Examination of Household Drinking Water Quality in the Dominican Republic

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Abstract

Introduction: Safely managed water is a basic need for all populations. However, the lack of global infrastructure decreases the provision of universal access to safely managed and improved water. In developing countries such as the Dominican Republic, contaminants are commonly found in water sources. Often, communities are expected to use those sources for household drinking water without any additional treatment. There is a need for understanding contaminants in household drinking water in the Dominican Republic. Therefore, the purpose of this study was to examine household drinking water quality in the Dominican Republic by determining the factors that contribute to household drinking water quality.

Results: A total of 1153 observations were collected through a four-month prospective cohort study from September 2005 to January 2006 from 186 households in Bonao, Dominican Republic. Evidence suggested that there was *E. coli* MPN/100mL variability among household drinking water was significantly related to water source used for collection, storage container, and household water treatment. Total coliform MPN/100mL variability in household drinking water was predicted by household water treatment, storage container, and water source used for collection. Mean turbidity NTU of household drinking water was mostly predicted by water treatment and water source used for water collection. Lastly, mean pH of household drinking water was solely predicted by water source for collection.

Conclusion: Understanding the factors that contribute to *E. coli*, total coliform, turbidity, and pH variability in household drinking water will help implement and promote programs that support water safety and management in developing countries to ensure that the community has access to safe and improved water.

Keywords: Dominican Republic, drinking water, *E. coli*, household, variability, water quality

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter I

Introduction

Safely managed and improved water is a basic need for all and should be accessible to all (United Nations, 2020). To achieve the goal of universal access to safely managed water, protection of public water sources and access to water treatment should be made available to all (World Health Organization, 2019). However, the lack of global infrastructure makes provision of universal access to safely managed water challenging (United Nations, 2020). Improving water quality is known to have a ripple effect, benefiting one's food production and other water usage, thus increasing one's quality of life (World Health Organization, 2019). Unbeknownst to many, the lack of access to improved water is not only prevalent in low- and middle-income countries. There are also some areas in high income countries that are without access to improved water (Riggs et al., 2017). Therefore, the lack of access to improved water, sanitation and hygiene is a global concern (United Nations, 2020).

Globally, safely managed water has increased from 61 to 71 percent between 2000 and 2017 (United Nations, 2020). To ensure that all countries have access to safely managed drinking water globally, the United Nations developed the Sustainable Development Goals (SDG) (United Nations, 2020). Specifically, the United Nations developed SDG 6, which ensures that all countries have available and sustainable management of water and sanitation. SDG 6 states that universal and equitable access to safe and affordable drinking water and improved hygiene for all should be achieved by 2030. To measure SDG 6, the United Nations are tracking if one has safely managed drinking water services available on the property or close enough when needed, and if it is free from contamination (United Nations, 2020). As of 2017, 6.5 billion people worldwide have access to an improved water source close to them (Joint Monitoring Program, 2017). However, improvement is still needed as 785 million people are still lacking access (United Nations, 2020). Achieving universal access to safe drinking water requires proper legislation and guidelines. Effort, cooperation, and collaboration are required from each country to achieve universal access to drinking water and improving hygiene worldwide. (United Nations, 2020).

Although water, sanitation, and hygiene issues have an impact on the entire population, those residing in developing countries suffer most from such issues (World Health Organization, 2019). That impact results in devastating health effects as 88% of deaths occur due to diarrheal diseases resulting from unsafe drinking water due to contaminated water sources (Rogers-Brown et al., 2015 and World Health Organization, 2019). Therefore, it is important to one's health that they have access to improved and safely managed water sources (United Nations, 2020). However, it is often difficult for developing countries to have access to safe and improved water sources due to the lack of funding and additional resources (Treacy, 2019). For instance, many developing countries have trouble maintaining water sources, which results in worsening water quality resulting from microbial contaminants and other pollutants (Treacy, 2019). Water sources should be sustainable for domestic use. The lack of trained professionals to test and maintain a water source's pH, temperature, turbidity, and other contaminants, result in many sources being contaminated and not safe for human consumption (World Health Organization, 2019).

When trying to maintain water sources, it is important to understand the variability of the source's contaminants and how this can contribute to improvements in water quality and in health. Previous studies have reported the positive effects of drinking water interventions that focus on improving water quality (Stauber et al., 2009). The interventions have resulted in a decrease in adverse health effects and mortality rates (Stauber et al., 2009). Understanding all of the factors that influence water quality for the implementation of water quality interventions is essential when trying to promote progress in developing countries that are in dire need.

The most common factors that contribute to water quality have been well researched. However, an examination of the underlying factors that contribute to microbial variability in drinking water is necessary. As mentioned, it is essential to examine all of the influential factors of water quality when trying to promote progress in developing countries that are in dire need. Therefore, it was vital to explore the gap in the literature by understanding the factors that resulted in microbial variability at the household level in developing countries. The purpose of this research was to explore the gap in the literature by understanding the factors that contribute to household drinking water quality in the Dominican Republic. Understanding the factors that contribute to *E. coli*, total coliform, turbidity, and pH variability can provide insight into factors that contribute to household water quality in developing counties, thus reducing disease and death and improving one's quality of life.

Chapter II

Literature Review

Worldwide overview

Globally, approximately 2 billion people use contaminated drinking water sources (World Health Organization, 2019). Access to safe water can help reduce illness and result in one having an improved life (Center for Disease Control and Prevention, 2020). Achieving safe drinking water requires measuring microbial and key chemical contaminants, which contribute to poor water quality in drinking water sources in many countries (World Health Organization, 2019). Understanding the drivers of microbial variability on water quality at the household level can result in the implementation of interventions used to improve water quality. Coliform bacteria, such as total coliforms and *Escherichia coli (E. coli),* are among the most common microbial contaminants that we can measure as indicators of possible fecal contamination (Fatemeh et al., 2014). This literature review will help create a better understanding of the importance of understanding the factors that influence microbial variability in household drinking water in developing countries such as the Dominican Republic.

Common factors that influence water quality

Physical contaminants

There are various indicators that influence and predict water quality and safety. One of these are physical contaminants, which mainly affect the appearance or other physical properties of water (Environmental Protection Agency, 2017). Sediment or organic material in water sources resulting from soil erosion and runoff results in natural physical contaminants in water sources that can contribute to the water's turbidity and pH (Cheprasov, 2016). However, not all physical contaminants are natural. Sewage being dumped in water sources is usually the result of human activity, which can result in inadequate water if not properly treated and managed before consumption. (Cheprasov, 2016).

As mentioned, physical contaminants contributing to inadequate water can be due to various things. Seasonal changes contributing to water quality are important aspects to consider when assessing physical contamination (Ouyang et al., 2006). For instance, in eastern developing countries, seasonal trends displayed higher concentrations of agricultural pollutants during wet seasons than dry seasons (Ling et al., 2017). High precipitation during wet season can increase deterioration and runoff draining into multiple water sources used for drinking water. Such water sources used for drinking water have to be protected and without protection, physical contamination of water will continue to increase (Environmental Protection Agency, 2017).

Chemical contaminants

Other types of indicators used to predict water quality and safety are chemical contaminants, which can occur naturally or manmade (Environmental Protection Agency, 2017). The Environmental Protection Agency currently regulates more than 65 chemical contaminants. However, key chemical contaminants are led, arsenic, nitrates, disinfection byproducts, and pesticides (Environmental Protection Agency, 2017). Such contaminants being present in water are also associated with adverse health effects, contributing to cancer, cardiovascular disease, neurological disease, and even miscarriages (Barrett, 2014). Thus, resulting in adverse health concerns for one’s consuming it.

Biological contaminants

Microbial indicators are often one of the main measures used to predict water safety in developing country settings (Barrett, 2014). Drinking water may reasonably be expected to contain at least small amounts of some of the previously mentioned contaminants. Total coliform bacteria consist of environmental and fecal types as many coliform bacteria indicate the presence of soil, and human and animal waste (Messner et al., 2017). In untreated groundwater, total coliforms detect surface or near surface entry into water sources often used for drinking (Invik et al., 2017). Although coliforms are easy to isolate, they are usually present in larger numbers and usually survive longer in an aquatic environment than viruses, parasites and pathogenic bacteria (Freese, 2019). Most forms of total coliforms do not result in disease under normal conditions; however, consuming doses of acute contaminants in the coliform group, such as *E. coli* can result in multiple health risks (Messner et al., 2017) According to the US Environmental Protection Agency, any form of total coliform in 100mL of water is deemed unacceptable in drinking water (Environmental Protection Agency, 2019). Therefore, all drinking water should be properly assessed and treated for coliform bacteria as it is used as a predictor of the presence or absence of additional contaminants (Environmental Protection Agency, 2019).

Additionally, *E. coli* is a special type of coliform bacteria that can be used to indicate fecal contamination and the presence of harmful organisms in water (Messner et al., 2017). It is recognized by the World Health Organization as an ‘essential parameter’ for measuring fecal contamination in water quality, and certain strains of *E. coli* strains are referred to as bacterial pathogens (World Health Organization, 2019 and Messner et al., 2017). The presence of *E. coli* indicates a strong likelihood that human or animal wastes are entering the water system, as it often grows in the intestinal tracts of animals and humans. (O' Flaherty et al., 2017). According to the World Health Organization and the Environmental Protection Agency, any concentration of *E. coli* in 100mL in drinking water sources is unacceptable and should not be present (Environmental Protection Agency, 2019 and World Health Organization, 2019).

Water source

Many water sources are used for purposes outside of drinking water, resulting in heavy pollution and an increase in contaminants (Center for Disease Control and Prevention, 2020). Unfortunately, groundwater runoff can spread contaminants from its original source to surface water sources (Denchak, 2018). Runoff between sources can result in an increase in contaminants, which insinuate the detrimental effects of unsanitary sanitation and hygiene practices in public water sources, thus, providing unsafe drinking water (Denchak, 2018). Understanding the environment that contributes to contamination will allow one to properly treat water sources, resulting in safely managed and improved water quality.

Globally, 71% of the population have access to basic water sources, and 6% have access to unimproved water sources (Joint Monitoring Program, 2017). Improved water sources are considered to be water sources protected from outside sources and unimproved water sources are the opposite (World Health Organization, 2017). Considering the definition, improved water sources should provide safe water. However, due to lack of maintenance and infrastructure, some improved water sources can be classified as having unsafe water (Shaheed et al., 2014). Additionally, many communities rely on surface and ground water to obtain their drinking water (Denchak, 2018). Surface water such as rivers, streams and lakes and ground water such as aquifers and wells, which may or may not be classified as improved are commonly used for drinking water in many countries (Environmental Protection Agency, 2019 and Denchak, 2018).

Bacterial variability

The variability of microbial contaminates in household drinking water can depend on seasonality, geographical location, water source, and other environmental factors that can influence water quality (Invik et al., 2017). To support, a 2017 study conducted by Invik et al., examined microbiological contaminants in rural well water. This study suggested that the presence of bacteria variability in well water was heavily related to season. According to Invik et al, the presence of microbial contaminants, total coliform and *E. coli*, was higher in northern areas during the warmer seasons (spring and summer) than in cooler seasons (fall and winter). The seasonal trend also supports seasonal health outcomes, such as infectious diseases that are associated with consuming contaminated water sources (Invik et al., 2017). It is important to understand that due to rainfall occurring more during warmer seasons, high presence of bacteria variability can be expected to influence water quality (Kostyla et al., 2015).

To further explain microbial variability, a 2015 study conducted by Kostyla et al also examined the difference in total coliform and *E. coli* during wet and dry seasons. According to Kostyla et al., concentrations of *E. coli* and total coliform increased significantly during wet seasons compared to dry seasons. It is believed that sanitation interacts with rainfall, contributing to the increase in microbial variability in water sources such as boreholes and piped systems, as they are more susceptible to seasonal variation than dug wells (Levy et al., 2009). Furthermore, the pattern of contamination was also greater in rural settings than urban settings which is an indicator of geographical location affecting microbial density (Kostyla et al., 2015).

In addition to the previously mentioned factors influencing water quality, geographical location can also influence water quality. For instance, according to Levy et al., (2009) concentrations of microbial bacteria in surface water were dependent on location. More specifically, variability of *E. coli* concentrations in water quality was observed at different locations in this study. However, the reported increase in bacteria can be caused by the number of people at the water collection site at the proposed times (Levy et al., 2009). One's hygiene practices such as bathing and handwashing in the different water sources that were used for household drinking water can contribute to the increase and influence water quality (Levy et al., 2009).

In contrast to previous studies, the 2009 study conducted by Levy et al. suggested that covering water storage containers was associated with an increase among microbial contaminants compared to not covering the storage container. The conflicting results of this study further supports the importance of understanding all of the factors that contribute to microbial variability in water (Levy et al., 2009). Understanding the factors that contribute to the increase in microbial variability will help improve sampling guidelines used to decrease bias and misleading data (World Health Organization, 2011). In addition, understanding why fluctuations of bacterial levels occur through improper techniques and seasonality will also help improve water quality for household drinking water (Levy et al., 2009).

Storage container

The proper storage container is necessary to influence water quality (Ogbozie et al., 2018). To ensure that water remains safe, it is important to store it in a container that protects the water from being re-contaminated (Center for Disease Control and Prevention, 2012). Storage conditions and improper storage containers contribute to contamination (Ogbozie et al., 2018). Essentially, it is ideal that a household uses a container with a small opening and a lid, a cover for the container opening, or dispensing devices such as pumps (Center for Disease Control and Prevention, 2012). In addition, narrow mouthed containers are recommended as they reduce the chance of recontamination of water (World Health Organization, 2017). Such improved containers protect household water from contamination that can occur through dippers and contaminated hands, thus influencing water quality (World Health Organization, 2017). Storing treated water in containers made from plastic, ceramic, and steel is recommended; however, due to inadequate resources, some households use clay containers (Center for Disease Control and Prevention, 2015).

Water Treatment

Total coliform and *E. coli* detection is used to measure water quality because they are considered to be non-pathogenic intestinal inhabitants that are present in feces, wastewater, and other fecal wastes in much larger numbers than pathogenic microbial contaminants (Hendricks and Pool, 2012). Because total coliform and *E. coli* can be present in large numbers, high concentrations express criteria and standards for measuring water quality (Hendricks and Pool, 2012). Treatment of water should occur according to the measurement of the pathogen detected. However, one should consider that properly treating drinking water requires various techniques and depending on the water source determines the treatment one should use (World Health Organization, 2017).

Improving water quality can occur through the practice of various methods. According to the Center for Disease Control and Prevention and the World Health Organization, developed and developing countries treat their community drinking water sources using the same methods (Center for Disease Control and Prevention, 2015 and World Health Organization, 2011). Community water treatment systems are comprised of multiple methods. Coagulation usually the first method of water treatment. Coagulation occurs by binding ions, thus creating a larger particle that can be filtered out. Sedimentation, which usually happens after coagulation and flocculation, results in larger particles becoming heavier and settling to the bottom of the water source. Filtration, which usually happens after sedimentation, resulting in the “clean” water left after sedimentation traveling through filters of various compounds (sand, ceramic, glass), removing microbial contaminants; and lastly, disinfection, which removes any contaminants remaining after filtration (Center for Disease Control, 2015 and World Health Organization, 2011). However, according to Josephine Treaty, some developing countries do not have the proper infrastructure to treat their water as efficiently and effectively as other countries; therefore, some of their treatment methods may differ (Treacy, 2019).

Household water treatment systems are comprised of many methods. For instance, some households boil their water for at least one to three minutes to treat contaminated water. Boiling household water tends to kill bacteria that can result in diarrheal diseases (Environmental Protection Agency, 2017). Some households use certain filtration systems to remove contaminants and large particles. Home filtration systems are more sustainable as they continue to operate under adverse economic, social, and environmental conditions (Meegoda, 2018). Lastly, many households disinfect water using chemicals. Treatment of water using chlorine compounds typically destroy pathogens (Hunter, 2009). However, disinfection can sometimes be ineffective as it depends on the volume of the water and size of container (Environmental Protection Agency, 2017).

Developing countries overview

Dominican Republic

As mentioned, water quality can depend on the country one resides on (Treacy, 2019). For instance, in the Dominican Republic, approximately 98% of urban and 90% of rural populations have access to safe and improved water sources, thus influencing water quality (Joint Monitoring Program, 2017). Improved water sources have the potential to provide safe water by their construction; however, many improved water sources are still contaminated and deemed unsafe. Conversely, water sources can be classified as a safe water source if it is collected from an improved water source and free of fecal and other contaminants (Joint Monitoring Program, 2017).

Additionally, one challenge developing countries face when trying to improve water quality for drinking water is the shortage of water in certain areas during some seasons (Treacy, 2019). Many areas of the Dominican Republic report tropical climates and some parts of the country suggests two wet seasons, thus increasing microbial contamination density in both areas rather than favoring one over the other (Treacy, 2019) Because many inhabitants of the Dominican Republic commonly use public water sources such as boreholes, wells, rainfall, springs, and surface water as their drinking water sources, these unpredictable climates can result in uneven distribution of water quality (Treacy, 2019). The uneven distribution of water sources results in an increase in microbial contaminants in some sources and water scarcity in others, which can ultimately influence water quality (Treacy, 2019). However, to combat the contamination of their water sources, many inhabitants in the Dominican Republic treat their drinking water by boiling, chlorination, and filtration to improve drinking water quality (Aiken et al., 2011).

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Chapter III

Manuscript

Introduction

Clean water is essential for an improved quality of life (World Health Organization, 2016). Many communities suffer harsh realities resulting from lack of access to clean water, an inadequate sanitation system, and scarcity of resources that are required to practice adequate hygiene worldwide. Inadequate water, sanitation, and hygiene, rest on the foundation of extreme poverty, lack of property tenure, lack of services, infrastructure, and an informal economy (United Nations, 2020). At-risk populations, such as those residing in developing countries, suffer most from water, sanitation, and hygiene related issues, resulting in devastating health effects (Cabral, 2010). The lack of adequate sanitation and reliable waste services have plagued households in developing countries such as the Dominican Republic, resulting in infant mortality, adverse health conditions, and the prevalence of diseases such as cholera, malaria, pneumonia, and bilharzia (Cabral, 2010). Microbial indicators such as total and fecal coliforms, *Escherichia coli (E. coli)*, are used as indicators of inadequate water, sanitation, and hygiene. Unfortunately, these microorganisms are often an indication of fecal contamination in water; which may increase disease and sometimes result in death (Rogers-Brown et al., 2015).

To some, access to an improved water source can result in the reduction of microbial contaminants in drinking water, ultimately decreasing disease and death; however, that is not always the case. Improved water source refers to water protected from an outside influence, such as piped water connections, and protected water sources such as protected springs or protected wells (Heitzinger et al., 2015). However, water sources considered to be improved are not guaranteed to be safe and free of microbial and physicochemical contaminants, thus emphasizing the need for safe water. As a result, even if considered improved, microbial and physicochemical contaminants can have a crucial impact on one's health outcomes (Rogers-Brown et al., 2015). Contaminants are commonly found in water sources in developing countries, and developing countries like the Dominican Republic, are still struggling to achieve access to safe and improved drinking water (Joint Monitoring Program, 2020). Due to poor water quality, 96.69% of the population have access to basic water services collected from an improved water source located no more than 30 minutes away (Joint Monitoring Program, 2020). Although 97% of inhabitants have access to basic drinking water, there is still a dire need for change as access to safely managed water is lacking.

Due to the lack of maintenance, sanitation services, and effective policies, it is difficult for inhabitants to have access to improved drinking water that is free of any microbial contaminants in the Dominican Republic (Treacy, 2019). Previous studies have suggested that many household drinking water interventions aimed towards improving water quality have reduced disease and death; therefore, substantially improving the health of the population at a household level (Stauber et al., 2009). Understanding all of the factors that influence water quality, such as water source, storage practices, water treatment, and season is essential for the implementation of water quality interventions in developing countries such as the Dominican Republic.

The factors that affect the concentration and variability of *E. coli*, total coliform, turbidity, and pH in household drinking water have not been well researched. Therefore, it was vital to explore the gap in the literature by understanding the factors that resulted in *E. coli*, total coliform, turbidity, and pH variability in household drinking water in the Dominican Republic. Understanding *E. coli*, total coliform, turbidity, and pH variability can provide insight into factors that contribute water quality in household drinking water in the Dominican Republic, thus reducing disease and death. The objective of this study was to examine household drinking water quality by determining the factors that contribute to variability of *E. coli,* total coliform, pH, and turbidity in the Dominican Republic. Weekly covariates such as water source, storage practices, and treatment were analyzed to determine how they impacted the following water quality parameters: pH, turbidity, total coliform MPN/100mL, and *E. coli* MPN/100mL.

Methods

Data Sources

The data used in this study were from a longitudinal cohort study done in Bonao, Dominican Republic (Stauber et al., 2009). The focus for this study was on data collected between August 2005 and January 2006. The analysis completed here was identified as non-human subjects research by Institutional Review Boards (IRB) at Georgia State University (Protocol H20453).

Study Population

Data was collected from six communities in Bonao, Dominican Republic from August 2005 to January 2006. Cross- sectional surveys were given by random selection of families located in communities Jayaco Arriba, KM 103, KM 101, KM 100, Majaguay, and Brisas del Yuna in the Dominican Republic.

Method of Data Collection

Data collected from this study included a longitudinal prospective cohort study that required weekly surveys and drinking water sample analysis at two-week intervals. Each household was visited approximately eight times during a four-month period from September 2005 to January 2006. Weekly interviews were conducted for each participating family and household water samples were collected from storage water containers biweekly. Data on water source, type of storage container, and household water treatment performed at each participating household was collected during each water sample collection visit.

Questions included the classification of storage containers by type of mouth of container used for storage (wide or narrow). Classification for narrow mouthed containers included gallon, bottle, double liter, and wide mouthed containers included cooking pot, jug/vase, cube/ bucket, jar, cask, and tank. Water sources were also included in the survey. Water sources were classified as piped, well water, rainwater, spring water, bottled water, and river water. Household water treatment (treated or untreated), and lastly, researchers observed certain hygienic behaviors and water usage of inhabitants during the interviews. Observations included observed household sanitation, hand and container washing practices, availability and presence of soap, and latrine and flush toilet usage.

Data Analysis

Survey data was analyzed using SAS 9.4. Although the design of the data used for this study is longitudinal, it was determined that the best-fit model for exploring whether there were any significant relationships indicated that there were little to no changes in household drinking water quality over the weeks of the study. Therefore, data was analyzed by conducting a hierarchical linear model to determine variability of *E. coli*, total coliform, turbidity, and pH in household water in the Dominican Republic. Hierarchical linear models contain both fixed and random-effect parameters that are generally applied when the data is grouped, clustered, or hierarchically organized. Using this model allowed precise estimates of the water quality parameters after accounting for variability at the household and neighborhood levels. While accounting for repeated measures and missing data, this model allowed for the examination of changes in water quality parameters in relation to each covariate used to measure household drinking water quality.

Covariates water source, storage practices, and water treatment were examined to determine how they influenced water quality parameters (pH, turbidity, total coliform MPN/100mL, *E. coli* MPN/100mL) in household drinking water in the Dominican Republic. Observations were recorded by household, which was nested by neighborhood. Using the hierarchical linear model approach for this study allowed the retention of repeated household measures that may have changed throughout the study, rather than taking an average per household on all measures. While conducting the analysis, piped water source was used as the reference group, untreated water was used as a reference group, and wide mouthed storage containers was used as a reference group as they were all expected to display high levels of contamination. Statistical significance was set at an alpha level 0.05, and 95% confidence intervals included adjusted results from models. Reported percent reductions and increases were computed by converting log reductions to percentages using formula: $P=(1-10^{-L}) *100$, where P is percent reduction and *L* is the log reduction (reported estimates).

Results

Demographics of Population

One hundred and eighty-six households were enrolled in the beginning of the longitudinal study, in September 2005; however, 22 households did not complete the study due to relocation or other contributing factors. As shown in Table 1, out of all of the communities, majority of the households were from the largest community, Brisas del Yuna, with 60 households. Communities KM 100 had 17 households; KM 101 had 23 households; and, KM 103 had 35 households. Lastly, there were 33 households from Jayaco Arriba, and 18 households were from Majaguay.

Table 1. Total number of households enrolled in longitudinal study by village in Bonao, Dominican Republic from 2005-2006.

VILLAGE	**HOUSEHOLD N (%)**
BRISAS DEL YUNA	60 (32)
JAYACO ARRIBA	33 (18)
KM 100	17 (9)
KM 101	23 (12)
KM 103	35 (19)
MAJAGUAY	18 (10)
TOTAL	**186**

Throughout the study, 1653 observations were collected during the study from September 2005 to January 2006. As shown in Table 2, majority of the observations were from the largest community, Brisas del Yuna, with 485 observations. Three hundred and eleven observations came from Jayaco Arriba. Communities KM 100 had 159 observations; KM 101 had 104 observations; and KM 103 had 338 observations. Lastly, 156 observations were from Majaguay.

Table 2. Total number of reported household observations by village in Bonao, Dominican Republic from 2005-2006.

VILLAGE	**OBSERVATIONS N (%)**
BRISAS DEL YUNA	485 (29)
JAYACO ARRIBA	311 (19)
KM 100	159 (10)
KM 101	204 (13)
KM 103	338 (20)
MAJAGUAY	156 (9)
TOTAL	**1653**

Baseline indicators of hygiene

A summary of baseline reports of hygiene and sanitation practices are reported in Table 3. Out of all households, there were 33 households that used shared latrines, 119 households used private latrines, <20 that used either a shared flush toilet or used a private one. One hundred and thirty-one households reported the use of soap; however, only 111 had visible soap on the premises. Fifty-three households displayed poor hygiene, and lastly, 159 reported that they washed their storage containers. Overall, 22 households did not complete the longitudinal study; therefore, data was classified as missing.

Table 3. Sanitation and hygiene practices reported by 186 households during baseline interview in Bonao, Dominican Republic from 2005-2006.

SANITATION & HYGIENE PRACTICES	**N (%)**
SHARED LATRINE	33 (18)
PRIVATE LATRINE	119 (64)
SHARED FLUSH TOILET	1 (0.5)
PRIVATE FLUSH TOILET	11 (6)
REPORTED SOAP IN HOME	131 (70)
VISIBILE SOAP IN HOME	111 (60)
POOR HYGIENE	53 (29)
CLEANS STORAGE CONTAINER	159 (85)

*Percentages reported are out of 186 households.

After examining general demographics, sanitation techniques, and hygienic behaviors within the household, it was important to provide summaries of the weekly covariates that were expected to contribute to *E. coli,* total coliform, turbidity, and pH variability in household drinking water. Presented in Table 4 is a description of the total number of weekly covariates reported from each household. Out of the observations provided by the households enrolled in this study, 43% of reports indicated the use of piped water sources. 27% of reports indicated the use of well water sources, less than 10% indicated the use of spring water and river water, and 11% indicated the use of bottled water and rainwater. 31% of reports that indicated use of treated water and majority of reports (69%) indicated use of untreated water. Lastly, 64% of reports indicated the use of storage containers with narrow mouths and 36% of reports indicated the use of wide mouthed containers.

Table 4. Covariates reported by each household during longitudinal study in Bonao, Dominican Republic from 2005-2006.

Weekly covariates	**N (%)**	**Total**
Source for water collection		
Piped	682 (43)	
Well	438 (27)	1603*
Rainwater	177 (11)	
Spring	77 (5)	
Bottled water	179 (11)	
River	59 (3)	
Missing=50		
Treatment		
Treated	509 (31)	1651*
Untreated	1142 (69)	
Missing= 2		

Storage Container Mouth		
Narrow	1050 (64)	1653
Wide	603 (36)	

*Indicates missing data

Without using the log-transformation of data, *E. coli* MPN/100mL was highly skewed and total coliform MPN/100mL was non-normal, as seen in figures 1 and 2. Therefore, log-transformations of *E. coli* MPN/100 mL and total coliform MPN/100mL were used to reduce skewness and make the distribution as close to normal as possible, which resulted in the reported geometric means. Arithmetic means were used for turbidity and pH because original data was close to normal.

Figure 1. Display of percent distributions of *E. coli* MPN/100mL before log transformations during water quality sampling from households in Bonao, Dominican Republic from 2005-2006.

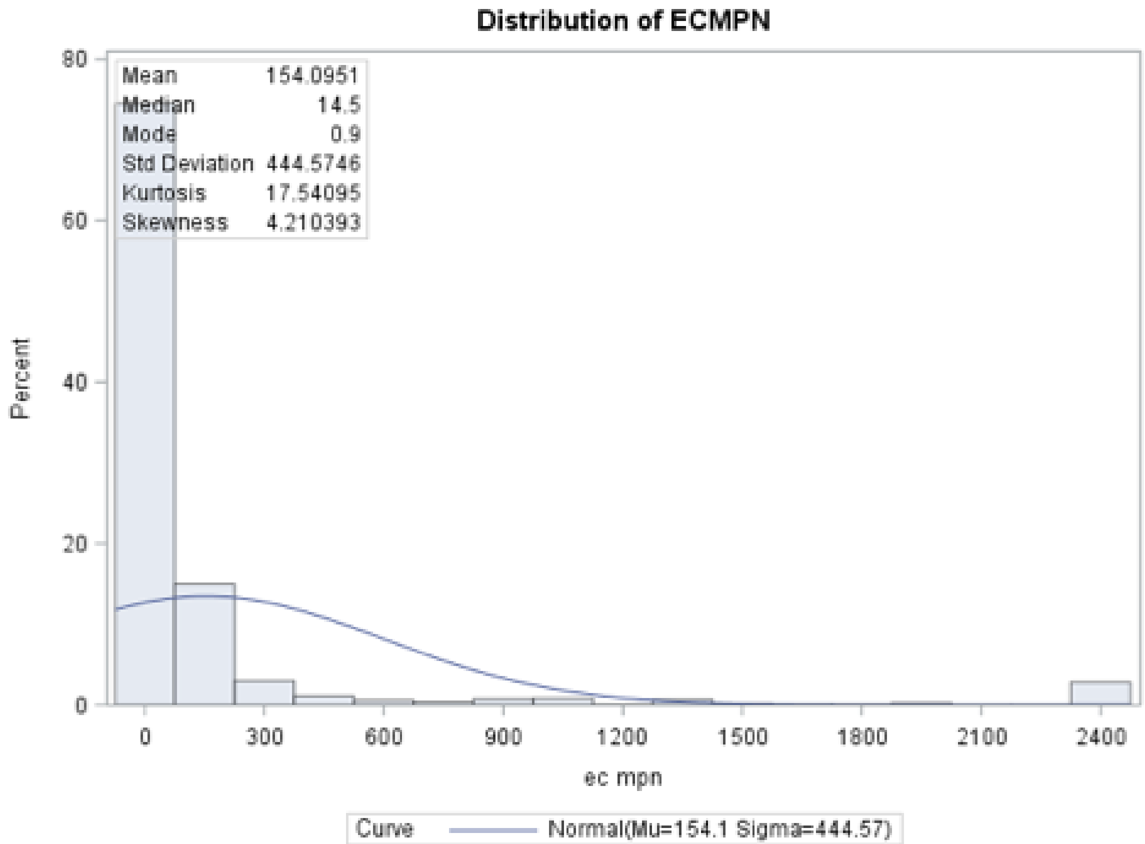
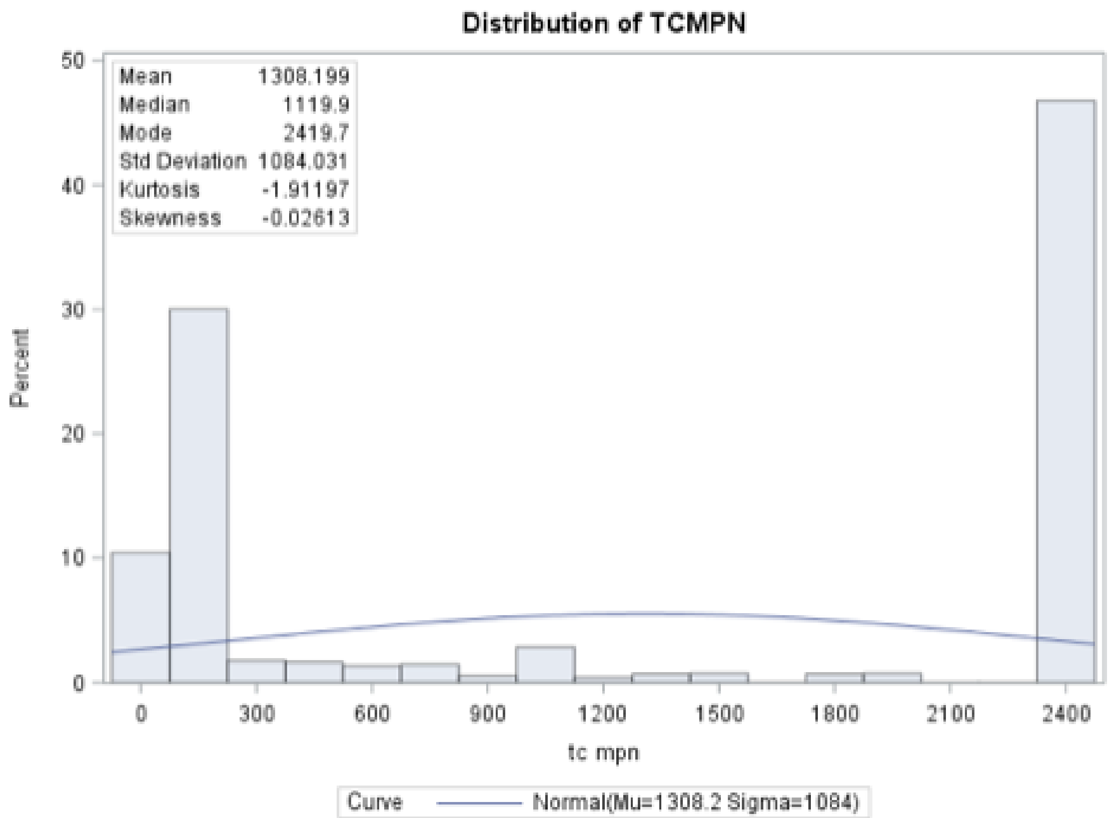


Figure 2. Display of percent distributions of total coliform MPN/100mL before log transformation during water quality sampling from households in Bonao, Dominican Republic from 2005-2006.



Before conducting the analysis, it was important to get an understanding of the distribution of the geometric mean of $\log_{10}$ *E. coli* MPN/100mL, geometric mean of $\log_{10}$ total coliform MPN/100mL, mean turbidity NTU, and mean pH among the households in the study. As shown in table 5, geometric mean *E. coli* levels among household samples were 1.2 $\log_{10}$ *E. coli* MPN/100mL. Geometric mean total coliform levels among household samples were 2.7 $\log_{10}$ total coliform MPN/100mL. Mean turbidity NTU levels among household samples were 2.3, and mean pH levels among household samples were 7.3.

Table 5. Percent distribution of mean, median, and interquartile range for geometric mean of $\log_{10}$ *E. coli* MPN/100mL, geometric mean of $\log_{10}$ total coliform MPN/100mL, mean turbidity NTU, and mean pH during water quality sampling from households in Bonao, Dominican Republic from 2005-2006.

Statistical Measures	$\mathbf{Log_{10}}$ ***E. coli*** **MPN/100mL**	$\mathbf{Log_{10}}$ **Total coliform MPN/100mL**	**Turbidity NTU**	**pH**
Mean	1.2	2.7	2.3	7.3
Median [IQR]	1.2 [0-1.9]	3.1 [2.3-3.4]	1.1 [0.6-2.7]	7.4 [7.0-7.7]

Analysis of household water variability and water quality parameters

E. coli

Using a hierarchical linear model, water source, storage practices, and household water treatment were analyzed to determine how they affected *E. coli*, as shown in table 6. Because repeated measures were recorded by household, which was nested by neighborhood, it was important to examine if neighborhood influenced *E. coli* variability. Essentially, *E. coli* levels were influenced by household, geometric mean $\log_{10}$ *E. coli* MPN/100mL levels ($p<0.0001$) at an 0.05 alpha level. However, geometric mean $\log_{10}$ *E. coli* MPN/100 mL levels were not influenced by neighborhood ($p=0.19$) at an 0.05 alpha level.

In the hierarchical linear model that controlled for water source and water treatment, storage container was a predictor of geometric mean of $\log_{10}$ *E. coli* MPN/100mL variability in household drinking water (p=0.003) at an 0.05 alpha level, as *E. coli* levels in narrow containers were reduced by 46%. Controlling for water source and storage container, household water treatment was a predictor of geometric mean $\log_{10}$ *E. coli* MPN/100mL variability (p=0.0003), as *E. coli* levels in treated water sources were reduced by 65%. Controlling for storage container and water treatment, water source was a predictor of *E. coli* variability in household drinking water. Compared to piped water sources, estimated geometric mean $\log_{10}$ *E. coli* MPN/100mL levels were lower on average in bottled water (75% reduction, p<0.0001), rainwater (81% reduction, p<0.0001), well water (34% reduction, p=0.02), and higher in river water (73% increase, p=0.004), at an 0.05 alpha level. Conversely, geometric mean $\log_{10}$ *E. coli* MPN/100mL levels did not vary among those who used piped water sources, compared to those who used spring water sources (p=0.06), at an 0.05 alpha level.

Total coliform

Using a hierarchical linear model, water source, storage practices, and household water treatment were analyzed to determine how they affected total coliform, as shown in table 6. Because repeated measures were recorded by household, which was nested by neighborhood, it was important to examine if neighborhood affected total coliform variability. Essentially, total coliform variability was influenced by households, geometric mean $\log_{10}$ total coliform MPN/100mL (p<0.0001) at an 0.05 alpha level. However, geometric mean $\log_{10}$ total coliform MPN/100mL levels were not influenced by neighborhood (p=0.17) at an 0.05 alpha level.

In the hierarchical linear model that controlled for water source and storage container, water treatment was a predictor of geometric mean $\log_{10}$ total coliform MPN/100mL variability (p=0.03) at an 0.05 alpha level, as there was a 28% reduction in total coliform levels. Conversely, when controlling for household water treatment and water source, storage container was not a predictor of geometric mean $\log_{10}$ total coliform MPN/100mL variability (p=0.29). Also, when controlling for water treatment and storage container, piped water sources were not a predictor of geometric mean $\log_{10}$ total coliform MPN/100mL variability when compared to bottled water (p=0.51), spring water (p=0.29), and well water (p=0.34) at an 0.05 alpha level. However, compared to piped water sources estimated geometric mean $\log_{10}$ total coliform MPN/100mL levels were lower on average in rainwater (44% reduction, p=0.01) and higher in river water (%55 increase, p=0.03), at an 0.05 alpha level.

Table 6. Results from hierarchical linear model analysis of $\log_{10}$ *E. coli* MPN/100mL and $\log_{10}$ total coliform MPN/100mL variability and household covariates used to examine household drinking water in Bonao, Dominican Republic from 2005-2006. Only significant percent reductions or increases were reported.

Household Covariates	Estimate (95% CI)	P-value	%Reduction or Increase	Estimate (95% CI)	P-value	% Reduction or Increase
	$\log_{10}$ *E. coli* MPN/100mL			**$\log_{10}$ Total coliform MPN/100mL**		
Neighborhood	0.007	0.19		0.009	0.17	
Household	0.12	<0.0001		0.108	<0.0001	

Treatment						
Treated	-0.46 (-0.59, -0.32)	0.0003	65% Red	-0.14 (-0.27, -0.01)	0.03	28% Red
Untreated	REF			REF		
Storage Container						
Narrow	-0.27 (-0.40, -0.13)	0.003	46% Red	-0.05 (-0.18, 0.07)	0.29	NOT SIG
Wide	REF			REF		
Water source						
Bottle water	-0.61 (-0.81, -0.41)	<0.0001	75% Red	0.05 (-0.24, 0.12)	0.51	NOT SIG
Rainwater	-0.73 (-0.96, -0.50)	<0.0001	81% Red	-0.25 (-0.45, -0.05)	0.01	44% Red
Spring	-0.27 (-0.57, 0.02)	0.06	NOT SIG	-0.14 (-0.42, 0.13)	0.29	NOT SIG
Well	-0.18 (-0.34, -0.02)	0.02	34% Red	-0.06 (-0.21, 0.08)	0.34	NOT SIG
River	0.57 (0.21, 0.93)	0.004	73% Inc	0.35 (0.01, 0.68)	0.03	55% Inc
Piped	REF			REF		

*Significance was measured using alpha level 0.05
**Abbreviations: Red= reduction, Inc= increase, Not Sig= Not significant
***Reported percent reductions or increases were computed by converting log reductions to percentages using formula: $P=(1-10^{-L}) *100$, where P is percent reduction and L is the log reduction (reported estimates).

Turbidity

Using a hierarchical linear model, water source, storage practices, and household water treatment were analyzed to determine how they affected turbidity, as shown in table 7. Because repeated measures were recorded by household, which was nested by neighborhood, it was important to examine if neighborhood affected mean turbidity NTU. Essentially, turbidity was influenced by households, mean turbidity NTU ($p<0.0001$). However, turbidity was not influenced by neighborhood, mean turbidity NTU ($p=0.10$).

In the hierarchical linear model that controlled for water source and storage container, household water treatment was a predictor of mean turbidity NTU among household drinking water ($p=0.02$) using an alpha level of 0.05. When controlling for water source and household water treatment, water container was not a predictor of mean turbidity NTU in household drinking water ($p=0.30$) using an alpha level of 0.05. When controlling for storage container and household water treatment, piped water source was a predictor of mean turbidity NTU when compared to bottled water sources ($p=0.004$), rainwater ($p=0.01$), and well water ($p=0.0002$) at an 0.05 alpha level. However, piped water sources were not a predictor of mean turbidity NTU when compared to river water (0.65) and spring water ($p=0.57$).

pH

Using a hierarchical linear model, water source, storage practices, and household water treatment were analyzed to determine how they affected pH, as shown in table 7. Because repeated measures were recorded by household, which was nested by neighborhood, it was important to examine if neighborhood affected mean pH. Essentially, mean pH differed significantly by household ($p<0.0001$) but not by neighborhood ($p=0.07$).

In the hierarchical linear model that controlled for storage container and household water treatment, piped water source was a predictor of mean pH when compared to bottled water sources ($p<0.0001$), rainwater ($p=0.01$), and well water ($p=0.0004$) at an 0.05 alpha level. However, piped water sources were not a predictor of mean pH variability when compared to river water (0.65) and spring water ($p=0.24$). When controlling for water source and storage container, household water treatment was not a predictor of mean pH among household drinking water ($p=0.11$) using an alpha level of 0.05. Lastly, when controlling for water source and household water treatment, water container was not a predictor of mean pH in household drinking water (p=0.12) using an alpha level of 0.05.

Table 7. Results from hierarchical linear model analysis of mean turbidity NTU and mean pH and household covariates used to examine household drinking water in Bonao, Dominican Republic from 2005-2006.

Household Covariates	**Estimate (95% CI)**	**P-value**	**Estimate (95% CI)**	**P-value**
	Turbidity NTU		**pH**	
Neighborhood	0.007	0.10	0.07	0.07
Household	0.12	<0.0001	0.108	<0.0001
Treatment				
Treated	0.80 (0.13, 1.48)	0.02	0.04 (-0.01, 0.11)	0.11
Untreated	REF		REF	
Storage Container				
Narrow	0.29 (-0.37, 0.97)	0.30	-0.04 (-0.11, 0.01)	0.12
Wide	REF		REF	
Water source				
Bottle water	-1.62 (-2.64, -0.60)	0.004	0.36 (-0.25, 0.47)	<0.0001
Rainwater	-1.58 (-2.82, -0.35)	0.01	0.16 (0.03, 0.29)	0.01
Spring	-0.41 (-1.96, 1.13)	0.57	0.10 (-0.07, 0.28)	0.24
Well	-1.99 (2.86, -1.13)	0.0002	-0.15 (-0.25, 0.05)	0.004
River	0.40 (-1.49, 2.30)	0.65	-0.04 (-0.25, 0.16)	0.65
Piped	REF		REF	

*Significance was measured using alpha level 0.05

Discussion

This study aimed to gain an understanding of household drinking water quality by examining the factors that contributed to *E. coli,* total coliform, turbidity, and pH in household drinking water. After conducting the analysis, it was concluded that *E. coli* MPN/100mL was greatly influenced by water source, water storage, and household water treatment, when compared to other water parameters: total coliform MPN/100mL, pH, and turbidity. Therefore, one can conclude that *E. coli* variability in household drinking water was dependent on the type of water storage, water source used to collect water, and if water was treated.

The examination indicated that water treatment influenced *E. coli* variability in household drinking water. This evidence further supports recent recommendations of using treated water as household drinking water (World Health Organization, 2016). In addition to water treatment, type of storage container also contributed to *E. coli* variability in household drinking water quality. This evidence supports recent literature as it states that re-contamination of household drinking water is more prevalent among households who use wide mouthed containers instead of narrow mouthed containers or containers without a small lid, a cover, or pump (Center for Disease Control and Prevention, 2015).

Lastly, water source also influenced *E. coli* variability in household drinking water. Households who used to piped water sources differed significantly from households who used bottled water, rainwater, well water, and river water. However, there was no influence among households who used piped water compared to those who used spring water. Therefore, it is necessary to assess the environment that contributed to *E. coli* variability in the mentioned water sources. Many inhabitants of the Dominican Republic commonly use public water sources such as boreholes, wells, rainfall, springs, and surface water as their drinking water sources. Such water sources are considered improved and not safe, and therefore may still be contaminated, which may have influenced the results. Also, the tropical climates that the Dominican Republic experiences could have contributed to an uneven distribution of water quality, as displayed in the results (Treaty, 2019).

This study also aimed to examine the factors that contributed to total coliform variability in household drinking water. The evidence suggested that total coliform was less sensitive to changes. After conducting the analysis, it was concluded that total coliform MPN/100mL in household drinking water was only influenced water source used to collect water and household water treatment. This conclusion was expected because if total coliform is present then *E. coli* may also be present. In other words, if we observe the factors that contribute to *E. coli* variability then those same factors may contribute total coliform variability.

The examination indicated that water treatment was a predictor of total coliform variability. This evidence further supports recommendations of using treated water as household drinking water (World Health Organization, 2016). In addition to treatment, type of storage container did not contribute to total coliform variability in household drinking water quality. Due to total coliform bacteria being common in soil or vegetation, fecal contamination could be unlikely, which could to why this evidence conflicts recent literature. This data insinuates that something other than container type could be a contributing factor in total coliform variability in household drinking water.

Water source was also not a predictor of total coliform variability in household drinking water. Households who used to piped water sources were not different from households who used bottled water, spring water, and well water. However, there was indication of increased total coliform among households who used rainwater and river water. Due to the results, it is necessary to assess which specific environmental factors contribute to total coliform variability in the mentioned water sources as total coliform concentration can be attributed to environmental factors.

This study also aimed to examine the factors that contributed to water quality parameter, turbidity NTU, in household drinking water. After conducting the analysis, it was concluded that water source and household water treatment was a predictor of water turbidity. The examination indicated that turbidity was influenced by water treatment. This can be because many inhabitants of the Dominican Republic often treat their water by boiling to improve drinking water quality, as boiling does not contribute to water appearance (Aiken et al., 2011). Conversely, storage container did not contribute to household drinking water turbidity. This does not support the idea that contamination could be prevented by having narrow mouthed containers. However, this could be due to source that water was collected from and treatment. Households who used to piped water sources did not differ from households who used spring water and river water. However, water turbidity among households who used bottled water, rainwater, and well water did differ, which can be expected as certain water sources have to abide by protection regulations. As turbidity is the measure of the degree to which water loses its transparency, it is important to further explore these conflicting results by further examining contributing factors of water source.

Lastly, this study also aimed to examine the factors that contributed to water quality parameter, pH, in household drinking water. After conducting the analysis, it was concluded that water pH in household drinking water was solely dependent on water source used to collect household drinking water. The examination indicated that household water treatment and storage container did not influence pH. Also, households who used piped water sources did not differ from households who used spring water and river water. However, the use of bottled water, rainwater, and well water did correspond to higher household pH. As previously mentioned, it is important to further explore the contributing factors that resulted in these conflicting results regarding water source. The results of this study further display that it is important to understand that safely managed water sources are more beneficial to water quality than improved water sources. As shown in this study, there were many sources classified as improved; however, those sources were still contaminated.

Study strengths and limitations

After examining the results, it is important to consider the possible strengths and limitations for this study. The main strength of this study would be the type of analysis used. Using the hierarchical linear model for this study allowed the retention of repeated household measures that may have changed throughout the study, rather than taking an average per household on all measures. One limitation would be the small sample size which resulted in insignificant results. As the power of the study increases with sample size, a small sample size may result in insignificant data. Therefore, the relatively low total number of households may have failed to provide accurate estimates of the varying levels of *E. coli* MPN/100mL, total coliform MPN/100mL in household drinking water, along with the turbidity, and pH of household drinking water. Another limitation would be that the sampling of households was not randomized. Unfortunately, households were chosen based on the presence of having a child under the age of five located in the home. This choice resulted in nonrandom sampling, which could lead to selection bias and reduce the generalizability of the study. Lastly, the data used for this study is approximately 15 years old. Therefore, it is possible that the situations displayed in the results have changed as the access to improved water has gotten better in the last 15 years.

Conclusion

The results of this study provide further confirmation that it is essential to understand the factors that contribute to *E. coli*, total coliform, turbidity, and pH variability in household drinking water in the Dominican Republic so that water quality can be safely managed and regulated. Like the Dominican Republic, many developing countries are not fortunate enough to have the infrastructures that provide them with the adequate resources to provide safe and improved water (Treacy, 2019). Therefore, there is a need to implement and promote programs that support water safety and management in developing countries to ensure that the community has access to safe and improved water and not only improved water. In addition, the findings of this study could recommend that one examines the underlying factors that contribute to the quality of water collected from multiple water sources used for household drinking water.

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