (Grube et al. 2020). The other islands with sizeable human populations, Santa Cruz and Isabela, rely on brackish groundwater for their water needs (Reyes et al. 2016; Walsh et al. 2010). The absence of drinking water infrastructure in Santa Cruz is one of the main water issues in the island. In addition, the basal aquifer proximity to urban area and the seawater intrusion and inefficient wastewater treatment have negatively affected the water quality of groundwater sources in Santa Cruz (Cristina Mateus et al. 2019).

Isabela is the youngest but largest island in the Galápagos on the western edge of the archipelago. A seahorse-shaped, volcanically active island formed from a geothermal hotspot in the Nazca plate, Isabela is famed for its natural beauty and the unique life found there (Bassett 2009). Isabela has the smallest population of the three main human-settled islands in the Galápagos with around 2344 permanent residents (Insitituto Nacional de Estadistica y Censos (INEC) 2015). Most residents are concentrated in Puerto Villamil, a small, low-elevation town on the southern coast. Puerto Villamil was founded in 1893 as a penal colony with fewer than 200 people but has maintained steady growth since the 1970s from economic opportunities in the fishing and tourism industries (Galapagos Conservancy 2020). Advertisements for snorkeling and highland excursions line the streets around town, targeting the island's more than 106,000 annual visitors (Izurieta and Wukitsch 2016). Tourism has had a significant impact on the town with a growth of 336% in accommodations and tourism-related businesses from 2007 to 2015 (Izurieta and Wukitsch 2016). This increasing human presence from population growth and tourism strains the limited water resources available on the island, resulting in residents' concern for availability and quality of clean water in the future (Houck 2017; Nicholas et al. 2019; Page et al. 2013; Walsh et al. 2010).

Rainwater on Isabela collects in underground aquifers forming a freshwater layer that sits on top of more dense, infiltrated seawater, forming a brackish water source requiring treatment for domestic use (Guyot-téphany et al. 2013). In 2014, a reverse-osmosis desalination plant was built on Isabela to treat this brackish groundwater and consistently produce drinking water for the island (Liu and D'Ozouville 2013). The desalination plant is managed by the municipality and uses two cells of membranes to filter water from La Poza San Vicente in the El Chapin region, but only one membrane remains functional (Mateus et al. 2020). Water from this region is pumped to two 300 m^3/day storage tanks, treated, and distributed throughout Puerto Villamil for 3 h in the morning and 3 h in the evening. However, treated water runs out before the 3 h are completed and untreated water continues to be pumped (Mateus et al. 2020). The municipality has plans to incrementally increase the size of storage tanks, but funding and potential issues with the effectiveness of water treatment (reported here) and the maintenance of the piping system (including sea water intrusion, leaks in home piping, and other issues) stand as barriers to improvement (personal communications with the municipality, 2019).

Our research team was encouraged to come to Puerto Villamil by residents who have routinely expressed concerns with their water. A previous study on Isabela found that 12 of the 20 mothers interviewed cited water as a significant issue in their lives, with one mother saying, "I wish you could take a sample of the tap water to a lab. It isn't even acceptable, even to bathe with" (Page et al. 2013). Other studies have reported that up to 70% of illnesses in Puerto Villamil may be related to contaminated water (Walsh et al. 2010). Inconsistent water availability in the Galápagos has led many households to invest in roof tanks and cisterns to store water. This long-term storage can increase the risk for contamination and has been associated with water-related diseases (Clasen and Bastable 2003; Houck et al. 2020). Many residents in the Galápagos rely on water sources outside the municipality for drinking and cooking, often purchasing bottled water to meet their needs. Research on Isabela has been limited because of its smaller population and greater isolation relative to the rest of the Galápagos archipelago, resulting in minimal information known about the state of the water environment and its relationship with the people who live there.

In summer 2019, a pilot study was conducted on Puerto Villamil, Isabela, Galápagos, to (1) profile household tap and drinking water through tests for fecal indicator bacteria and physicochemical measurements, (2) contextualize residential water insecurity using household observation and survey data, and (3) profile water provided by the municipal water treatment plant through tests for fecal indicator bacteria and physicochemical measurements. This work aims to build on previous investigations into the water environment of the Galápagos. It will also help inform authorities, decision-makers, inhabitants, and researchers on potential areas for interventions and in-depth study.

4.2 Methods

4.2.1 Study Location and Population

Data for this research was collected during June–July 2019 in Puerto Villamil, Isabela, Galápagos, by researchers from the Galapagos Science Center (GSC), University of North Carolina at Chapel Hill (UNC-CH), and Universidad de San Francisco de Quito (USFQ) in conjunction with the municipal government of Isabela. This research is part of a larger study on the dual burden of disease in the Galápagos related to food, water, and psychological well-being. Data included point-of-use water sampling (n = 70) and individual survey results (n = 106) from 35 households. Municipal workers initially identified three households from each of the 14 neighborhoods of Puerto Villamil interested in participating, and additional households were recruited via convenience sampling.

This study was approved by Institutional Review Boards at the University of North Carolina at Chapel Hill and USFQ. All participants gave written consent through provided English and Spanish consent forms prior to data collection. Microbial water quality results from this study were reported to the municipal government, and individual households received results from their own samples along with appropriate household treatment recommendations based on World Health Organization (WHO) guidelines (World Health Organization 2017).

4.2.2 Household Water Sampling

A total of 84 water samples from 35 households (n = 70), municipal treatment plant operative units (n = 12), and controls (n = 2) were collected for fecal indicator bacterial, physicochemical, and metal analyses. Sterile 120 mL vessels were used to collect two samples from each household, one from a tap water source and a second from the principal drinking water source used by the household (Table 4.1). For metal analyses, 30 mL of each sample were filtered using 0.45 μm syringe filters and preserved in a 2% nitric acid concentration in plastic bottles. The main household drinking water sources in this study were three bottled water providers (54%), bottled water directly from the treatment plant (9%), self-filtered tap water (9%), and rainwater collected from the highlands (6%). Many households did not disclose their drinking water provider (23%). In situ parameters for each source were measured during the initial meeting with each household. Microbial analysis required samples to be processed within 12 h of collection, with the requisite infrastructure set up in the Water Quality Laboratory at the Galápagos Science Center (GSC) on San Cristóbal Island. Households were sampled a single time during five morning 4-h collection periods in early July. Twelve samples were also collected from the operative units of the municipal desalination water treatment plant on two separate days: the groundwater source (n = 2), untreated tank filling station (n = 1), plant

Table 4.1 Drinking water sources of sampled households (n = 35) Puerto Villamil, 2019

Source	n	(%)
Private bottled water provider 1	8	(22.9)
Private bottled water provider 2	7	(20.0)
Private bottled water provider 3	4	(11.4)
[a]Municipal bottled water	3	(8.6)
Filtered tap water from municipality	3	(8.6)
Rainwater from the highlands	2	(5.7)
Did not know provider/chose not to disclose	8	(22.9)

[a]Some municipal treatment plant workers directly bottled water at the plant

influent tank (n = 2), plant effluent tank (n = 4), and bottling tank (n = 3). Bottled water purchased from local stores served as controls for microbial analyses. After each collection period, a cooler with the samples, controls, and icepacks were sent by plane to San Cristóbal for collection and same-day processing at the Water Quality Laboratory at the GSC.

Each water sample was analyzed for fecal indicator bacteria including total coliforms and *Escherichia coli* (*E. coli*) using the IDEXX Colilert-18 method (IDEXX Laboratories 2017) as described previously (Grube et al. 2020). Colilert media and 100 mL of each sample were combined in a Quanti-Tray/2000, sealed by an IDEXX Quanti-Tray Sealer, and incubated at 35 °C for 18 h. After incubation, wells were counted for yellow coloration indicating total coliform presence and fluorescence under UV light indicating *E. coli* presence. Total coliform and *E. coli* enumeration followed manufacturer guidelines to estimate the most probable number (MPN) per 100 mL sample based on a Poisson statistical distribution (IDEXX Laboratories 2017).

All sources were also analyzed for in situ parameters including temperature, dissolved oxygen (DO), conductivity, salinity, and pH. A YSI ProDSS handheld water quality meter (Yellow Springs OH, USA) was used to collect measurements from a sterilized container filled with water from each source. Measurements were recorded three times and averaged for each sample.

Metals dissolved in water were analyzed using an adapted APHA (American Public Health Association) 3500 method. Filtered and acidified samples were analyzed using a Thermo Scientific iCAP 7400 ICP-OES at the Laboratory of Environmental Engineering at USFQ (LIA-USFQ). Calibration curves were constructed employing a 100 mg/L multi-element standard solution 6 for ICP, grade Trace CERT (Sigma Aldrich, St. Louis, MO, USA). Blank samples with at least 8 replicates were analyzed to obtain the standard deviation which was multiplied by 3 to obtain the limit of detection (LD) and by to 10 to obtain the limit of quantification (LQ). Quality control for metal analysis was conducted by employing a NIST certified reference material (CRM 1640a) (NIST, Gaithersburg, MD, USA) every ten samples (Table S1). The recovery percentages were calculated to determine the matrix effects and to measure the accurateness of the method. All the concentrations of metals were corrected based on the percentage of recoveries obtained in each analysis, ranging from 91% to 102%.

4.2.3 Individual Household Surveys

All members of households included in water sampling were asked to complete a survey, with a parent filling out the survey for children and adolescents under the age of 15. Open Data Kit software (ODK 2019) was used to code, collect, and back up surveys and results. Survey sections were adapted from previous research on San Cristóbal, other studies in similar contexts, and validation studies for survey tools in similar contexts. Survey items included de-identified household and sociodemographic information, followed by questions on water access, security, practices, and perceptions related to household and community water. The questionnaire included an adapted water security scale from the Household Water InSecurity Experiences (HWISE) scale (Young et al. 2019).

The self-identified head of household answered questions related to water security, practices, and perceptions. Extensive efforts were made to include as many household members as possible in the study, sometimes going to a work site or returning to a home multiple times to finish incomplete surveys. A total of 65 adults out of 106 total participants from 34 of the 35 study households completed the survey (Table 4.2).

4.2.4 Data Analysis

Data was processed in spreadsheets where it was cleaned and aggregated into a single file. Data was imported into SAS version 9.4 (Cary, NC) for analysis. Standard errors are included for physicochemical parameters and microbial analyses. Microbial results below the lower limit of detection (LLOD) due to IDEXX testing were assigned a value of $\frac{\text{LLOD}}{\sqrt{2}}$ (0.7 MPN per 100 mL); results above the upper limit were assigned a value of the upper limit (2491.6 MPN per 100 mL). The data was log-transformed to better model a normal distribution. These adjustments were made by following common methods (Finkelstein and Verma 2001; Gerhard et al. 2017; Grube et al. 2020) in an effort to include microbial results outside of the quantification range for the Colilert test in estimations of fecal contamination of community water. World Health Organization guidelines for Drinking Water Quality (DWQ) were consulted for health risks associated with *E. coli* and total coliform concentrations (World Health Organization 2017).

Table 4.2 Characteristics of adult survey participants (n = 65) collected from 34 sampled households in Puerto Villamil, Isabela, 2019

	n	%
Gender		
Female	38	58.5
Male	27	41.5
Highest education		
None	1	1.5
Primary	12	18.6
Secondary	48	73.8
Post-secondary	4	6.1
Income range		
1 basic salary	16	47.1
2–5 basic salaries	15	44.1
>5 basic salaries	3	8.8
Ethnicity		
Mestizo	54	83.1
Other	11	16.9
Birth location		
Galapagos islands	30	46.2
Mainland Ecuador	30	46.2
Other	5	7.7
Marital status		
Married	38	58.5
Other	27	41.5
Children		
Has children	56	86.2
No children	9	13.8
Age of all participants (n = 106)		
<5	10	9.4
5–17	31	29.2
18–64	59	55.7
>65	6	5.7

4.3 Results

4.3.1 Water Quality

Fecal indicator bacteria were measured in tap (one sample) and drinking water (one sample) sources from 35 households in Puerto Villamil and 12 samples from the water treatment plant. Total coliforms were measured at concentrations above the LLOD (1 MPN per 100 mL) in 93% (n = 65) of total samples and *E.coli* in 33% (n = 23) of total samples. Tap water sources had a higher geometric mean for total coliforms ($\bar{x}$ =804 MPN per 100 mL) compared to drinking water sources ($\bar{x}$ =135 MPN per 100 mL). The geometric mean for *E. coli* was low in both household tap ($\bar{x}$ =1.04 MPN per 100 mL) and drinking ($\bar{x}$ =1.08 MPN per 100 mL) water samples. *E. coli* was detectable in 29% (n = 10) of drinking water samples, 37% (n = 13) of tap water samples, and 54% (n = 19) of total households. The associated health risk from *E. coli* contamination is shown in Table 4.3. Based on WHO drinking water quality guidelines, any drinking water sample with *E. coli* concentrations >1 MPN per 100 mL is considered unsafe (World Health Organization 2017). According to this criterion, most household drinking water samples were considered low health risk (71%), with a smaller proportion at medium (26%) and high (3%) risk. Samples from the water treatment plant had a high geometric mean for total coliforms (source, $\bar{x}$ = 117; influent, $\bar{x}$ = 1414; effluent, 1916 MPN per 100 mL) with *E. coli* levels below the LLOD in all but one sample from the groundwater source (2 MPN per 100 mL). No coliforms of either type were detected in controls.

4.3.2 Physicochemical Parameters

The conductivity of tap water ($\bar{x}$ =1190, σ = 210 μs/cm) was much higher than that of drinking water ($\bar{x}$ =110, σ = 270 μs/cm), and the salinity of tap sources (μ = 0.59, σ = 0.10 ppt) was 0.57 ppt higher than that of drinking water (μ = 0.05, σ = 0.14 ppt). The pH, temperature, and DO content were also higher in tap water sources compared to drinking water. Results from the water treatment plant showed similar physicochemical measurements at the source, pre- and post-treatment. Physicochemical characteristics of both household and water treatment plant samples are displayed in Table 4.4.

Table 4.3 Health risk associated with *E. coli* concentrations in tap and drinking water from households (n = 35) in Puerto Villamil, Isabela, 2019

Health risk[a]	Drinking water		Tap water		Drinking or tap water[b]	
Low	25	(71%)	22	(63%)	16	(45.7%)
Moderate	9	(26%)	12	(34%)	17	(48.6%)
High	1	(3%)	1	(3%)	2	(5.7%)

[a]Associated health risk based on WHO (2017) DWQ guidelines determined by *E. coli* concentration: low (<1 MPN per 100 mL), moderate (1–10 MPN per 100 mL), and high (>10 MPN per 100 mL)

[b]The highest *E. coli* concentration from the drinking or tap source for each household was used to calculate the combined risk

Table 4.4 Microbiological and physicochemical results of drinking and tap water samples from surveyed households (n = 35) and municipal water treatment plant samples (n = 12) in Puerto Villamil, Isabela, 2019

Parameters	Units	WHO limits[a]	Household (drinking)		Household (tap)		Treatment plant (source)		Treatment plant (influent)		Treatment plant (effluent)	
			Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
Temperature	°C	No guideline	23.1	4.53	25.8	3.40	25.2	2.76	24.9	2.11	25.0	2.80
DO	mg/L	No guideline	7.96	0.37	8.09	0.31	7.15	0.09	8.01	0.08	7.67	0.06
Conductivity	μs/cm	1660	110	270	1190	210	1200	290	1110	260	1190	300
Salinity	ppt	No guideline	0.05	0.14	0.59	0.10	0.56	0.15	0.50	0.11	0.60	0.11
pH	pH	6.5–9.5	7.04	0.49	7.86	0.26	7.82	0.34	7.88	0.31	7.84	0.30
TC	$\log_{10}$ MPN	0.00	2.13	1.11	2.98	0.49	2.07	1.68	3.15	0.60	3.28	0.14
E. coli	$\log_{10}$ MPN	0.00	0.03	0.44	0.09	0.30	0.09	0.12	0.00	N/A	0.00	N/A

[a]Maximum permissible level of measurement from WHO drinking water quality guidelines (World Health Organization 2017)

Table 4.5 Metals of interest concentrations in drinking and tap water samples from surveyed households (n = 35) and municipal water treatment plant samples (n = 12) in Puerto Villamil, Isabela, 2019

Parameters	Units	WHO limits[a]	Drinking water		Tap water		Treatment plant (effluent)	
			Mean	σ	Mean	σ	Mean	σ
Copper	μg/L	2000	34.33(n = 18)	10.19	26.68(n = 34)	17.24	10.20(n = 12)	5.31
Chromium	μg/L	50	13.25(n = 6)	11.47	8.73(n = 5)	7.57	11.89(n = 1)	0.89
Barium	μg/L	1300	6.36(n = 9)	2.27	–	–	–	–
Nickel	μg/L	70	–	–	6.08(n = 2)	1.00	–	–

[a]Maximum permissible level of measurement from WHO drinking water quality guidelines (World Health Organization 2017)
n represents the number of samples with reported values above the limit of quantification (LQ)

4.3.3 Metal Analyses

Measurements of metals of importance according to the WHO guidelines are shown in Table 4.5. Only a limited number of samples reported values higher than the limit of quantification (LQ) for copper, chromium, barium, and nickel. All measurements for arsenic were below the detection limit (LD = 6.73 mg L^{-1}), with a WHO established limit of 0.01 mg/L. Similar scenarios were found for cadmium, with all samples being below the detection or quantification limit (LD = 0.87 μg/L, LQ = 1.01 μg/L, WHO limit = 3 μg/L), and lead (LD = 5.23 μg/L, LQ = 17.43 μg/L, WHO limit = 10 μg/L).

4.3.4 Household Water Insecurity

Of the 34 households that filled out the survey, 32 completed the section on water insecurity (Table 4.6). The majority of households reported minimal water insecurity based on the adapted HWISE scale, with 3 of the 32 households finishing with a score above 11, the cutoff for water insecurity. Twelve of the households received a score of 0, responding "Never" to all water security questions, and 75% of households scored below 4.

Items with relatively high response variation were further analyzed to understand potential issues with water security and access. Within the prior 4 weeks: 22% of households reported "worrying about not having enough water" often (more than 10 times within the time frame), 31% said that their main water supply had been limited at least once, and 31% responded that someone in their household had been upset with their water situation at least once. When asked to rate their satisfaction with their water situation on a scale from 1 (lowest) to 5 (highest), 34% of households reported a rating of 1, with 75% giving a rating of 3 or below.

4.4 Discussion

This research investigated the water environment in Puerto Villamil, Isabela, Galápagos, through an analysis of household water based on microbiological and physicochemical parameters and security issues. Over half of households tested positive for *E. coli*, including 29% with detectable contamination in the drinking water. This places households in at least "moderate" risk for disease based on WHO DWQ guidelines and drinking water standards set by the Ecuadorian Institute of Normalization (INEN) that state *E. coli* and any fecal coliform bacteria should not be detectable in any 100 mL sample of water directly intended for drinking (Instituto Ecuatoriano de Normalización 2011; World Health Organization 2017).

The mean value for *E. coli* in drinking water on Isabela (1.08 MPN per 100 mL) was similar to values found on San Cristóbal (1.6 MPN per 100 mL) following the construction of their water treatment plant in 2013 (Gerhard et al. 2017). Log-transformed *E. coli* measurements differed slightly from recent results on San Cristobal (Grube et al. 2020). Freshwater source and influent water on San Cristobal had detectable *E. coli*, whereas all source, influent, and effluent sample but one source water sample from Isabela did not. Total coliforms were detectable and high in sources from both Isabela and San Cristobal (95% CI >2.00 $\log_{10}$ MPN per 100 mL); however, effluent and distributed water samples from San Cristobal showed less detected total coliforms (95% CI <1.50 $\log_{10}$ MPN per 100 mL) than effluent and tap water samples from Isabela in this study. The only other external value of *E. coli* concentration in a household on Isabela reported 1011 MPN per 100 mL in a single Isabela household, much greater than concentrations reported here (Lopez and Rueda 2010). *E. coli* concentrations in tap water provided by the

Table 4.6 Household water insecurity (n = 32) question distribution from adapted HWISE scale (Young et al. 2019)

Water security questions	Never	Hardly ever	Occasionally	Often or always
In the past 4 weeks…	(0 times)	(1–2 times)	(3–10 times)	(>10 times)
1. How often were you or a family member worried about not having enough water for all your household needs?	65.6%	12.5%	–	21.9%
2. How often has the water supply for your main water source been interrupted or limited? (e.g., issues with water pressure or had less water than usual)	68.8%	18.8%	6.3%	6.3%
3. How often have you not been able to wash clothes in your home due to lack of water?	78.1%	12.5%	3.1%	6.3%
4. How often did you or someone in your home have to change schedules/plans due to problems with the water situation?	90.6%	3.1%	6.2%	–
5. How often did you or someone in your home have to change what you were eating because there were problems with water?	87.5%	6.3%	3.1%	3.1%
6. How often did you or someone in your family not wash your hands or wash your child's face due to problems with water?	90.6%	9.4%	–	–
7. How often have you or someone in your family had to leave the house without bathing due to problems with water? (e.g., there was not enough water, or the water was dirty)	87.5%	12.5	–	–
8. How often have you or a member of your household not drank as much water as you would like?	87.5%	6.3%	–	6.3%
9. How often have you or someone in your household been upset about the water situation?	68.8%	25.0%	3.1%	3.1%
10. How often have you or someone in your household gone to sleep thirsty because there was no water to drink?	84.4%	6.3%	3.1%	6.3%
11. How often has there been no drinking water in your home?	84.4%	9.4%	3.1%	3.1%
12. How often did water problems cause you or someone in your home to feel ashamed/excluded/stigmatized?	93.8%	3.1%	–	3.1%

Reponses for each item were scored as follows: "Never (0 times)" = 0, "Hardly ever (1–2 times)" = 1, "Occasionally (3–10 times)" = 2, and "Often (11–20 times)" and "Always (more than 20 times)" = 3. Reponses of "I don't know" or "Does not apply" were also given a score of 0 for those items. A cumulative HWISE scale score was calculated for each household by taking the sum of the 12-item scale, with a total of 12 or more indicating household water insecurity municipality was very similar to drinking water, whereas the total coliform concentrations were drastically higher overall and higher in tap water than in drinking water. Total coliforms are a less specific indicator of fecal contamination than *E. coli* and can originate from environmental contaminants such as leaves, soil, and other animal debris (Liu and D'Ozouville 2013). However, high total coliforms can point to low system integrity that may be at risk for further contamination. In total, 54% and 100% of households had detectable concentrations of *E. coli* and total coliforms in either their tap or drinking water sources, showing high prevalence of community water contamination.

Conductivity and salinity were of particular importance because of long-standing community concerns over untreated and overly salty water. Tap water conductivity was relatively high, yet within applicable drinking water standards from INEN and WHO. Although tap water salinity was much lower than seawater levels (~35 ppt), INEN guidelines state that high levels of salts, bad taste or odor, and other similar issues that could be indicated by physicochemical measurements should not be present in water for drinking (Instituto Ecuatoriano de Normalización 2011). In comparison, drinking water samples from varied sources had much lower conductivity, salinity, and pH levels that were generally acceptable to residents.

Groundwater source, influent, and effluent measurements from the treatment plant on Isabela showed high conductivity, salinity, and pH closely resembling household tap water samples. While results are limited by high variability in the few measurements taken for fecal coliforms, nevertheless, the similarities in physicochemical measurements and contamination levels – especially conductivity, salinity, and pH – between water at the treatment plant and measurements taken when it arrived in household taps indicate minimal effective treatment. No substantial differences between influent and effluent (pre- and post-treatment) samples at the plant were detected, while elevated fecal contamination and physicochemical measurements continued throughout the piped supply, storage in roof tanks and cisterns, and tap dispensing in the home. Effective treatment of water supplied to households from the desalination plant was not observed in this study.

Metal analyses are of significant importance because information about possible sources of contamination can be provided. Naturally occurring elements such as barium and chromium were found to be below the limit established by the WHO guidelines for drinking water (1300 $\mu g\ L^{-1}$ for barium and 50 $\mu g\ L^{-1}$ for chromium) in drinking, tap, and treatment plant water samples. In the case of arsenic, no information could be obtained because all samples were found to be below the detection limit. Cadmium values were all below the limit of detection or quantification, showing no significant contamination from industrial sources in all the water samples analyzed as expected. Contamination from pipes and fittings was also found to be insignificant as all copper, lead, and nickel values were below the established limits by the WHO guidelines (World Health Organization 2017).

Desalination plants have been recognized as costly and ineffective in many settings around the world (Bhattacharjee 2007; Brady et al. 2009; Ghaffour et al. 2013). Chlorine disinfection was not conducted at the drinking water treatment plant (Personal communications with the municipality, 2019). However, chlorine disinfection can reduce microbial contamination, and residual chlorine was found to have a negative moderate relationship with microbial contamination on San Cristobal, indicating chlorine disinfection may help reduce the environmental microbial contamination of piped water coming from the municipal treatment plant and being stored at and piped to homes (Grube et al. 2020). Additional expertise in water treatment and engineering are likely needed to consistently produce high-quality drinking water on Isabela Island.

Residents raised abundant concerns about the tap water in surveys, saying that it was not drinkable, untreated, too salty, or dirty or that it would make them sick. All residents instead used other sources for drinking water, most commonly through private bottled water sources and rainwater collection. Residents listed three private companies that filtered water and sold 5-gallon jugs of water around town. Small samples of each source type, hesitancy of households to disclose provider, and inability to collect data from the providers did not allow for further analysis. However, most residents stated they would prefer to receive piped drinking water and that they thought it was the municipality's responsibility to supply household water.

The adapted HWISE scale showed minimal household water insecurity across the study domain. A substantial proportion of households reported having no problems across all items in the scale. However, other survey responses conflicted with these results. When asked directly, 28% of residents responded that they had problems with their water, and 75% were unsatisfied with their water situation. Household water security (75% participating households) may be over-represented in this study because the HWISE scale may have been insufficient for this setting; many items emphasize absolute water quantity, while concerns in the community centered on variability in water quality. Most residents had enough water to perform daily tasks like washing clothes or bathing, yet a third of households worried about having enough water for "needs" like drinking and cooking. While households may have ample water supply most of the time, concerns center on the safety of water for consumption consistent with findings of fecal coliforms within post-treatment tap water supplies. Residents of San Cristobal and Isabela often use roof tanks or cisterns to store water, and on San Cristobal, these storage methods provided for availability yet caused treated water to mix with untreated water during storage because variabilities in contamination of treated water from the plant throughout the day (Grube et al. 2020). Clear issues with confidence in the safety of available water, the cost of procuring water from a private source, and issues with variability in water quality and availability are substantial issues regardless of households being classified as generally water secure based on the HWISE scale and may contribute to psychological stress and related disease (Jepson 2014; Wutich and Ragsdale 2008). This variability may be further exacerbated during times of drought and other low-supply periods not captured in this study.

The results of this study may be limited by a cross-sectional study design including nonrandom convenience sampling with a low sample size. Variance estimates, survey sampling corrections, and the ability to perform statistical tests were impacted by sample size limitations. Previous studies on San Cristóbal have reported differences in water security according to socioeconomic status and urbanicity (Nicholas et al. 2019). Convenience sampling and partnership with local government included many local businesses and other residents who may have been of a higher socioeconomic status in the study offering potential systematic bias and an underrepresentation of water insecurity prevalence. Participants also showed noticeable survey fatigue, which may have reduced variability in responses.

This research focused on multiple dimensions of the household water environment in Puerto Villamil and offers useful information for future interventions and research. A longitudinal study on water with multiple time periods for data collection might better elucidate other aspects of water insecurity, including seasonality. High seasonal variation in fecal contamination in drinking water, with greater contamination during the wet season, has been relevant in many studies, including work on San Cristobal (Grube et al. 2020; Kostyla et al. 2015). Data for this research was collected during the beginning of the dry season in the Galápagos (June–November), likely underestimating the magnitude of contamination in community water. In the past, there have been reports that some Puerto Villamil residents sometimes dispose of wastewater in volcanic cracks and fissures near their homes (Walsh et al. 2010). During heavy rainfall periods, source groundwater may be exposed to increased runoff resulting in greater contamination.

These issues are further compounded by the inability of the municipal desalination plant to treat and provide enough water for Puerto Villamil. Evaluation of the desalination plant or recommending cost-effective interventions is beyond the scope of this research. However, these results highlight the need for additional measures to safeguard the water and health of residents. This problem will continue to grow in the future with record numbers of tourists visiting the Galápagos each year, putting further strain on the small island's limited resources.

4.5 Conclusion

Fecal indicator tests show high total coliform concentrations in both household drinking and tap water samples but generally low levels of *E. coli*. These results, along with physicochemical data, point to unreliable and ineffective treatment from the municipal desalination plant. Metals are not a concern of contamination in any part of the water system and water consumption on the island. Households reported general water security, but data showed a general dissatisfaction with the current water environment and a desire for safe, potable drinking water provided by the municipality. Almost all households purchased water from small private providers on the island, with high variability in microbial quality that could not be qualitatively assessed in this study. These results highlight the need and desire by residents for additional attention and investment into a sustainable source of potable water in the coming years. Municipality treatment plant operators and other workers suggested increasing the capacity of the desalination plant to meet these needs, but more research is needed to identify a cost-effective and sustainable solution.

Educational interventions for residents supporting behaviors including proper cistern cleaning practices and boiling all water intended for consumption are also recommended in addition to addressing water supply structures.

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