41st WEDC International Conference, Egerton University, Nakuru, Kenya, 2018

TRANSFORMATION TOWARDS SUSTAINABLE
AND RESILIENT WASH SERVICES

E. coli contamination of mountain springs used for drinking water and drilled well alternatives

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PAPER 3064

Millions of people in developing communities drink water from springs on bedrock mountain slopes. Previous studies show E. coli causing many sampled springs on populated mountain slopes in southwest China to provide unsafe drinking water (Chitwood 2007a). Such studies are rare, but recently a reconnaissance study was initiated in a watershed in the Dominican Republic where more than 25,000 people, spread out across small communities and one town, rely on mountain springs. E. coli testing shows many of these springs to be unsafe. Water users live downslope and distant from the springs and receive spring water via pipelines. Likely, the E. coli originates from sparse livestock grazing up-slope from springs. Small wells drilled using portable rock coring machines and completed using novel continuous seals attached above the water intake zone are proposed to access safe drinking water drawn from permeable fractures tens of meters below ground, avoiding contamination near surface.

Introduction

WHO and UNICEF report that approximately 1.5 billion people worldwide living in rural areas lack access to a safely managed drinking water source (WHO and UNICEF 2017). There are hundreds of millions of people living in mountainous areas (Messerli et al. 2004). Many in such communities rely on mountain springs for their drinking water. These springs or seeps often produce water with desirable aesthetic characteristics, making it palatable (e.g., cool temperature, low turbidity) and the perceptions can be that it is free of contamination. However, very few studies have been conducted to study the degree of faecal contamination at mountain springs, which are relied upon by many millions of people globally.

In the literature, the available data of bacteriological water testing results for mountain springs has been reported by Chitwood (2007a, 2007b) and Cherry et al. (2013). These studies were conducted in four mountainous areas in southwest China. Subsistence farming communities living in these areas obtain water directly from springs where individuals fill their water containers (buckets, pails, and bottles) from pipes built into spring boxes or cisterns, which are constructed to capture and pool the spring water.

There are many scholarly articles on the development of mountains, but not many address mountain spring hydrology and hydrogeology. The water discharging at mountain springs is thought to be comprised of both shallow and deep groundwater flowing in rock fractures (joints and fissures). It is presumed that springs are fed by groundwater in zones recharged at higher elevations where there is less human and animal presence (Cherry et al. 2013), and that long groundwater flow paths have lower pathogen concentrations (Page et al. 2012). It is theorized that contamination is constrained to shallow groundwater flow or surface runoff, rather than deeper groundwater flow paths, as coliform bacteria prefer warm temperatures and thus live closest to earth's surface (Vendrell *et al.,* 2013).

Mountain hydrogeology is poorly understood partly due to the difficulties of drilling monitoring wells on steep terrain, ecologically sensitive areas, and overgrown sites. Mountains are generally formed on hard bedrock preventing use of conventional well drilling machines. However, low-cost, portable rock-coring systems produced for mineral exploration have very recently been used for drilling rock coreholes and installing monitoring wells in sandstone and dolostone in California and Ontario (Pierce et al. 2018). These drills have not been used to study mountain hydrogeology. The overarching research project involves investigating how groundwater flows to springs and how pathogens and nitrate enter the spring domain (which includes the spring, adjacent and up-slope area generating surficial runoff to the spring, and the presumed areas of recharge for groundwater which discharges at the spring), utilizing portable rock-corers to drill in bedrock to substantial depths for installation of conventional monitoring wells and new types of monitoring devices best suited for understanding subsurface flow. The research goal is to determine the path of entry of bacterial contamination and nitrate at mountain springs and whether deeper groundwater flow to springs yields safer drinking water.

This study of mountain springs carried out in the Dominican Republic (D.R.) is similar to the studies conducted in China, and is the first part of the overarching research project mentioned previously. In the study area of the D.R., mountain springs provide water for many small communities in one basin. The study encompasses the sampling and testing of water at mountain springs, as the first step in determining the degree and extent of faecal contamination at these drinking water access points. Whereas the studies in China by Chitwood concern springs where people get their water directly from the source in areas closer to where people live and farm, most of the individuals in the study area of the D.R. get their water from spring-fed gravity flow piped water systems.

Study area: El Cercado and vicinity, Dominican Republic

The study area is a rural basin in the San Juan province of the D.R., approximately 22 kilometres east of the border with Haiti. As of 2012, the town had a population of about 25,000. The town name in English means "the enclosed"; the town centre lies in a basin, approximately 20 by 20 kilometres, located in the larger watershed for the Macasías River. The town centre is at 730 metres above mean sea level (AMSL) and is surrounded by mountains, with peaks ranging from 762 to 2,100 meters AMSL. These mountains provide valuable groundwater resources, in the form of springs, for the communities' drinking and other water needs. Typically, communities build (with or without outside assistance) spring-fed, gravity flow water systems, which deliver water to yard or community taps via networks of galvanized iron and/or PVC distribution pipes. The basin is not entirely closed as there is a river running through the centre of town and into the next province. The water flowing in the river is an accumulation of spring water, rainwater runoff, and wastewater. This basin was selected as the study area to determine whether the findings at mountain springs in China, where bacteriological contamination of springs is common, also occurs in this mountainous area of the D.R. This basin was also chosen because of the availability of strong logistical support.

Methodology

The research involves assessment of the basin in which the town of El Cercado is located (referred hereafter as the El Cercado basin) to determine the locations and characteristics of springs and their water quality. The primary objective of this research, which is part of the larger project detailed in the previous section, is to better understand the presence and extent of faecal contamination at these drinking water sources. The investigation has been conducted over two trips to the study area, and will recommence during a third trip in mid-2018.

During summer 2017, from mid-May to early-June, the lead author, as a graduate student, and team conducted a three-week long assessment of the basin terrain and spring sources, plus water quality sampling and testing (for six water quality parameters). A total of eight springs were assessed on the first trip. A second trip in January 2018 involved the same assessments, sampling, testing, with the addition of two more water quality tests at six more springs.

Information was collected on the history of the springs; communities served by the sources; land use, flora, and fauna at and up-slope from the sources; observed water clarity, flow, and seasonal variations of both; presence of exposed bedrock; and presence and repair history of spring box infrastructure. Where spring water passed over exposed bedrock, a rock sample was taken.

The water testing methodology aims to conduct many types of tests in the study area without sending samples to an offsite laboratory. These onsite tests are conducted at the spring or later the same day at the local lodging in the town of El Cercado. Onsite testing is a priority for those chemical and physical parameters, such as pH and temperature, which must be measured upon sampling right at the spring to avoid changes in samples due to atmospheric exposure. The other onsite testing is done to minimize cost and produce results that can be assessed immediately and taken into account in the decision making for the next steps in the sampling program.

Spring water was tested onsite for pH, temperature, total dissolved solids (TDS), and electrical conductance (EC) utilizing a Hanna Portable ph/EC/TDS/˚C Meter (model number HI9813-5) and probe. This was accomplished using a 500-mL Nalgene sampling bottle, rinsed in source water prior to sampling. Concentrations of E. coli were measured using the Aquagenx Compartment Bag Test (CBT). The sample for this test was collected in a sterile 100-mL whirlpack sample bag; the testing was conducted in the evening the same day. Alkalinity was measured using the Hach Digital Titrator Model; nitrate was measured with the Hach Nitrate/Nitrite Test Kit. One sample was taken for the alkalinity and nitrate testing with a 500-mL Nalgene bottle, rinsed with source water; these two tests were conducted in the evening the same day as sampling. During the second trip, water samples were collected (using the same procedure as described previously with a 500-mL Nalgene bottle) and taken back to North America for chloride testing, using a Vernier chloride ion-selective electrode. For both trips, water samples will be tested for major ions and isotopes in North America.

Results and discussion

The location (terrain settings and proximity to communities) of the springs varied widely. Some springs were observed to have lower flow and generally were located at lower elevations (less than 760 meters AMSL), while others at higher elevations (greater than 915 metres AMSL) generally showed higher flow (Photographs 1 and 2). The lower flow springs are closer to and typically provide water for smaller communities, while the largest spring, and headwaters of the river that runs through town, provides water for the town centre and a few adjacent communities; this latter spring was located furthest from human development than any other spring assess during the assessment periods. Generally, the springs located on the highest mountains in the basin are located in tree-covered ravines or gullies, while the lower elevation springs are located on hillsides (i.e., not in a ravine or gully, see Photograph 2). At all springs, the land use at or up-slope from the spring was characterized, through observation, as forested area or agro-pastoral. The bedrock seen throughout the study area is carbonate rock (limestone) which is highly fractured and jointed (Photograph 3).

Photograph 1. High elevation (1,280 metres AMSL), high flow spring in the El Cercado basin shows spring box and conduction pipe to downstream community

Photograph 2. Lower elevation (685 metres AMSL), lower flow spring in the basin; conduction pipe to downstream community lies in the spring pool and is not shown in the photograph

Photograph 3. Bedrock outcropping near mid-elevation mountain spring in El Cercado, showing fractures and joints

Ten of the springs had spring boxes (Figure 1). This type of infrastructure is intended to serve two purposes. First, it captures the spring water into a tank or pool, making it easier for piping to downstream communities and on-site collection by humans. Secondly, it is intended to protect the spring water from contamination. To construct a spring box, first the hillside at the spring is cleared of vegetation and large stones are placed on the slope at the location of discharge. These stones are held in place by metal wire mesh or screen. A concrete box is then constructed around this stone wall. The box has several exit pipes for cleaning out sediment, release of air, and flow to communities. The box also has a metal lid with a locking mechanism to prevent vandalism or access to the pooled water in the box. Of the spring boxes assessed in the study area, only one was in good condition. The rest were in various states of disrepair, or were crudely constructed. The risk of contamination to water is high, even for a properly constructed and maintained spring box, especially at the points where the box walls meet the earth (Figure 1), at the lid if it is not water-tight, and at the runoff area up-slope.

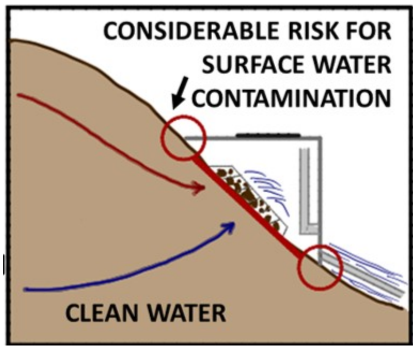

Figure 1. Diagram of mountain spring box; shows proposed conceptual model with likely contaminated (red) shallow groundwater flow, and cleaner water (blue flow path) originating from deep upwelling groundwater

Results for temperature, pH, EC, TDS, E. coli, alkalinity, and nitrate are presented for both trips to the study area. Temperature values of spring water varied from 18 and 27 degrees Celsius, and generally decreased with increasing elevation of the spring. Values of pH ranged from 6.8 to 8.1. The total dissolved solids concentrations (in parts per million) ranged from 198 to 917, and electrical conductance, measured in millisiemens per centimetre, ranged from 0.27 to 1.26. Alkalinity values varied from 116 to 550 mg/L as $CaCO_3$. The CBT results for E. coli ranged from 0 to greater than 100 MPN/100 mL. Four of the sampling locations had values of 0, therefore more than 70% of the sampled locations had some level of faecal contamination. Of these, six had the highest level, and were deemed "unsafe," according to Aquagenx scoring. The samples which were tested for nitrate had a concentration ranging from 2 to 8 mg/L NO_3^- -N (measured as nitrate nitrogen), or 8.8 to 35.2 mg/L expressed as nitrate. These nitrate values fell below the guideline value of 50 mg/L as nitrate, which is based on short-term exposure for infants, as reported by the World Health Organization (Speijers, et al., 2011).

This study area differs from the studies conducted in China by Chitwood in that the areas adjacent to springs in El Cercado are not developed or occupied by dwellings and establishments; rather they are surrounded by forests and agro-pastoral lands. In China, it is evident that having large numbers of animals and people living near the springs generates substantial waste from the animals, human defecation, and latrines. This waste infiltrates the ground and enters the shallow groundwater flow at the water table, or travels as surficial runoff, contaminating nearby springs. However, in the El Cercado basin, it is less obvious what could be contaminating the groundwater with bacteria at these spring sources. We theorize that sparse livestock grazing could be the source of contamination. Given the link between indicator coliform bacteria and health threatening viruses and other pathogens (Health Canada 2017), it is imperative to understand how bacteria enter the spring domain in the El Cercado basin, where springs are not heavily threatened by human activity. Virus analyses are not included as part of this study because for these to be insightful, there needs to be frequent sampling over a representative time period, making the analysis cost-prohibitive.

Given the results of these studies thus far, and finding the presence of faecal contamination, it is evident that water quality is a problem at springs in two study areas with different geologic characteristics in different parts of the world. In both cases, the spring water is not protected from faecal sources of bacteria along surface or shallow subsurface flow paths, leading to unreliable water quality that can affect community and personal health and lead to increased cases of water-related illness. There are several possibilities that can be pursued to ameliorate this problem, including in-line chlorination or household water treatment. The latter option has previously been implemented in the El Cercado basin, with minimal success, where ceramic filters at households are commonly unused, and individuals do not typically take measures to disinfect the tap water prior to consumption. Another option would mean passing and enforcing statutes or rules to exclude animals from accessing the runoff areas up-slope of the springs. This is likely not realistic, given the reliance on this water by the animals for survival and, in turn, their role in the economy in these rural communities.

A fourth option, which we seek to pursue, is to drill small-yield wells at mountain springs (Figure 2) using the methods designed and demonstrated by Pierce et al. (2018) and proposed conceptually by Cherry et al. (2013 and 2017) based on the results of Chitwood. In the El Cercado basin, there are generally no roads leading to springs which are in good condition to support a well drilling rig. Drilling of wells can thus only be achieved with portable drills that can be carried up the mountains. The proposed research methodology requires: (1) portable rock drills that can drill holes deep enough to avoid contamination, (2) a procedure to reliably seal the well casing along its length, so that surface contamination does not enter the well intake at the bottom of the casing, and (3) knowledge of fractured rock hydrogeology. These three requirements have been advanced substantially by field research into the nature of fracture networks, groundwater flow, and contaminant transport and fate, conducted by the G360 Institute for Groundwater Research at the University of Guelph, Canada (Parker et al. 2012; Cilona et al. 2016; and Pierce et al. 2018).

The premise of the portable drills method is that the bottom segment of the drill hole will encounter fractures that are part of the active groundwater flow system in the network of nearly ubiquitous fractures in the rock. The fact that the springs exist means that there are fractures conducting substantial groundwater flow and therefore the aim of the drilling is to tap into the fracture network. The fact that the springs, used as water resources by communities, exist year-round means that groundwater is a significant contributor to spring flow, even in times of drought. Pierce et al. (2018) have shown that portable drills can be used for drilling in bedrock, approximately 15 metres below ground surface, installing monitoring wells with reliable seals at sites in California and Canada, and delineating contamination in bedrock. These monitoring wells required pumping water for purging and sampling and, therefore, this methodology should be easily implemented for the purpose of making water supply wells in developing communities.

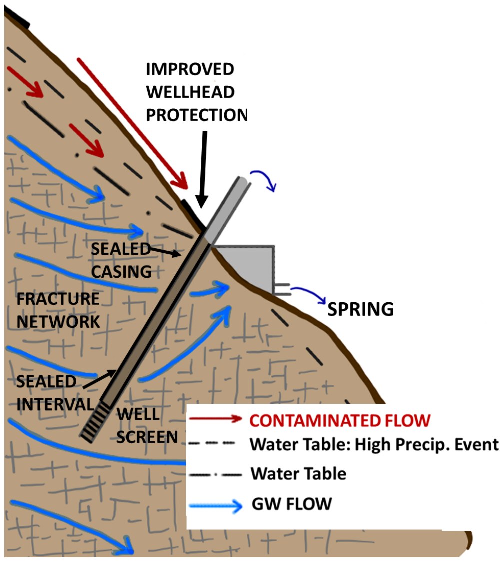

Figure 2. Diagonally drilled spring well, showing sealed interval which prevents contaminated groundwater from entering the well and isolates the well screen for intake of groundwater from a presumably contamination-free flow zone

It is presumed that these small-yield wells at mountain springs will be drilled deep enough to bypass the contaminated shallow groundwater flow and tap into the cleaner, deeper groundwater flow, 10 to 20 metres below ground surface. This deeper groundwater is believed to originate as rainfall and runoff recharged at higher elevations where there are fewer animals and human activity (Parker et al. 2011); the longer groundwater flow paths for this higher-elevation recharge have lower pathogen concentrations (Page et al. 2012). These wells would take the place of having water piped from spring boxes, where contamination is more prevalent and likely. The well would be connected to the existing gravity flow piped distribution system, with clean water being delivered to surface without the use of pumps due to flowing artesian conditions.

Conclusions and recommendations

Spring sources in the El Cercado basin of the D.R. were assessed and water was sampled and tested. Given faecal contamination measured at many mountain springs in a study by Chitwood in southwest China, and the previous discussion on proximity of humans and animals to spring sources, initially, it was not surprising to find contamination at the springs visited in this mountainous area in the D.R. However, upon determining that land use activities around the D.R. springs showed considerably less anthropogenic activity than in the study areas reported on by Chitwood, the sources of contamination are not so apparent. We propose that sparse cattle grazing is the main contaminant source. Given that these springs are the sole sources providing drinking water to rural mountainous communities, further investigation of contamination at the springs is needed and possibilities for avoiding contamination need to be assessed.

Moving forward, the study will include a continuation of assessments and testing at all springs that can be found in the El Cercado basin, with the addition of flow measurements and geological study. Investigations of land use at and up-slope from the sources will be intensified, and include study of aerial images on Google Earth, most of which have been recently updated from 2002 aerials. We estimate that there are between 15 - 20 springs in the basin that have not yet been located for these assessments and testing.

The use of portable rock drilling machines to create wells offers considerable potential to provide access to safer groundwater for mountainous communities in the D.R. The next steps of the research detailed involve proving, demonstrating, and implementing the mountain wells concept in the D.R., where there is supporting infrastructure and a collaborative network. Then, further activities would focus on transferring the small wells capability to other developing areas (e.g., in Haiti), particularly less-served, more impoverished communities where the need is more urgent.

Acknowledgements

The authors acknowledge the Engineering for Development (E4D – e4d.mercer.edu) and Mercer On Mission (MOM – mom.mercer.edu) programs at Mercer University. The former provides students with the appropriate skills to work as engineering professionals in the humanitarian and development sectors, both internationally and domestically. MOM consists of numerous Mercer faculty-led programs to various countries, with a focus on conducting sustainable service and research activities to improve quality of life among target populations. Through MOM, E4D is working with rural communities in El Cercado, D.R.

The authors also acknowledge the following individuals: Joana Petersen, community organizer for the Catholic parish in the study area, for her tireless work helping with logistics and connecting us to knowledgeable technicians and water committee members who have helped with this study; Ryan Schweitzer, a partner in this research from the beginning, for his insight into Dominican water systems and culture; Derek Chitwood for sharing experiences from his work and research in China; Robert Ingleton, now retired, for developing the innovative method for sealing wells in small-diameter drill holes; and Neil Shaw for his relentless pursuit of better drilling technology for small wells in bedrock.

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