Seasonality of drinking water sources and the impact of drinking water source on enteric infections among children in Limpopo, South Africa

Kathy H. Nguyen\textsuperscript{a}, Darwin J. Operario\textsuperscript{b}, Mzwakhe E. Nyathi\textsuperscript{c}, Courtney L. Hill\textsuperscript{d}, James A. Smith\textsuperscript{d}, Richard L. Guerrant\textsuperscript{b}, Amidou Samie\textsuperscript{e}, Rebecca A. Dillingham\textsuperscript{b}, Pascal O. Bessong\textsuperscript{e}, Elizabeth T. Rogawski McQuade\textsuperscript{a,b}

\textsuperscript{a}Department of Public Health Sciences, University of Virginia, Charlottesville, VA 22908 USA
\textsuperscript{b}Division of Infectious Diseases and International Health, University of Virginia, Charlottesville, VA 22908 USA
\textsuperscript{c}Department of Animal Science, University of Venda, Limpopo Province, Thohoyandou, 0950 South Africa
\textsuperscript{d}Department of Engineering Systems and Environment, University of Virginia, Charlottesville, VA 22904 USA
\textsuperscript{e}Department of Microbiology, University of Venda, Limpopo Province, Thohoyandou, 0950 South Africa

Abstract

Enteric infections and water-related illnesses are more frequent during times of relative water abundance, especially in regions that experience bimodal rainfall patterns. However, it is unclear how seasonal changes in water availability and drinking water source types affect enteric infections in young children. This study investigated seasonal shifts in primary drinking water source type and the effect of water source type on enteric pathogen prevalence in stool samples from 404 children below age 5 in rural communities in Limpopo Province, South Africa. From wet to dry season, 4.6% (n=16) of households switched from a source with a higher risk of contamination to a source with lower risk, with the majority switching to municipal water during the dry season. In contrast, 2.6% (n=9) of households switched from a source with a lower risk of contamination to a source with higher risk. 74.5% (n=301) of the total households experienced interruptions in their water supply, regardless of source type. There were no significant differences in enteric pathogen prevalence between drinking water sources. Intermittent municipal water distribution and household water use and storage practices may have a larger impact on enteric
infections than water source type. The limited differences in enteric pathogen prevalence in children by water source could also be due to other exposure pathways in addition to drinking water, for example through direct contact and food-borne transmission.

**Keywords**
seasonality; water quality; pathogen; enteric infection; water source; access

**Introduction**

Water quality varies greatly across South Africa, with rural areas being the most vulnerable to poor water access and/or quality (Meissner et al., 2018; Mellor et al., 2012). Health outcomes of poor drinking water quality include enteric infections, diarrhea, childhood stunting, anxiety and depression, and death (Abia et al., 2017; Liu et al., 2014; Pickering et al., 2019; Workman & Ureksoy, 2017). In South Africa, diarrhea is one of the leading causes of death among young children (Dorrington et al., 2014). Water, sanitation, and hygiene measures remain critically important to reduce exposure to pathogens causing water-borne illness, especially among children in low-resource settings, who are at the greatest risk from enteric infections and their associated symptoms and complications (Brown et al., 2013; Cumming et al., 2019; McQuade et al., 2019).

Households may change their water source due to seasonal variations in rainfall and water availability or maintenance and governance issues (Bisung et al., 2015; Dos Santos et al., 2017; Heleba, 2011; Majuru et al., 2012). Therefore, access to water can vary across seasons and throughout the year. Differences in water source types used in the wet versus dry seasons may have different health implications and contribute to the seasonality of enteric infections observed in many contexts (Lal et al., 2012), such as the seasonality of *Shigella* in Limpopo, South Africa (Rogawski McQuade et al., 2020). For example, there may be an increase in infections in times of relative water abundance or the wet season (Ashbolt, 2015). This can be due to reductions in water quality, such as increased chemical or microbial contamination from runoff (Ngoye & Machiya, 2004; Ouyang et al., 2006). In contrast, during times of water scarcity or the dry season, lack of water may negatively influence health due to unsanitary conditions, inadequate water availability for consumption and hygiene, and the reliance on alternative sources of water. Alternative water sources can increase the risk of water-related diseases if they are of lower water quality (Bradley & Bartram, 2013). Low-income households are the most vulnerable during periods of low water abundance (Majuru et al., 2016). Additionally, seasonality can affect resource mobilization and external support availability in communities (Holmatov et al., 2017; Kelly et al., 2018).

The risk of fecal contamination varies by water source type (Kostyla et al., 2015). Improved water sources include piped water, public tap or standpipe, borehole, protected dug well or spring, and rainwater. In contrast, unimproved water sources include unprotected dug well or spring, tanker truck, and surface water from rivers, dams, lakes, ponds, streams, canals, or irrigation channels (WHO & UNICEF, 2016). Unimproved water sources have significantly
higher risk of being contaminated compared to improved water sources (Shields et al., 2015; Kumpel & Nelson, 2016). The use of water sources with higher contamination during times of lower water abundance is one reason why water-related disease prevalence may differ across seasons (Pearson et al., 2016).

We previously assessed total coliform bacteria and E. coli in local water sources (Edokpayi et al., 2018) and samples of drinking water from households (manuscript under review) within a community in Limpopo, South Africa. We documented high levels of contamination of water sources in this area, which changed seasonally. Here, we further analyze data collected during this study to describe changes in primary water sources of households across wet and dry seasons and investigate how water source type affects the risk of enteric infections in children under the age of 5 in this community.

### Material and Methods

**Procedures**

We analyzed data from a randomized controlled trial of the impact of low-cost point-of-use water treatment technologies on enteric infections and linear growth among children in Limpopo, South Africa. The study design and primary results have been previously reported (Hill et al., 2020). Briefly, the study enrolled one child under the age of 3 from 404 households in rural villages from the Dzimauli community in Limpopo, South Africa. Participant households were recruited from 18 villages and completed a baseline questionnaire between June-November 2016. Smaller villages were combined into two larger groups (n=40 in Group 1 and n=64 in Group 2) for data analysis. The remainder of villages were analyzed by village (Figure 1).

The baseline questionnaire included questions relating to demographics, primary drinking water sources, and water use practices of the child and their household. Primary drinking water sources were classified into 5 categories: municipal, surface water from tap/pipe, directly from surface, groundwater, and other/unknown. The five water source types are defined in Table 1. Mutale Water Works is the municipal water treatment plant for the communities in this study, as shown in Figure 1. However, not all households necessarily receive and use municipal water due to inadequate infrastructure and intermittent supply. Demographics recorded for each child included age, sex, and socioeconomic status, defined by the WAMI index, a score based on water and sanitation access, asset ownership, maternal education, and average monthly household income (Psaki et al., 2014). Additionally, the primary caregivers’ demographics were collected, including their mother’s age and education level. Water use practices included drinking water storage type and treatment. Drinking water storage types included metal and plastic buckets, jerry cans, and plastic bottles, while typical drinking water treatment included letting the water stand and settle, adding chlorine, boiling, and no treatment.

Field researchers conducted follow-up questionnaires and collected a stool sample from the youngest child under 3 years of age every 3 months. During each visit, a questionnaire was given to the child’s caregiver to collect information on primary water sources, water use practices, and recent health information about the child, including diarrhea in the past 7
days. Stool samples were stored at −70°C before testing, which was conducted in batches every 6 months. DNA was extracted from stool using the Qiagen QIAamp Fast DNA Stool MiniKit (Qiagen, Valencia, VA, USA) and tested for enteropathogens using multiplex real-time PCR, as previously described (Hill et al., 2020). Targeted genes for amplification identified enteroaggregative E. coli (EAEC), enterohemorrhagic E. coli (EHEC/EPEC), Giardia, Campylobacter, Cryptosporidium, enterotoxigenic E. coli (ETEC), Shigella, and adenovirus (Liu et al., 2014). Detections at a PCR cycle threshold of <35 were considered positive as previously (Hill et al., 2020).

Data Analysis

All analyses were conducted using SAS software (version 9.4). We categorized the wet season from November to March, and the dry season from April to October. We categorized drinking water source for each household by season and assessed changes in primary water source between wet and dry seasons. In a minority of cases, households used more than 2 types of water sources during one wet/dry season, in which case, the water source for that season was categorized as “mixed.” If a change in water source occurred between seasons, the change was noted if it was to a water source with a higher risk or lower risk of contamination. “Municipal” and “groundwater” were classified as low risk, improved water sources while “surface water from tap/pipe,” directly from surface water,” and “Other/unknown” was classified as high risk, unimproved water sources (WHO & UNICEF, 2016).

We estimated prevalence ratios for the effects of primary water source on the prevalence of enteric infections using log-binomial regression. Poisson regression was used for a combined outcome of the total count of positive pathogen detections. Generalized estimating equations were used in both models to account for correlation between stool samples from the same child, and models were adjusted for age, socioeconomic status, season (wet/dry), and randomization group for the water treatment intervention.

Results

Study participants were geographically distributed within the Dzimauli community in Limpopo, South Africa. 30.7% (n=124) of study participants were from Village A, 18.8% (n=76) from Village B, 18.3% (n=74) from Village D, 15.8% (n=64) from Group 2, 9.9% (n=40) from Group 1, and 6.4% (n=26) from Village C (Figure 1). Surface water from tap/pipe was the most common source of drinking water in 4 out of the 6 village groups. In the remaining 2 village groupings, the most common source of drinking water was municipal. Village A had the largest number of participants (n=124) with 89% (n=110) relying on municipal water and most of the rest (8%, n=10) obtaining surface water from tap/pipe as their primary source of drinking water. Approximately a third (n=21, 32.8%) of participants in Group 2 obtained their drinking water directly from surface water (Figure 1).

The study population consisted of 404 children under the age of 3, with the highest percentage of children (38.4%) being under the age of 1 year old. 48.3% of the study children were male and 51.7% were female. Across both study years, 41.6% (n=168) households used municipal water as their primary source of drinking water, 36.1% (n=146) used surface water from tap/pipe, 6.7% (n=27) used direct collection from surface water,
11.9% (n=48) used groundwater, and 3.7% (n=15) used another or unknown source (Table 2). No form of drinking water treatment was used in most households across drinking water source groups (n=342, 84.7%). While water treatment was rare prior to consumption, boiling water was the most used form of treatment (n=33, 8.2%). In terms of drinking water storage, the majority of participants used covered storage vessels (n=328, 81.2%), with jerrycans (n=200, 49.5%) being the most common, followed by plastic buckets (n=162, 40.1%), regardless of their water source. Water supply was not continuously available (was interrupted) for 14.8% (n=4) of those who relied on direct collection from surface water, but interruptions were much more common for those who relied on municipal (n=165, 98.2%), surface water from tap/pipe (n=110, 75.3%), and groundwater (n=21, 43.8%; Table 2).

In terms of childhood growth, the highest prevalence of stunting at baseline was found among children who used other/unknown water sources (n=7, 53.9%), while the highest prevalence of underweight was found among children who used direct collection from surface water (n=4, 14.8%). Lastly, wasting was most common among children who used groundwater (n=4, 8.5%). Across all groups, the average age of the child’s mother was 28 years old, with the most common school grade completed by the mother being secondary school. The average socioeconomic status score was the lowest for those who used directly from surface water (mean WAMI score: 0.63) compared to the other groups (mean WAMI score: 0.80).

**Seasonality of Water Sources**

Changes in primary drinking water sources across wet and dry seasons over the 2 years of the study were rare. A majority of the households (n=275, 78.3%) used the same water source year-round (Table 3). Of those that changed water sources, 2.6% (n=9) switched to a higher risk source. The majority of those who changed to a higher risk source (n=6, 66.7%) went from using groundwater during the wet season to surface water during the dry season. Contrastingly, 4.6% (n=16) of households switched to a lower risk source, with the majority switching to municipal water during the dry season (Table 3).

**Enteric infections**

Overall, EAEC, EHEC/EPEC, and *Giardia* infections were the most prevalent across the different water source groups (Figure 2). While the prevalence ratios for some enteric infections suggested small differences in infection prevalence across drinking water source types, the estimates were imprecise given the small numbers of infections for some water sources (Table 4). There were no significant differences in enteric infections between drinking water sources. Additionally, there were no differences in the total number of pathogens detected among children drinking surface water from tap/pipe (adjusted prevalence ratio (aPR): 0.99, 95% CI: 0.89, 1.10), directly from surface (aPR: 0.92, 95% CI: 0.70, 1.20), groundwater (aPR: 0.98, 95% CI: 0.87, 1.11), and other/unknown source (aPR: 0.95, 95% CI: 0.71, 1.27) compared to municipal water. The prevalence of *Giardia* and ETEC infections among children who drank groundwater were 1.21 (95% CI: 0.94, 1.55) and 1.19 (95% CI: 0.84, 1.69) times the prevalence of those infections among those who drank municipal water over the 2-year follow-up period (Table 4). EHEC/EPEC infections
among children who relied directly from surface water was 1.19 (95% CI: 0.87, 1.62) times as likely as those infections among those who relied on municipal water.

Discussion

We investigated seasonal shifts in primary drinking water source type and the effect of water source type on pathogen prevalence in children in rural communities in Limpopo Province, South Africa. Overall, changes in primary drinking water sources across seasons were small. Higher risk sources were more common during the wet season. Both of these findings were similarly found in a study by Pearson et al. (2016) in Uganda and Tanzania. Our study area and those in Pearson et al. (2016) in rural communities exhibit a unimodal dry/wet seasonality with an extended dry season in a semi-arid climate. Pearson et al. (2016) found that more households used lower risk sources during the dry season, compared to the wet season, as we did in South Africa. Lower risk source usage in the dry season would suggest lowest risk for enteric infections in the dry season according to Kostyla et al. (2015). This is additionally supported from earlier microbiological analyses of water samples from our study area that found that bacterial levels of surface water sources were higher in the wet season than in the dry season (Edokpayi et al., 2018). The increase in bacteria during the wet season could be caused by increased runoff carrying bacteria from contaminated sources to these bodies of water.

There were no significant differences in enteric pathogen prevalence between drinking water sources. Earlier microbiological analysis from this study (Edokpayi et al, 2018) found that while municipal water never tested positive for fecal contamination from E. coli from 2016-2017, intermittent water distribution and prolonged storage made municipal water an inconsistent water source with high risk of recontamination during storage. There was a high prevalence of total coliform bacteria in household-stored water in those who used municipal water, even though the municipal water had no fecal contaminants when sampled directly from the tap (Edokpayi et al., 2018). Intermittent availability could therefore result in similar levels of contamination between “high risk” and “low risk” water sources and could explain why households might switch from lower risk municipal water to a higher risk source regardless of season. Prior research suggests that water contamination often occurs during storage through the use of water transfer devices, using a hand or bowl to transfer from the storage container for consumption (Heitzinger et al., 2015; Packiyam et al., 2016; Wright et al., 2018). These factors may have a larger effect on enteric infection than water source type, since a majority of households experienced interrupted water supply and practiced no form of drinking water treatment regardless of water source type. Water quantity and consistency of availability for consumption and hygiene may ultimately be more important for preventing transmission of certain enteric pathogens than contamination of the water source.

The limited effects of water source on enteric pathogen prevalence in children could also be due to the fact that children were exposed through other pathways in addition to drinking water. All of the pathogens observed are transmitted via the fecal-oral route, where direct person-to-person contact and indirect contact through contaminated food are examples of other potential transmission pathways through which children could be exposed (Anin-
Baidoo et al., 2016; Penakalapati et al., 2017). Specifically, *Campylobacter* is a leading foodborne bacterial pathogen, generally through undercooked meat and raw milk, while *Shigella* tends to be transmitted from person-to-person (Lampel et al., 2018; Luangtongkum et al., 2009). Additionally, this study was limited by only analyzing primary drinking water source data. We did not consider that households may use more than one drinking water source or use separate sources for different household purposes, like cooking and bathing. Children could be exposed to enteric pathogens through water or contact with infected persons from outside sources, for example neighbors, non-household family members, or daycare centers, or through eating contaminated foods.

Access to safe and clean drinking water is a critical determinant of health, with social, economic, and environmental consequences. Especially among young children who are at the greatest risk for enteric infections, contaminated drinking water can contribute to environmental enteropathy, a syndrome marked by increased intestinal permeability, impaired immune function in the gut, and malabsorption, which may lead to child growth stunting (Korpe and Petri, 2012). Because households’ primary drinking water source can vary across seasons, water sources and the potential for seasonal differences are key components that need to be evaluated to ensure equitable access to safe drinking water year-round. Future research could involve qualitatively investigating the decision-making process behind drinking water source choice and reasons for changes in water sources. Understanding these dynamics as well as how water is used and stored are important to reduce enteric pathogen exposure from high risk sources and could be useful in community planning, distribution, and management of clean water.

Increasing access to, and the consistency of, the municipal water supply are clear opportunities to improve water quality in Limpopo. Access to municipal water varied by village in the same community, but was not related to distance from the municipal water treatment plant. This may reflect varied ability of the traditional leadership across villages to negotiate with the municipal leadership to improve water access based on the requests of community members. Previous research in Dzimauli has documented strong citizen engagement through traditional authority structures to advocate for improved water services (Bulled, 2017). However, these engagement efforts may be more successful among individuals with higher socioeconomic or political status, ultimately resulting in inequitable access. The South African constitution documents that water is a human right (Bill of Rights, 1996); continued advocacy to ensure continuous supply equitably throughout communities is a key step towards achieving this right for all. Increasing access to and consistency of municipal water is one of the many opportunities to improve health outcomes in this community.

**Acknowledgments**

Role of the funding source

This work was supported by the Thrasher Research Fund (grant 13923 to ETRM), the U.S. National Academies of Sciences and USAID (grant AID-OAA-A-11-00012 to POB), the National Research Foundation of South Africa (grant 114725 to POB), the National Science Foundation (grant CBET-1438619 to JAS), the National Institutes of Health, Fogarty International Center (grant D43TW009359 to RLG, ETRM, JNE, DMK), and the National Institutes of Health, National Institute of Allergy and Infectious Diseases (grant K01AI130326 to ETRM). Student
effort was supported by the University of Virginia (UVA) Jefferson Public Citizens Program, the UVA Center for Global Health, and the National Institutes of Health, National Institute on Minority Health and Health Disparities (grant T37MD008659 to RAD). The funders had no involvement in the collection, analysis, or interpretation of data; in writing the report; or in the decision to submit the article for publication. The opinions, findings, conclusions or recommendations are those of the authors alone and do not necessarily reflect the views of NAS, USAID, the National Research Foundation of South Africa, the Thrasher Research Fund, NSF or the NIH.

References

1. Abia ALK, Schaefer L, Ubomba-Jaswa E, & Le Roux W (2017). Abundance of pathogenic Escherichia coli virulence-associated genes in well and borehole water used for domestic purposes in a peri-urban community of South Africa. International journal of environmental research and public health, 14(3), 320.

2. Anim-Baidoo I, Narh CA, Oddei D, Brown CA, Enweronu-Laryea C, Bandoh B, … & Ayeh-Kumi PF (2016). Giardia lamblia infections in children in Ghana. The Pan African Medical Journal, 24.

3. Ashbolt NJ (2015). Microbial contamination of drinking water and human health from community water systems. Current environmental health reports, 2(1), 95–106. [PubMed: 25821716]

4. Bill of Rights. Section 27(1)(b) of the Constitution of the Republic of South Africa Act 108 1996

5. Bisung E, Elliott SJ, Abudho B, Schuster-Wallace CJ, & Karanja DM (2015). Dreaming of toilets: Using photovoice to explore knowledge, attitudes and practices around water–health linkages in rural Kenya. Health & place, 31, 208–215. [PubMed: 25576836]

6. Bradley DJ, & Bartram JK (2013). Domestic water and sanitation as water security: monitoring, concepts and strategy. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 371(2002), 20120420.

7. Brown J, & Cumming O (2020). Stool-based pathogen detection offers advantages as an outcome measure for water, sanitation, and hygiene trials. The American Journal of Tropical Medicine and Hygiene, 102(2), 260–261. [PubMed: 31701856]

8. Brown J, Cairncross S, & Ensink JH (2013). Water, sanitation, hygiene and enteric infections in children. Archives of disease in childhood, 98(8), 629–634. [PubMed: 23761692]

9. Bulled N, (2017). The effects of water insecurity and emotional distress on civic action for improved water infrastructure in rural South Africa. Medical anthropology quarterly, 31(1), pp.133–154. [PubMed: 26698378]

10. Cumming O, Arnold BF, Ban R, Clasen T, Mills JE, Freeman MC, … & Joshton RB (2019). The implications of three major new trials for the effect of water, sanitation and hygiene on childhood diarrhea and stunting: a consensus statement. BMC medicine, 17(1), 1–9. [PubMed: 30651111]

11. Dorrington R, Bradshaw D, Laubscher R, & Nannan N (2014). Rapid mortality surveillance report 2012. Cape Town: South African Medical Research Council.

12. Dos Santos S, Adams EA, Neville G, Wada Y, De Sherbinin A, Bernhardt EM, & Adamo SB (2017). Urban growth and water access in sub-Saharan Africa: Progress, challenges, and emerging research directions. Science of the Total Environment, 607, 497–508.

13. Edokpayi JN, Rogawski ET, Kahler DM, Hill CL, Reynolds C, Nyathi E, … & Dillingham R (2018). Challenges to sustainable safe drinking water: a case study of water quality and use across seasons in rural communities in Limpopo province, South Africa. Water, 10(2), 159. [PubMed: 30595910]

14. Heitzinger K, Rocha CA, Quick RE, Montano SM, Tilley DH Jr, Mock CN, … & Hawes SE (2015). “Improved” but not necessarily safe: an assessment of fecal contamination of household drinking water in rural Peru. The American journal of tropical medicine and hygiene, 93(3), 501–508. [PubMed: 26195455]

15. Heleba S (2011). The right of access to sufficient water in South Africa: How far have we come?. Law, Democracy & Development, 15(1).

16. Hill CL, McCain K, Nyathi ME, Edokpayi JN, Kahler DM, Operario D1, … & Samie A (2020). Impact of Low-Cost Point-of-Use Water Treatment Technologies on Enteric Infections and Growth among Children in Limpopo, South Africa. The American Journal of Tropical Medicine and Hygiene, tpmd200228
17. Holmatov B, Lautze J, Manthrithilake H, & Makin I (2017). Water security for productive economies: Applying an assessment framework in southern Africa. Physics and Chemistry of the Earth, Parts A/B/C, 100, 258–269.

18. Kelly E, Shields KF, Cronk R, Lee K, Behnke N, Klug T, & Bartram J (2018). Seasonality, water use and community management of water systems in rural settings: Qualitative evidence from Ghana, Kenya, and Zambia. Science of the Total Environment, 628, 715–721.

19. Korpe PS, & Petri WA Jr (2012). Environmental enteropathy: critical implications of a poorly understood condition. Trends in molecular medicine, 18(6), 328–336. [PubMed: 22633998]

20. Kostyla C, Bain R, Cronk R, & Bartram J (2015). Seasonal variation of fecal contamination in drinking water sources in developing countries: a systematic review. Science of the Total Environment, 514, 333–343.

21. Kumpel E, & Nelson KL (2016). Intermittent water supply: prevalence, practice, and microbial water quality. Environmental science & technology, 50(2), 542–553. [PubMed: 26670120]

22. Lal A, Hales S, French N, & Baker MG (2012). Seasonality in human zoonotic enteric diseases: a systematic review. PLoS One. 2012;7(4):e31883. [PubMed: 22485127]

23. Lampel KA, Formal SB, & Maurelli AT (2018). A Brief History of Shigella. EcoSal Plus, 8(1).

24. Liu J, Kabir F, Mannen J, Lertsethtakarn P, Begum S, Gratz J, … & Platts-Mills JA (2014). Development and assessment of molecular diagnostic tests for 15 enteropathogens causing childhood diarrhoea: a multicentre study. The Lancet Infectious Diseases, 14(8), 716–724. [PubMed: 25022434]

25. Luangtongkum T, Jeon B, Han J, Plummer P, Logue CM, & Zhang Q (2009). Antibiotic resistance in Campylobacter: emergence, transmission and persistence.

26. Majuru B, Jalige P, & Hunter PR (2012). Assessing rural small community water supply in Limpopo, South Africa: Water service benchmarks and reliability. Science of the Total Environment, 435, 479–486.

27. Majuru B, Suhreke M, & Hunter PR (2016). How do households respond to unreliable water supplies? A systematic review. International journal of environmental research and public health, 13(12), 1222.

28. Meissner R, Funke N, Nortje K, Jacobs-Mata I, Moyo E, Steyn M, … & Nohayi N (2018). Water security at local government level in South Africa: a qualitative interview-based analysis. The Lancet Planetary Health, 2, S17.

29. Mellor JE, Smith JA, Learmonth GP, Netshandama VO, & Dillingham RA (2012). Modeling the complexities of water, hygiene, and health in Limpopo Province, South Africa. Environmental science & technology, 46(24), 13512–13520. [PubMed: 23186073]

30. Ngoye E, & Machiwa JF (2004). The influence of land-use patterns in the Ruvu river watershed on water quality in the river system. Physics and Chemistry of the Earth, Parts A/B/C, 29(15-18), 1161–1166.

31. Ouyang Y, Nkedi-Kizza P, Wu QT, Shinde D, & Huang CH (2006). Assessment of seasonal variations in surface water quality. Water research, 40(20), 3800–3810. [PubMed: 17069873]

32. Packiyam R, Kanang S, Pachaiyappan S, & Narayanan U (2016). Effect of storage containers on coliforms in household drinking water. International Journal of Current Microbiology and Applied Sciences, 5(1), 461–477.

33. Pearson AL, Zwickle A, Namanya J, Rzotkiewicz A, & Mwita E (2016). Seasonal shifts in primary water source type: a comparison of largely pastoral communities in Uganda and Tanzania. International journal of environmental research and public health, 13(2), 169. [PubMed: 26828507]

34. Penakalapati G, Swarthout J, Delahoy MJ, Mcauliley L, Wodnik B, Levy K, Freeman MC. Exposure to Animal Feces and Human Health: A Systematic Review and Proposed Research Priorities. Environ Sci Technol. 2017;51(20):11537–11552. doi:10.1021/acs.est.7b02811. [PubMed: 28926696]

35. Pickering AJ, Null C, Winch PJ, Mangwadu G, Arnold BF, Prendergast AJ, … & Stewart CP (2019). The WASH benefits and SHINE trials: interpretation of WASH intervention effects on linear growth and diarrhoea. The Lancet Global Health, 7(8), e1139–e1146. [PubMed: 31303300]
36. Psaki SR, Seidman JC, Miller M, Gottlieb M, Bhutta ZA, Ahmed T, … & Kosek M (2014). Measuring socioeconomic status in multicountry studies: results from the eight-country MAL-ED study. Population health metrics, 12(1), 8. [PubMed: 24656134]

37. Rogawski McQuade ET, Platts-Mills JA, Gratz J, Zhang J, Moulton LH, Mutasa K, … & Humphrey JH (2019). Impact of water quality, sanitation, handwashing, and nutritional interventions on enteric infections in rural Zimbabwe: the Sanitation Hygiene Infant Nutrition Efficacy (SHINE) Trial. The Journal of infectious diseases, 1379, 1–8.

38. Rogawski McQuade ET, Shaheen F, Kabir F, Rizvi A, Platts-Mills JA, Aziz F, … & Lima AA (2020). Epidemiology of Shigella infections and diarrhea in the first two years of life using culture-independent diagnostics in 8 low-resource settings. PLOS Neglected Tropical Diseases, 14(8), e0008536. [PubMed: 32804926]

39. Shields KF, Bain RE, Cronk R, Wright JA, & Bartram J (2015). Association of supply type with fecal contamination of source water and household stored drinking water in developing countries: a bivariate meta-analysis. Environmental health perspectives, 123(12), 1222–1231. [PubMed: 25956006]

40. WHO & UNICEF. (2016). Improved and unimproved water sources and sanitation facilities. Geneva: WHO/UNIFEC Joint Monitoring Programme (JMP) for Water Supply and Sanitation.

41. Workman CL, & Ureksoy H (2017). Water insecurity in a syndemic context: Understanding the psycho-emotional stress of water insecurity in Lesotho, Africa. Social Science & Medicine, 179, 52–60. [PubMed: 28254659]

42. Wright CJ, Sargeant JM, Edge VL, Ford JD, Farahbakhsh K, Shiwak I, … & IHACC Research Team. (2018). Water quality and health in northern Canada: stored drinking water and acute gastrointestinal illness in Labrador Inuit. Environmental Science and Pollution Research, 25(33), 32975–32987. [PubMed: 28702908]
Highlights

• We report water source seasonality and effects on enteric infections in children
• Changes in primary drinking water sources between wet and dry seasons were rare
• There were no differences in enteric infection prevalence by drinking water source
• Municipal water availability varied by village and was intermittent
• Multiple exposure pathways likely lead to enteric infections in young children
Figure 1.
Map of study villages with prevalence of primary drinking water sources. Top left inset map highlights the Dzimauli community (study area; black point), in Limpopo province (light tan), South Africa (green). The location of the municipal water treatment plant, Mutale Water Works, is highlighted with a purple triangle. Source: ArcMap GIS.
Figure 2.
Prevalence of enteric infections over 2 years of follow-up by primary drinking water source among 404 children. Error bars denote standard errors. EAEC: enteroaggregative E. coli. EHEC/EPEC: enterohemorrhagic E. coli/enteropathogenic E. coli. ETEC: enterotoxigenic E. coli.
Table 1: Primary Drinking Water Source Type Classification

| Water Source Type           | Definition                                                                 |
|-----------------------------|-----------------------------------------------------------------------------|
| Municipal                   | Piped from municipal water treatment plant                                  |
| Surface water from tap/pipe | Piped from local surface water sources, such as the Mutale River, a lined canal, pond, or a shallow/hand-dug well |
| Directly from surface       | Directly obtained from local surface water sources                           |
| Groundwater                 | Obtained from a spring or borehole                                           |
| Other/unknown               | Other or unknown water source                                                |
Table 2:
Baseline characteristics by primary drinking water source among 404 children.

| Primary Drinking Water Source | Municipal (n=168) | Surface water from tap/pipe (n=146) | Directly from surface water (n=27) | Groundwater (n=48) | Other/unknown (n=15) |
|--------------------------------|-------------------|-------------------------------------|---------------------------------|-------------------|---------------------|
| Child Characteristics          |                   |                                     |                                 |                   |                     |
| Sex, n (%)                     |                   |                                     |                                 |                   |                     |
| Male                           | 82 (48.8%)        | 72 (49.3%)                          | 13 (48.2%)                      | 21 (43.8%)        | 7 (46.7%)           |
| Female                         | 86 (51.2%)        | 74 (50.7%)                          | 14 (51.8%)                      | 27 (56.2%)        | 8 (53.3%)           |
| Average Age of Child (years), n (%) |               |                                     |                                 |                   |                     |
| <1                             | 60 (35.7%)        | 60 (41.1%)                          | 11 (40.7%)                      | 15 (31.3%)        | 9 (60.0%)           |
| 1-2                            | 62 (36.9%)        | 52 (35.6%)                          | 8 (29.6%)                       | 20 (41.7%)        | 4 (26.7%)           |
| 2-3                            | 46 (27.4%)        | 34 (23.3%)                          | 8 (29.6%)                       | 13 (27.0%)        | 2 (13.3%)           |
| Socioeconomic Status Score (WAMI) * |             |                                     |                                 |                   |                     |
| Mean (SD)                      | 0.80 (±0.10)      | 0.78 (±0.10)                        | 0.63 (±0.10)                    | 0.80 (±0.13)      | 0.83 (±0.09)        |
| Length/height-for-age z-score at baseline | | | | | |
| Mean (SD)                      | −1.41 (±1.22)     | −1.38 (±1.28)                       | −1.43 (±1.38)                   | −1.18 (±1.23)     | −1.38 (±1.98)       |
| Height-for-weight z-score at baseline | | | | | |
| Mean (SD)                      | −0.35 (±1.19)     | −0.28 (±1.21)                       | −0.58 (±1.46)                   | −0.34 (±1.22)     | −0.21 (±1.31)       |
| Stunted at baseline, n (%) †    | 54 (32.5%)        | 45 (31.9%)                          | 9 (33.3%)                       | 10 (21.3%)        | 7 (53.9%)           |
| Underweight at baseline, n (%) † | 15 (9.0%)       | 10 (6.9%)                           | 4 (14.8%)                       | 4 (8.3%)          | 1 (6.7%)            |
| Wasted at baseline, n (%) †     | 6 (3.6%)          | 4 (2.8%)                            | 1 (3.7%)                        | 4 (8.5%)          | 0                   |
| Child's Mother's Demographics  |                   |                                     |                                 |                   |                     |
| Mother's age, mean (SD; years) | 27.7 (±6.7)       | 28.0 (±6.5)                         | 29.0 (±7.8)                     | 28.0 (±6.4)       | 25.6 (±5.6)         |
| Highest school grade level of mother, n (%) | | | | | |
| None                           | 1 (0.6%)          | 0                                   | 0                               | 0                 | 0                   |
| Primary                        | 7 (4.2%)          | 4 (2.8%)                            | 2 (7.4%)                        | 1 (2.1%)          | 0                   |
| Secondary                      | 99 (58.9%)        | 90 (62.9%)                          | 17 (63.0%)                      | 23 (47.9%)        | 8 (57.1%)           |
| Matriculation                  | 36 (21.4%)        | 41 (28.7%)                          | 7 (25.9%)                       | 11 (22.9%)        | 2 (14.3%)           |
| Undergraduate                   | 18 (10.7%)        | 6 (4.2%)                            | 1 (3.7%)                        | 7 (14.6%)         | 4 (28.6%)           |
| Post-graduate                  | 7 (4.2%)          | 2 (1.4%)                            | 0                               | 6 (12.5%)         | 0                   |
| Missing                        | 0                 | 0                                   | 3                               | 0                 | 1                   |
| Water Use Practices            |                   |                                     |                                 |                   |                     |
| Typical drinking water treatment, n (%) |               |                                     |                                 |                   |                     |
| Let stand and settle           | 8 (4.8%)          | 2 (1.3%)                            | 0                               | 1 (2.1%)          | 0                   |
| Add bleach/chlorine            | 5 (3.0%)          | 8 (5.5%)                            | 1 (3.7%)                        | 1 (2.1%)          | 0                   |
| Boil                           | 12 (7.1%)         | 14 (9.6%)                           | 1 (3.7%)                        | 6 (12.5%)         | 0                   |
| Other                          | 3 (1.8%)          | 0                                   | 0                               | 0                 | 0                   |
| None                           | 140 (83.3%)       | 122 (83.6%)                         | 25 (92.6%)                      | 40 (83.3%)        | 15 (100.0%)         |
| Primary Drinking Water Source | Municipal (n=168) | Surface water from tap/pipe (n=146) | Directly from surface water (n=27) | Groundwater (n=48) | Other/unknown (n=15) |
|------------------------------|-------------------|-------------------------------------|-----------------------------------|-------------------|---------------------|
| Covered water storage vessels, n (%) | 138 (82.1%) | 122 (83.6%) | 14 (51.9%) | 41 (85.4%) | 13 (86.7%) |
| Metal buckets | 5 (3.0%) | 6 (4.1%) | 0 | 0 | 0 |
| Plastic buckets | 71 (42.3%) | 57 (39.0%) | 10 (37.0%) | 21 (43.8%) | 3 (20.0%) |
| Jerry can | 81 (48.2%) | 74 (50.7%) | 16 (59.3%) | 20 (41.7%) | 9 (60.0%) |
| Plastic bottles | 1 (0.6%) | 2 (1.4%) | 1 (3.7%) | 1 (2.1%) | 0 |
| Other | 10 (6.0%) | 7 (4.8%) | 0 | 6 (12.5%) | 3 (20.0%) |
| Continuous main water supply, n (%) | 3 (1.8%) | 36 (24.7%) | 23 (85.2%) | 27 (56.3%) | 14 (93.3%) |
| Continuous | 165 (98.2%) | 110 (75.3%) | 4 (14.8%) | 21 (43.8%) | 1 (6.7%) |

*Psaki et al., 2014
†Baseline length/height unavailable for 10 (2.5%) children; baseline weight unavailable for 1 (0.2%) child.
Table 3:
Number of participants who changed their primary drinking water source from the wet to dry season over 2 years.

| Wet Season Water Source | Dry Season Water Source | Municipal | Surface Water from Tap/ Pipe | Directly from Surface | Groundwater | Other/ Unknown | Mixed | Wet Season Total |
|-------------------------|-------------------------|-----------|-----------------------------|-----------------------|-------------|----------------|-------|-----------------|
| Municipal               | 121                     | 2         | 1                           | 1                     | 0           | 7              | 132   |
| Surface Water from Tap/ Pipe | 8                  | 102       | 2                           | 3                     | 0           | 15             | 130   |
| Directly from Surface   | 0                       | 0         | 9                           | 1                     | 0           | 5              | 15    |
| Groundwater             | 1                       | 5         | 1                           | 43                    | 0           | 11             | 61    |
| Other/Unknown           | 2                       | 1         | 0                           | 2                     | 0           | 1              | 6     |
| Mixed                   | 3                       | 2         | 0                           | 0                     | 0           | 2              | 7     |
| Dry Season Total        | 135                     | 112       | 13                          | 50                    | 0           | 41             | 351   |
Table 4:
Effect of primary drinking water source on prevalence of enteric pathogens over 2 years

| Pathogen | Drinking Water Source         | Samples Tested N | Positive Cases N (% | Prevalence Ratio* (95% CI) |
|----------|------------------------------|------------------|---------------------|---------------------------|
| EAEC     | Municipal                    | 461              | 189 (41.0)          | 1                         |
|          | Surface Water from Tap/Pipe  | 373              | 151 (40.5)          | 1.02 (0.88, 1.18)         |
|          | Directly from Surface        | 43               | 12 (27.9)           | 0.78 (0.43, 1.40)         |
|          | Groundwater                  | 225              | 88 (39.1)           | 0.96 (0.81, 1.13)         |
|          | Other/Unknown                | 13               | 7 (53.9)            | 1.00 (0.53, 1.88)         |
| EHEC/EPEC| Municipal                    | 440              | 181 (41.1)          | 1                         |
|          | Surface Water from Tap/Pipe  | 369              | 158 (42.8)          | 1.05 (0.89, 1.23)         |
|          | Directly from Surface        | 41               | 18 (43.9)           | 1.19 (0.87, 1.62)         |
|          | Groundwater                  | 214              | 91 (42.5)           | 1.04 (0.87, 1.24)         |
|          | Other/Unknown                | 10               | 5 (50.0)            | 1.22 (0.68, 2.18)         |
| Giardia  | Municipal                    | 462              | 149 (32.3)          | 1.00                      |
|          | Surface Water from Tap/Pipe  | 375              | 121 (32.4)          | 1.03 (0.82, 1.29)         |
|          | Directly from Surface        | 43               | 13 (30.2)           | 0.91 (0.60, 1.39)         |
|          | Groundwater                  | 225              | 85 (37.8)           | 1.21 (0.94, 1.55)         |
|          | Other/Unknown                | 13               | 5 (38.5)            | 1.44 (0.77, 2.69)         |
| Campylobacter | Municipal            | 459              | 33 (7.2)            | 1                         |
|          | Surface Water from Tap/Pipe  | 371              | 24 (6.5)            | 0.92 (0.56, 1.51)         |
|          | Directly from Surface        | 43               | 2 (4.7)             | 0.91 (0.22, 3.71)         |
|          | Groundwater                  | 224              | 12 (5.4)            | 0.72 (0.38, 1.37)         |
|          | Other/Unknown                | 12               | 0 (0.0)             | -                         |
| Cryptosporidium | Municipal       | 461              | 15 (3.4)            | 1                         |
|          | Surface Water from Tap/Pipe  | 373              | 9 (2.4)             | 0.68 (0.32, 1.47)         |
|          | Directly from Surface        | 43               | 1 (2.3)             | 0.68 (0.08, 5.64)         |
|          | Groundwater                  | 225              | 7 (3.1)             | 1.03 (0.44, 2.38)         |
|          | Other/Unknown                | 12               | 0 (0.0)             | -                         |
| ETEC     | Municipal                    | 431              | 66 (15.3)           | 1                         |
|          | Surface Water from Tap/Pipe  | 358              | 53 (14.8)           | 0.99 (0.71, 1.38)         |
|          | Directly from Surface        | 41               | 4 (9.8)             | 0.78 (0.32, 1.93)         |
|          | Groundwater                  | 210              | 41 (19.5)           | 1.19 (0.84, 1.69)         |
|          | Other/Unknown                | 10               | 2 (20.0)            | 1.42 (0.51, 3.94)         |
| Shigella | Municipal                    | 458              | 64 (14.0)           | 1                         |
|          | Surface Water from Tap/Pipe  | 374              | 51 (13.6)           | 0.96 (0.69, 1.33)         |
|          | Directly from Surface        | 43               | 4 (9.3)             | 0.72 (0.32, 1.64)         |
|          | Groundwater                  | 224              | 32 (14.3)           | 1.02 (0.71, 1.46)         |
|          | Other/Unknown                | 13               | 1 (7.7)             | 0.49 (0.08, 3.18)         |
| Adenovirus | Municipal                    | 441              | 139 (31.5)          | 1                         |
|          | Surface Water from Tap/Pipe  | 342              | 103 (30.1)          | 0.95 (0.77, 1.17)         |
|          | Directly from Surface        | 35               | 13 (37.1)           | 1.25 (0.82, 1.92)         |
| Pathogen                  | Drinking Water Source       | Samples Tested N | Positive Cases N (%) | Prevalence Ratio* (95% CI) |
|---------------------------|----------------------------|-----------------|----------------------|----------------------------|
|                           | Groundwater                | 205             | 50 (24.4)            | 0.78 (0.59, 1.03)          |
|                           | Other/Unknown              | 11              | 4 (36.7)             | 0.99 (0.48, 2.07)          |
|                           | Total Pathogens Detected†  |                 |                      |                            |
|                           | Municipal                  | 462             | 1.81 (±1.41)         | 1                          |
|                           | Surface Water from Tap/Pipe| 375             | 1.79 (±1.41)         | 0.99 (0.89-1.10)           |
|                           | Directly from Surface      | 43              | 1.56 (±1.20)         | 0.92 (0.70-1.20)           |
|                           | Groundwater                | 225             | 1.80 (±1.41)         | 0.98 (0.87-1.11)           |
|                           | Other/Unknown              | 13              | 1.85 (±0.90)         | 0.95 (0.71-1.27)           |

* Adjusted for age, SES, season, and water treatment randomization group

† Effects estimated are mean (standard deviation) number of pathogens detected and detection rate ratios.