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Impact of Water-Vending Kiosks and Hygiene Education on Household Drinking Water Quality in Rural Ghana

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Abstract. Innovative solutions are essential to improving global access to potable water for nearly 1 billion people. This study presents an independent investigation of one alternative by examining for-profit water-vending kiosks, WaterHealth Centers (WHCs), in rural Ghana to determine their association with household drinking water quality. WHCs' design includes surface water treatment using filtration and ultraviolet light disinfection along with community-based hygiene education. Analyses of water samples for *Escherichia coli* and household surveys from 49 households across five villages collected one time per year for 3 years indicate that households using WHCs had improved water quality compared with households using untreated surface water (adjusted incidence rate ratio = 0.07, 95% confidence interval = 0.02, 0.21). However, only 38% of households used WHCs by the third year, and 60% of those households had *E. coli* in their water. Recontamination during water transport and storage is an obstacle to maintaining WHC-vended water quality.

INTRODUCTION

Improving access to potable water remains a significant global public health challenge despite decades of effort and billions of dollars spent ameliorating poor drinking water quality. Although piped treated water systems remain the goal for providing safe drinking water, many nations are unable to provide the infrastructure, energy, and treatment technology needed to provide reliable potable water supplies because of costs and lack of political will.[1] The absence of potable drinking water combined with inadequate sanitation and hygiene contributes to 9.1% of the global burden of disease, leading to an annual estimate of four billion cases of diarrhea and 1.9 million deaths among children under 5 years.[2,3] Furthermore, the health of rural populations is particularly at risk because of waterborne and water-related diseases associated with limited access to potable water, comprising 84% of the estimated 884 million people without access to improved water.[4]

Since the establishment of the Millennium Development Goals (MDGs), renewed emphasis has been placed on finding viable alternatives to providing potable water for rural communities. Small water enterprises (SWEs) have been suggested as one alternative and have gained attention from the water sector as a means to increase access for populations beyond the reach of piped systems.[5,6] SWEs have several characteristics that make them particularly well-suited to rural, poor households, including a lack of upfront connection fees that facilitate customer choice regarding the quantity of water purchased and the ability to operate in remote locations despite variable terrain and distance to urban centers. However, there is little evidence about the quality of water supplied by these generally unmonitored providers.[7]

BACKGROUND

In 2008, the Johns Hopkins University Center for Water and Health (JHUCWH) began a 3-year prospective observational study evaluating one type of SWE, a water-vending kiosk, marketed as WaterHealth Centers (WHCs). WHCs were designed to provide potable water and offer hygiene education while mobilizing communities to promote the use of WHCs' treated water.

SWEs. SWEs are increasingly recognized as alternatives to piped water systems for improving access to drinking water in otherwise hard-to-reach, low-income communities where piped water systems do not exist. SWEs are community-based vendors and can be found in low-income countries throughout the world. SWE water delivery ranges from mobile units, such as tanker trucks and door-to-door vendors who cart water by hand, to stationary water points, such as kiosks or standpipes. SWEs operate in a wide variety of settings, often beginning operations when there is a scarcity of water and reaching even the most remote regions, despite harsh terrain and governmental boundaries.[8,9] One study in East Africa found a steep rise in the number of SWEs over a 30-year period beginning in 1967, with up to 60% of households in both low- and medium-income urban populations becoming reliant on SWEs as their primary water source by 1997.[10] Another study suggests that more people are served each day in developing cities by SWEs than public utilities.[6]

SWEs have several characteristics that make them particularly suitable for delivering water to low-income, rural communities. SWEs tend to be profit-driven operations that are more flexible to consumer demands compared with public utility systems.[11] SWEs also have the advantage that financing for the capital investment can be rolled into the variable component of user fees without requiring households to pay large upfront connection fees that often prove cost-prohibitive for low-income households. A number of studies have found a diversity in the relative cost of vended water compared with piped water along with a varying willingness to pay for water among households in developing countries.[12,13] A key finding reported by Whittington and others[14] is the importance of local social, physical, and economic contexts on the community's willingness to financially support water supply interventions.

However, SWEs generally operate outside any regulatory system or quality parameters and therefore, provide drinking

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water of questionable quality. A recent literature review conducted in advance of this study found a complete lack of rigorous data examining the effectiveness of SWEs in delivering potable water, despite the growing prevalence of water vendors.[7] With market demands encouraging SWE development, an evidence base is critically needed to evaluate the public health impact of SWE drinking water supplies, especially in low-income, rural populations.

Ghana. In the West African country of Ghana, the government projects that 41% of the rural population does not have access to improved drinking water sources, whereas 92% lack adequate sanitation.[15,16] As a result of limited access to potable water and sanitation, enteric diseases are among the leading causes of morbidity and mortality among Ghana's young children, with approximately 9% of deaths in children less than 5 years of age caused by diarrheal diseases.[17] Additionally, a national self-reported health survey estimated that 20% of children less than 5 years of age had diarrhea in the previous 2 weeks.[16]

Poor water quality contributes to the burden of diarrheal diseases through a number of waterborne pathogens, including bacteria, viruses, and protozoa, that are transmitted through the fecal–oral route. Examples of waterborne pathogens that cause diarrheal diseases include bacteria such as Enterotoxigenic *Escherichia coli* and *Vibrio cholerae*, viruses such as Noroviruses and adenoviruses, and protozoa such as *Cryptosporidium parvum* and *Giardia lamblia*. Bloody diarrhea or dysentery can be caused by a number of different agents, including *Shigella*, *Camplylobacter*, and *Salmonella* species. Ghana has other disabling diseases associated with drinking water sources such as schistosomiasis, also known as bilharzia, which is prevalent across much of the country and can be transmitted to humans during drinking water collection from surface water bodies.[18,19]

A variety of SWEs have become active in Ghana in recent years, although their prevalence has not been well-documented. Water vendors include tanker trucks, protected well operators, and sachet vendors. Sachets, also known as "pure water," are pre-packaged plastic bags containing 500 mL water. Sachets have become particularly popular in Ghana because of their convenience, widespread availability, and the impression that they are safe to drink; however, several studies have shown a wide range of microbiological and chemical quality in sachets.[20–22] Although Ghana has comprehensive drinking water quality standards implemented through the Ghana Standards Board, there is little enforcement in water vending markets. Nonetheless, Ghana is poised to improve its population's access to potable water, because it benefits from several decades of stable governance and recent institutional attention focusing on improving water services for rural populations.

WHCs. WaterHealth International (WHI) began establishing WHCs in Ghana in 2007 through its subsidiary, WaterHealth Ghana (WHG), after having installed more than 200 kiosks in India and the Philippines. The first WHC in Africa was constructed as a pilot site in Afuaman in the Ga West district of the Greater Accra region in 2007 to introduce this kiosk concept on the continent. WHI's model has garnered attention among international donors and corporate sponsors because of its stated goal of financially sustainable, high-quality, and affordable water available to whole communities.[23] The WHCs in this study were purchased for an initial cost of $50,000 from WHG through a partnership between the village and a non-governmental organization (NGO), Safe Water Network (SWN). The WHCs are locally operated and maintained under a management contract with WHG, and the facilities provide vended potable water at a relatively low fee compared with other vended water. The fees collected at the WHC are accrued in a community account that is expected to pay for the operations and maintenance contract along with the initial capital expenses.

WHI and SWN established WHC site selection criteria for the kiosks installed in this study. According to these criteria, villages must have shown a need for improved drinking water through their reliance on unimproved water sources. Additionally, villages must have a population of at least 2,000 people, a reliable electricity supply, an adequate perennial surface water supply, and centrally located land designated by the community for construction of the kiosk. Each selected village was expected to have one WHC constructed within 1 km of the water source. Permission to operate in the community was first obtained from district and local leaders.

The WHCs in this study house multistage filtration that begins with rapid sand followed by activated carbon and 5- and 1-micron cartridge filters. A patented ultraviolet disinfection technology, known as UV Waterworks, follows filtration. The treatment system is designed to treat water in batches of up to 65,000 L of surface water per day to meet World Health Organization Drinking-Water Quality Guidelines for microbiological, physical, and chemical quality. WHG operating procedures call for monthly water quality monitoring, with samples collected from finished water at the point of sale and analyzed at the Water Research Institute in Accra. The operator checks the taste, color, and odor of finished water samples daily at the WHC. Additionally, WHG's plans for each village project include hygiene education and community mobilization programs implemented by a local NGO. By WHI design, these programs are initiated before construction of the WHC to promote community use of the kiosk along with safe water and hygiene practices.

The JHUCWH study was an independent evaluation, and no funding was received from either WHI (the purveyor of WHCs), or SWN (the philanthropic NGO that supported the intervention). This article describes the impact that the WHCs and hygiene education had on the microbiological quality of drinking water in households where water sampling and surveys were conducted in 2008, 2009, and 2010.

MATERIALS AND METHODS

In 2008, JHUCWH began the study in six villages in Ghana. All villages had been found to meet the eligibility criteria set by WHI and SWN as appropriate for construction of a WHC. Five of the villages were scheduled to have a WHC constructed in late 2008, whereas the sixth village was slated as a potential future site. These villages included Amasaman, Dzemeni, Manhean, Oduman, and Pokuase. Manhean was later dropped from the study in 2009 when construction of the WHC was indefinitely suspended because of disagreement within the village over the intended location, thereby no longer meeting WHC selection criteria as defined by WHI and SWN. The village of Pokrom was included from the beginning of the study as a comparison village, because it met the selection criteria and was a candidate site for WHC construction in the future. Although not a true control since it was not randomly selected, Pokrom serves as a comparison that aids in understanding changes unassociated with WHCs.

Formative research was conducted in several of the study villages in June and July of 2008 to inform the design of the research.[24] Interviews, focus group discussions, and digital recordings of water collection patterns led to a number of key findings on household water practices that may impact household water quality. One key finding was that households commonly collect water from multiple sources and distinguish among these sources for differing purposes, such as drinking, cooking, cleaning, and bathing. Sources of water included surface water (rivers and springs), sachets, protected wells, unprotected shallow hand-dug wells, and rainwater along with water vended from tanker trucks and other tanks. This variety of water sources within a household may lead to inadvertent mixing of water and cross-contamination. Observations also confirmed that women and children were the primary water collectors, whereas women oversaw water storage and use within the household.[24]

Baseline community surveys were conducted in each of the villages in August of 2008. To conduct the surveys, each village was first hand-mapped to identify household locations. Households were then selected for inclusion in the study using systematic random sampling. With the total number of households in each village known, a sampling interval, *i*, was selected to give a total of 100 households from across the village for the larger health study. A random start was determined, and every *i*th household was contacted. Every 10th household from the health study was also asked to participate in the water quality study that is presented here. Only households that had at least one child 12 years of age or younger and a mother or other adult female caregiver 18 years of age or older were eligible to be enrolled in the study. Mothers or other adult female caregivers were chosen to be respondents for the household surveys, because the formative research showed that they would be the best informed about water collection and handling, household hygiene, and the health of household members in Ghana. If a household was found to be ineligible, the next closest household was contacted.

The household survey questionnaire incorporated over 30 key indicators related to household water quality, including household demographics, local drinking water sources, time to collect water, household treatment of water, water collection and storage, hygiene behaviors, and sanitation. The questionnaire was translated into the local languages of Ga, Ewe, and Akan/Twi and then back-translated to English to ensure accuracy. All survey fieldwork was conducted in English or a local language of the respondent's choice (Ga, Ewe, or Akan/Twi) in collaboration with Marketing and Social Research International, Accra Ghana. All surveyors were trained on the protection of human subjects and how to reliably and accurately record data. Each year, the questionnaire was piloted in a neighborhood in Accra to validate translations.

During the survey implementation, JHUCWH collected a water sample at every 10th household from stored drinking water supplies. A duplicate sample was also collected from one household in each village for quality control. Sampling was conducted using individually wrapped sterile pipettes, and samples were collected in Whirl-Pak bags (eNasco, Fort Atkinson, WI) for processing. All samples were then stored on ice in insulated coolers and transported to the field laboratory in Accra within 12 hours. A 0.1% Peptone solution (Invitrogen, Carlsbad, CA) was used to bring the total volume of samples that contained less than 100 mL to 100 mL for analysis. Two negative controls, each containing 100 mL 0.1% Peptone solution, were also analyzed for each batch of samples.

Microbiological water quality was determined using *E. coli* as an indicator of fecal contamination. Indicator organisms are commonly used to determine potability instead of testing for the hundreds of possible individual contaminants that may be present.[25] Fecal coliform is the most readily available indicator test of potential contamination by diarrheal disease-causing agents. *E. coli* is a specific fecal coliform indicative of contamination from the feces of warm-blooded organisms. The presence of *E. coli* in drinking water signifies recent fecal contamination and indicates that the water is very likely unsafe to drink.

Analysis for *E. coli* was completed using the IDEXX Colilert Quanti-tray system (IDEXX Laboratories, Westbrook, ME). In the IDEXX Colilert system, a reagent is added to 100-mL water samples, which are then poured into a 97-well Quanti-tray, sealed, and incubated at 37°C for 24 ± 2 hours. A most probable number (MPN) of *E. coli* present in the water sample is determined from the number of wells that produce a yellow color, indicating the presence of coliform bacteria, along with a blue-white fluoresce under long-wave ultraviolet light as a result of a β-glucuronidase reaction to the reagent. The maximum detection limit of this system is > 2,419.6 MPN/100 mL when run without dilution, whereas the minimum limit of detection is < 1 MPN/100 mL. For analyses, any samples with the maximum detectable counts were assigned the value 2,420 MPN/100 mL, whereas samples at the minimum detection level were assigned 0.0 MPN/100 mL.

WHCs were constructed by WHG in the villages of Amasaman, Dzemeni, Oduman, and Pokuase between the baseline survey in 2008 and the next survey 1 year later. Subsequent household sampling was conducted in the same households at 1-year intervals in August of 2009 and 2010 to control for possible effects of seasonal changes in source water quality.

Data analysis was conducted in Baltimore, Maryland using STATA 12.1 (StataCorp, College Station, TX). Longitudinal models using negative binomial regression and generalized estimating equations (GEEs) along with robust standard errors to adjust for recurrent observations of *E. coli* MPN/100 mL in drinking water from the same households across years were fitted to assess the effect of the covariates on *E. coli* incidence rate.[26,27] Adjusted models generated incidence rate ratios (IRRs), where a ratio of the incidence of *E. coli* MPN/100 mL in households using one water source was compared with the incidence of the reference group (that is, households using surface water) with all other variables held constant. Furthermore, percent reduction in household drinking water *E. coli* MPN/100 mL associated with a water source relative to surface water was calculated as 100 × (IRR-1).

A negative binomial regression model was chosen over a Poisson model because of the overdispersion of the dependent count variable, *E. coli* MPN/100 mL. Furthermore, the Vuong test was used to examine the need for a zero-inflated negative binomial model compared with a standard negative binomial model, and this test fails to reject the standard negative binomial model. The use of GEE is supported by our primary interest in the average effect on household water quality associated with drinking water source across the study population with repeated measures in households and the potential for correlation between households in the same village.[28] The working correlation matrix was compared across models with independent, exchangeable, and unstructured correlations to choose the most appropriate covariance structure. Additionally, sensitivity analyses were conducted with and without the village of Pokrom to examine the potential for this comparison village to skew results.

An asset index was calculated through principle components analysis (PCA) that was specific to the study site and based on self-reported household ownership of durable goods and household characteristics consistent with the Ghana Demographic and Health Survey to be contextually relevant.[16] Household water and sanitation indicators were not used to construct the asset index, because we were interested in their individual association with household water quality. PCA was used to create a unique household relative score with weighting of the variables equal across the study. Households were assigned scores based on binary responses to asset ownership and household characteristics using corresponding eigen vectors of the first principle component as a measure of relative wealth.[29] Household scores were then classified into quintiles for subsequent analyses. A variable indicating the number of people in the household was created using four groupings to have a more parsimonious model, because households ranged from 2 to 10 people. The first group in the household size variable corresponds to two people in the household; the second group corresponds with three people. The third group corresponds with four to six people; the fourth group corresponds with 7–10 people.

Univariate analyses were conducted to examine associations between household variables and water quality. Models were then constructed that included household variables found to be significant in univariate analyses to adjust for potential confounding. Additional analyses were conducted by including variables not found to be significant in univariate models one at a time in multivariate models to determine if they exhibited confounding in conjunction with other variables. A significance level $\alpha = 0.05$ was used.

Informed consent was obtained from all adult participants. Study protocols were reviewed and approved by the Johns Hopkins Bloomberg School of Public Health Institutional Review Board and the University of Ghana School of Public Health before the commencement of fieldwork.

RESULTS

Forty-nine households across five villages (Figure 1) were included in analyses; one household in Pokuase was dropped from the water quality study, because another household was sampled in error at baseline. No households refused to take part in the water quality study. Quality control duplicate samples were all within an acceptable margin of error, and there was no detectable *E. coli* in the negative controls. Thirteen households dropped out of the study from the first year to the last year (27%) because of the following reasons: nine households moved out of the village, and four households were away for extended periods during the study visits. There was no significant difference in the means of baseline drinking water quality in households lost by year 3 and all study households at baseline in analyses conducted both with and without Pokrom, the village that did not receive a WHC. A comparison of baseline household covariates in the total study and those households lost to follow-up shows that slightly more households were lost from the village of Oduman, where five households were lost by 2010, compared with two or three households in the other villages. Additionally, respondents tended to be younger in lost households (27.3 versus 32.6 years of age). Other household covariates, such as household size and asset index values, were similar between lost households and the total study.

FIGURE 1. Study sites numbered 1–5 in southern Ghana. Villages are shown in their region, with (1) Pokrom in the Eastern region; (2) Amasaman, (4) Oduman, and (5) Pokuase in the Greater Accra region; and (3) Dzemeni in the Volta region.

Baseline. Household baseline demographics (Table 1) show that Pokuase has significantly smaller households, with a mean of 3.7 people/household, compared with the overall sample mean of 5.2 people/household ($P = 0.009$), whereas Dzemeni has marginally larger households with a mean of

TABLE 1
Baseline demographics of water quality study households in five villages in 2008

	Amasaman	Dzemeni	Oduman	Pokuase	Pokrom*	Total
Estimated total population	5,000	4,447	1,922	15,323	2,181	28,873
Study population	45	71	55	33	49	253
Total households	10	10	10	9	10	49
Percent females	53	51	49	64	45	51
Mean household size (range)	4.5 (3–7)	7.1 (3–10)	5.5 (3–9)	3.7 (2–6)	4.9 (3–8)	5.2 (2–10)
Children < 5 years	5	17	13	8	4	47
Children < 13 years	16	34	27	14	24	115
Respondent age (in years) mean (range)	34.3 (23–51)	34.8 (21–55)	30.8 (23–39)	30.9 (20–43)	32 (23–47)	32.6 (20–55)
Respondent education						
< 1 year or none	1	3	3	0	2	18%
Primary	1	2	1	1	4	18%
Middle/JSS	7	5	3	6	4	51%
Secondary/SSS	1	0	2	1	0	8%
More than secondary	0	0	1	1	0	4%
Cooking fuel						
Charcoal	8	7	8	6	5	69%
Wood/straw	0	3	0	0	5	16%
LPG/natural gas	2	0	2	3	0	14%
Household assets						
Mobile phone	9	6	8	7	5	71%
TV	8	6	8	6	7	71%
Radio	8	8	9	8	9	86%
Motorcycle, tractor, or horse	0	0	0	0	0	0%
Bicycle	1	2	0	2	3	16%
Car	1	0	3	1	0	10%
Refrigerator	5	3	5	2	2	35%
Electricity	8	8	8	6	9	80%
Drinking water source						
Surface	0	4	0	0	8	25%
Sachet	8	0	0	5	0	27%
Protected well	0	0	0	1	1	4%
Rainwater	1	6	0	2	1	20%
Other vendors	1	0	1	1	0	6%
Unknown	0	0	9	0	0	18%
Sanitary facility						
None	0	4	1	0	2	14%
Shared latrine	9	6	9	7	6	76%
Private latrine	1	0	0	0	2	6%
Public flush toilet	0	0	0	2	0	4%

*Non-intervention village.
JSS = junior secondary school; SSS = senior secondary school; LPG = liquefied petroleum gas.

7.1 people/households (P = 0.051). Across the water study population at baseline, a majority of households had electricity (80%), mobile phones (71%), televisions (71%), and radios (86%), whereas few households had access to private latrines (6%) or private transportation (bicycles = 16%, cars = 10%, and motorcycles = 0%). The primary drinking water sources at baseline included surface waters (springs, rivers, and lake), rainwater, protected and unprotected wells, sachets, and other private vendors such as tankers. Sachets were the largest source of sampled household drinking water at baseline (27%), whereas surface water (25%) and rainwater (20%) were also common. The original source of stored household water that was sampled at baseline was inadvertently not recorded for most households in the village of Oduman but was likely to include sachets and river and well water based on these households' responses to usual source of drinking water during the household survey. Baseline estimated village populations are based on SWN estimates for Amasaman and government projections for Dzemeni, Oduman, Pokuase, and Pokrom.

Post-construction results. Figure 2 shows the relative decline in *E. coli* MPN/100 mL in drinking water stored within households over the course of this study in both intervention and non-intervention villages. The box plot illustrates that intervention village households had lower average *E. coli* contamination than non-intervention households during each year of the study.

Overall, the lowest levels of *E. coli* contamination in stored drinking water when compared with other sources across all

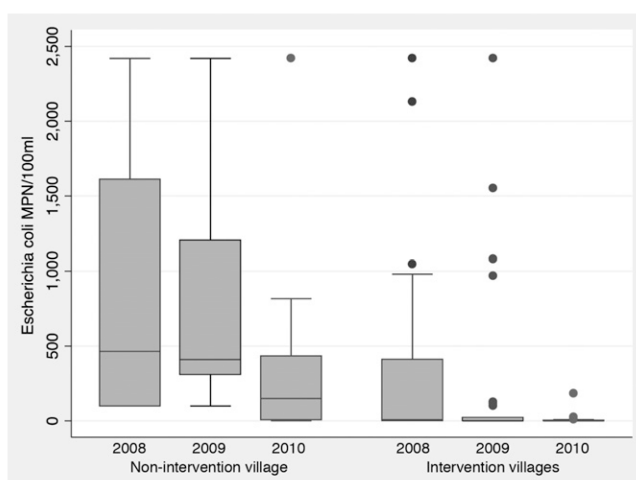

FIGURE 2. Box plot of household stored drinking water quality across one non-intervention village and four intervention villages by year.

TABLE 2
Summary statistics of *E. coli* MPN/100 mL in five villages by source and year

	n	Percent	Mean	Median	Range
WHC					
2008	N/A	N/A	N/A	N/A	N/A
2009	5	11	341.0	23.0	0, 1,553
2010	10	28	21.1	1.5	0, 183
Surface					
2008	12	25	1,037.5	520.0	100, 2,420
2009	12	26	787.2	580.5	117, 2,420
2010	9	25	476.8	162.0	1, 2,420
Sachet					
2008	13	27	0.4	0.0	0, 4
2009	22	48	0.9	0.0	0, 9
2010	13	36	1.0	0.0	0, 12
Rainwater					
2008	10	20	112.2	29.0	0, 410
2009	2	4	13.5	13.5	5, 22
2010	3	8	10.7	4.0	1, 27
Protected well					
2008	2	4	540.0	540.0	100, 980
2009	1	2	100.0	100.0	–
2010	1	3	1.0	1.0	–
Unprotected well					
2008	0	0	–	–	–
2009	4	9	661.3	111.5	2, 2,420
2010	0	0	–	–	–
Other vendors*					
2008	3	6	276.3	79.0	0, 750
2009	0	0	–	–	–
2010	0	0	–	–	–
Unknown 2008	9	18	787.3	410.0	1, 2,420
Total					
2008	49	100	460.7	100.0	0, 2,420
2009	46	100	303.1	4.5	0, 2,420
2010	36	100	126.3	1.0	0, 2,420

*Other vendor includes tanker trucks and polytanks.

TABLE 3
Comparison of household drinking water sources from year 1 to year 3 in the villages of Amasaman, Dzemeni, Oduman, and Pokuase where WHCs were constructed after year 1

	Year 3 water sample source			
Year 1 water sample source	WHC	Sachets	Rainwater	Total
Surface	2	0	0	2
Sachets	0	10	0	10
Protected well	0	1	0	1
Rainwater	6	1	0	7
Other vendor	1	1	0	2
Unknown	1	0	3	4
Total	10	13	3	26

3 years were found in households that used sachets for drinking water (Table 2). The median contamination for sachets each year, 0.0 *E. coli* MPN/100 mL, corresponds to the non-detect value of < 1 *E. coli* MPN/100 mL. Households that relied on surface water sources for drinking tended to have the greatest contamination in stored water each year. Of 15 samples collected from households using the WHC for drinking water (5 in 2009 and 10 in 2010), 40% (N = 6) had no detectable levels of *E. coli*, whereas 60% (N = 9) had a range of 2–1,553 *E. coli* MPN/100 mL.

In the second year of the study, household visits found that only 5 of 36 households (14%) in intervention villages used the WHC for drinking water, increasing to 10 of 26 households (38%) by the third year. Additionally, several of the WHCs were only operational for a few weeks before the second sampling because of delays in completion encountered at several of the kiosks. Analyses of finished water samples collected at the kiosk in years 2 and 3 indicate that the WHC water met World Health Organization Guidelines for Drinking-Water Quality at the point of sale 91% of the time, with 3 of 32 samples having the low level of 1–2 *E. coli* MPN/100 mL.

Most households that became customers of the WHC for drinking water in 2010 had initially relied on free water sources at baseline, having switched primarily from rainwater (60%) and surface water (20%) (Table 3). In contrast, all households that purchased sachets at baseline and were followed for all 3 years continued to rely on sachets for their drinking water in both 2009 and 2010. Additionally, most villages tended to exhibit common drinking water collection patterns among households (Figure 3). For example, households in Amasaman and Pokuase relied heavily on sachets throughout the study, whereas Dzemeni households tended to switch from surface water to the WHC. Households in Pokrom, where no WHC was available, tended to continue collecting water from surface sources rather than purchase sachets or water from protected wells.

Treating water in the household was not found to be a common practice; 16% (N = 8) of surveyed households reported using any treatment of their drinking water during the previous week in 2008, 7% (N = 3) of surveyed households reported using any treatment of their drinking water during the previous week in 2009, and 17% (N = 6) of surveyed households reported using any treatment of their drinking water during the previous week in 2010. The most common types of treatment that respondents reported using were filtering through a cloth, boiling, and adding alum or camphor balls. This last treatment, camphor balls or naphthalene, was the most prevalent treatment used by study households, accounting for 47% of household treatment. Naphthalene treatment was found in three of five villages: Amasaman, Oduman, and Pokrom. During the course of this study, none of the households reported using any drinking water treatment that would provide residual protection, such as chlorine.

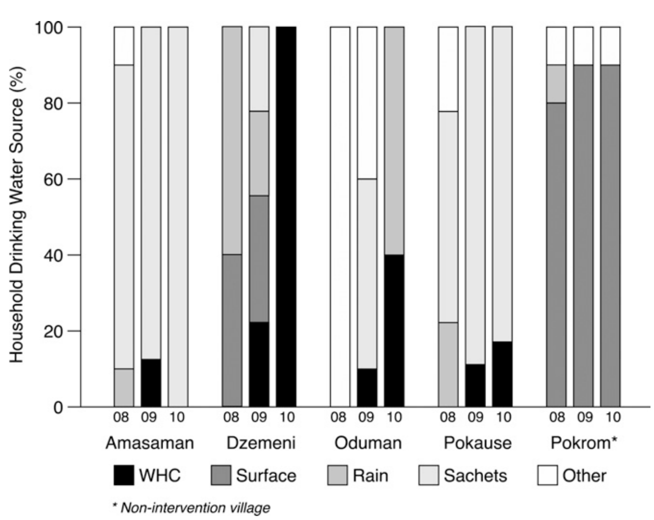

FIGURE 3. Household drinking water source for samples collected from 2008 to 2010 by village.

Univariate analyses found the WHCs, sachets, and rainwater were all associated with improved drinking water quality compared with the use of surface water for household drinking water, whereas the total number of people living in a household was associated with fecal contamination: an increasingly greater incidence of *E. coli* contamination was associated with larger households. Additionally, univariate analysis of drinking water quality by study year found a trend to a reduction in *E. coli* incidence compared with the baseline year. All intervention villages were also found to have lower incidence of contamination compared with the village without the intervention, Pokrom. A higher household asset index score, corresponding to greater relative household wealth, was associated with reduced *E. coli* contamination in the drinking water, whereas education level of the respondent was also significant in univariate analyses. With respondents with less than 1 year of education as the reference group, respondents with primary, middle, or secondary education had increased *E. coli* incidence, whereas respondents with post-secondary education had significantly reduced *E. coli* incidence in univariate analyses.

In previous studies, hygiene practices have been linked to household water quality.[30–32] However, self-reported handwashing behaviors with or without soap before preparing food or after defecation and presence of soap and sanitation facilities were not found to be associated with household drinking water quality in this study and were not included in the final model. At baseline, 47% of respondents reported washing hands before preparing food the prior day, whereas 43% reported using soap to wash hands. These practices did not improve over time, despite hygiene education being integral to the WHC design. Self-reported handwashing before preparing food dropped to 33% and handwashing with soap dropped to 25% by the third year.

Longitudinal negative binomial models using GEE examined the relative impact of drinking water source controlled for household relative wealth, respondent's education, household size, village, and study year. The model measures the association between water source and the incidence of *E. coli* MPN/100 mL adjusted for the covariates listed above. The Vuong test indicated that a zero-inflated negative binomial regression was not necessary over a standard negative binomial regression. The results indicate that households had significantly improved drinking water quality when they used water from WHCs, sachets, rainwater, protected wells, or other vendors compared with surface water sources when controlled for household covariates (Table 4). The greatest comparative improvement in water quality came from households using sachets as their drinking water source, with almost 100% relative reduction in *E. coli* MPN/100 mL (adjusted IRR [adj. IRR] = 0.0001, 95% confidence interval [CI] = 0.00004, 0.0005). Other drinking water sources also associated with significant relative reductions in *E. coli* contamination compared with surface water were other vendors, with 96% reduction (adj. IRR = 0.04, 95% CI = 0.009, 0.21), rainwater, with 94% reduction (adj. IRR = 0.06, 95% CI = 0.02, 0.17), WHCs, with 93% reduction (adj. IRR = 0.07, 95% CI = 0.02, 0.21), and protected wells, with 93% reduction (adj. IRR = 0.07, 95% CI = 0.04,0.12). In other words, households that use WHCs are estimated to have *E. coli* contamination that is approximately 93% less than households that use surface water when household asset index, respondent's education, household size, village, and year are held constant. Households that used unprotected shallow wells for their drinking water source were not found to have a significant difference in *E. coli* contamination compared with households using surface water (adj. IRR = 0.65, 95% CI = 0.09, 4.53). It must be noted that protected wells (N = 4), unprotected wells (N = 4), and other vendors (N = 3) are estimated on very low sample sizes, and therefore, results for these categories may be less robust.

Table 4

Adjusted regression model of *E. coli* MPN/100 mL within stored household drinking water from 2008 to 2010 (significant results are shown in bold)

E. coli MPN/100 mL	IRR	*P* value	95% CI
Drinking water source			
Surface	Reference	–	–
WHC	**0.07**	**< 0.001**	**0.02–0.21**
Sachets	**0.0001**	**< 0.001**	**0.00004–0.0005**
Protected wells	**0.07**	**< 0.001**	**0.04–0.12**
Rainwater	**0.06**	**< 0.001**	**0.02–0.17**
Other vendors	**0.04**	**< 0.001**	**0.009–0.21**
Unprotected wells	0.65	0.66	0.09–4.53
Unknown	0.70	0.66	0.14–3.44
Asset index	0.82	0.07	0.67–1.01
Education			
Primary school or less	Reference	–	–
Middle school/JSS	1.14	0.58	0.71–1.85
Secondary school/SSS	1.75	0.25	0.68–4.54
Beyond secondary	**0.38**	**< 0.001**	**0.01–0.12**
Total number of people in household			
2	Reference	–	–
3	**5.13**	**0.01**	**1.45–18.21**
4, 5, or 6	**5.18**	**< 0.01**	**1.54–17.47**
7, 8, 9, or 10	**6.92**	**< 0.01**	**1.93–24.83**
Village			
Pokrom	Reference	–	–
Amasaman	2.20	0.23	0.61–7.92
Dzemeni	**0.38**	**0.05**	**0.14–0.98**
Oduman	1.05	0.94	0.31–3.57
Pokuase	**21.13**	**< 0.001**	**7.06–63.22**
Year			
1	Reference	–	–
2	0.56	0.08	0.30–1.07
3	0.50	0.24	0.15–1.61

JSS = junior secondary school; SSS = senior secondary school.

An increased asset index score corresponding to greater relative household resources tended to be associated with reduced *E. coli* contamination but was not found to be significant (adj. IRR = 0.82, 95% CI = 0.67, 1.01). Households in which the respondent had a post-secondary education were found to be significantly associated with a 62% reduction in the incidence of *E. coli* in their drinking water (adj. IRR = 0.38, 95% CI = 0.01, 0.12). It should be noted that the result for respondents with post-secondary education is also based on a small sample size (N = 4) and should be interpreted with caution.

The total number of people in a household was found to affect the level of *E. coli* contamination, with larger households associated with approximately five to seven times greater incidence of contamination compared with the reference group, households consisting of two people, when holding all other variables constant. Furthermore, households in the village of Dzemeni were found to have a significant relative reduction in the incidence of *E. coli* in their drinking water compared with Pokrom, the village that did not have a WHC (adj. IRR = 0.38, 95% CI = 0.14, 0.98), whereas Pokuase had a significantly higher relative incidence of *E. coli* (adj. IRR = 21.13, 95% CI = 7.06, 63.22). This result for Pokuase is unexpected given that Pokuase households rely primarily on sachets, which tend to have the lowest contamination, whereas Pokrom households rely primarily on surface waters, which have the highest levels of contamination (Figure 3 and Table 1). This seemingly spurious result has a wide confidence interval and may reflect that most of Pokuase's variability was explained by other indicators, such as the source of drinking water.

DISCUSSION

Our findings indicate that the key to improving household drinking water quality is in having households take up alternatives to surface water sources. Although use of WHCs was associated with improved household water quality compared with households using surface water, similar improvements were also found in households using sachets, protected wells, rainwater, and other vendors for their drinking water supplies.

There is also evidence that water quality degrades during transport from the WHC and within household storage, leading to fecal contamination at the point of use. This finding corroborates previously documented evidence and presents a strong argument in favor of residual protection, such as a chlorine residual, to ensure that household water supplies remain microbiologically safe to drink.[30] Residual protection added before vending the water at a WHC could protect the water quality along the path from purchase to household storage and uses, ensuring that the effects of the WHC's advanced technology are sustained. Our study found that WHC water without residual protection became recontaminated with *E. coli* 60% of the time.

Recontamination can occur in multiple ways. Unclean hands in contact with stored water are a commonly described cause of introducing fecal contaminants.[33] Regions with low access to sanitation, such as these villages, where only 6% of households had a private latrine, are especially vulnerable to recontamination through hand contact.[34] It is also possible that households may mix water from multiple sources in household storage vessels, such as adding surface water to WHC water, leading to recontamination. Additionally, the vessels used for collecting and storing water may be contaminated, and therefore, WHC water may become recontaminated at the time of purchase. Multiple types of vessels for collecting water were observed in each village, including large basins, buckets, and plastic jerry cans ("Kufuor gallons"). Additionally, most households stored water in large barrels or plastic receptacles. Although the jerry cans provide some protection from recontamination with their opening being too small for hands to fit inside, the prevailing habit of transferring water to larger containers within the home introduced another point of potential recontamination. Furthermore, although the source of water currently in household storage containers was recorded and used in the analyses, it is possible that a household stored water from multiple sources in the same container depending on a variety of factors, including availability, cost, rainfall, and season.

Behaviors around hygiene, water collection, treatment, and storage are clearly essential to the potability of the final drinking water at the point of use. However, impacting household behaviors to protect water quality is challenging. The finding that increased education did not necessarily correspond to improved household drinking water quality may indicate a lack of hygiene training in the population and the uneven uptake of hygiene messages. This study highlights the need for sustained and comprehensive household hygiene education to maintain potable water supplies, especially when there is no residual protection in the water.

An interesting and unexpected finding of this study was the previously undocumented use of camphor balls, or naphthalene, in drinking water. When queried about this practice, respondents related that it was a long-time practice passed down by recent generations to improve the water, perhaps based on the inaccurate assumption that these compounds would be an effective larvacide in stored water. Anecdotal evidence collected subsequently suggests that this practice is not isolated to these villages (personal communication). No known benefit could be discerned from a literature review, whereas potential harm is suggested from a United States Environmental Protection Agency toxicology review that has classified chronic exposure to naphthalene as a possible human carcinogen.[35]

Maintenance of the WHC treatment system will be critical to its continued provision of potable water. Although water analyses of samples collected at the WHC point of sale found relatively low levels of *E. coli* contamination in only 9% of samples, these results indicate a potential pathway for harmful microbiological contaminants to enter household water supplies. Microbiological testing more frequently than monthly is necessary to allow early detection of contamination and reduce risks of health impacts, especially during times when source waters may change in quality such as rainy periods.[25]

Completion of the WHC construction was delayed in several villages because of modifications to treatment systems related to properties of source waters for the WHCs. Some of the unanticipated challenges included the presence of elevated manganese that gave a strong yellow color to the water and high organic loads that rapidly fouled filters, affected taste, and imparted a musty odor. In addition, the source for one WHC was impacted by runoff from a highway that was adjacent to the intake. Each of these problems necessitated revisions to the affected WHC and elevated the costs of the treatment system. It is likely that these issues could have been identified before the commencement of construction had there been adequate study of the source waters.

Several previous studies of sachet water have found them to have variable water quality.[20–22] Our study also found some variation in quality, but on average, households using sachet water for drinking had lower levels of *E. coli* contamination than all other stored sources of drinking water. Sachets provide some protection of water quality because of their sealed plastic bag, which prevents contamination from occurring during transport and storage as long as the bag remains sealed. However, their quality is only as good as the water that is packaged; the sachet industry is poorly regulated, and the cost is up to forty times higher than other vended water. It should be noted that the cost of 500-mL sachets was generally the same as 18–20 L WHC and other vended water that were sold by the container, starting at 5 pesewas (approximately \$0.03) in 2008 and rising to 10 pesewas (approximately \$0.06) by 2010. With the growing use of sachets occurring in many regions of Ghana, improved monitoring to ensure the quality of the packaged water is required.

The ideal study design would have included a randomized controlled trial where the water intervention, the WHC along with hygiene education and community mobilization, was randomly assigned to villages.[36] However, this design was not possible in this study, because village selection was not under the control of the research team. Therefore, there may have been uncontrolled confounders caused by non-randomization of the intervention. Additionally, the upfront costs and specific site selection criteria required for the WHC construction along with the lack of randomization of the intervention limit the generalizability of this study's findings. The WHC's $50,000 initial cost, dependence on a reliable electricity supply, and requirement for a convenient perennial water supply narrow the applicability of WHCs in many rural developing communities.

The limited sample size for this water quality study was further reduced by a 27% household dropout rate that hampered the ability to detect differences in water quality. Additionally, only 38% of the study population in intervention villages chose to use the WHC, further limiting the ability to ascribe affects of WHCs on household water supplies. Additional research into the factors affecting drinking water choice in the study villages was undertaken as a result of these findings and will be reported separately.

CONCLUSION

Innovative SWEs with entrepreneurial approaches are being encouraged globally as attempts to address the lack of potable water. With the greatest number of countries lagging in access to safe water as measured by the MDGs, sub-Saharan Africa has a strong potential to be very receptive to public–private partnerships such as the one offered by WHI.[3] This study provides an important initial understanding of the benefits and limitations of WHCs. WHCs offer advanced treatment that can disinfect contaminated source waters, but without chlorination or other residual protection, recontamination will likely reduce the quality of the water, undermine the technology, and render the water unsafe. It is recommended that additional studies be conducted on SWEs using randomized controlled trials to build on this initial examination of their impacts on household water quality.

Sustained and frequent monitoring of the water quality at the point of sale is critical to understanding if advanced treatment systems, such as those systems housed in the WHCs, can provide a potable water supply. Equally necessary for improving water quality is sustained hygiene education to prevent potentially harmful practices, such as adding naphthalene to drinking water, and ensure protection of water from unintended contaminants, such as *E. coli*.

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