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Water quality at points-of-use in the Galapagos Islands

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ABSTRACT

Piped drinking water is often considered a gold standard for protecting public health but research is needed to explicitly evaluate the effect of centralized treatment systems on water quality in developing world settings. This study examined the effect of a new drinking water treatment plant (DWTP) on microbial drinking water quality at the point-of-use on San Cristobal Island, Galapagos using fecal indicator bacteria total coliforms and *Escherichia coli*. Samples were collected during six collection periods before and after operation of the DWTP began from the freshwater sources (n = 4), the finished water (n = 6), and 50 sites throughout the distribution system (n = 287). This study found that there was a significant decrease in contamination by total coliforms (two orders of magnitude) and *E. coli* (one order of magnitude) after DWTP operation began ($p < 0.001$). However, during at least one post-construction collection cycle, total coliforms and *E. coli* were still found at 66% and 28% of points-of-use (n = 50), respectively. During the final collection period, conventional methods were augmented with human-specific *Bacteroides* assays – validated herein – with the goal of elucidating possible microbial contamination sources.

Results show that *E. coli* contamination was not predictive of contamination by human wastes and suggests that observed indicator bacteria contamination may have environmental origins. Together these findings highlight the necessity of a holistic approach to drinking water infrastructure improvements in order to deliver high quality water through to the point-of-use.

1. Introduction

Diarrheal diseases are the sixth-leading cause of premature death worldwide, above tuberculosis, malaria, and traffic accidents (Lopez et al., 2006). Diarrhea can be caused by a range of viral, bacterial, and protozoan pathogens, which increases the complexity of addressing this problem (Fischer-Walker et al., 2013). The United Nations aimed to halve the proportion of the world population without sustainable access to drinking water between the years of 1990 and 2015 (United Nations, 2015). As a result, nearly two billion people gained access to piped drinking water (United Nations, 2015). These improvements will no doubt improve public health. However, research is needed to explicitly evaluate the effect of piped drinking water on point-of-use water quality in developing world settings. It is possible for drinking water quality to deteriorate between treatment and the point-of-use, in which case the false presumption of safety may inadvertently increase the public health risk of water-borne disease (Bain et al., 2014; Rufener et al., 2010; Wright et al., 2004). For example, it has been reported that access to protected sources may reduce the rate at which consumers observe precautions such as boiling drinking water prior to consumption (Lindskog and Lindskog, 1988). As a result, improving access to drinking water without ensuring its quality may have unintended negative impacts on human health.

This study examined point-of-use water quality on the Galapagos Islands of Ecuador, an area with piped drinking water that is also undergoing infrastructure improvements. Ecotourism to the islands has grown exponentially from 2000 tourists in the year 1960 to 120,000 tourists in 2005 (Epler, 2007). The popularity of ecotourism creates a framework called the Galapagos Paradox where increasing strain is placed on the "pristine" environment that many

Abbreviations: DWTP, drinking water treatment plant; FIB, fecal indicator bacteria; LLOD, lower limit of detection; MPN, most probable number; MST, microbial source tracking; WHO, World Health Organization.

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tourists hope to enjoy (Quiroga, 2009). Among other stressors, the strain that tourism places on the drinking water infrastructure has contributed to drinking water quality problems that have persisted for decades (Liu and D'Ozouville, 2013; Reyes et al., 2015).

Effective drinking water infrastructure requires access to quality source water. On San Cristobal Island, the source water is from two freshwater lakes – La Toma de Los Americanos (Los Americanos) and Cerro Gato – in the highlands of the island. These two sources are fed by rainwater during the rainy season and have sufficient capacity to provide 30 L per second of water flow to the drinking water treatment plant (DWTP) year-round through the dry season. San Cristobal draws its drinking water entirely from these surface reservoirs rather than subsurface reservoirs like two of the other inhabited islands on the archipelago – Santa Cruz and Isabela.

A project to replace the DWTP and distribution system on San Cristobal Island is underway. Construction of a new DWTP began in late 2012, and the new DWTP began operations in September 2013. This DWTP includes treatment processes common to modern drinking water treatment systems including rapid mixing, coagulation, flocculation, sedimentation, filtration, and chlorine gas disinfection. An infrastructure improvement project is ongoing as the drinking water distribution infrastructure is replaced; however, several problems that may allow for post-collection contamination continue to affect the distribution system. The distribution system is not consistently pressurized, instead operating as a gravity-fed system a few hours each day. Negative hydraulic pressure associated with interrupted service can draw contamination into water pipes from the surrounding environment (Lee and Schwab, 2005).

Municipal sewer lines have also been laid immediately below the drinking water distribution system in the ongoing infrastructure improvement project. The vast majority (79%) of households are connected to municipal sewer lines for waste management while a smaller proportion (19%) of households uses septic tanks. The wastewater treatment plant on the island was not in operation during the time period of this study, and wastewater from the piped system was discharged directly to the ocean. For houses with septic tanks, the volcanic rock conditions likely prevent septic fields from functioning properly and may allow inadvertent contamination resulting from negative hydraulic pressure associated with inconsistent water delivery.

Lack of consistent water availability necessitates the use of storage cisterns at points-of-use. Several studies have found increases in contamination during household storage and at least one study has identified the household level as the point at which the largest impact on public health can be made (Clasen and Bastable, 2003; Eshcol et al., 2009; Kær Jensen et al., 2002; Levy et al., 2008; Rufener et al., 2010; Wright et al., 2004). The cisterns on San Cristobal were above-ground plastic storage tanks. These cisterns are filled from the top by hoses that shutoff using a simple fill valve, so the opportunity for feedback into the distribution from cisterns is eliminated. Domestic animals are often near the cisterns on household property and may represent a possible route of contamination, but the likelihood of this contamination is reduced given the overwhelming majority of cisterns were covered. Variable cistern residence times also complicate the calculation of doses for residual disinfection of finished water. Despite the improvements made to the infrastructure, lack of consideration for the effects of intermittent water delivery and point-of-use water storage may allow bacteria in the environment to infiltrate the system and, under certain conditions, multiply.

This study establishes baseline measurements of drinking water quality at various points of the distribution system on the island of San Cristobal over a two year period and provides the most comprehensive spatial representation of microbial drinking water quality on any island in the Galapagos archipelago to date. Furthermore, this study examines the effect of a newly constructed drinking water treatment plant on microbial water quality, both in terms of comparisons between years and in terms of compliance with established World Health Organization (WHO) Guidelines.

This study also evaluates the sources of observed fecal contamination through microbial source tracking (MST) methods. Because of spatially widespread microbial contamination observed during the first year of the study, human-specific assays were used to narrow the list of possible sources for microbial contamination. Several studies have applied this approach to drinking water source quality monitoring; however, few have applied it to drinking water quality monitoring through the distribution system (Åström et al., 2015; Marti et al., 2013). This is one of the first studies to apply MST methods to examine drinking water quality at the point-of-use in South America.

2. Methods

2.1. Site selection

The study area of San Cristobal Island includes the two main population centers: El Progreso (population of 500, altitude 700 m) and Puerto Baquerizo Moreno (population of 5400, altitude 0–70 m) (Fig. 1). This study also included the freshwater sources (Los Americanos and Cerro Gato) and the DWTP (altitude 700 m) – all located on San Cristobal. During June 2013, 50 sample sites from 15 neighborhoods on the island of San Cristobal were selected to represent locations throughout the drinking water distribution system. Each of these sites was also subject to post-distribution storage – typically in the form of rooftop or ground-level cisterns where water was stored prior to household use.

2.2. Sample collection

A total of 143 point-of-use water samples from 50 sites along the distribution system were collected in three collection periods, which occurred in 7–10 day intervals in June and July 2013. A total of 144 samples from the same 50 sites were collected during three collection periods at the same intervals during the same months in 2014. Every effort was made to collect a sample from each site during each collection period, but inconsistent business hours and shifting schedules occasionally prevented collection from sites within 48 h of the start of a collection period. In these instances, the site was skipped for that collection period. The two freshwater sources for the island (Los Americanos and Cerro Gato) were included in the study to assess microbial contamination from the beginning to the end of the treatment and distribution processes. Construction of the new DWTP using a treatment process involving flocculation, sedimentation, rapid filtration, and chlorine-gas disinfection was completed in September 2013. Samples were collected weekly from the new DWTP in 2014.

Water samples of 100 mL were collected in vacuum sealed, sterile 120 mL vessels containing sodium thiosulfate from all 50 sample collection sites during each collection period. The samples were placed in a cooler with ice packs and taken to the Galapagos Science Center for enumeration of total coliform and *E. coli* using the IDEXX Colilert® method (Westbrook, ME USA) within 12 h of sample collection. Permit requirements limited the number of collection opportunities at the freshwater sources; however, there was one collection period in 2013 and three collection periods in 2014. Water (500 mL) was collected from each point-of-use during the final collection period in 2014 in double-washed and autoclaved glass laboratory bottles for MST analysis.