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Microbiological effectiveness of household water treatment technologies under field use conditions in rural Tanzania

Hussein Mohamed[1,2], Thomas Clasen[3], Robert Mussa Njee[4], Hamisi M. Malebo[5], Stephen Mbuligwe[2] and Joe Brown[6]

1 *School of Public Health, Muhimbili University of Health and Allied Sciences, Dar es Salaam, Tanzania*
2 *School of Environmental Science and Technology, Ardhi University, Dar es Salaam, Tanzania*
3 *Ministry of Health and Social Welfare, Dar es Salaam, Tanzania*
4 *National Institute for Medical Research, Dar es Salaam, Tanzania*
5 *Rollins School of Public Health, Emory University, Atlanta, GA, USA*
6 *School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA, USA*

Abstract

OBJECTIVES To assess the microbiological effectiveness of several household water treatment and safe storage (HWTS) options *in situ* in Tanzania, before consideration for national scale-up of HWTS.

METHODS Participating households received supplies and instructions for practicing six HWTS methods on a rotating 5-week basis. We analysed 1202 paired samples (source and treated) of drinking water from 390 households, across all technologies. Samples were analysed for thermotolerant (TTC) coliforms, an indicator of faecal contamination, to measure effectiveness of treatment *in situ*.

RESULTS All HWTS methods improved microbial water quality, with reductions in TTC of 99.3% for boiling, 99.4% for Waterguard™ brand sodium hypochlorite solution, 99.5% for a ceramic pot filter, 99.5% for Aquatab® sodium dichloroisocyanurate (NaDCC) tablets, 99.6% for P&G Purifier of Water™ flocculent/disinfectant sachets, and 99.7% for a ceramic siphon filter. Microbiological performance was relatively high compared with other field studies and differences in microbial reductions between technologies were not statistically significant.

CONCLUSIONS Given that microbiological performance across technologies was comparable, decisions regarding scale-up should be based on other factors, including uptake in the target population and correct, consistent, and sustained use over time.

keywords household water treatment, water quality

Introduction

Approximately 80% of Tanzania's 45 million people live in rural areas [1]. It is estimated that 46% of Tanzania's rural population have no access to "improved" water sources [2] and many more may lack access to consistently safe water. Common drinking-water sources include shallow wells, ponds, streams, rivers and lakes, which are often used for multiple purposes. These and other unimproved sources are likely to be highly contaminated with faecal pathogens [3]. As a result, much of the Tanzanian population is at high risk of waterborne enteric infections. Dehydration due to severe diarrhoea is a major cause of morbidity and mortality in young children in Tanzania [4]; the infant mortality rate is about 12% [5]. Diarrhoeal diseases may be associated with drinking contaminated water [6], unhygienic practices [7], and inappropriate disposal of excreta [8].

While the Government of Tanzania is taking steps to provide improved water supplies to rural areas, household water treatment and safe storage (HWTS) provides a potential interim solution that may reduce waterborne pathogen exposures [9]. The approach is not new. In the 1970s, the Government initiated a campaign known as Man Is Health (*Mtu ni Afya* in Kiswahili language) in which people were encouraged to boil drinking water. While boiling continues to be the most common HWTS method, other methods have been widely promoted in Tanzania. According to the most recent Demographic and Health Survey [5], an estimated 53% of surveyed households reported employing one or more measures to improve safety of drinking water at homes, boiling being used by 47% of urban and 24% of rural surveyed households, respectively.

Evidence suggests that HWTS improves the microbial water quality and may reduce the risk of diarrhoeal disease morbidity [10–13]. In the most recent systematic review of the reduction of diarrhoeal disease attributable to HWTS, it was reported that for householders relying on unimproved water supplies, household-based chlorination combined with safe storage was associated with a 36% (95% CI: 28–45%) reduction in the risk of diarrhoea; the pooled risk reduction for filtration combined with safe storage was 59% (95% CI: 50–67%) [13]. Despite clear evidence of microbial effectiveness of various HWTS methods in laboratory and field settings, health effect estimates are subject to considerable bias and may have been overestimated in unblinded studies using subjective, self-reported outcome measures [14–16]. Health impacts may be driven by a number of context-specific factors, including the underlying risk of waterborne disease, effectiveness of technologies in reducing microbes in water, and achieving high adherence to the practice [17].

We undertook this study in the context of a UNICEF-funded pilot programme to assess the viability of scaling HWTS across rural Tanzania. Commonly available and novel technologies with potential for scale were selected by UNICEF and the study team for field testing. These included boiling, chlorination (sodium hypochlorite solution and NaDCC tablets), locally produced ceramic pot filters, ceramic siphon filters and combined flocculent/disinfectant sachets. The primary outcome variable was reduction of thermotolerant coliforms (TTC) in household drinking water following use of the technologies *in situ*.

Methods

Site selection and enrolment of participating households

We conducted this study between April–December 2012 in remote villages of Kisarawe and Geita districts, about 50 and 1500 km from Dar es Salaam city, respectively. We selected these two districts because of their different socio-cultural, ecological, and historical characteristics, with the goal of increasing potential generalizability of the results for scale-up across rural Tanzania. We selected four villages, two in each district, for participation in this study after consultation with local leaders and an assessment of logistical issues.

This sub-study of microbiological effectiveness constituted part of a larger initiative entitled *Strengthening the Government of Tanzania's knowledge and capacity in providing effective guidance on Household Water Treatment and Safe Storage: Collaborative HWTS research to reduce morbidity and mortality due to waterborne diseases at scale of poor women and children across Tanzania.*

Participating households were randomly selected after a household census was done in all four villages. Names for the head of the household were taken for all households that could be visited and found. Heads of households were then asked for their consent to participate in the study. Final selection of participating households was done randomly via a public lottery. We enrolled a total of 603 households (292 in Kisarawe and 311 in Geita Districts) following informed consent procedures approved by Medical Research Coordinating Committee of the National Institute for Medical Research.

Provision of HWTS to participating households

On a rotating basis every 5 weeks, each participating household received one of six HWTS methods used in the pilot programme: (i) locally produced rocket stoves for boiling; (ii) Tulip® brand ceramic siphon filters; (iii) Waterguard™ brand 1.25% sodium hypochlorite solution; (iv) Aquatab® brand 67 mg NaDCC tablets; (v) PuR® brand flocculent/disinfectant sachets (now branded as the P&G Purifier of Water™) and (vi), locally-produced silver-treated ceramic pot filters manufactured by Safe Water Ceramics of East Africa.

Boiling as an HWTS method was prevalent across the four communities before the trial, whereas other methods were generally new to users. All participating households received training on the proper use of each technology every 2 weeks throughout the trial, orally and in writing, according to manufacturer instructions. Each household was also provided with a safe storage container intended to guard against recontamination of water once treated. Two types of safe storage containers were provided: 30 l food-grade, high-density polyethylene (HDPE) container for use with ceramic pot filters and a 20 l bucket for other methods.

The ceramic pot filters allowed for filtrate to be stored safely after treatment by nesting the pot filter into the storage container, similar to designs described previously [18]. For siphon filters, two 20 l buckets were supplied: one bucket for untreated water and another (placed 0.7 m below, for head) for filtered water. The lower bucket was fixed with a tap to allow drinking water collection. For chlorination methods, two 20 l containers were supplied: one for untreated water and one for post-chlorination product water, fitted with a tap. In addition to a rocket stove, participants boiling water also received a safe storage container with tap and instructions for use.

Sample collection

We stratified the population by the type of HWTS being used and then randomly selected eight households from each group for water quality sampling on each sampling day, based on the maximum number of microbial samples that could be processed daily. Timing of sampling visits was unannounced to households. Samples were collected from 390 (65%) of the total 603 study households in both districts. We aseptically collected two (300 ml) samples of stored water from participating households, in Whirl-Pak bags (Nasco, Fort Artkinson, WI, USA) containing sodium thiosulphate to neutralize any chlorine that may have been present. One sample was drawn from stored water that the householder reported to be treated by the method assigned to that household at that time; the other was drawn from stored water that the householder reported to be untreated. For samples that were reportedly treated with chlorine (Waterguard, Aquatabs or PuR), analyses were carried out immediately upon sampling of reportedly treated water to determine free available chlorine (FAC) (mg/l), pH, and turbidity (NTU). The FAC (mg/l) and pH were measured by using the N, N-diethyl-*p*-phenylenediamine (DPD) colorimetric method with a digital Hach Portable DR/890 Colorimeter (Hach Company, Loveland, CO, USA) and turbidity was measured by turbidity tube (DelAgua, Robbens Institute, Surrey, UK). We set exclusion criteria for water which was treated with chlorine containing compounds that in cases where turbidity was <5 NTU, pH 6.5-8, and FAC > 0.2 mg/l, samples were not collected for microbial analyses, as the water met safety criteria for point-of-use water disinfection [19]. For treated water that did not meet these conditions, and for all samples of untreated water and water reportedly treated by other treatment methods (boiling, ceramic pot filtration, and siphon filtration), samples were returned to the lab for microbiological analysis. During sample collection, we also observed and recorded type of water treatment options used, how and where reported treated water was stored (container type).

Sample processing and analyses

Samples (treated and untreated) were processed in duplicate and analysed within 2 h of collection. We enumerated thermotolerant coliforms (TTC) using the membrane filtration method followed by incubation on selective media. In this method, water samples are passed through a 0.45 μm membrane filter (Millipore, Bedford, MA, USA) and incubated on membrane lauryl sulphate media (Oxoid Limited, Basingstoke, Hampshire, UK) at 44 ± 0.5°C for 18 h in an Oxfam Delagua portable incubator (Robbens Institute, Surrey, UK). We processed 100 and 10 ml of sample, respectively, for reportedly treated and untreated water, with results of duplicate samples reported as TTC per 100 ml. We processed one negative control sample as every fourth assay using sterile wash water.

Data analyses

We double-entered data in Excel and performed statistical analyses using Stata Release 11.0 (StataCorp., College Station, TX, USA) primarily on log-transformed microbial count data; non-detects were assigned a value of 1 for calculation of geometric means and log reductions. For the TTC counts which were too numerous to count (TNTC), we assigned a value of 300 for the plate as the upper bound of countability for the assay and therefore a minimum value. Following checks for normality, we used parametric statistical tests (*t*-tests and ANOVA) to compare log-transformed TTC counts of paired treated and untreated water samples across treatment methods.

Results

A total of 1202 pairs of samples were included in the analysis, collected from 390 households. Demographic information for the respondent community is given in Table 1. All treatment methods achieved significant reduction in TTC (Tables 2 and 3). Treatment by boiling resulted in an arithmetic mean 2.2 $\log_{10}$ reduction in TTC (95% CI 1.9–2.2). Similar arithmetic mean reductions were achieved across the other technologies: CWP (2.3 $\log_{10}$, 95% CI 2.1–2.5), PuR sachets (2.4 $\log_{10}$, 95% CI 2.2–2.5); the ceramic siphon filter (2.5 $\log_{10}$, 95% CI 2.4–2.7); Waterguard (2.2 $\log_{10}$, 95% CI 1.9–2.4); Aquatabs (2.5 $\log_{10}$, 95% CI 2.4–2.6). With the exception of boiling, the log mean and percent reduction of TTC by treatment methods did not vary significantly by district (Table 3).

The relative safety of product water can also be estimated using log-levels of TTC in product water, to indicate the safety of water once treated (Table 2). Using <10 TTC per 100 ml as an indicator of low microbial risk [20], the majority of samples treated by all methods met this criterion: boiling (70% of samples), ceramic pot filters (72%), PuR (64%), siphon filters (86%), Waterguard (73%), and Aquatabs (81%).

Table 1 Socio-economic characteristics of the study population

	Geita	Kisarawe	Total
Gender of respondent			
Male	41 (16.2%)	29 (17.6%)	70 (17.9%)
Female	184 (81.8%)	136 (82.4%)	320 (82.1%)
Total	225	165	390
Age of respondent			
12–18	16 (7.1%)	5 (3.0%)	21 (5.4%)
19–38	130 (57.8%)	103 (62.4%)	233 (59.7%)
39–58	62 (27.6%)	34 (20.6%)	96 (24.6%)
59–65	12 (5.3%)	15 (10.2%)	27 (6.9%)
67–97	5 (2.2%)	8 (4.8%)	13 (3.3%)
Total	225	165	390
Respondent position in the household			
Head	202 (89.8%)	144 (87.3%)	346 (88.7%)
Daughter	17 (7.6%)	14 (8.5%)	31 (7.9%)
Son	1 (0.4%)	3 (1.8%)	4 (1%)
Close relative	5 (2.2%)	4 (2.4%)	9 (2.3%)
Total	225	165	390
Primary respondent formal education level			
No formal education	91 (40.4%)	68 (41.2%)	159 (40.8%)
Primary education	112 (49.8%)	86 (52.1%)	198 (50.8%)
Secondary education	16 (7.1%)	5 (3.0%)	21 (5.4%)
High education	3 (1.3%)	2 (1.2%)	5 (1.3%)
Adult education	3 (1.3%)	4 (2.4%)	7 (1.8%)
Total	225	165	390
Reported primary drinking water source			
(i) Public dug well	108 (48%)	135 (81.8%)	243 (62.3%)
(ii) Private dug well	74 (33%)	13 (7.9%)	87 (22.3%)
(iii) Private tube well	24 (10.7%)	6 (3.6%)	30 (7.7%)
(iv) Tanker/vendor	18 (8%)	8 (4.8%)	26 (6.7%)
(v) Stored rain water	1 (0.4%)	3 (1.9%)	4 (1%)
Total	225	165	390

Discussion

All candidate HWTS methods improved microbial water quality at the point of use. This study is unique among other studies of HWTS performance in that rotating use of technologies among households enabled the direct comparison of six technologies *in situ* while holding user-specific variables constant; user behaviour has been shown to be closely related to effectiveness [21]. There were no significant differences in the level of microbiological effectiveness achieved across technologies, however, though sample size and pre-treatment microbial counts limited our ability to detect fine differences between LRVs and detect high reductions, respectively. *In situ*, all technologies consistently met WHO criteria for "protective" treatment of drinking-water on the basis of bacterial reduction, which requires a mean 99% (2 $\log_{10}$) reduction in bacteria [19], though WHO performance recommendations are based on laboratory challenge data as well as reductions of viruses and protozoa. Bacterial reductions reported here are comparable though generally high in relation to previously reported estimates of HWTS field performance [19]. Relatively high bacterial reduction may have been achieved partly because: participants were provided with trial HWTS technologies together with safe storage containers to safeguard post-treatment contamination (91% of users stored water correctly, based on our observations); follow-up on correct use of the technologies was provided at regular intervals to participants; and the study period overall was relatively brief after introduction of the method and training. At household visits, the data collection team encouraged consistent and correct use of the method. Thus, though this study comparatively assessed technology performance under actual household use conditions, the context was still an intervention and therefore findings may represent an idealized context that differs in important ways from at-scale implementation programs, which generally may receive limited "software" support. This study did not measure adherence and could not estimate long-term

Table 2 Summary of microbial reductions achieved by HWTS methods across all sources and in both districts

				Percentage of total samples by $\log_{10}$ level (TTC/100 ml)			
Method	*n*	Sample type	TTC count $\log_{10}$ mean (95% CI)*	<1	1–10	11–100	101–1000
Boiling	157	Untreated	≥2.9 (2.8, 3.0)	1.3	1.9	8.9	88
	157	Reported Treated	≥0.71 (0.57, 0.85)	43	24	19	14
Ceramic pot Filter	90	Untreated	≥2.9 (2.7, 3.0)	2.2	1.1	6.7	90
	90	Reported Treated	≥0.59 (0.42, 0.76)	47	26	20	7.7
PuR	86	Untreated	≥2.9 (2.7, 3.0)	0	0	5.8	94
	86	Reported Treated	≥0.49 (0.33, 0.66)	54	27	11	9.3
Ceramic siphon filter	83	Untreated	≥2.9 (2.8, 3.1)	2.4	0	2.4	95
	83	Reported Treated	≥0.38 (0.25, 0.51)	54	31	12	2.4
Waterguard	91	Untreated	≥2.8 (2.5, 3.0)	7.7	3.3	1.1	88
	91	Reported Treated	≥0.55 (0.39, 0.70)	54	19	21	6.6
Aquatabs	94	Untreated	≥2.9 (2.8, 3.1)	1.1	2.1	4.3	93
	94	Reported Treated	≥0.44 (0.30, 0.59)	47	34	13	6.4

n, number of samples; TTC, thermotolerant coliform.

Table 3 Mean $\log_{10}$ reduction values (LRV)* for each method by district

	Log_{10} mean (cfu/100 ml) untreated		Log_{10} mean (cfu/100 ml) treated		LRV*		Percent reduction			
Method	Geita	Kisarawe	Geita	Kisarawe	Geita	Kisarawe	Geita	Kisarawe	Combined log mean reduction	Mean combined percent reduction
Boiling	3.0	2.7	0.44 (n = 98)	1.2 (n = 59)	2.5	1.5†	99.7	97.1†	≥2.2 (1.97–2.31)	≥99.3
Ceramic pot filter	2.8	2.9	0.60 (n = 54)	0.57 (n = 36)	2.2	2.4	99.4	99.6	≥2.3 (2.01–2.49)	≥99.5
PuR	2.8	2.9	0.24 (n = 48)	0.80 (n = 38)	2.6	2.1	99.7	99.1	≥2.4 (2.18–2.53)	≥99.6
Siphon filter	2.9	3.0	0.34 (n = 52)	0.44 (n = 31)	2.5	2.6	99.7	99.7	≥2.5 (2.35–2.73)	≥99.7
Waterguard	3.0	2.5	0.39 (n = 49)	0.73 (n = 42)	2.6	1.8	99.7	98.3	≥2.2 (1.96–2.45)	≥99.4
Aquatabs	2.9	2.9	0.34 (n = 55)	0.59 (n = 39)	2.6	2.4	99.7	99.6	≥2.5 (2.31–2.64)	≥99.5

*Log_{10} reduction values are computed as $\log_{10}$ (pre-treatment TTC count) – $\log_{10}$ (post-treatment TTC count), where post-treatment TTC count is given a value of 1 in the case of non-detects (TTC <1 cfu/100 ml) and pre-treatment TTC counts are assigned a value of 300 cfu per plate as the upper detection limit where colonies were too numerous to count (32.3% of untreated water samples). Therefore, we have indicated values are greater than or equal to means where greater than or equal figures have been included in mean calculations.

†Significantly different at $\alpha = 0.05$.

microbiological effectiveness achieved by the methods. Also, although LRV were high across all HWTS technologies, approximately 50% of treated samples did not meet safety criteria of <1 TTC/100 ml.

Boiling achieved a mean overall microbial reduction of 99.3% (2.2 $\log_{10}$), consistent with one study from peri-urban India where boiling reduced TTC by 99% (n = 1088, [22]. Other estimates of faecal indicator bacteria (FIB) reductions by boiling are generally lower, including those from rural Guatemala (86.2% of TTC, n = 206, [23], Vietnam (97% of TTC, 95% CI 96.3–97.5%, n = 245, [24]); and Cambodia (98.5% of *E. coli*, 95% CI 98–99%, n = 369, [25]). Though boiling is highly effective against all classes of pathogens, it may be unreliable in field settings, partly due to the variability of boiling in practice and the risk of re-contamination in storage [25–27]. The relatively high microbial effectiveness of boiling in this study may be attributable to the safe storage container provided along with the rocket stove. The rocket stove itself, as a highly efficient cooking device that can quickly reach high temperatures, may have helped ensure that water boiling was adequate for achieving microbial reductions.

One of the advantages of boiling as HWTS technology is that it is effective even in very turbid waters [28]. Nevertheless, 14% of the boiled water samples contained

101–1000 TTC/ml, consistent with high microbial risk [20], possibly due to post-treatment contamination. Safe storage containers may not have been washed well or could have been washed with contaminated water.

Despite limitations, boiling is the most common form of HWTS in Tanzania, used by 47% of urban and 24% of rural households, as compared with chlorination (4.5% and 1.5%, respectively) [5]. There was a statistical difference in the reduction of TTC by boiling in the two study districts, with slightly higher reductions observed in Geita. The reason for this difference is unclear and cannot be explained by the other data we collected. Nevertheless, the two districts have different cultures and potentially different water handling behaviours, which are factors that can influence HWTS and its effectiveness in field settings [23].

Ceramic pot filters are supported by a number of laboratory and field studies [29]. In this study, ceramic pot filters (with a 30 l safe storage container) significantly improved water quality, achieving a mean overall TTC reduction of 99.5% (95% CI 99.1–99.7%). These findings are generally comparable with field-based bacterial reductions reported previously for this technology, for example in studies from Cambodia reporting *E. coli* reductions of 99% (95% CI 98.9–99.4%, $n = 485$) and 98% (95% CI 96.8–98.7%, $n = 203$) [30, 31]. High microbial removal performance of ceramic pot filters has also demonstrated been demonstrated where input water is highly contaminated, for example in Nigeria where results indicated removal of *E. coli* of >99.99% ($n = 30$), [32]. Comparing the two study districts, the overall performance of filters in Kisarawe (99.6%) was slightly higher than in Geita district (99.4%), though the differences was not statistically significant. Our findings suggest that ceramic pot filters have potential to improve drinking water quality in rural Tanzania, similar to other settings [18].

There is limited published information on the microbial effectiveness of ceramic siphon filters, which function similarly to other ceramic filters (microporous matrix, amended with colloidal silver) though they operate by pressure rather than gravity. The microbial reductions we observed were higher than the findings by [33], where the average percent removals were 90.7% for total coliform and 94.1% for *E. coli*. Similarly, a field study in Ghana revealed removal of *E. coli* at 96% by siphon filters [34]. Like other HWTS technologies, laboratory testing has suggested high efficacy is achievable, >99.99% [34, 35]. The principal advantage of siphon filters is that they tend to have an increased flow rate over the relatively slow gravity-driven ceramic pot filters, though they also are more complex to use, requiring two buckets and lacking an integrated safe storage container to receive treated water directly. The risk of recontamination after treatment is greater for ceramic siphon filters than ceramic pot filters, but we observed no difference between the two with respect to TTC reduction in field use conditions.

Aquatabs and Waterguard were promising chlorine disinfection methods piloted in the study. Functionally similar in delivering free chlorine to water, their observed microbial reductions were similar: the $\log_{10}$ reduction of Aquatabs was ≥2.5 (2.31–2.64) *vs.* ≥2.2 (1.96–2.45) for Waterguard. In practice, Waterguard dosing was less straightforward to users than the tablet form of Aquatabs, and the liquid solution may have been susceptible to reductions in strength over time. The longer shelf life of Aquatabs may be more suited to rural Tanzania.

The physical-chemical properties of untreated water have been observed to limit *in situ* microbial reductions by HWTS methods, including chlorination [21, 36, 37]. In this study, the effectiveness of both Waterguard and Aquatabs in Kisarawe district was lower than that in Geita district, probably because of the overall much higher turbidity observed in Kisarawe both in source and household drinking water samples [37]. Turbidity is known to negatively affect water disinfection by chlorine [37–40] by exerting chlorine demand. Because highly turbid source waters are common across rural Tanzania [37], chlorination-only technologies may not be as widely effective as other HWTS options. High turbidity can also limit the effectiveness of ceramic and other filtration technologies via rapid clogging, requiring frequent cleaning by users and potentially a reduced life span [29].

The combined flocculent-disinfectant, PuR, (now branded as the P&G Purifier of Water™), like other technologies in this study, reduced TTC by more than 99% *in situ*. In laboratory studies, the product reduced bacteria in water up to 99.9999% [41]. Effectiveness may be generally high even in highly turbid water [42]; its effectiveness did not significantly differ between Geita and Kisarawe (Table 3).

Limitations

This study had a number of limitations. First, microbial performance for HWTS may vary widely by pre-treatment water quality, and though we encountered a diverse range of characteristics in source waters, these results are only generalizable to the extent that these waters are representative. Second, results indicate an idealized intervention context, where users are supplied with regular re-enforcement of messaging and instructions on proper use and this may not be consistent with at-scale implementation programs. Third, the period of use for each intervention was relatively short, so long-term effectiveness (and long-term behaviours influencing effectiveness) is not captured here. These results should be interpreted as high compared with a typical implementation which may lack on-going support to users. Fourth, we use the bacterial indicator of thermotolerant coliforms (sometimes known as faecal coliforms) which may or may not be the best available bacterial performance indicators for these technologies, and whose reductions can tell us nothing about reductions by virus or protozoa. Lastly, we can only infer generally that microbial reductions following use of HWTS would meaningfully contribute to better health among users. This is outside the scope of our current analysis.

Conclusions

Household water treatment and safe storage performance in the field, in contrast with laboratory efficacy, is known to be limited in practice [19], owing to a variety of technology, behavioural, population and context-specific factors [21]. Effectiveness is also limited by the pre-treatment microbial count. We found that reductions of waterborne bacteria across all technologies to be generally consistent with previous studies of HWTS effectiveness. Since each pilot HWTS method revealed comparable microbiological performance under actual use conditions, we propose that decisions related to scaling up access should be primarily influenced by other considerations, including adherence (correct, consistent and sustained use), cost and factors related to sustainability, all of which have been shown to be of central importance to the ability of HWTS to achieve its desired aim: the reduction of waterborne disease.

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Corresponding Author Joe Brown, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA. E-mail: joe.brown@ce.gatech.edu