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Use of Household Water Treatment and Safe Storage Methods in Acute Emergency Response: Case Study Results from Nepal, Indonesia, Kenya, and Haiti

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ABSTRACT: Household water treatment (HWTS) methods, such as boiling or chlorination, have long been recommended in emergencies. While there is increasing evidence of HWTS efficacy in the development context, effectiveness in the acute emergency context has not been rigorously assessed. We investigated HWTS effectiveness in response to four acute emergencies by surveying 1521 targeted households and testing stored water for free chlorine residual and fecal indicators. We defined "effective use" as the percentage of the targeted population with contaminated household water who used the HWTS method to improve stored drinking water microbiological quality to internationally accepted levels. Chlorine-based methods were distributed in all four emergencies and filters in one emergency. Effective use ranged widely, from 0–67.5%, with only one pre-existing chlorine program in Haiti and unpromoted boiling use in Indonesia reaching >20%. More successful programs provided an effective HWTS method, with the necessary supplies and training provided, to households with contaminated water who were familiar with the method before the emergency. HWTS can be effective at reducing the risk of unsafe drinking water in the acute emergency context. Additionally, by focusing on whether interventions actually improve drinking water quality in vulnerable households, "effective use" provides an important program evaluation metric.

■ INTRODUCTION

An estimated 4 billion cases of diarrhea each year, causing 1.87 million deaths in children under five years of age, are caused by unsafe drinking water, poor sanitation, and poor hygiene.[1] Environmental health interventions to reduce this disease burden include improved water sources, household water treatment and safe storage (HWTS), handwashing with soap, and sanitation.[2,3] HWTS methods such as boiling, chlorination, flocculant/disinfectant powder, solar disinfection, and filtration have been shown in the development context to improve household water microbiological quality or reduce diarrheal disease in users.[4,5] Based on this evidence, the World Health Organization (WHO) and the United Nations Children's Fund (UNICEF) recommend HWTS as one option to provide safe drinking water for the 780 million without access to improved water supplies and the millions more drinking microbiologically unsafe water from improved sources.[6,7] While there is uncertainty over the actual impact of HWTS in the absence of bias—as well as the technologies that lead to sustainable, consistent use over time—HWTS is widely promoted in the development context and reportedly used by more that 1.1 billion worldwide.[8−10]

Safe drinking water is also an immediate priority in most emergencies.[11] When normal water supplies are interrupted or compromised due to natural disasters, complex emergencies, or outbreaks, responders have often encouraged affected populations to boil or disinfect their drinking water to ensure its microbiological integrity. Because of increased risk from waterborne disease, HWTS could potentially be an effective emergency response intervention in (1) response to flooding events or natural disasters that lead to displacement;[12] (2) complex emergency settings when relief cannot progress to development; and (3) response to outbreaks caused by untreated drinking water, especially cholera outbreaks, which are currently increasing in severity and quantity throughout Africa.[13] HWTS may also be especially effective during the acute phase of an emergency when responders cannot yet reach the affected population with longer-term solutions, when the goal is to provide safe drinking water until normal sources are restored.

However, differences between the emergency and development contexts may affect HWTS effectiveness, as emergency have higher crude mortality rates,[14] higher likelihood of outbreaks due to population migration,[15] higher level of funding available affecting what options are selected,[16] and competing priorities for staff time. These differences raise questions about the generalizability of HWTS results from development into emergency situations.

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A recent survey of emergency responders confirmed that promotion of HWTS methods is common in emergency response.[17] Forty survey respondents described 75 projects using one or more HWTS methods in emergencies. However, a literature review revealed little rigorous evidence, particularly in the acute emergency context, on the effectiveness of efforts to promote HWTS among vulnerable populations to ensure correct use of the intervention that reduced their risk of diarrheal disease by rendering their water safe to drink.[17] The goal of the work presented herein was to assess the effectiveness of HWTS technologies distributed in the acute emergency situation in order to make a recommendation on how to implement HWTS in this context.

METHODS

Study Design. UNICEF and Oxfam Great Britain (Oxfam/GB) commissioned this research to assess the effectiveness of HWTS technologies distributed in four acute emergency situations (between weeks 4 and 8 after emergency onset). To assess risk reduction in this specific acute emergency time frame, all evaluations were completed in 3−4 weeks within 8 weeks of emergency onset. This mandated a cross-sectional study design. The study was approved by the Ethics Committee of the London School of Hygiene and Tropical Medicine (LSHTM).

Because the specific context before arrival was unknown, we prepared a mixed-method assessment methodology that was subsequently modified for each specific context. Our protocol included five components: situation and spatial analysis, household surveys, water quality testing, qualitative interviews with responders, and collection of the total cost of the response from the responding nongovernmental organization (NGO).

Effective Use. Most emergency response evaluations are based solely on inputs (such as chlorine tablets delivered), coverage (such as number of people served), or reported use (from household reports). While direct assessments of health impact are rarely possible in the critical acute stage of an emergency, it is nevertheless important to target interventions to those at risk and provide them with solutions that mitigate that risk. In this evaluation, we use "effective use" to capture the extent to which a population at risk from waterborne disease used an HWTS method to minimize their risk. Thus, "effective use" is the percent of targeted households whose water was fecally contaminated that used the intervention to improve their water quality to internationally accepted standards. The contaminated/uncontaminated breakpoint was calculated two ways: (1) if the untreated water had ≥1 CFU/100 mL of *Escherichia coli* or thermotolerant coliform before treatment and <1 after (the WHO definition of safe water);[18] and (2) the same calculation, but using the "low-risk" guideline value of 10 CFU/100 mL as the breakpoint.[19] A secondary outcome variable for chlorine-based technologies was free chlorine residual (FCR) levels in household-treated water. We also measured turbidity in treated and untreated water samples because reductions in turbidity have been associated with increased user acceptance of HWTS technologies and improved microbiological outcomes.[20] All water quality data were entered into Microsoft Excel (Redmond, WA, USA), cleaned, and analyzed using Excel and Stata 10.1 (College Station, TX, USA).

Site and Responder Selection. Study sites were mutually agreed upon by LSHTM, UNICEF, and Oxfam/GB based on the following criteria: (1) the emergency occurred in a high-diarrheal disease risk emergency such as a flood, outbreak, or displacement event; (2) multiple HWTS technologies were distributed; (3) water supply options were also installed as part of emergency response; (4) the affected population had various levels of training and exposure to HWTS technologies; and (5) the study was logistically feasible. Deployment occurred after organizations on the ground confirmed the emergency met the inclusion criteria, a host organization was identified, and all parties approved the particular emergency.

Situation Analysis. Upon arrival at each emergency, we determined the scope of HWTS distributions by communicating with the water, sanitation, and hygiene cluster coordinating the response, HWTS promoters, emergency responders, and HWTS manufacturers. The objective was to determine what HWTS technologies were available in country, which products had actually been distributed to households, and which households had received the products. We then mapped the location and size of the affected and HWTS-targeted populations to develop an appropriate sampling strategy for household surveys and water sampling. We included all responders we identified to have promoted HWTS for surveying and analysis, except one responder (in Haiti) that was too small to include in analysis.

Sampling Strategy. Our objective was to assess the extent households reportedly reached by responders were actually using HWTS ("confirmed use") and whether such use was improving their drinking water quality from unsafe to safe levels ("effective use"). Thus, our sample frame was drawn from households that responders reported covering in their respective campaigns. In Nepal, Kenya, and the liquid chlorine distribution in Indonesia, random population-based sampling by geographical unit in population proportionate to size methodology was used, as all households in a certain geography were targeted for HWTS method distribution. In the chlorine tablet distribution program in Indonesia and in all programs investigated in Haiti, random sampling of HWTS method recipients based on recipient lists or recipient identification was conducted, as distributions were not localized to a geographic area.

Household Surveys. Each case study included a household survey using the standard template modified for the specific context and HWTS technologies distributed. The surveys consisted of questions on respondent and household characteristics, effect of the emergency, household assets, diarrhea prevalence, and water knowledge and source before and after the emergency; water storage in the home; the use of, preferences for, and knowledge of each HWTS method received; and questions about, water quality testing of and collection of current treated and untreated stored household drinking water. On average, there were about 30 questions on household characteristics, 10−20 questions per HWTS method received, and 10−15 questions on current household water. Surveys were translated into the appropriate local language, back-translated to ensure accuracy, and were printed before arrival at the emergency location. Survey training and pretesting occurred during one to two days of enumerator training, and any necessary survey edits were hand-edited into the survey forms by enumerators. All survey data were entered into Microsoft Excel (Redmond, WA, USA), cleaned, and analyzed using Stata 10.1 (College Station, TX, USA).

Costs Data. Qualitative interviews were conducted with logistics staff of the responding organizations, and if available, response cost information was collected.

Water Sampling and Analysis. At each household surveyed, a treated water sample (if the head of household reported it was available) and an untreated water sample (from the same source if treated water was available) was collected aseptically in sterile 125 mL WhirlPak bags with sodium thiosulfate to inactivate any chlorine residual present. Samples were stored on ice until analyzed for microbiological indicators using membrane filtration on a Millipore (Billerica, MA, USA) portable filtration stand. Samples were diluted appropriately with sterile buffered water, filtered aseptically through a 45 μm Millipore filter, placed in a plastic Petri dish with a pad soaked with selective media, including mFC media to measure fecal (thermotolerant) coliforms (incubated at 44.5 °C) or mColiBlue24 media to test for total coliforms and *E. coli* (incubated at 35−37 °C). Negative controls of boiled water were sampled every 20 plates, and 10% of samples were duplicated. mFC media was replaced after the first two emergencies by mColiBlue24 media due to the higher resistance of mColiBlue24 to deviations in incubation temperature in resource limited environments.[21] All standard procedures for microbiological testing were met, except holding time before the sample was fully processed was extended from 8 to 12 h in some environments due to travel logistics.[22]

Enumerators were trained to test FCR using a Hach ColorWheel test kit (Loveland, CO, USA) at all households reporting water treated with a chlorine-based HWTS method or stored tanker truck water at the time of the household survey. Confirmed use was calculated as the percent of the targeted population with ≥0.2 mg/L FCR. Turbidity was measured with a LaMotte 2020 turbidimeter (Chestertown, MD, USA) calibrated weekly with nonexpired stock calibration solutions within 24 h of collection.

Data Analysis. Data was entered into Microsoft Excel, cleaned, and exported into Stata 10.1 for analysis. We conducted univariate analysis to investigate correlations between indicators of use (FCR presence, *E. coli* reduction, reported treatment) and household/respondent characteristics (as measured by a p value of <0.05 by Chi-squared analysis).

RESULTS

Characteristics of Emergencies Investigated. Between August 2009 and March 2010, four acute emergencies were investigated: (1) a cholera outbreak in Jajarkot, Nepal; (2) an earthquake in West Sumatra, Indonesia; (3) a flooding event during a cholera epidemic in Turkana, Kenya; and (4) the January 2010 earthquake that caused significant displacement in Haiti (Table 1). These case studies represented a diverse range of emergency situations, geographical settings, affected population sizes, responding organizations, and implementation strategies (Table 1). The HWTS implementation strategies included the following: (1) a continuous community-based distribution of three interchangeable chlorine-based products with community education by existing local NGO Nepal Water for Health in Nepal; (2) nonfood item (NFI) kit distribution that included liquid chlorine (sodium hypochlorite) or tablet chlorine with a single training at distribution by international NGOs CARE and Rotary (ShelterBox) in Indonesia; (3) NFI-kit distribution including liquid chlorine and a flocculant/disinfectant with a single training by national NGO Kenya Red Cross Society in Kenya; and (4) various strategies in Haiti, including continuous community-based distribution of chlorine tablets with training by community health workers and safe storage container provision by local NGO Deep Springs

Table 1. Characteristics of Four Emergencies Investigated

	Nepal	Indonesia	Kenya	Haiti
date investigated	July 31−August 22, 2009	November 1−22, 2009	January 20− February 5, 2010	February 14−March 13, 2010
emergency type	cholera	earthquake	flooding/cholera	displacement/earthquake
diarrheal disease risk	high	low	high	high
setting	extreme rural, mountains	urban, peri-urban	extreme rural, desert	urban to mountainous
affected population	140 000 homes	181 665 homes	5592 homes	600 000 homes
population targeted with HWTS	1565 homes in 2 subdistricts	1578 homes in 2 programs	5592 homes in 4 communities	4618 homes in 6 programs
responders	local NGOs there before the emergency	NGOs arrived after the emergency	NGOs arrived after the emergency	local NGOs there before the emergency and one new NGO
HWTS intervention types	liquid chlorine (Piyush, WaterGuard); chlorine tablets (Aquatabs)	liquid chlorine (Air Rahmat); chlorine tablets (Rotary)	chlorine tablets (Aquatabs); flocculant/disinfectant (PuR)	chlorine tablets (Aquatabs); liquid chlorine (Gadyen Dlo); ceramic filters; biosand filters
HWTS technologies in country before emergency	all (prepositioned for anticipated flooding)	all (available locally)	all (prepositioned for anticipated flooding)	all (available from local NGOs using HWTS) except Aquatabs
distribution strategy	continuous in community	NFI kit distribution	NFI kit distribution	varied, from NFI kit distribution to continuous in community
programmatic support	$16,886 U.S. for the program	not possible to obtain	$37,750 U.S. for the program	not possible to obtain
sustainability	none—products not available in affected area	none—products not available in affected area	none—products not available in affected area	potential—products available locally

Table 2. Summary of Selected Survey Results

	Nepal	Indonesia	Kenya	Haiti
surveyed households (number)	400	270	409	442
average (min−max) respondent age (years)	34.4 (11−80)	44.7 (15−92)	38.1 (16−72)	38.2 (7−78)
% female respondents	51.0	81.5	89.2	60.5
average (min−max) female respondent school (years)	1.3 (0−12)	5.8 (0−17)	0.3 (0−12)	7.1 (0−20)
% female head of households who can read	(not asked)	82.8	7.9	70.8
% who live in the same place as before emergency	99.3	39.0	65.0	29.3
% of respondents reporting damage to home	(not asked)	99.6	98.5	80.7
% with covered stored household water	63.8	(not asked)	97.8	98.7
% reporting child diarrhea in last 24 h	5.4	40.9	17.4	44.3
% reporting adult diarrhea in last 24 h	6.0	14.0	9.7	14.7
% using improved water source on day of survey	57.3	63.3	78.6	71.8
% of respondents with water source within 30 min	89.5	100	18.2	93.7
increased use of improved sources after emergency (compared to reported pre-emergency source)	No	yes ($p = 0.018$)	yes ($p < 0.001$)	No
% who feel water is safe to drink	82.0	96.3	76.5	65.5
% who feel water is safe to drink because it is clear	83.2	93.3	75.4	3.5
top three self-identified health problems after the emergency	hospital too far, water, garbage	cough, flu, fever	malaria, fever, food shortage	food shortage, diarrhea, stress
% self-reporting water as a health problem after emergency	24.2	0	6.4	44.0
% self-reporting diarrhea as health problem after emergency	16.4	13.3	8.6	19.0
% knowing at least one HWTS method before emergency	5.2 (4.3% boiling)	100 (100% boiling)	98.8 (92.9% boiling)	88.7 (72.9% Aquatabs)
% targeted population receiving at least one HWTS method	97.0	84.3	89.5	96.2

International (DSI), NFI kit distribution of Aquatabs with no training by international NGO Haiti Response Coalition, and distributions of filters with one training by local NGOs FilterPure and Clean Water for Haiti. The responders included in the study reported targeting a total of 13 353 households.

Overall, the HWTS technologies distributed were mostly chlorine tablets or liquid, although filters were distributed in Haiti and flocculant/disinfectant sachets were distributed in Kenya. All HWTS technologies distributed in the acute emergency context were prepositioned or available in country (or within driving distance to the country) before the emergency, with the exception of Aquatabs in Haiti and ShelterBox tablets in Indonesia, which were flown in.

Household Surveys. A total of 1521 household surveys were completed among the four emergencies, representing 7.3−25.6% of the population reportedly reached by responders. Large differences in household/respondent characteristics and water treatment practices were seen between the four emergencies (Table 2), including access to improved water sources (in both Indonesia and Kenya access increased postemergency) and reported pre-emergency knowledge of HWTS, from 5.2% reporting knowing at least one HWTS method in Nepal (mainly boiling) to 98.8−100% in Kenya and Indonesia (also mainly boiling) and 88.7% in Haiti (mainly Aquatabs). In all emergencies, >80% of the surveyed population reported receiving at least one HWTS method from an NGO. Of note is that household water storage containers were varied in Nepal as families improvised containers (pots, water jugs, etc) required for chlorine-based treatment; in Indonesia most families used thermoses for storing reported-boiled water; in Kenya families used 20 L jerry cans or collapsible containers distributed in the emergency; and in Haiti families mostly used buckets with lids or (for those receiving Aquatabs from DSI) a specialized 5 gallon bucket with lid and tap distributed in the emergency.

Reported HWTS Use Knowledge. Large differences were seen in HWTS method knowledge, with a range from 0.5% to 72.9% in the recipients' pre-emergency knowledge of the HWTS technologies they received in the acute emergency (Table 3). Across all emergencies, the majority of recipients of Aquatabs chlorine tablets reported correct knowledge of use (add one tablet to a specific volume of water and wait 30 min before drinking) (Table 3). Only 1.4% of respondents reported how to correctly use the ShelterBox tablets, which (while distributed in Indonesia) were labeled in written English directions on the box only and distributed with minimal training. Only 2.3% of respondents could correctly identify all five steps specified for use of PuR (renamed "Purifier of Water") brand of flocculant/disinfectant.

Reported Use of HWTS. Between 1.4% and 93.3% of recipients of chlorine-based HWTS technologies reported having treated water on the day of the unannounced survey visits, with the lowest rates in the Indonesia and Kenya NFI kit distributions (1.4−12.7%) and the highest in the DSI Aquatabs (78.5−93.3%) and filter distributions (52.9−72.1%) in Haiti (Table 3). Additionally, even though boiling was not promoted by an NGO in Indonesia, 88.1% of the total Indonesian surveyed population reported boiling.

Confirmed Use of HWTS. Overall, 11.7% of the targeted population in Kenya, 18.5% in Nepal, and between 16.6% (in spontaneous settlements of hurricane-displaced populations in urban areas) and 89.5% (in DSI rural areas) in Haiti had adequate (≥0.2 mg/L) FCR in their drinking water from the distributed chlorine-based HWTS technologies (Table 3). The lowest rates of confirmed use were seen in Indonesia (no household had ShelterBox-treated water available), and the highest rate was seen in rural areas of the DSI program in Haiti.

Table 3. Summary of Results on Promotion and Use

	Nepal			Indonesia		Kenya		Haiti		
HWTS method	Aquatabs	WaterGuard	Piyush	Air Rahmat	ShelterBox	Aquatabs	PuR	Aquatabs	ceramic	biosand
no. households targeted in programs[a]	1565 (3 products distributed to all)			954	624	5592 (both products)		unknown (HRC) 2880 (DSI)	350	238
most common water sources	protected and unprotected springs			piped, rainwater, surface water		tap, borehole, river		protected, tanker unprotected	protected	protected, tanker
no. (%) of households surveyed who received HWTS method (n = households surveyed)	313 (78.3%)	53 (17.7%)	177 (44.3%)	97 (84.3%)	70 (100%)	337 (82.4%)	261 (63.8%)	252 (91.6–95.4%)	43 (100%)	51 (100%)
% knew HWTS method distributed before emergency	0.5	1.0	0.5	18.9 (chlorine)		10.0	1.2	72.9	2.0 (knew filter)	
% received household training	3.8	0	0.6	0	–	3.3	2.3	26.4	16.3	35.3
% received group training	94.6	100	98.9	95.9	–	96.1	96.9	55.2	83.7	54.9
% know correct use of method (n = recipients)	53.0	–	44.9	13.4	1.4	89.9	2.3	53.1 (HRC) 81.7 (DSI)	–	–
% reporting treated water in house today (n = recipients)	9.9	47.2	36.2	6.2	1.4	15.4	9.2	21.7 (HRC) 93.3 (DSI)	72.1	52.9
% with correct FCR (n = reported treatment)	51.6	24.0	41.5	50	–	52.1	63.6	61.1 (HRC) 86.7 (DSI)	–	–
% with adequate FCR (n = reported treatment)	87.1	56.0	50.1	50	–	62.5	63.6	68.5 (HRC) 95.9 (DSI)	–	–
main reason for use (n = recipients)	prevents disease			cleans water	–	cleans water		cleans water		
main reason for disuse (n = recipients)	product finished	taste/smell	using other	water clear	–	product finished		product finished	broken	no water
% reporting treated water in house today (n = total population for all but Haiti (recipients))	8.3	6.3	15.8	not enough use to calculate		12.7	5.9	21.7–93.3	72.1	52.9
% with adequate FCR (n = total population for all but Haiti (recipients))	6.8	3.5	8.3			7.9	3.7	16.6–89.5	–	–
overall treated water in emergency (n = targeted population)	18.5% with FCR (households received rotating multiple products)			0% distributed technologies but 88.1% report boiling		11.7% with FCR		between 16.6 and 89.5% of recipients have FCR in chlorine-based programs.		

[a]Reported by emergency responders participating in the study. All other data collected in household surveys and water sampling.

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Table 4. Summary of Results on Microbiological Effectiveness

	reported use (recipients)	confirmed use (recipients)	use summary	% untreated water with <1 CFU/100 mL	% households with ≥1 before treatment and <1 CFU/100 mL after (*n* = reported treaters with treated−untreated water pairs)	effective use at 1 CFU/100 mL breakpoint (*n* = recipients)	effective use at 10 CFU/100 mL breakpoint (*n* = recipients)
Nepal							
Aquatabs	8.3%	6.8%	18.5% with FCR	no data collected.			
WaterGuard	6.3%	3.5%					
Piyush	15.8%	8.3%					
Indonesia							
Air Rahmat	6.2%	0.9%	not enough use to calculate−0%				
ShelterBox	1.4%	1.4%	not enough use to calculate−0%				
boiling	88.1%	–	88.1%	24.6%	23.9%	21.1%	27.5%
Kenya							
Aquatabs	12.7%	7.9%	11.7% with FCR	46.5%	41.9%	5.3%	4.4%
PuR	5.9%	3.7%		22.2%	38.9%	2.3%	2.3%
Haiti							
Aquatabs—DSI rural	93.3%	89.5%	89.5%	13.8%	72.4%	67.5%	53.1%
Aquatabs—DSI urban	78.5%	53.8%	53.8%			56.8%	44.7%
Aquatabs—settlements	21.7%	16.6%	16.6%	7.7%	61.5%	13.0%	10.0%
ceramic filters	72.1%	–	72.1%	55.2%	27.6%	19.8%	10.8%
biosand filters	52.9%	–	52.9%	15.8%	15.8%	8.4%	19.5%

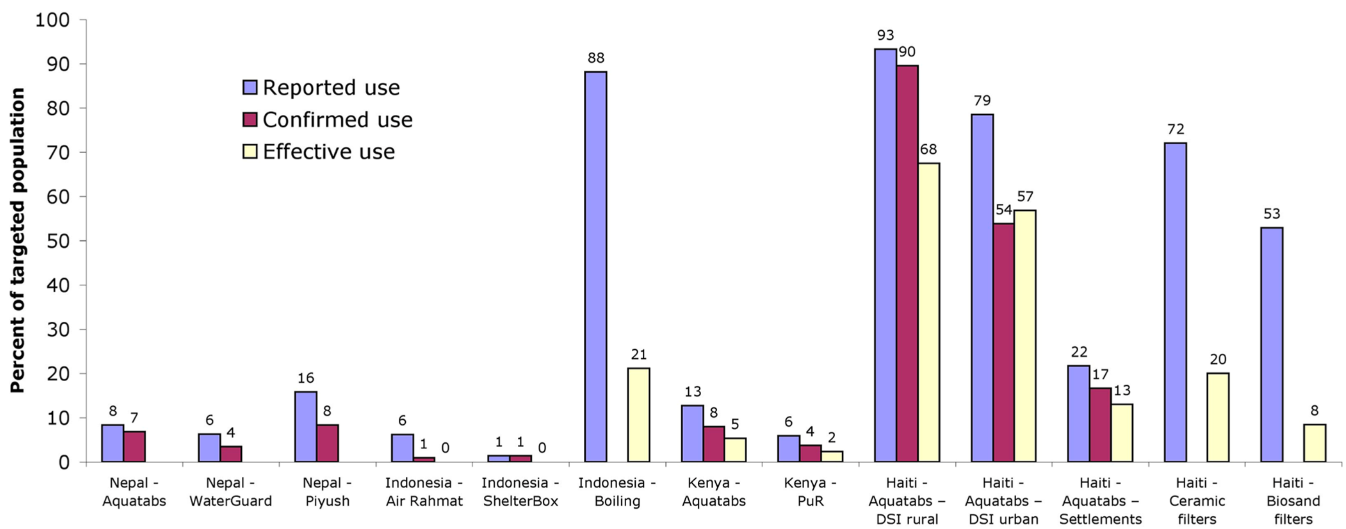

Figure 1. Graphical representation of reported, confirmed, and effective use (by targeted population).

Effective Use of HWTS. Effective use was calculated for all emergencies except Nepal, where microbiological sampling was discontinued due to inability to incubate at 44.5 °C in the remote mountainous region. Among the 1565 households surveyed who were targeted to receive chlorine-based HWTS products, 290 (18.5%) had FCR in their drinking water at the time of the unannounced survey visit (Table 4). At a total reported 60 day program cost of $16,886 U.S., this is equivalent to $58.23 U.S. per household with FCR or ~$1 U.S./household with FCR/day.

In Indonesia, there was not sufficient use of the distributed products (Air Rahmat and ShelterBox tablets) to calculate effective use, but there was sufficient data for boiling. Overall, 23.9% of households who reported boiling and had treated−untreated water pairs reduced their household thermotolerant coliform concentration from ≥1 to <1 CFU/100 mL. By multiplying the percent of households who reported boiling (88.1%) by the percent reducing their fecal coliform concentration (23.9%), an effective use percentage of 21.1% is determined. Thus, 21.1% of surveyed households (the targeted population) were using boiling to effectively treat their water to internationally accepted standards. This was at no cost to NGOs, as this was background water treatment. As subsidized propane was the main fuel source in this area, the time and fuel costs of boiling to the households were also minimal.

In Kenya, 12.7% and 5.9% of households surveyed reported using Aquatabs and PuR, respectively. Overall, 41.9% of 43 Aquatabs-reporting households and 38.9% of 18 PuR-reporting households with treated−untreated water pairs reduced their *E. coli* concentration from ≥1 to <1 CFU/100 mL. Thus, effective use in the recipient population rate was 5.3% for Aquatabs-treated waters and 2.3% for PuR-treated waters or 7.6% in total. Of the 5592 total households targeted, 425 (7.6%) had microbiologically improved water. At a total program cost of \$37,500 U.S., this is \$88.23 U.S. per household for an average of 97.6 days of treatment or ~\$1 U.S./household with microbiological improved water/day.

In Haiti, the percent of treated−untreated water pairs effectively treated from ≥1 to <1 CFU/100 mL *E. coli* ranged from 15.8% (biosand filters, $n = 19$) to 27.6% (ceramic filters, $n = 29$) to 61.5% (Aquatabs in spontaneous settlements, $n = 13$) to 72.4% (DSI Aquatabs/safe storage program, $n = 58$). Please note the biosand filters were installed incorrectly (without a standing water layer above the sand layer) that inhibited the development of the biologically activated layer and microbiological removal. Also, note the high percentage of households with clean water before treatment in the ceramic filter households (55.2%). By multiplying by reported use, the effective use of the technologies in the recipient population was 8.4% (biosand filters), 19.8% (ceramic filters), 13.0% (Aquatabs in spontaneous settlements), and 56.8−67.5% (Aquatabs in DSI urban and rural households). Overall, the DSI Aquatabs program reached 1186 rural homes and 638 urban homes with water effectively treated to the 1 CFU/100 mL breakpoint, the ceramic filter program 35 families, and the biosand filter program 20 families. Cost data was not available in this emergency.

In all emergencies, effective use numbers calculated using a breakpoint of ≥10 to <10 CFU/100 mL did not meaningfully change the results (Table 4). A graphical representation of reported, confirmed, and effective use is presented in Figure 1.

A significant percentage (7.7−55.2%) of untreated household water samples had <1 CFU/100 mL of *E. coli* and thus did not need treatment (Table 4). The lowest percentage of already clean water was seen in spontaneous settlements in Haiti and the highest percentage in recipients of ceramic filters in Haiti.

Associations between Household Characteristics and HWTS Use. In Nepal, knowing any HWTS method before the emergency, covering household drinking water, and receiving group training were correlated with reported treatment, and female respondent attending any school and knowing a method before the emergency were associated with FCR presence. In Indonesia, people were more likely to report boiling if the female respondent attended school, if the home had moved, since the emergency, and if the household used an improved source (possibly because reported boilers were more likely to seek protected sources). In Kenya, group training was associated with reported treated water. In Haiti, households were more likely to report treatment if they had not moved, since the earthquake, used an unprotected source, and believed their drinking water was safe. Please note that it is possible households believed their drinking water was safe because they had treated it. Within the DSI only data set, households were more likely to have FCR in their drinking water if they used a unprotected source and were of lower socio-economic status.

■ DISCUSSION

We investigated HWTS implementations in four acute emergencies representing a diverse range of emergency situations, geographical settings, affected population sizes, and implementation strategies. Our investigation offered an opportunity to assess the effectiveness, rather than the efficacy, of HWTS distributions in the emergency situation. Rather than rely on products distributed or rates of coverage or use, we use "effective use" to designate those households that were reached by the HWTS method, were relying on unsafe drinking water, and used the method to render their water safe for drinking. Overall, our results suggest that HWTS can be effective and suitable under some circumstances.

The HWTS projects with the highest rates of effective use combined three factors: (1) they targeted households with contaminated water, such as those using unimproved sources; (2) they provided a HWTS method that effectively treated the water; and (3) they provided this method to a population who was familiar with that product, willing to use it, and trained in its use with the necessary supplies provided. When these factors came together, such as the DSI project targeting rural earthquake-affected households in Haiti that provided Aquatabs and a safe storage container to a population familiar with chlorine-based HWTS technologies, high effective use was observed. When one factor was missing—such as lack of contaminated water in the ceramic filter distribution in Haiti, or a working product in the biosand filter distribution in Haiti, or a population who was trained sufficiently to use the product correctly as in the PuR distribution in Kenya, or a population willing to use the products in the chlorine-based product distributions in Indonesia—effective use drops considerably. Additionally, effective use was <15% in all NFI kit distributions, with products with more than two steps to operate (PuR, biosand filters (including maintenance)), and when training was not provided. The two programs with the highest effective use (DSI Aquatabs in Haiti and boiling in Indonesia) both existed in country before the emergency occurred and had a safe water storage component (distributed buckets with taps in Haiti and household thermoses in Indonesia). The low number of households reached with effective water treatment, and the subsequent relatively high cost per household reached with effective treatment, highlights the fact that HWTS technologies may have a role in acute emergency response but that that role may not be widespread distribution. Instead, the role of HWTS may be limited to targeting households with poor water quality that cannot be reached by other interventions, such as tanker trucked water or source rehabilitation.

Population characteristics associated with HWTS use included the following: (1) where female respondents attend school; (2) those who seek to protect stored drinking water (such as covered storage container, using an improved sources); (3) those who have knowledge indicators (knowing HWTS before emergency, training); and (4) those considering themselves at risk (unimproved sources, lower SES). Although these associations are not adjusted for other covariates, they do provide valuable insights.

HWTS has advantages compared to other options (such as water supply development) in terms of being rapidly deployable, fast to distribute, and shown to improve the quality of stored household water. However, HWTS has drawbacks as well, including placing the responsibility for water treatment at the individual household rather than the centralized level, necessitating training and follow-up, the availability of appropriate materials, and understanding and accepting that a (potentially large) portion of the target population will not use the method correctly to improve their water quality.

For organizations planning to implement HWTS in the acute emergency situation, we recommend the following:

- Preposition HWTS methods before the emergency.
- After onset, develop an integrated response strategy that includes HWTS if appropriate.

- Select HWTS options that are appropriate for the water quality, logistical, and cultural conditions of the emergency. If possible, link to pre-existing HWTS programs in country.
- Provide the affected population with sufficient amounts of the HWTS method, a safe storage container, and all the equipment and materials to use and/or maintain the method.
- Train the recipients appropriately, including follow-up trainings for complex methods.
- Understand NFI kit distribution will likely lead to low uptake of HWTS methods.
- Conduct evaluations using simple, robust metrics to assess program effectiveness, and share these results.

Our work was limited by logistical issues such as electricity access, challenges of working in the acute emergency context, and which emergencies occurred during the time allotted for the study. Survey methodologies were different in each context based on what information was available. Chlorine-based technologies were studied most frequently, simply because chlorine-based technologies were distributed. The cross-sectional study design allowed for calculation of risk reduction at only one point in the emergency, although we note the goal of emergency response programs are to provide safe drinking water only until normal safe sources are restored. Cost data collected was self-reported by the responders. While "effective use" is a useful proxy, we acknowledge its shortcomings as it does not investigate other transmission pathways or reduction of other fecal–oral pathogens or chemical contaminants such as arsenic or fluoride. We do note that, if a method does not effectively reduce *E. coli*, it is not likely to reduce other fecal–oral pathogens.

Further research evaluating the use of HWTS in the emergency, and development, contexts is indicated to more fully characterize and expand our knowledge base on effectiveness, as opposed to efficacy, of HWTS technologies. It is highly recommended that future research include implementation-based case studies using robust mixed-methods protocols to investigate real-world HWTS implementations because (1) research aimed at demonstrating HWTS technology efficacy does not inform responders on how to make better decisions, as laboratory efficacy and field effectiveness are not necessarily related. For example, PuR was the most efficacious intervention studied herein,[23] but one of the least effective; (2) research that does not quantify untreated water quality does not provide information on risk reduction; (3) research promoting one HWTS intervention type over another does not account realities such as not all HWTS technologies can be carried on the backs of porters three days into mountainous areas or shipped in planes landing on makeshift airstrips, which were necessary in Nepal and Haiti, respectively; and (4) research not investigating cost implications does not inform responders who must weigh the question of whether to provide a higher efficacy more expensive method or a less expensive method with higher effectiveness.

Implementation-based research will assist responders in improving field practice and providing safe drinking water to affected populations. The research methodology developed herein is robust and can be used to assess the effectiveness of both water programs and other health products—soap, mosquito bednets, and condoms—in the acute emergency, and development, contexts.

Finally, we recommend using "effective use" in program evaluations of HWTS, including development settings and research. This metric uses tools—survey questions and microbiological indicator testing—that are routinely available. Even if it were possible to assess health impacts, effective use is an additional supplementary metric, since it can objectively ascertain (1) who was reached by the intervention; (2) whether they were at risk of waterborne disease; and (3) whether such use was effective in reducing their risk. These are the essential factors for determining the potential to prevent disease.

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Notes

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