2017

SOURCE PROTECTION AND DRINKING WATER QUALITY IN THE COMARCA NGÄBE-BUGLÉ, PANAMA

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SOURCE PROTECTION AND DRINKING WATER QUALITY IN THE COMARCA NGÄBE-BUGLÉ, PANAMA

By

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A THESIS

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Civil Engineering

MICHIGAN TECHNOLOGICAL UNIVERSITY

2017

This thesis has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Civil Engineering.

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Preface

The data collection and analysis, as well as writing were the sole work of the author, Leigh Burgess Miller, with advice and editing primarily by David Watkins and additional review by Kari Henquinet and Brian Barkdoll. A modified version of this thesis is planned for journal submission in the near future.

Acknowledgements

I owe great thanks to Dr. David Watkins for all his help transforming my moldy notes into something logical and readable. I also thank Dr. Kari Henquinet and Dr. Brian Barkdoll for their guidance.

Many thanks to Leyre Alegre-Figuero for editing the Spanish translation of my abstract.

I received help and wisdom from many organizations in Panama including CATHALAC, MINSA—in particular Yireh Concepción, and MiAmbiente.

The Peace Corps Panama office staff inspired and encouraged me throughout my time in Panama. In particular, I'd like to thank Franklin Cano and Laura Havenga for helping me find online data, Jessica Glenn for her excellent construction material price guide, and Melissa Meno and Antonella Finis for being great supervisors

The many water committee members and community leaders, who gave their time and energy to guide me to sample sites, include Eliser Andrade, Ariel Arena, Abelardo Armuelles, Horacio Flores, Eufemia Gallardo, Tino Gallardo, Isael Pedrol, Alfredo Pinto, and Alexis Rodriguez. I am especially thankful to Jose Chavez, Miguel Mora, and Narciso Vejerano for their friendship, enthusiasm, and emotional support.

The Vejeranos, my host family, truly helped me survive. They taught me everything from washing clothes on a rock to using icy hot on scorpion stings, and so much in between.

Peace Corps volunteers who opened their homes, hearts, and big brains to help me complete this project include Erin Storck, Eric Balas, Sean Schrag-Toso, Carl Evans, Jordan Mayer, the Puerco power crew: Marlana Hinkley and Maria Briones, and the incomparable MC Moritz. Eternal gratitude to Katie Snyder, who hiked in glass jars of pesto.

Lastly, I am incredibly grateful to my family: my parents, who braved the jungle to visit and support me; Darby, my "mule" and benefactor; Martina, Megan, and Gwenn for video-chatting despite many dropped calls; and Rob Clark, for everything.

List of Abbreviations

ANAM	*Autoridad Nacional del Ambiente*—National Environmental Authority, now MiAmbiente
CATHALAC	*Centro del Agua del Trópico Húmedo para America Latina y el Caribe*—Water Center for the Humid Tropics of Latin America and The Caribbean
CAWST	Centre for Affordable Water and Sanitation Technology
CFU	Colony-Forming Units
CI	Confidence Interval
COPANIT	Comisión Panameña de Normas Industriales y Técnicas—Panamanian Commission on Technical and Industrial Rules
DGNTI	Dirección General de Normas y Tecnología Industrial—General Committee on Rules and Technical Industries
DISAPAS	Dirección del Subsector de Agua Potable y Alcantarillado Sanitario—Water Supply and Sewer Subsector Committee
E. coli	*Eschericha coli*
ETESA	Empresa de Transmisión Eléctrica—Electrical Transmission Company
FTP	Fideicomiso Ecológico de Panamá—Ecological Trust of Panama
GPS	Global Positioning System
m	Meters
MDG	Millenium Development Goals
MiAmbiente	Minesterio del Ambiente—Ministry of the Environment
MINSA	Minesterio de Salud—Ministry of Health
ml	Milliliters
MPN	Most Probable Number
NGO	Non-Governmental Organization
NTU	Nephelometric Turbidity Units
OR	Odds Ratio
p	Statistical probability
ppm	Parts per million
UN	United Nations
U.S.	United States
WASH	Water, Sanitation and Hygiene
WHO	World Health Organization

Abstract

The goal of this study was to identify practical, cost-effective drinking water source protection measures in the Comarca Ngäbe-Buglé, a remote indigenous region of Panama. Water samples from 40 spring captures were tested for *E. coli* and total coliforms, and quality results were then compared with maintenance and source protection criteria using odds ratios. The water was contaminated; only two samples passed Panamanian drinking water standards--0 CFU/100 ml for *E. coli* and 3 CFU/100 ml for total coliforms. Mean *E. coli* was 187 CFU/100 ml and mean total coliforms was 2036 CFU/100 ml. Few odds ratio tests of source protection practices produced statistically significant results. However, the presence of animals within ten meters of the source and cleaning out the spring capture structure had statistically significant relationships with water quality at some contamination thresholds. Surprisingly, at one threshold, the presence of surface water near the spring was unrelated to water quality. Protecting water sources from livestock can be complicated in this region by ambiguous land tenure laws. Likewise, cleaning and basic maintenance are often done on a volunteer basis, and thus subject to the limitations of the community management model. Panamanian and foreign organizations seeking to improve drinking water source quality should consider these complex issues and offer financial and technical support as they encourage source protection improvements.

El objetivo del estudio fue identificar las medidas de protección prácticas y rentables de las fuentes de agua potable en la Comarca Ngäbe-Buglé, una región indígena de Panamá. Se analizó el agua de 40 tomas para detectar Escherica coli y coliformes totales, así como la calidad del agua y se comparó con el mantenimiento de la toma y la protección de la fuente mediante una estadística llamada 'oportunidad relativa'. Las aguas estaban contaminadas: la media de Escherica coli fue 187 UFC/100 ml y la de coliformes totales fue 2036 UFC/100 ml. Los dos niveles de contaminación están muy por encima de los estándares de agua potable panameños (0 CFU/100 ml para Escherica coli y 3 CFU/100 ml para coliformes totales). Pocas 'odds ratios' de las prácticas de protección de la fuente produjeron resultados estadísticamente significativos. Sin embargo, la presencia de animales de granja en los diez metros alrededor de la fuente y la limpieza de la toma tenían relaciones estadísticamente significativas con la calidad del agua en algunos umbrales de contaminación. Sorprendentemente, la presencia del agua superficial cerca de la toma no estaba relacionada con la calidad del agua en un umbral. La protección de fuentes de agua del ganado puede ser complicada en esta región por la tenencia ambigua de la tierra. Asimismo, la limpieza y el mantenimiento básicos a menudo se hacen de manera voluntaria, así que, está sujeto a las limitaciones del modelo de manejo comunitario. Las organizaciones panameñas y extranjeras que buscan mejorar la calidad de las aguas deben considerar estas cuestiones complejas y ofrecer apoyo financiero y técnico a las Juntas Administradores de Acueductos Rurales para fomentar la mejora de la protección de fuente.

1. Introduction[1]

Over the past 25 years, 2.6 billion people have gained access to improved drinking water sources (UN 2015). However, rural areas lag behind urban ones in both coverage and quality (Bain *et al*. 2014a, 2014b). Despite an impressive increase in global access to clean drinking water, an estimated 1.8 billion people drink water contaminated by feces (Bain *et al*. 2014a).

This study focuses on the Comarca Ngäbe-Buglé, an indigenous region in western Panama. In Panama, national averages show high levels of water access, 98% in urban areas, and 89% in rural areas (UN 2016), but these statistics fail to capture access levels in the most remote communities and the differences between indigenous and Latino communities. According to 2010 Panamanian census data, 91% of the Comarca Ngäbe-Buglé lives in extreme poverty and only 59% have access to piped water sources (MDG Joint Programmes 2013).

In 2014, the leading cause of death in the Comarca Ngäbe-Buglé was diarrhea and gastroenteritis from infection (MINSA 2014). Contaminated water often causes diarrhea, and improving water supply leads to health benefits (WHO 2006).

While many studies have examined the relationship between sanitary practices and microbiological quality in urban and peri-urban settings throughout the world (Howard *et al.* 2003, Patrick *et al*. 2011, Omer *et al.* 2014), and some studies have included rural communities in provincial-wide studies (Cronin *et al.* 2006, Admassu *et al.* 2004, Gwimbi 2011), there are few examples of research that delves into the range of remote rural water quality issues seen in the Comarca Ngäbe-Buglé. The Panamanian Health Ministry (MINSA) has recently made an effort to evaluate drinking water quality in the region, but its current testing method makes it impossible to collect samples from many hard-to-access communities, such as those included in this study. Furthermore, no previous attempts have been made to systematically evaluate the contamination risks to drinking water sources in the region.

Drinking water in the Comarca Ngäbe-Buglé is dominated by gravity-fed water systems from shallow groundwater springs because of affordability and ease of maintenance. Shallow groundwater springs in fine soils store water and release it during the dry season (Van Sickle 2016), providing year-round water sources. Concrete structures called ‘spring captures’ or ‘spring boxes’ are built around the springs to protect them from surface water contamination and direct their flow into the water system. Figure 1 shows a schematic of a protected spring.

These springs feed water systems that serve small, remote communities. All the systems in the study were constructed with funding and labor from community-based volunteer committees, local politicians, MINSA and its Water Supply and Sewer Subsector Committee (DISAPAS), an NGO called Waterlines, or the United States Peace Corps. The author lived in the Comarca Ngäbe-Buglé for two years as a Peace Corps volunteer.

[1] Material in this chapter is planned for journal submission.

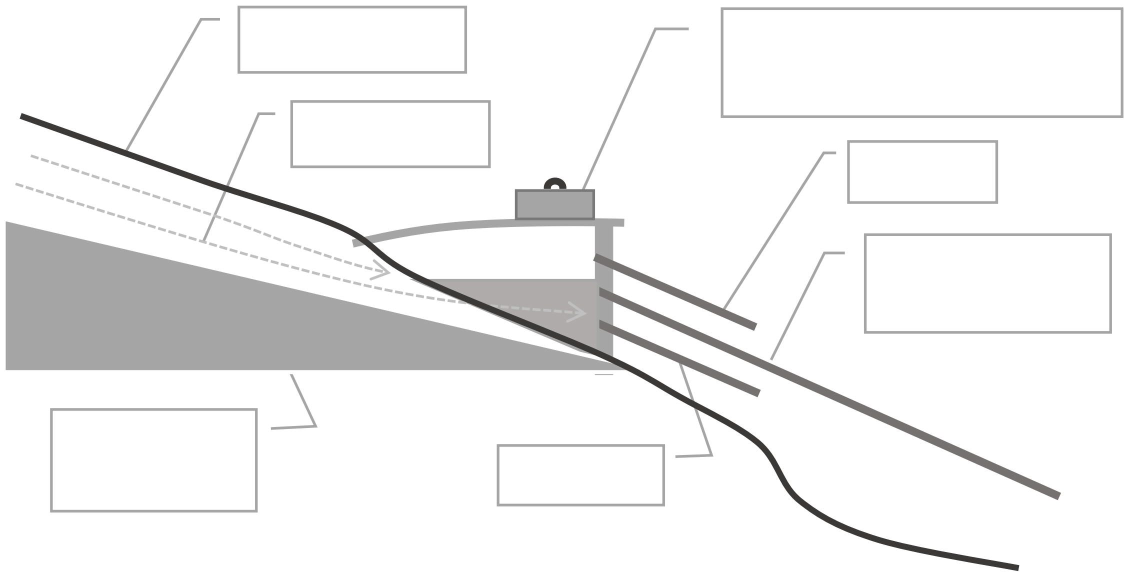

Figure 1. Schematic of a protected spring with a spring capture structure

The community-based volunteer committees operate and maintain the water systems on a volunteer basis. They are charged with raising funds from community beneficiaries and providing labor for all repairs, typically on a volunteer basis. While this ensures community participation in water system decisions, the community management model has limitations that are discussed more extensively in Section 4.2.

Protected springs are subject to many potential quality issues and contaminant pathways such as nearby livestock, structural faults, and poor drainage. One inexpensive method for evaluating water quality is the sanitary survey. Sanitary surveys evaluate the condition of the spring capture structure and potential sources of contamination nearby. World Health Organization (WHO) guidelines emphasize the importance of a broad approach to water quality monitoring that includes visual inspections of sources and water systems (WHO 2006). Sanitary surveys have been compared with water quality tests to better understand contamination pathways in other studies (Howard *et al*. 2003, Patrick *et al*. 2011, Cronin *et al.* 2006).

In this study, source quality was also evaluated by sampling for *Escherichia coli* (*E. coli*) and total coliforms. *E. coli* is a thermotolerant genus of coliform bacteria that is the standard indicator of animal or human fecal contamination (WHO 2006). Total coliform measurements capture a larger group of bacteria—including *E. coli* as well as non-pathogenic species naturally present in the environment—and are typically used as indicators of biofilm formation in treated systems (WHO 2006).

Water quality in the region was expected to be poor based on MINSA testing from 2015. Further, a report on the Quebrada Caracol water system showed poor sanitary conditions, a high risk of contamination, and the presence of aerobic bacteria, coliforms, *E. coli*, and

enterobacteriaceae (which includes salmonella, Yersinia, and Shigella: all pathogens) (Stoolmiller *et al.* 2015).

This study was limited to source quality evaluation. While there are many water, sanitation, and hygiene (WASH) interventions for improving health outcomes, such as handwashing, safe water storage, and point-of-use treatments, protecting watersheds and improving water quality at the source can reduce treatment needs (Postel and Thompson 2005).

Protected groundwater sources are currently presumed potable by organizations developing water infrastructure in the Comarca Ngäbe-Buglé. It is assumed that the soil provides adequate filtration and spring capture structures are effective in preventing contamination. It is vital to test the validity of these assumptions as part of the effort to provide clean water. After evaluating source quality and potential contaminant pathways, this paper provides recommendations for cost-effective source protection improvements and explores the community context of those recommendations.

2. Methods[2]

2.1 Study sites

The study took place in the Southern Comarca Ngäbe-Buglé, with sites in the Nole Duima, Munä, and Mironó districts. Figure 2 shows the general location of the study sites. The majority of sources were clustered on two hills, Cerro Ceniza (Munä) and Cerro Iglesias (Nole Duima), where the author had a social network that allowed access to sample locations and reliable water system information. An additional eleven sites in Mironó were sampled at the request of Peace Corps volunteers who wanted water quality data for their communities.

To choose sites on Cerro Ceniza and Cerro Iglesias, the author interviewed community members and Peace Corps volunteers and developed a list of communities with drinking water sources on the two hills. Accurate maps of the area are rare and do not typically include drinking water sources; guides, usually Peace Corps volunteers or community leaders, were essential for finding water source locations.

Additional criteria limited the testing sites. Only water sources with protective spring capture structures were sampled—not unprotected springs that were proposed water sources. The sites had to be within a two-hour hike of a location where samples could be plated, typically a Peace Corps volunteer's house.

The study sites represented a range of management styles and operation and maintenance practices. Water systems varied in size from a community of 1,000 people to a service area with just a few households and a municipal building. The age of systems ranged from a few months to thirty years old. While the majority of sources served systems in working condition, at least two were completely non-functional.

[2] Material in this chapter is planned for journal submission.

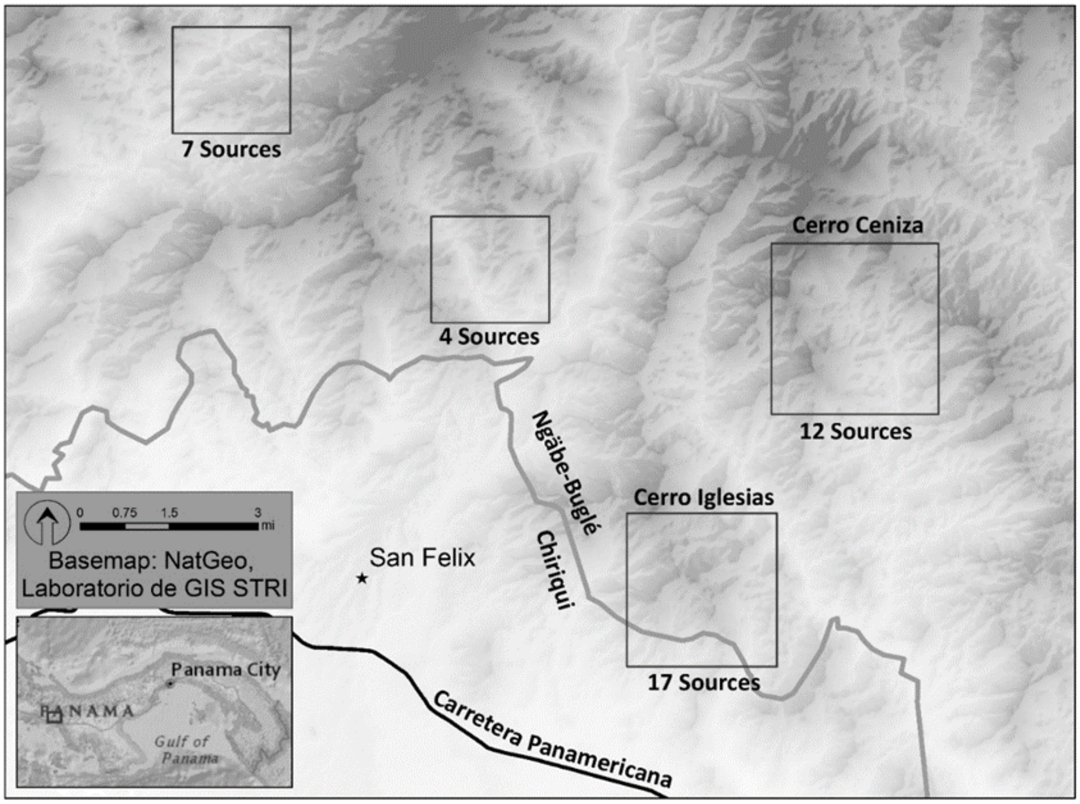

Figure 2. Study locations (map created for this work by R.W. Clark)

2.2 Sampling procedure

The samples were taken at a total of 40 spring sources. The majority of sampling occurred in April, May, and June of 2016, during the transition from the dry season to the rainy season. The worst quality was expected during this transition period. Tropical countries with wet and dry seasons often have lowest water quality at the beginning of the wet season as contaminants that have built up over the dry season wash out of the soil (Wright 1986, Kostyla *et al*. 2015). Three sources (Lino and Marciano on Cerro Ceniza and Quebrada Caracol on Cerro Iglesias) were sampled monthly to track seasonal variation of water quality.

The samples were collected in the company of a guide. Background information, described in the following section, and weather conditions were recorded before travelling to the source. GPS coordinates and photographs were collected at each site. Sanitary surveys were completed by visual inspection with the input of the guide (see 2.3 for more information). Water quality samples were collected at the spring capture access hatch where possible, and otherwise from the cleanout (after flushing the sediment) or the transmission line near the source (see 2.4). Lastly, flow data was collected at the cleanout or transmission line when possible.

Within a month of the sample date, the author delivered sanitary surveys, water quality results, and recommendations for water treatment methods to local water committee or community leaders to inform them of quality issues and potential source improvements. The results were delivered in writing and pictorially, as well as verbally, when possible.

2.3 Sanitary survey

The source protection at each site was evaluated using a ten-question sanitary survey developed by the WHO (WHO 2006) and adapted and translated by the Centre for Affordable Water and Sanitation Technology (CAWST), a Canadian NGO. The Spanish translation was used in the field; the English version is shown in Table 1.

Table 1: Sanitary survey

Question	Response
1. Is the collection or spring box absent or faulty?	Y/N
2. Is the masonry or backfill area protecting the spring faulty or eroded?	Y/N
3. If there is a spring box, is there an unsanitary inspection cover?	Y/N
4. Does the spring box contain contaminating silt or animals?	Y/N
5. Is there an air vent in the masonry and is it unsanitary?	Y/N
6. Is there an overflow pipe, is it unsanitary?	Y/N
7. Is the fence around the spring inadequate?	Y/N
8. Can animals have access to within 10 m of the spring?	Y/N
9. Is the diversion ditch above the spring absent or not working properly?	Y/N
10. Are there any other sources of contamination uphill of the spring (e.g. latrines, waste)?	Y/N
Risk of contamination (add the number of 'Yes' answers):	....../10
Source: "Sanitary Inspection Form: Protected Spring" by CAWST (www.cawst.org) licensed under CC	

The survey was implemented following the instructions on the form, and additional criteria were used to determine answers. For example, 'unsanitary inspection covers' were considered to include structures with absent or incomplete covers, as well as those lacking a raised rim to prevent surface water entry. Notes on these additional criteria can be found in Appendix A.

The Panamanian Ministry of the Environment (MiAmbiente, previously ANAM) and MINSA are increasingly promoting watershed protection, especially in areas near water capture structures (ANAM 2011, FTP 2008). Unfortunately, the recommendations are not always practicable, because of the land tenure issues. For example, both organizations suggest a minimum protected radius of 50 meters around the source; MiAmbiente recommends a 200-meter radius in steep topography. Section 4.3 provides a more extensive discussion of the implementation barriers to protecting lands around water sources.

In addition to the sanitary survey, spring sources were surveyed for the following criteria,

- Latrines within 30 m—a common source of groundwater contamination (Lewis *et al.* 1980)
- Surface water in source area—found to be linked to water quality in a similar study in Kampala, Uganda (Howard *et al.* 2003)
- Compliance with MiAmbiente recommendations for fence radius, per FTP (2008)
- General assessment of whether or not the source is protected either physically, by the landowner, or by legal status
- History of the spring capture, including the construction date and original funding source, where available
- Frequency of cleanings, especially if the spring capture had been recently cleaned

2.4 Microbiological quality test

The microbiological test used was the Coliscan Easygel© kit from Micrology Labs. The kit tests for *E. coli* using chromogenic media; dyes activate in the presence of Beta-galactosidase, an enzyme produced by coliforms, and Beta-glucuronidase, which is specific to most species of *E. coli*. *E. coli* colonies can be identified as a mixture of the two distinct dye colors.

Easygel© was rated in the 'best' category for precision compared to similar products (Bain *et al.* 2012), and samples can be incubated at ambient temperatures (Micrology Labs 2016). Ambient temperature incubation can produce robust results in *E. coli* sampling in countries with mean temperatures over 25°C (Brown 2011). Monthly average temperatures in the study area range between 26.1 °C and 27.7°C (ETESA 2016).

However, one study recommended that Easygel© only be used in combination with a 20-mL H_2S test for drinking water because of the former's higher detection limit and 17% rate of false negatives (Chuang *et al.* 2011). Easygel© has a 5 ml maximum sample volume, which would require either 20 plates per sample or vacuum filtration for a detection limit of 1 CFU/100 ml. The standard volume in U.S. water quality testing is 100 ml (Bain *et al.* 2012). On the other hand, finding accurate sampling methods that are feasible in remote locations with financial constraints and no electricity or laboratory facilities is a challenge, and meeting U.S. water quality testing standards is not always crucial for evaluating water sources (Abramson *et al*. 2013).

Laboratory methods practiced in U.S. water sampling facilities were not feasible in the remote study locations. However, the testing method generally followed manufacturer instructions (Micrology Labs 2016). A detailed description of the testing procedure follows.

As per manufacturer recommendations, the Easygel© bottles were stored in a freezer in San Felix, Chiriquí. The bottles were used for samples within two weeks of removal from the freezer. Easygel© bottles can be stored at room temperature for up to a month with no adverse effects (Micrology Labs 2016). Sterile petri dishes from the test kit were stored in original packaging at ambient temperature.

Samples were collected from spring capture access hatches where possible. An attempt was made to avoid collecting floating organic matter and sediments that were present in some of the sample sites. Where the access hatch could not be opened, samples were either collected from the cleanout pipe, after allowing the sediments to flush out and the flow to equalize, or from the transmission line at a disconnected section near the source.

Water samples were collected in 28-ounce plastic screw-top jars. The jars were used for multiple samples but disinfected between uses with 70% rubbing alcohol. To disinfect, the jars were rinsed with a few tablespoons of alcohol and then agitated for two minutes. After emptying the alcohol, the jar was triple-rinsed with water from the source before the sample was collected.

Samples were transported to a plating location within two hours of collection. Sample volumes were 1-4 ml, depending on expected quality, in order to keep colonies within a countable range. Sample volumes were measured with a Sawyer water filtration backwashing syringe that was rinsed with alcohol between uses and then triple-rinsed with the sample water before use. The sample was transferred from the syringe directly to the Easygel© bottle, capped, mixed by inverting three times, and then poured into the sterile petri plates from the kit.

Samples were counted after incubation at ambient temperature for 48 hours. During the incubation period, plated samples were stored in lidded plastic or glass containers, packed in paper to reduce excessive humidity—which could interfere with gel setting—and kept out of direct sunlight. Plates were not stored inverted because this caused separation of the gel and plate. Each plate was photographed and then inverted for counting. Depending on the lighting conditions, a piece of white paper and/or lamp were used to make colonies more visible. Colonies were marked to avoid double-counting. Plates with no visible *E. coli* or other coliform colonies were recorded as zero counts despite higher detection limits. Plates with more than 300 colonies were recorded as 300+. Used plates were disposed of following manufacturer-recommended methods. To test for a false positive result, the method was performed with water treated by boiling for five minutes. No colonies formed.

2.5 Other water quality parameters

To characterize water quality in the study area, temperature, ammonia, total and free chlorine, alkalinity, and pH were measured in July 2016 at five sites on Cerro Iglesias and four sites on Cerro Ceniza. Temperature was measured with a glass mercury thermometer. Ammonia, total chlorine, free chlorine, and alkalinity were measured with a Hach five-in-one water quality test strip. The pH was also measured by the Hach five-in-one test strip, as well as a Macherey-Nagel pH-Fix 0-14 PT test strip. Turbidity was measured using a LaMotte 2020i turbidimeter (SN-MI 10295) calibrated between each measurement with distilled water.

2.6 Data analysis

Water quality testing and sanitary survey data were recorded by hand and then entered into Microsoft Excel® software for analysis. Five entry error checks were performed by verifying

that all values on a randomly selected page of the data notebook had been correctly entered. A general check on all the data was performed during translation from Spanish to English.

Odds ratios were calculated to evaluate relationships between water quality and source protection. The odds ratio is a relative measure of the likelihood of specific outcomes for two given treatments. For example, how likely is a source to exceed an *E. coli* or total coliform threshold for two cases, the "faulty practice" and the "improved practice." The statistic is commonly used in medicine to compare groups of patients receiving different treatments (McHugh 2009); it can also be used to evaluate contamination pathways in drinking water sources (Howard *et al*. 2003, Patrick *et al.* 2011).

The odds ratio is calculated as follows,

$$Odds\ Ratio\ (OR):\ \frac{a/b}{c/d} = \frac{a \times d}{b \times c}$$

where,

> *a* – number of samples with bad outcomes (e.g. *E. coli* above a certain threshold), in groups with standard (unimproved) treatment (e.g. faulty protection practices)
>
> *b* – number samples with bad outcomes (e.g. *E. coli* above a certain threshold), in groups with improved treatment (e.g. improved protection practices)
>
> *c* – number of samples with good outcomes (e.g. *E. coli* below a certain threshold), in groups with standard (unimproved) treatment (e.g. faulty protection practices)
>
> *d* – number of samples with good outcomes (e.g. *E. coli* below a certain threshold), in groups with improved treatment (e.g. improved protection practices)

In cases where *a*, *b*, *c*, or *d* have zero values, each group was increased by 0.5 to approximate an odds ratio value (Medcalc 2016). Where $a = b = 0$ or $c = d = 0$, the odds ratio is undefined.

Odds ratios were interpreted based on values of the one-sided Fisher's Exact Probability. The probability test was used to evaluate the hypothesis that WHO-recommended practices would improve water quality, expressed as $OR > 1$. Fisher's Exact Probability test was selected for *p* value calculation because of its simplicity and utility for contingency tables containing zeroes (McHugh 2009). Two thresholds were selected for statistical significance, $p < 0.05$ and $p < 0.1$.

Confidence intervals were calculated for odds ratios using the method described by Sheshkin (2004). Statistical formulas are shown in Appendix B. Complete odds ratio, Fisher's Exact Probability (*p*), and confidence interval results are shown in Appendix C.

Five microbial quality thresholds were used to group samples for odds ratios: (1) *E. coli* > 0 CFU/100 ml, (2) *E. coli* > 100 CFU/100 ml, (3) *E. coli* > 200 CFU/100 ml, (4) total coliforms > 1000 CFU/100 ml, and (5) total coliforms > 1500 CFU/100 ml. The first *E. coli* threshold is the MINSA standard for untreated sources (DGNTI 1999). The second *E. coli* threshold was

selected based on the finding that *E. coli* levels of 100 CFU/100 ml may have similar health impacts in tropical environments as lower contamination levels (Moe *et al*. 1991). Total coliforms were consistently higher than the MINSA standard of 3 CFU/100 ml (DGNTI 1999); thus, this standard could not be used as a threshold in odds ratio calculations. The remaining thresholds were selected to explore relationships between source protection and quality at higher contamination levels. These thresholds were determined by plotting *E. coli* and coliform counts on a log scale for each protection practice and visually estimating the mean of the log values.

In some cases, samples were taken at a given site on multiple dates. These samples are not independent; therefore, *E. coli* and total coliform counts from the same location were averaged for odds ratio tests, except where sanitary survey results had changed between the two sample dates. In those cases, the samples were counted as separate samples only when calculating the odds ratio for the relevant sanitary practice. Samples at the same location were also counted separately when evaluating the seasonal variation, but were still averaged within each season.

In a few cases, the gel separated from the plate and colonies could not be counted, but it was apparent whether *E. coli* and other coliforms were present or absent. Uncountable plates where *E. coli* or coliforms were absent were counted as zero values. Uncountable plates with *E. coli* present were only used to calculate odds ratios for the *E. coli* > 0 CFU/100 ml threshold.

At some sites, there were multiple spring captures—denoted in the data by "left" and "right" or "#1" and "#2". Distances between such captures varied from 3 m to 200 m. These are treated as independent samples because the structures are separate and may be capturing unconnected sources. However, for ease of sampling, some systems were sampled at a junction box of two sources instead of individual access hatches, in which case they were evaluated as one spring. In one case, results from two spring boxes were averaged and grouped with sample results from the junction box from other months.

3. Results[3]

3.1 Water quality parameters

In general, the spring source water quality was very poor. Out of 69 samples, all but two exceeded Panamanian water quality standards for *E. coli* or total coliforms (DGNTI 1999).

Other water quality parameters were measured at eight spring sources on Cerro Ceniza and Cerro Iglesias in June 2016 to give a broader picture of water quality in the area. A summary of the parameters is shown in Table 2. The complete data set is included in Appendix D.

[3] Material in this chapter is planned for journal submission.

Table 2: Water quality parameters

Temperature	24 – 26 °C
pH	6 - 7
Ammonia (ppm NH_3-N)	0.25-0.50
Total chlorine (ppm) **Free chlorine (ppm)**	0 0
Alkalinity (ppm $CaCO_3$)	Mode: 120 Low: 40
Turbidity (NTU)	0.22 – 19.5*
** Panamanian drinking water standard for turbidity is a maximum of 1.0 NTU (DGNTI 1999), WHO recommends turbidity less than 5 NTU (WHO 2006)*	

3.2 Odds ratios

Odds ratios were used to compare sources grouped by protection or maintenance practice, season, weather conditions, or location, with respect to the five quality thresholds previously discussed. Large odds ratios indicate a relationship between the faulty practice and contamination at the given threshold. An odds ratio of one indicates no difference between faulty and improved practices with respect to contamination; an odds ratio of less than one can also be interpreted as no difference for WHO-recommended sanitary practices, which are expected to improve water quality.

Odds ratio calculations were impacted by group sizes; some groups had much less variety. Table 3 shows the number of samples that fell into each category of source protection, maintenance practice, and other criteria used to calculate odds ratio.

Table 3: Numbers of samples for odds ratio calculations

	Yes (true)	No (false)
Lack of spring box	0	40
Masonry or backfill area faulty or eroded	20	21
Unsanitary inspection cover	13	28
Contaminating silt or animals	36	4
Unsanitary air vent	11	29
Unsanitary overflow pipe	29	11
Inadequate fence	28	12
Animals within 10 m of spring	20	20
Diversion ditch absent or faulty	35	5
Uphill contamination (e.g. latrines, waste)	22	18
Lacking source protection	22	18
Failure to comply with MiAmbiente regulations for fence radius	40	0
Latrines within 30 m	7	33
Surface water	17	28
Not cleaned within the last month	28	11
Cleaned less than once per year	4	18
Wet season	28	17
Wet season excluding October through December	28	17
Rain	16	29
Cerro Ceniza (no: Cerro Iglesias)	12	17

3.2.1 Sanitary survey

Table 4 shows the odds ratios calculated for the various protection practices at *E. coli* thresholds of 0, 100, and 200 CFU/100 ml, along with confidence intervals and significance levels. There is a wide range of odds ratios, from 0.22 to 22.5. There are few statistically significant relationships, but spring captures cleaned in the month before the sample date and annually both show consistently high odds ratios that suggest a strong relationship between this maintenance practice and reduced *E. coli* contamination. Presence of animals within 10 meters of the source, such as cows or chickens, also shows an odds ratio significantly greater than one for E. coli > 200 CFU/100 ml. Table 5 shows the odds ratios for total coliform thresholds. There are no statistically significant odds ratios. Both “lack of spring box” and “compliance with MiAmbiente regulations for fence radius” were removed from the tables because there were no cases in the faulty group and the improved group, respectively, and odds ratios could not be calculated.

Table 4: Odds ratios for *E. coli* thresholds

	E. coli > 0 CFU/100 ml				*E. coli* > 100 CFU/100 ml				*E. coli* > 200 CFU/100 ml			
	Odds Ratio	*p-value*	95% Confidence Interval		Odds Ratio	*p-value*	95% Confidence Interval		Odds Ratio	*p-value*	95% Confidence Interval	
Masonry or backfill area faulty or eroded	1.39	0.221	0.39	88.8	0.71	0.245	0.18	54.0	0.60	0.259	0.12	48.2
Unsanitary inspection cover	1.20	0.258	0.31	75.7	0.38	0.171	0.07	43.4	0.67	0.311	0.11	47.5
Contaminating silt or animals	5.31	0.147	0.50	106	4.60[a]	0.226	0.23	57.8	3.00[a]	0.360	0.15	49.3
Unsanitary air vent	0.44	0.147	0.11	49.3	1.02	0.312	0.21	55.7	0.88	0.345	0.15	49.2
Unsanitary overflow pipe	0.46	0.178	0.10	48.8	0.36	0.124	0.08	43.3	0.63	0.281	0.12	47.0
Inadequate fence	1.10	0.271	0.28	69.1	1.19	0.301	0.25	60.1	0.63	0.281	0.12	47.0
Animals within 10 m of spring	1.52	0.207	0.43	92.1	2.80	0.110	0.65	132	4.91	0.061**	0.84	191
Diversion ditch absent or faulty	2.54	0.235	0.37	83.2	1.82	0.377	0.18	52.6	3.82[a]	0.272	0.19	53.7
Uphill contamination (e.g. latrines, waste)	1.40	0.223	0.39	86.3	2.04	0.180	0.48	94.6	0.93	0.307	0.20	54.2
Lacking source protection	2.14	0.132	0.59	127	1.20	0.272	0.29	65.5	1.79	0.246	0.36	74.7
Latrines within 30 m	1.84	0.274	0.31	73.6	1.22	0.354	0.19	53.6	0.69	0.409	0.07	42.3
Surface water	0.73	0.214	0.22	68.6	0.22	0.054**	0.04	45.6	0.44	0.209	0.08	49.0
Not cleaned within the last month	9.78	0.004***	1.96	1830	7.86	0.039***	0.87	198	11.17[a]	0.036***	0.59	114
Cleaned less than once per year	7.29[a]	0.137	0.34	43.0	9.75	0.082**	0.78	96.9	22.5	0.027***	1.51	405

[a]*Added 0.5 to all groups to calculate an approximate odds ratio*

****p < 0.05*

***p < 0.10*

Table 5: Odds ratios for total coliform thresholds

	Total coliforms > 1000 CFU/100 ml				Total coliforms > 1500 CFU/100 ml			
	Odds Ratio	*p-value*	95% Confidence Interval		Odds Ratio	*p-value*	95% Confidence Interval	
Masonry or backfill area faulty or eroded	0.94	0.270	0.24	57.5	1.25	0.247	0.34	69.7
Unsanitary inspection cover	0.36	0.133	0.07	40.5	0.37	0.143	0.07	40.5
Contaminating silt or animals	3.82	0.262	0.45	83.9	2.27	0.374	0.27	59.1
Unsanitary air vent	1.25	0.302	0.25	57.5	1.25	0.289	0.27	59.7
Unsanitary overflow pipe	0.32	0.136	0.06	39.1	1.08	0.289	0.25	57.1
Inadequate fence	1.19	0.291	0.26	58.6	1.08	0.289	0.25	57.1
Animals within 10 m of spring	1.60	0.224	0.40	76.1	1.43	0.233	0.38	73.0
Diversion ditch absent or faulty	1.15	0.370	0.17	48.5	1.71	0.320	0.25	57.1
Uphill contamination (e.g. latrines, waste)	1.03	0.273	0.26	58.2	0.70	0.233	0.18	50.2
Lacking source protection	1.03	0.273	0.26	58.2	1.11	0.262	0.29	62.2
Latrines within 30 m	1.22	0.352	0.19	50.9	0.41	0.224	0.06	39.7
Surface water	1.96	0.177	0.48	101	2.10	0.142	0.56	118
Not cleaned within the last month	1.13	0.319	0.22	52.2	0.70	0.291	0.14	44.5
Cleaned less than once per year	1.67	0.431	0.13	23.5	3.00	0.314	0.25	29.3

3.2.2 Season

Odds ratios were calculated to compare dry and wet season groups over all five quality thresholds. The dates of the wet and dry season were determined by graphing spring capture flow data collected during sampling and estimating the start and end of low flows. The dry season was taken as December 16, 2015 through May 20, 2016.

There were no statistically significant results. Odds ratios comparing dry and wet season contamination for *E. coli* thresholds ranged between 0.81 and 2.57, with *p* values ranging from 0.109 to 0.284.

Odds ratios were also evaluated excluding wet season values from October through December, before the dry season. Post-dry season flows (April through June) are expected to have the worst quality (Wright 1986, Kostyla *et al*. 2015). However, no statistically significant relationship was found; odds ratios ranged from 0.46 to 2.00, with *p* values from 0.157 to 0.243.

Graphs of seasonal changes at Quebrada Caracol, Marciano, and Lino sources did not appear to show a relationship between flow variation and water quality except in one case; total coliform contamination seemed to follow flow rate variation at the Marciano spring capture. Figure 3 shows seasonal flow and total coliform variation at the Marciano spring capture.

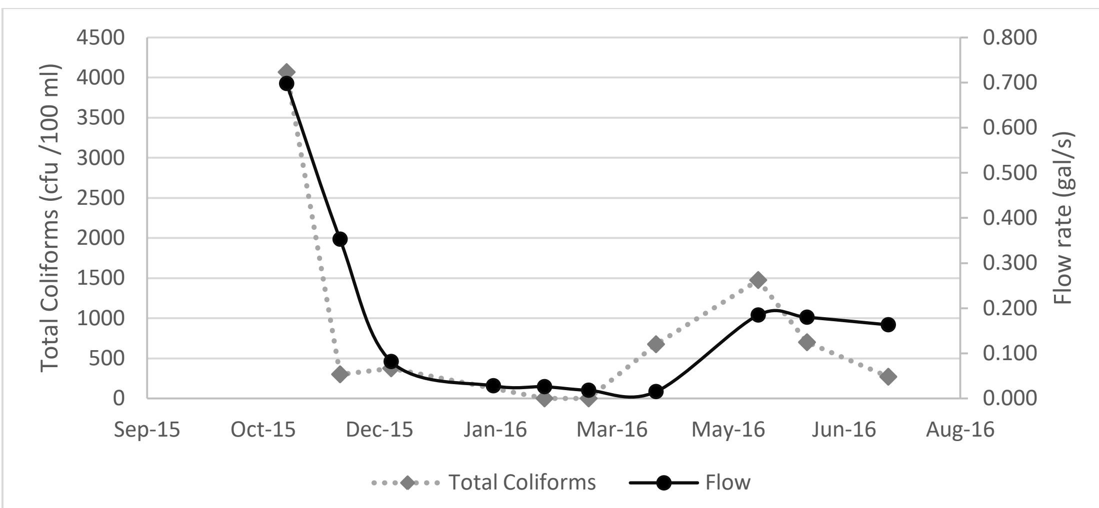

Figure 3. Seasonal variation in flow and total coliforms at Marciano spring capture

3.2.3 Weather

Weather conditions were recorded on sampling days. Odds ratios were calculated for two groups: sample days with and without rain. The only statistically significant result was an odds ratio of 6.50 with a *p* value of 0.019, linking rain and total coliform levels over 1000 CFU/100 ml. Odds ratios for other quality thresholds ranged from 0.48 to 2.36, with *p* values between 0.120 and 0.228.

3.2.4 Cerro Ceniza and Cerro Iglesias

Despite their proximity, Cerro Ceniza and Cerro Iglesias are managed differently. Cerro Iglesias has a protected region at the crown of the hill where no agricultural activity is permitted, whereas ranching and crop cultivation reach the highest slopes of Cerro Ceniza. Both hills have clusters of groundwater springs that serve communities stretching down the hillsides.

Odds ratios were calculated comparing Cerro Ceniza and Cerro Iglesias spring captures, with the hypothesis that Cerro Ceniza was more likely to be contaminated. There was no strong evidence to support or reject this hypothesis. Odds ratios over the five quality thresholds ranged from 1.00 to 1.64 with p values from 0.272 to 0.313.

3.3 Data quality control

3.3.1 Multi-plate samples

To evaluate the precision of the data collected, eleven samples were double-plated—water from the same jar was plated twice consecutively. In addition, two samples were plated five times and one sample was plated six times. The double plates had an average percent difference of 44% for *E. coli* and 35% for total coliforms. Standard deviation for all multi-plate samples ranged from 0 to 141 CFU/100 ml, with a mean of 36 for *E. coli*, and 18 to 1255 CFU/100 ml, with a mean of 422 for total coliforms. The average coefficient of variation (the ratio of the standard deviation to the mean) was 58% for *E. coli* and 30% for total coliforms, and 11% for *E. coli* and 4% for total coliforms when calculated with log 10 counts per Brown *et al.* 2011. “Previously reported coefficients of variation, a measure of repeatability (Hendricks and Robey 1936), for *E. coli* in single laboratory tests range from 3.3 to 27.3% (Brenner et al. 1993) and 8.6 to 40.6% overall (inter-laboratory, AOAC 1989)” (page 921, Brown *et al.* 2011). Coefficients of variation from this study fall within the range, suggesting the method used provides repeatable results.

3.3.2 Comparison to MINSA data

MINSA periodically samples water quality in the Comarca Ngäbe-Buglé in collaboration with community leaders and Peace Corps volunteers. It limits test locations by a maximum transport time of six hours to the San Felix laboratory. The MINSA lab evaluates 100 ml samples using Collilert©, producing estimates of MPN for both *E. coli* and total coliforms. The MINSA water samples were taken in February and June 2015, several months before the beginning of this study.

Table 6: Water quality data comparison for three locations

	Quebrada Caracol		Marciano		Lino	
	E. coli	Total coliforms	*E. coli*	Total coliforms	*E. coli*	Total coliforms
MINSA results	83.9	58.6*	0	2419.6	0	2419.6
Results from this study	125	1925	400	4466.7	33.3	2500
	350	6700	250	550	1350	2700
	0	1850	25	400	25	2325
	50	3550	0	0	0	1350
	2050	3350	0	0	350	400
	0	11400	0	675	0	1175
	1100	5400	0	1475	400	1762.5
	200	5450	100	800	0	565
	375	4575	0	270	50	4125
	4050	11550			300	6225
	650	4425				
	70.8	2854.2				

MINSA water quality results are shaded
****As reported in MINSA records. Possible clerical error, lower than recorded E. coli for same sample***

Table 6 shows the comparison of water quality data from this study to MINSA water quality data from 2015 for the same locations. To test whether samples from this study produced reasonable results, MINSA test results from Quebrada Caracol and Cerro Ceniza were compared to the range of values from monthly samples from Quebrada Caracol, Lino, and Marciano sources. For Quebrada Caracol, the MINSA *E. coli* value agreed well with the distribution from this study; however, the total coliform value reported by MINSA was much lower than any values recorded by this study. MINSA sampled the Cerro Ceniza Abajo system at the tank, not the individual sources, but *E. coli* and total coliform values from their sample fell within the ranges for both Marciano and Lino spring captures.

4. Discussion[4]

4.1 Assessment of results

The odds ratio analysis produced some interesting results; however, a surprising number of odds ratios were less than or equal to one, indicating that water quality is not strongly related to contamination risks tested in this study. Far from suggesting that WHO recommendations are ineffective, this is most likely the result of lack of diversity in sample sites. It is important to note that the *p* values are large for most of these results which indicates that these odds ratios may be a reflection of random variation in sampling. The majority of sites had

[4] Material in this chapter is planned for journal submission.

contaminated water and multiple poor sanitary practices, making it difficult to isolate the effect of any individual practice. Therefore, a more conclusive study would include a larger number and variety of sites.

4.1.1 Sanitary surveys

Sanitary practices with statistically significant odds ratios included keeping animals more than ten meters away from the source and regularly cleaning spring capture structures. The implementation of those measures is discussed in Section 4.3. Surprisingly, drainage of surface water was not related to water quality at a threshold of 200 CFU/100 ml for *E. coli*. However, this is not to say these sanitary practices should be discontinued. All of the WHO recommendations are most likely beneficial, although most are not statistically confirmed by this study.

4.1.2 Season and weather

A few statistically significant odds ratios suggest there is some relationship between rainfall and total coliform levels, though it is not strongly demonstrated in this study. This relationship should inform sampling regimes as well as maintenance plans. Though no strong trends in seasonal variation were observed in the three spring captures that were monitored on a monthly basis, water samples should be collected in the wet season to capture the lowest quality values. Water managers should expect higher contamination during rain events and take measures to protect the community.

4.1.3 Protected lands

Although this study provides no evidence to promote or discredit the value of protecting the higher elevations of Cerro Iglesias for water quality purposes, watershed protection has many benefits. Anecdotally, dry season flows have increased since the region of Cerro Iglesias above existing communities was designated as protected.

4.1.4 Data quality control

When calculated with log 10 counts, per Brown *et al.* 2011, the sample method appears to be repeatable. Except in one case, the MINSA samples were within the range of values seen in this study for water quality at the Quebrada Caracol, Marciano, and Lino sources. This agreement shows relative water quality results in agreement with those produced by the more rigorous testing methods implemented by MINSA.

4.1.5 Opportunities for further study

While this study brings to light the high contamination levels in drinking water sources in the Comarca Ngäbe-Buglé and identifies two important sanitary risks that are contributing to the problem, there is ample opportunity to further explore the causes of contamination. Testing for other pathogens, especially parasites, could further help in prioritizing sanitary risks. A longer-term study would be more effective in illustrating seasonal quality variation, and whether it is more significant in some spring sources. An important question that was not answered by this study is whether ineffective soil filtration or poor source protection are more culpable in spring contamination. Answering this question would require a better understanding of the underlying geology, soil structure, and groundwater flow in the area. A dye study or monitoring isotope levels would both be potential methods to determine the

travel time from rain drop to spring water. However, these methods would be expensive and logistically challenging in this remote region.

4.2 Community management in the Comarca Ngäbe-Buglé

During long hikes in the company of water managers and Peace Corps volunteers deeply concerned with maintenance and water quality issues, the author collected extensive notes on the challenges they faced. These notes on informal conversations, combined with the sanitary surveys and standard questions about source history, comprised a dataset that gave insight into the realities of managing water systems in the Comarca Ngäbe-Buglé.

Coding was used to conceptualize common themes such as "land tenure" and "relationship to Peace Corps" per Corbin and Strauss (1998). Of particular interest were associations between maintenance practices and themes of leadership and burnout, community cohesiveness, and relationship with the Peace Corps. Land tenure, dispersion of communities, and conflict were other themes that emerged from the coded notes. These important concepts were especially striking where the author's expectation of quality varied from the microbiological test results.

Many of the challenges faced by water committees were common in other regions relying on community management. Water system development in the Comarca Ngäbe-Buglé has followed the community management model, which requires communities to demonstrate willingness to pay and contribute part of the initial construction costs—a minimum of 25% for Peace Corps projects, and all of the operation and maintenance costs. The community management model was developed in response to failures of governments to provide rural water access; it was a move to include communities in water utility decision-making (Harvey and Reed 2007). While empowering communities to choose the appropriate solutions for their water needs has improved access outcomes, it fails to support sustainable water systems in many communities (Moriarty *et al*. 2013). The issues stem from unrealistic expectations of the financial and volunteer labor capacity, as well as an idealization of community cohesion that would never be expected in wealthier countries (Harvey and Reed 2007). Financial and technical support should not be the sole responsibility of poor, rural communities in order to receive the basic human right of water access (Moriarty *et al*. 2013). Resource-strapped communities should have the right to opt out of carrying the responsibility for maintaining their water systems (Harvey and Reed 2007).

In Panama, the community management system was formalized by *Decretos Ejecutivos* (executive decrees by the President of Panama) N. 28 and N. 40 in 1994, which required rural communities to form democratically elected, non-profit volunteer groups to manage and operate their own water systems. While these community organizations were ultimately responsible for financing operations and maintenance (see Table 7 for estimated costs), they were to receive technical support and training from MINSA. In 2014, *Decreto Ejecutivo* N. 1839 elaborated on the roles and responsibilities of community organizations, water users, and MINSA in water system management. The new decree lays out sanctions for organizations and users that do not comply with the new regulations, including fines for organizations who fail to chlorinate the water supply.

In reality, few communities receive support, training, or even visits from MINSA. While MINSA has an office of technicians, it is understaffed, with one technician per district. Roughly seven technicians are charged with supporting a dispersed population of 300,000 with limited road access. A post-project assessment of systems constructed as partnerships between Peace Corps and communities showed systems tended to deteriorate after a few years and recommended institutionalized support mechanisms, such as circuit riders, to provide continuing support (Suzuki 2010). Promised government funding for water quality monitoring and training, including a regional training facility for community water organizations, has failed to materialize in the Comarca Ngäbe-Buglé.

Many community water managers have limited knowledge and resources for water system repair. Common repairs include plastic bags instead of glue for connecting pipe sections, using fire to mold plastic pipe fittings, and piercing a hole in the pipe then putting in a stick to serve as an air release valve—all inadequate repairs that can cause contamination (Suzuki 2010). Even if they are aware the laws exist, water managers may ignore them in favor of practical solutions that do not cause community conflict. For example, the new law sets minimum water fees of $3.00/month in dispersed rural communities, such as those in the Comarca Ngäbe-Buglé. Current fees range from $0.25 to $1.00 per month, and many users are unwilling or unable to pay those. Water managers are unlikely to raise fees, and also unlikely to face any consequences for failing to do so, just as they do not receive the benefits laid out in the legislation.

In making recommendations for source protection improvements, it is important to consider the resources required for various solutions. Construction materials and transportation are the largest expenses. As previously mentioned, maintenance labor is typically on a volunteer basis, and therefore "free," but still represents a cost. Inspiring community-wide workdays requires political capital and incentives because it comes at the cost of lost opportunity for subsistence farming.

During the course of this study, the author had the opportunity to speak with many community leaders and Peace Corps volunteers about the challenges and strengths of their water systems. Perhaps the most effective way to communicate the challenges that face water managers seeking to implement source protections is to give concrete examples of their struggles, including financial challenges.

4.3 Implementation challenges

Barriers to implementing source improvements and adequate maintenance practices in community water systems include cost and labor. Table 7 shows the estimated costs of each recommended sanitary improvement (full budgets are shown in Appendix E). The challenges of labor are discussed below.

Table 7: Costs of source improvements

Issue	Range of Cost Including Labor		Range of Cost Without Labor	
Lacking spring box	$274	$460	$210	$300
Masonry or backfill area faulty or eroded	$43	$51	$27	$35
Unsanitary inspection cover	$53	$61	$37	$45
Contaminating silt or animals/infrequent cleaning	$2	$8	$0	$0
Unsanitary air vent	$5	$19	$3	$11
Unsanitary overflow pipe	$7	$26	$5	$18
Inadequate fence (10 m) [200 m]	($72) [$770]	($246) [$11,210]	($40) [$610]	($150) [$11,050]
Animals within 10 m of spring	$0	$660	$0	$500
Diversion ditch absent or faulty/surface water	$8	$84	$0	$20
Uphill contamination (e.g. latrines, waste)	$0	$114	$0	$50
Unprotected source	$0	$50	$0	$50

The market value of labor in the author's home community was about $8 per day for eight hours of unskilled work. A typical volunteer work day was four to eight hours and also required food, either brought pot-luck style by the work day participants, provided by a community leader, or a combination of the two. Typically, each family on the water system is responsible for sending one worker or cook to the work day. Some communities levy fines against families who miss work days without an excuse in the range of $1 to $3 per missed day.

Even basic maintenance such as cutting the vegetation that grows along the pipeline—an important part of preventing roots from damaging the pipe—is labor-intensive work since it was done completely by hand with machetes. Repairing a broken section of pipe might include excavating a six-foot section with a pick ax or iron bar to remove rocks, an exhausting process. Tools were frequently damaged from over-use or lost, another cost borne by volunteers. Repairing a pick ax handle was a lengthy process that involved shaping a new one from the heartwood of a specific tree and using a machete to whittle it down to the appropriate girth.

Seemingly small repairs can also be challenging, as in the example of adding a mesh screen to an overflow pipe to prevent animals and insects from entering through it to the spring capture. The function of an overflow pipe is to allow excess flows—above what can be conveyed by the transmission line—to escape from the spring capture structure. The lack of an overflow pipe can cause backpressure to build and damage the spring capture structure, or worse, reroute spring flows away from the capture structure. Buying a small piece of screen to install would include travelling to and from San Felix (where the mesh would hopefully be available) at a

cost of $2 to $10 and four to six hours to make the purchase. Materials are often paid for out of pocket, since many water systems do not collect sufficient fees to meet maintenance needs. The water manager would then need to find or buy a cutting tool to trim the mesh to the appropriate size, then hike to the source to install it. Many water managers did not find this repair to be worth their time.

In one case, the overflow was rendered less sanitary when a community member cut off the pipe to repair another part of the system, increasing the likelihood that animals could enter the capture structure. Another common unsanitary practice was blocking overflow pipes with plastic bags filled with rocks or soil. Many community water managers, not understanding the hydraulic principles that govern pipe flow, assume blocking the overflow would generate more flow in the system when in reality it can damage the spring capture structure and contaminate the source.

Understanding general implementation challenges is key to promoting realistic solutions for drinking water source improvements. It is also important to describe challenges specific to the contamination risks identified by the odds ratio analysis.

4.3.1 Animals within 10 meters

Fecal contamination from cows and chickens is an issue for many water sources. Many springs are near houses because people settle near the springs as a water source. Often, there are few options for spring sources, and ones in populated areas must be used. Households typically keep chickens as a source of protein, and cattle are a common investment. Cattle owners need water to maintain their herd through the dry season.

In one community, cattle used a water source that was directly uphill of the spring capture. The situation was complicated by the fact that the source was not on Comarca land and was owned by a Latino living in San Felix. He had a verbal agreement with the community that they could use the lower source (inconvenient for watering cattle because of the steep terrain), which was also on his land, provided they did not interfere with his cattle farming activities. This source had very high levels of contamination.

Inside the Comarca, lands can be community owned or privately owned by only Ngäbe or Buglé people (Runk 2012). MiAmbiente grants water rights to communities that request them for a community source per their recognition of the universal right to clean drinking water (ANAM 2011). In practice, private landowners can still prevent access. In order to reach water sources, water managers often must pass through privately owned lands, sometimes adjacent to homes. Private landowners might decide to restrict access, especially if there are conflicts between the family and the water manager.

MiAmbiente and MINSA encourage water managers to get a legal document protecting the right to use the source and land immediately around it. In one case, despite having this paperwork, a water manager discovered that a landowner was cutting the pipe to the system because he wanted the source for his personal use and cattle. The water manager repaired the pipe each time the landowner cut it, until the landowner simply grew tired of cutting the pipe and gave up. Several communities tried to avoid this problem by buying the land around

the source, or otherwise appeasing landowners. In one community, they were granted land in exchange for constructing a separate water system for the landowner, who would not be included in the community system. Other systems were designed to provide a tap stand near the source for use by nearby land owners or cattle, at a cost to hydraulic pressure in the system but with the benefit of avoiding conflict with the landowner.

4.3.2 Cleaning spring capture structures

Cleaning out a spring capture structure entails hiking to the source, opening the hatch and cleanout pipe, and scooping out the accumulated sediments with a bowl or cup. The walls and lid should also be washed down, and this process continued until the structure is clean and the water runs clear. The time commitment is significant; cleaning out the spring capture could take anywhere from an hour-and-a-half to seven hours, depending on the distance from the community to the source. The Peace Corps recommends four annual cleanings: at the beginning of the dry season (after high flows at the end of the wet season), at the beginning of the wet season, and twice more during the wet season. However, the required frequency for cleaning out capture structures depends on the quality of the groundwater spring and spring capture structure. In reality, whether or not a spring capture is cleaned depends on the will of volunteers who manage the aqueduct. In a few cases, water managers had cleaned the source in advance of the sample date to show the system at its best to a visitor. One community, where the source was nearby, cleaned the spring capture every two weeks because of the high sediment content of the spring. In the absence of frequent cleanings, users complained that water was brown and unappealing. Others were not so diligent, experiencing periodically high turbidity, especially during heavy rain events. In one town, water users often left taps running after heavy rains to clean out turbid water before collecting it for drinking, cooking, or even laundry.

5. Conclusion[5]

The goal of this study was to identify practical, cost-effective drinking water source protection measures in the Comarca Ngäbe-Buglé, a remote indigenous region of Panama. Two source protection practices were identified through statistical analysis of bacterial counts as top priorities to address the substandard drinking water source quality in the region,

(1) Preventing animals (such as cows, chickens, horses, and pigs) from approaching within 10 meters of drinking water sources
(2) Frequent cleaning of spring capture structures

Since rain events were also associated with heightened levels of total coliforms, sources should have more frequent cleanings at these times. Additionally, water quality sampling schemes should include wet season measurements to ensure they capture worst-case quality.

Simple tests that indicate the presence of fecal bacteria and sanitary surveys are useful tools for communities and MINSA officials that cannot afford frequent complex microbiological

[5] Material in this chapter is planned for journal submission.

testing. Over the course of the study, at least one water system manager implemented source protection improvements after receiving the sanitary inspection results. Encouraging water committees to include sanitary surveys and frequent cleanings in their source maintenance regime would be a good step for NGOs, Peace Corps Volunteers, and MINSA officials in the Comarca Ngäbe-Buglé seeking to improve water quality. For other contamination risks that are more challenging to implement, or less well known, organizations should provide more extensive training and resources.

Because of the complicated nature of land tenure in the Comarca, some communities will continue to struggle in relocating livestock from the area around their drinking water source. Understanding the complex issues that hinder implementation will allow more creative and impactful approaches to addressing this problem, such as compromises with the land owner described in the previous section.

Increasing treatment will also be an important part of reducing diarrhea in the region. Despite efforts by MINSA, Waterlines, and the Peace Corps to promote water treatment, only two of the systems were delivering chlorinated water at the time of sampling, and in both cases the water manager admitted chlorination was inconsistent. Water managers cited users disliking the taste, faulty chlorinators, confusion about appropriate dose, and the inconvenience and expense of travelling to MINSA facilities to get free chlorine tablets (where they were not consistently available) as reasons for not treating the water supply.

It is tempting to see the results of this study as a set of intuitive and easy-to-follow recommendations. None of the WHO-recommended practices highlighted by the sanitary survey are revolutionary solutions to water contamination issues. Nevertheless, simple water system maintenance is often a great challenge in remote communities in the Comarca Ngäbe-Buglé for reasons that are not immediately apparent to outsiders or even to Panamanians from other regions.

The implementation of source protection methods can only be achieved in the long run with increased financial and technical support for remote, rural communities on the part of the Panamanian government. It should fund training programs dictated by the *Dectretos Ejecutivos* and expand the role of MINSA in assisting water committees to include providing funds for operations, maintenance, and management in areas that are unable to cope with the administrative burden of managing a water system. This could include mediating disputes and agreements between community managers and landowners, training community managers on the importance and appropriate frequency for cleaning, and providing a regional fund for maintenance labor and materials. Other organizations, such as the Peace Corps, could be tapped to contribute to these training efforts. Capable community water managers should receive the financial and technical support they need to continue maintaining systems, but communities with no capacity or time to manage a water system should not be deprived of the basic human right of water, nor sentenced to illness, diarrhea and – in too many cases – needless death.

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Appendices

Appendix A - Notes on additional criteria for sanitary survey responses

Table A: Additional criteria for sanitary survey responses	
Question	Notes
1. Is the collection or spring box absent or faulty?	No spring boxes were "absent or faulty" because the author took this to mean there was either no capture structure (outside the scope of this study) or it was completely non-functional.
2. Is the masonry or backfill area protecting the spring faulty or eroded?	A common backfill erosion involved a rock coming out of the backfill leaving a hole.
3. If there is a spring box, is there an unsanitary inspection cover?	Unsanitary inspection covers included cracked or broken lids as well as lids with no raised rim.
4. Does the spring box contain contaminating silt or animals?	Animals commonly found inside the springs were spiders and freshwater crabs.
5. Is there an air vent in the masonry and is it unsanitary?	A sanitary air vent had a cap with a small hole or a bent section to prevent the easy entry of animals and other contaminants.
6. Is there an overflow pipe, is it unsanitary?	A sanitary overflow had a method of preventing animals from entering such as a mesh screen.
7. Is the fence around the spring inadequate?	An adequate fence had to be in good repair and enclose at least a 10 m radius around the source.
8. Can animals have access to within 10 m of the spring?	The frequent presence of animals was determined by interviewing the guide, looking for evidence of animals (droppings, paths that were used for animal passage, presence of households nearby who kept livestock), and included animal passage downstream of the source, as they could potentially stray close to the structure and cause contamination.
9. Is the diversion ditch above the spring absent or not working properly?	
10. Are there any other sources of contamination uphill of the spring (e.g., latrines, waste)?	Contaminants were taken to specifically include solid waste, agrochemicals, and latrines within 30m. The presence of these was determined by interviewing the guide and visual inspection.

Appendix B - Statistical formulas

Fisher's Exact Probability, one-sided (McHugh 2009)

$$\mathrm{p} = \frac{(\mathrm{a}+\mathrm{b})!\,(\boldsymbol{c}+\boldsymbol{d})!\,(a+c)!\,(b+d)!}{\boldsymbol{n}!\,\boldsymbol{a}!\,\boldsymbol{b}!\,\boldsymbol{c}!\,\boldsymbol{d}!}$$

where,

a – number of samples with bad outcomes (e.g. *E. coli* above a certain threshold), in groups with standard (unimproved) treatment (e.g. faulty protection practices)

b – number of samples with bad outcomes (e.g. *E. coli* above a certain threshold), in groups with improved treatment (e.g. improved protection practices)

c – number of samples with good outcomes (e.g. *E. coli* below a certain threshold), in groups with standard (unimproved) treatment (e.g. faulty protection practices)

d – number of samples with good outcomes (e.g. *E. coli* below a certain threshold), in groups with improved treatment (e.g. improved protection practices)

95% Confidence Interval (CI) (Sheshkin 2004)

$$\exp(\ln OR - 1.96 * SE),$$

$$\exp(\ln OR + 1.96 * SE)$$

$$SE\{\ln OR\} = \sqrt{\frac{1}{a}+\frac{1}{b}+\frac{1}{c}+\frac{1}{d}}$$

Appendix C - Complete odds ratio tables

Table C.1: Complete odds ratio calculation over '0' E. coli CFU/100 ml threshold

	a) yes, E. coli > 0	b) no, E. coli > 0	c) yes, 0 E. coli	d) no, 0 E. coli	OR	SUM	p	SE {ln(OR)}	95% CI, low bound	95% CI, high bound
1. Is the collection or spring box absent or faulty?	0	24	0	16	#DIV/0!	40	1.000	#DIV/0!	#DIV/0!	#DIV/0!
2. Is the masonry or backfill area protecting the spring faulty or eroded?	13	12	7	9	1.39	41	0.221	0.64	0.39	88.8
3. If there is a spring box, is there an unsanitary inspection cover?	8	16	5	12	1.20	41	0.258	0.69	0.31	75.7
4. Does the spring box contain contaminating silt or animals?	23	1	13	3	5.31	40	0.147	1.21	0.50	106
5. Is there an air vent in the masonry and is it unsanitary?	5	19	6	10	0.44	40	0.147	0.72	0.11	49.3
6. Is there an overflow pipe, is it unsanitary?	16	8	13	3	0.46	40	0.178	0.77	0.10	48.8
7. Is the fence around the spring inadequate?	17	7	11	5	1.10	40	0.271	0.70	0.28	69.1

Table C.1 continued

8. Can animals have access to within 10 m of the spring?	13	11	7	9	1.52	40	0.207	0.65	0.43	92.1
9. Is the diversion ditch above the spring absent or not working properly?	22	2	13	3	2.54	40	0.235	0.98	0.37	83.2
10. Are there any other sources of contamination uphill of the spring (e.g. latrines, waste)?	14	10	8	8	1.40	40	0.223	0.65	0.39	86.3
Additional Questions										
Does the source lack protection? (answer no if it is legally protected OR has a fence)	15	9	7	9	2.14	40	0.132	0.66	0.59	127
If there is a fence, does it fail to comply with MiAmbiente recommendations?	24	0	16	0	#DIV/0!	40	1.000	#DIV/0!	#DIV/0!	#DIV/0!
Are there latrines within 30 m of the spring?	5	19	2	14	1.84	40	0.274	0.91	0.31	73.6
Is there surface water near the spring on the date of the sample?	9	17	8	11	0.73	45	0.214	0.62	0.22	68.6
Not cleaned in the last month?	22	3	6	8	9.78	39	0.004	0.82	1.96	1834
Not cleaned at least once a year?	4	10	0	8	7.29	22	0.137	1.56	0.34	43.0
Not built or renovated in the last three years?	12	11	9	6	0.73	38	0.235	0.67	0.19	55.7

Table C.2: Complete odds ratio calculation over 100 E. coli CFU/100 ml threshold

	a) yes, E. coli > 100	b) no, E. coli > 100	c) yes, E. coli <= 100	d) no, E. coli <= 100	OR	SUM	p	SE{ln (OR)}	95% CI, low bound	95% CI, high bound
1. Is the collection or spring box absent or faulty?	0	11	0	26	#DIV/0!	37	1	#DIV/0!	#DIV/0!	#DIV/0!
2. Is the masonry or backfill area protecting the spring faulty or eroded?	5	7	13	13	0.71	38	0.245	0.7	0.18	54
3. If there is a spring box, is there an unsanitary inspection cover?	2	9	10	17	0.38	38	0.171	0.88	0.07	43.4
4. Does the spring box contain contaminating silt or animals?	11	0	22	4	4.6	37	0.226	1.53	0.23	57.8
5. Is there an air vent in the masonry and is it unsanitary?	3	8	7	19	1.02	37	0.312	0.81	0.21	55.7
6. Is there an overflow pipe, is it unsanitary?	6	5	20	6	0.36	37	0.124	0.76	0.08	43.3
7. Is the fence around the spring inadequate?	8	3	18	8	1.19	37	0.301	0.8	0.25	60.1

Table C.2 continued										
8. Can animals have access to within 10 m of the spring?	7	4	10	16	2.8	37	0.11	0.75	0.65	132
9. Is the diversion ditch above the spring absent or not working properly?	10	1	22	4	1.82	37	0.377	1.18	0.18	52.6
10. Are there any other sources of contamination uphill of the spring (e.g. latrines, waste)?	7	4	12	14	2.04	37	0.18	0.74	0.48	94.6
Additional Questions										
Does the source lack protection? (answer no if it is legally protected OR has a fence)	6	5	13	13	1.2	37	0.272	0.72	0.29	65.5
If there is a fence, does it fail to comply with MiAmbiente recommendations?	11	0	26	0	#DIV/0!	37	1	#DIV/0!	#DIV/0!	#DIV/0!
Are there latrines within 30 m of the spring?	2	9	4	22	1.22	37	0.354	0.95	0.19	53.6
Is there surface water near the spring on the date of the sample?	2	11	13	16	0.22	42	0.054	0.85	0.04	45.6
Not cleaned in the last month?	11	1	14	10	7.86	36	0.039	1.12	0.87	198
Not cleaned at least once a year?	3	4	1	13	9.75	21	0.082	1.29	0.78	96.9
Not built or renovated in the last three years?	6	5	14	10	0.86	35	0.279	0.73	0.2	52.2

Table C.3: Complete odds ratio calculation over 200 E. coli CFU/100 ml threshold

	a) yes, total E. coli > 200	b) no, E. coli > 200	c) yes, E. coli <= 200	d) no, E. coli <= 200	OR	SUM	p	SE{ln (OR)}	95% CI, low bound	95% CI, high bound
1. Is the collection or spring box absent or faulty?	0	8	0	29	#DIV/0!	37	1	#DIV/0!	#DIV/0!	#DIV/0!
2. Is the masonry or backfill area protecting the spring faulty or eroded?	3	5	15	15	0.6	38	0.259	0.82	0.12	48.2
3. If there is a spring box, is there an unsanitary inspection cover?	2	6	10	20	0.67	38	0.311	0.9	0.11	47.5
4. Does the spring box contain contaminating silt or animals?	8	0	25	4	3	37	0.36	1.54	0.15	49.3
5. Is there an air vent in the masonry and is it unsanitary?	2	6	8	21	0.88	37	0.345	0.92	0.15	49.2
6. Is there an overflow pipe, is it unsanitary?	5	3	21	8	0.63	37	0.281	0.84	0.12	47
7. Is the fence around the spring inadequate?	5	3	21	8	0.63	37	0.281	0.84	0.12	47
8. Can animals have access to within 10 m of the spring?	6	2	11	18	4.91	37	0.061	0.9	0.84	191

Table C.3 continued

9. Is the diversion ditch above the spring absent or not working properly?	8	0	24	5	3.82	37	0.272	1.53	0.19	53.7
10. Are there any other sources of contamination uphill of the spring (e.g. latrines, waste)?	4	4	15	14	0.93	37	0.307	0.8	0.2	54.2
Additional Questions										
Does the source lack protection? (answer no if it is legally protected OR has a fence)	5	3	14	15	1.79	37	0.246	0.82	0.36	74.7
If there is a fence, does it fail to comply with MiAmbiente recommendations?	8	0	29	0	#DIV/0!	37	1	#DIV/0!	#DIV/0!	#DIV/0!
Are there latrines within 30 m of the spring?	1	7	5	24	0.69	37	0.409	1.18	0.07	42.3
Is there surface water near the spring on the date of the sample?	2	7	13	20	0.44	42	0.209	0.88	0.08	49
Not cleaned in the last month?	8	0	17	11	11.17	36	0.036	1.5	0.59	114
Not cleaned at least once a year?	3	2	1	15	22.5	21	0.027	1.38	1.51	405
Not built or renovated in the last three years?	6	2	14	13	2.79	35	0.173	0.9	0.47	88.8

Table C.4: Complete odds ratio calculation over 1000 total coliform CFU/100 ml threshold

	a) yes, total coliforms > 1000	b) no, total coliforms > 1000	c) yes, total coliforms<= 1000	d) no, total coliforms <= 1000	OR	SUM	p	SE{ln (OR)}	95% CI, low bound	95% CI, high bound
1. Is the collection or spring box absent or faulty?	0	22	0	13	#DIV/0!	35	1	#DIV/0!	#DIV/0!	#DIV/0!
2. Is the masonry or backfill area protecting the spring faulty or eroded?	12	11	7	6	0.94	36	0.27	0.7	0.24	57.5
3. If there is a spring box, is there an unsanitary inspection cover?	4	18	5	8	0.36	35	0.133	0.79	0.07	40.5
4. Does the spring box contain contaminating silt or animals?	21	1	11	2	3.82	35	0.262	1.1	0.45	83.9
5. Is there an air vent in the masonry and is it unsanitary?	6	16	3	10	1.25	35	0.302	0.81	0.25	57.5
6. Is there an overflow pipe, is it unsanitary?	14	8	11	2	0.32	35	0.136	0.89	0.06	39.1
7. Is the fence around the spring inadequate?	16	6	9	4	1.19	35	0.291	0.77	0.26	58.6

Table C.4 continued

8. Can animals have access to within 10 m of the spring?	11	11	5	8	1.6	35	0.224	0.71	0.4	76.1
9. Is the diversion ditch above the spring absent or not working properly?	19	3	11	2	1.15	35	0.37	0.99	0.17	48.5
10. Are there any other sources of contamination uphill of the spring (e.g. latrines, waste)?	12	10	7	6	1.03	35	0.273	0.7	0.26	58.2
Additional Questions										
Does the source lack protection? (answer no if it is legally protected OR has a fence)	12	10	7	6	1.03	35	0.273	0.7	0.26	58.2
If there is a fence, does it fail to comply with MiAmbiente recommendations?	22	0	13	0	#DIV/0!	35	1	#DIV/0!	#DIV/0!	#DIV/0!
Are there latrines within 30 m of the spring?	4	18	2	11	1.22	35	0.352	0.95	0.19	50.9
Is there surface water near the spring on the date of the sample?	11	14	4	10	1.96	39	0.177	0.72	0.48	101
Not cleaned in the last month?	17	5	9	3	1.13	34	0.319	0.84	0.22	52.2
Not cleaned at least once a year?	3	9	1	5	1.67	18	0.431	1.28	0.13	23.5
Not built or renovated in the last three years?	12	8	6	7	1.75	33	0.208	0.72	0.43	76.2

Table C.5: Complete odds ratio calculation over 1500 total coliform CFU/100 ml threshold

	a) yes, total coliforms > 1500	b) no, total coliforms > 1500	c) yes, total coliforms <= 1500	d) no, total coliforms <= 1500	OR	SUM	p	SE{ln (OR)}	95% CI, low bound	95% CI, high bound
1. Is the collection or spring box absent or faulty?	0	18	0	17	#DIV/0!	35	1	#DIV/0!	#DIV/0!	#DIV/0!
2. Is the masonry or backfill area protecting the spring faulty or eroded?	10	8	9	9	1.25	36	0.247	0.67	0.34	69.7
3. If there is a spring box, is there an unsanitary inspection cover?	3	15	6	11	0.37	35	0.143	0.81	0.07	40.5
4. Does the spring box contain contaminating silt or animals?	17	1	15	2	2.27	35	0.374	1.09	0.27	59.1
5. Is there an air vent in the masonry and is it unsanitary?	5	13	4	13	1.25	35	0.289	0.78	0.27	59.7
6. Is there an overflow pipe, is it unsanitary?	13	5	12	5	1.08	35	0.289	0.75	0.25	57.1
7. Is the fence around the spring inadequate?	13	5	12	5	1.08	35	0.289	0.75	0.25	57.1
8. Can animals have access to within 10 m of the spring?	9	9	7	10	1.43	35	0.233	0.68	0.38	73

Table C.5 continued

9. Is the diversion ditch above the spring absent or not working properly?	16	2	14	3	1.71	35	0.32	0.98	0.25	57.1
10. Are there any other sources of contamination uphill of the spring (e.g. latrines, waste)?	9	9	10	7	0.7	35	0.233	0.68	0.18	50.2
Additional Questions										
Does the source lack protection? (answer no if it is legally protected OR has a fence)	10	8	9	8	1.11	35	0.262	0.68	0.29	62.2
If there is a fence, does it fail to comply with MiAmbiente recommendations?	18	0	17	0	#DIV/0!	35	1	#DIV/0!	#DIV/0!	#DIV/0!
Are there latrines within 30 m of the spring?	2	16	4	13	0.41	35	0.224	0.94	0.06	39.7
Is there surface water near the spring on the date of the sample?	9	10	6	14	2.1	39	0.142	0.67	0.56	118
Not cleaned in the last month?	14	5	12	3	0.7	34	0.291	0.83	0.14	44.5
Not cleaned at least once a year?	3	7	1	7	3	18	0.314	1.27	0.25	29.3
Not built or renovated in the last three years?	10	6	8	9	1.88	33	0.188	0.71	0.47	82.4

Table C.6: complete odds ratios for Season and weather at all thresholds

	a) faulty, E. coli > 0	b) good, E. coli > 0	c) faulty, E. Coli = 0	d) good, E. Coli = 0	OR	SUM	p	SE{ln(OR)}	95% CI, low bound	95% CI, high bound
Rain on sample date?	11	16	5	13	1.79	45	0.173	0.66	0.49	119
Wet Season?	17	10	11	7	1.08	45	0.243	0.63	0.32	83.7
Post dry season wet season?	17	10	11	7	1.08	45	0.243	0.63	0.32	83.7
E. Coli > 100 cfu/100 ml										
Rain on sample date?	6	8	7	21	2.25	42	0.139	0.69	0.58	130
Wet Season?	8	5	17	12	1.13	42	0.262	0.68	0.30	75.0
Post dry season wet season?	7	7	18	10	0.56	42	0.177	0.66	0.15	56.5
E. Coli > 200 cfu/100 ml										
Rain on sample date?	2	8	11	21	0.48	42	0.228	0.87	0.09	49.7
Wet Season?	5	4	20	13	0.81	42	0.284	0.76	0.18	60.2
Post dry season wet season?	4	5	21	12	0.46	42	0.176	0.76	0.10	51.4
Total coliforms > 1000 cfu/100 ml										
Rain on sample date?	13	12	2	12	6.50	39	0.019	0.86	1.20	409
Wet Season?	18	7	7	7	2.57	39	0.109	0.70	0.66	141
Post dry season wet season?	17	8	8	6	1.59	39	0.215	0.69	0.41	87.5
Total coliforms > 1500 cfu/100 ml										
Rain on sample date?	10	11	5	13	2.36	39	0.120	0.68	0.62	131
Wet Season?	16	6	9	8	2.37	39	0.120	0.68	0.62	132
Post dry season wet season?	15	6	10	8	2.00	39	0.157	0.68	0.53	110

Table C.7: Odds ratio comparison of Cerro Ceniza and Cerro Iglesias at all thresholds

a. Ceniza, E. coli present	b. Iglesias, E. Coli present	c. Ceniza, no E. coli	d. Iglesias, no E. coli	OR	SUM	Fisher's p	SE{ln(OR)}	95% CI, low bound	95% CI, high bound
9	11	3	6	1.64	29	0.272	0.84	0.32	54.0
a. Ceniza, E. coli >100	b. Iglesias, >100	c. Ceniza, E. coli <=100	d. Iglesias, E. coli <=100	OR		Fisher's p	SE{ln(OR)}	95% CI, low bound	95% CI, high bound
4	5	8	11	1.10	28	0.313	0.82	0.22	43.3
a. Ceniza, E. coli >200	b. Iglesias, >200	c. Ceniza, E. coli <=200	d. Iglesias, E. coli <=200	OR		Fisher's p	SE{ln(OR)}	95% CI, low bound	95% CI, high bound
4	4	8	12	1.50	28	0.290	0.84	0.29	49.3
a. Ceniza, total coliforms >1000	b. Iglesias, total coliforms >1000	c. Ceniza, total coliforms <=1000	d. Iglesias, total coliforms <=1000	OR		Fisher's p	SE{ln(OR)}	95% CI, low bound	95% CI, high bound
8	8	4	6	1.50	26	0.280	0.82	0.30	47.1
a. Ceniza, total coliforms >1500	b. Iglesias, total coliforms >1500	c. Ceniza, total coliforms <=1500	d. Iglesias, total coliforms <=1500	OR		Fisher's p	SE{ln(OR)}	95% CI, low bound	95% CI, high bound
6	7	6	7	1.00	26	0.305	0.79	0.21	39.5

Appendix D – Water quality parameters

Table D.1: Water quality parameters

Name of Source	Sample Date	Temp (°C)	Ammonia (ppm NH_3 - N)	Total Chlorine (ppm)	Free Chlorine (ppm)	Alkalinity (ppm CaCO3)	pH (5 in 1)	pH	Turbidity (ntu)
Duima	16-Jul-16	24	0.5	0	0	40	6.8	6.5	0.22
Cerro Iglesias No. 1 Left	16-Jul-16	24	0.5	0	0	120	7	7	0.55
Cerro Iglesias No. 1 Right	16-Jul-16	24.1	0.5	0	0	120	6.8	6.5	1.34
Guari #2	16-Jul-16	24.8	0.5	0	0	120	6.8	6.5	0.54
Cerro Puerco	18-Jul-16	25.8	0.5	0	0	120	6.5	6.5	2.45
Valentina	18-Jul-16	24.5	0.5	0	0	120	6.5	6	3.75
Marciano	18-Jul-16	25	0.25	0	0	120	6.5	6.5	0.91
Lino	18-Jul-16	25.5	0.25	0	0	120	6.5	6	1.3
Quebrada Caracol	19-Jul-16	26	0.375	0	0	120	6.8	6	19.5

Appendix E – Source improvement budgets

Issue	Materials and Tools	Land	Transport	Labor	Total Range	Total Without Labor
Lacking spring box	$200	$0 - $50	$10 - $50	$64 - $160	$274 - $460	$210 - $300
Masonry or backfill area faulty or eroded	$25	$0	$2 - $10	$16	$43 - $51	$27 - $35
Unsanitary inspection cover	$35	$0	$2 - $10	$16	$53 - $61	$37 - $45
Contaminating silt or animals/ infrequent cleaning	$0	$0	$0	$2 - $8	$2 - $8	$0
Unsanitary air vent	$1	$0	$2 - $10	$2 - $8	$5 - $19	$3 - $11
Unsanitary overflow pipe	$3 - $8	$0	$2 - $10	$2 - $8	$7 - $26	$5 - $18
Inadequate fence (10 m) [200 m]	($30 - $50) [$600 - $1000]	($0 - $50) [$0 - $10,000]	$10 - $50	($32 - $96) [$160]	($72 - $246) [$770 – $11,210]	($40 - $150) [$610 - $11,050]
Animals within 10 m of spring	$0	$0 - $500	$0	$0 - $160	$0 - $660	$0 - $500
Diversion ditch absent or faulty/ surface water	$0 - $20	$0	$0	$8 - $64	$8 - $84	$0 - $20
Uphill contamination (e.g. latrines, waste)	$0	$0 - $50	$0	$0 - $64	$0 - $114	$0 - $50
Unprotected source	$0	$0 - $50	$0	$0	$0 - $50	$0 - $50

Appendix F – Permission letter for Figure 2

Rob Clark 6:43 PM (2 minutes ago)

to me

I, Robert Clark, created this map for Leigh Miller expressly for her thesis and authorize its use under a creative commons Attribution 4.0 International license.

E-signed

11/14/2016

Robert Clark