Microbiologic effectiveness of boiling and safe water storage in South Sulawesi, Indonesia

Samir V. Sodha, M. Menon, K. Trivedi, A. Ati, M. E. Figueroa, R. Ainslie, K. Wannemuehler and R. Quick

ABSTRACT

In Indonesia, where diarrhea remains a major cause of mortality among children <5 years, the government promotes boiling of drinking water. We assessed the impact of boiling on water quality in South Sulawesi. We surveyed randomly selected households with at least one child <5 years old in two rural districts and tested source and stored water samples for *Escherichia coli* contamination. Among 242 households, 96% of source and 51% of stored water samples yielded *E. coli*. Unboiled water samples, obtained from 15% of households, were more likely to yield *E. coli* than boiled samples [prevalence ratios (PR) = 2.0, 95% confidence interval (CI) 1.7–2.5]. Water stored in wide-mouthed (PR = 1.4, 95% CI = 1.1–1.8) or uncovered (PR = 1.8, 95% CI = 1.3–2.4) containers, or observed to be touched by the respondent's hands (PR = 1.6, 95% CI = 1.3–2.1) was more likely to yield *E. coli.* A multivariable model showed that households that did not boil water were more likely to have contaminated stored water than households that did boil water (PR = 1.9, 95% CI = 1.5–2.3). Although this study demonstrated the effectiveness of boiling in reducing contamination, overall impact on water quality was suboptimal. Future studies are needed to identify factors behind the success of boiling water in Indonesia to inform efforts to scale up other effective water treatment practices.

Key words | contamination, household, point-of-use, storage, water

Samir V. Sodha (corresponding author)
M. Menon
K. Trivedi
K. Wannemuehler
R. Quick
Centers for Disease Control and Prevention,
Division of Foodborne, Waterborne, and Environmental Diseases,
1600 Clifton Road,
MS E-05 Atlanta, GA 30333,
USA
E-mail: *ssodha@cdc.gov*

A. Ati
M. E. Figueroa
R. Ainslie
Johns Hopkins Bloomberg School of Public Health,
The Center for Communications Program,
Baltimore, MD 21202,
USA

INTRODUCTION

Diarrheal diseases kill an estimated 1.9 million children under 5 years old each year globally (Boschi-Pinto *et al.* 2008). WHO estimates that over 880 million people, or 13% of the world's population, lack access to improved water supplies, an important contributing factor to the diarrheal disease burden (WHO 2008a, b). Tens of millions more are at risk from improved but unsafe drinking water sources. To protect the health of these large populations at risk, a number of point-of-use (POU) water treatment interventions have been developed, field tested and promoted after demonstrating effectiveness at improving microbiologic water quality and preventing diarrhea (Wright *et al.* 2004; Fewtrell *et al.* 2005; Arnold & Colford 2007; Clasen *et al.* 2007; Waddington *et al.* 2009).

One of the oldest, most widely promoted and most frequently practiced POU method is boiling (Sobsey 2002). Compared with other POU interventions, boiling can be time consuming, costly, and damaging to the environment. Despite this, promotion of boiling in some countries has resulted in widespread use of the practice, particularly among wealthier and less vulnerable populations (Rosa & Clasen 2010). The practice can result in improvement in water quality, but not a complete removal of risk (Clasen *et al.* 2008a, b; Rosa & Clasen 2010). When practiced correctly, boiling effectively disinfects water; however if not practiced correctly, boiling has minimal impact on water quality (Luby *et al.* 2000; Gupta *et al.* 2007).

In Indonesia, boiling has been actively and consistently promoted by the government for decades (Prihartono *et al.* 1994), yet diarrheal diseases remain the second leading cause of morbidity and mortality among children less than 5 years old (Sunoto 1985; WHO 2008a, b). To explore factors

doi: 10.2166/wh.2011.255

influencing the effectiveness of boiling in Indonesia, we examined the impact of boiling on microbiologic quality of stored water in a study of water treatment and storage practices in a population that was participating in an evaluation of a water supply and sanitation program in South Sulawesi, Indonesia in 2007.

METHODS

Evaluation design

For purposes of the water treatment and storage evaluation, we conducted a baseline cross-sectional household survey in villages enrolled in CARE Indonesia's Sulawesi Water and Sanitation Hygiene (SWASH) program, which was designed to provide water supply and sanitation infrastructure in low-income communities.

In addition to the survey, we tested source and stored water for microbial quality in a 20% subsample of evaluation households. This paper will focus on this subsample.

Evaluation population

We enrolled 48 of 50 low-income communities in Bantaeng and Maros Districts that were targeted for the SWASH program; two were excluded because of poor accessibility. The SWASH program enrolled sets of villages at different times or phases. During March–April 2007, we conducted baseline surveys of 15 communities from Bantaeng and 15 communities from Maros after their enrollment into SWASH phase I. During October–November 2007, we surveyed 7 communities from Bantaeng and 11 communities from Maros after their enrollment into SWASH phase II.

Sample selection

Sample sizes were calculated for the evaluation of water treatment and storage practices in the SWASH population. To conduct this evaluation in SWASH communities, we used population estimates for all 48 communities and determined that we would need to sample approximately 17% of all households. For each community, we randomly selected our starting point and then approached every sixth house for enrollment. Only households with at least one child under 5 years old and a female head of household at least 18 years old were included in the evaluation. If a household refused or did not meet these inclusion criteria, adjacent households were approached until a household was successfully enrolled. Less than 1% of eligible households refused enrollment. Among the approximately 1,200 households enrolled, we selected every fifth for microbiologic testing of source and stored water. This paper focuses on these households.

Data collection

We developed a questionnaire that included information about household demographic and socioeconomic characteristics, water sources and collection, water storage, water treatment, and hygiene and sanitation practices. The questionnaire was translated into Bahasa Indonesia and back-translated into English. Trained local interviewers from the region surveyed the female heads of household.

Water testing and observation

Following the survey, interviewers obtained stored water samples in sterile sample jars by asking the respondent for a glass of drinking water from their usual drinking water container. Interviewers observed the storage containers and water handling practices at the time of sample collection and then asked respondents about the treatment status of the collected sample. Water samples were placed in a cooler on ice and tested within eight hours. We analyzed the samples for contamination by *Escherichia coli* (*E. coli*) using Colilert® tests with Quanti-Trays [www.idexx.com (accessed 15 March 2011)] to determine the most probable number (MPN) estimate of colony counts/100 mL sample. Using this method, the 49 large and 48 small wells in the Quanti-Trays are observed for color changes after incubation with a reagent. The number of positive wells is used to estimate MPN counts that range from 1 to 2,419/100 mL (Edberg *et al.* 1988).

Data analysis

Questionnaire and laboratory data were entered into Microsoft Access 2003. Analysis was completed using SAS 9.1

software (SAS Institute, Cary, NC) and SUDAAN v10.0. To classify households by a wealth index, we used principal component analysis (PCA) methodology in which household assets were assigned values and then summed to create an asset score for each household (Hatcher 1994). Assets related to water infrastructure, stove type, or fuel source were excluded in the PCA. Asset scores were used to place households into quintiles for data analysis. Consistent with similar studies, we $\log_{10}$-transformed *E. coli* MPN estimates because of their tendency for a skewed distribution (Clasen *et al.* 2008a, b; Rosa *et al.* 2010). To account for the lower and upper limits of detection, we converted MPN findings of <1 to 0.1 and doubled the MPN value for >2,419.6–4,839.2.

Log_{10} reduction between source and stored water samples was estimated by calculating the mean of the difference of the $\log_{10}$ values. Similarly, phase-specific log-reduction estimates were also calculated. Geometric means of source and stored water samples were estimated by calculating the mean and confidence limits on the $\log_{10}$-scale and then transforming back to the original scale. Unadjusted prevalence ratios (PR), model-adjusted PR and corresponding confidence limits were calculated based on the marginal predictions (Bieler *et al.* 2010). All confidence limits were calculated taking into account stratification (district) and clustering (community) using the Taylor series method of variance estimation in SUDAAN (Binder 1983).

Ethics

We obtained informed consent from all participating households. Institutional review boards at University of Indonesia, Centers for Disease Control and Prevention (protocol 4804), and Johns Hopkins Bloomberg School of Public Health (CHR# H.52.06.02.03.E1) reviewed and approved the protocol.

RESULTS

Demographics and wealth index

A total of 242 households (127 in Bantaeng; 115 in Maros) with 301 children under 5 years old were included in this analysis (Table 1). The median age of respondents was 30 years (range 18–60 years). Of 242 respondents, 72% had a primary school education or less, including 13% with no formal education. The median number of household residents was five (range 2–12).

Of the two project districts, Bantaeng had younger respondents (median age 27), with lower education levels, and was relatively poorer than Maros with 32% in the poorest quintile and 30% in the second poorest quintile. Only 7% were in the wealthiest quintile. In Maros, 7% were placed in the poorest and 10% in the second poorest quintiles, while 33% were in the wealthiest quintile.

Water source, storage and treatment

Among all households, 90% (93% in Bantaeng, 87% in Maros) had improved water sources (Table 2). Only 1% of households had access to municipal water inside the home, but 72% reported having piped water to their home or yard, and 8% reported using a public tap (13% in Bantaeng, 3% in Maros) as the main source of water. When asked in an open-ended fashion about condition or quality of the water source, 59% felt it was 'clean'; 1% believed it to be 'dirty'. When asked about safety of the main water source, 98% felt their water was safe to drink.

Narrow-mouthed containers were used for water storage in 50% of households; 97% of containers were observed to be covered.

Among 242 respondents, 214 (88%) reported that they treated their drinking water, 81% in Bantaeng and 97% in Maros (Table 3). Among 214 respondents who treated their water, 212 (99%) reported boiling. When respondents who reported boiling their water were asked about their perceptions of boiling, 83% said boiling was practical, 73% said it was easy, and 90% believed it was cheap. Only 4% felt that boiling was difficult. Among 28 respondents who did not treat water, 10 (36%) said non-treatment of water was a habit while 6 (21%) believed their source water was already safe. Of 27 households with wealth index data available who did not treat water, 20 (74%) were in the poorest three quintiles.

Boiling water

Among 212 respondents who reported boiling water, 92% reported using wood as fuel; 81% of these respondents

Table 1 | Demographic and socioeconomic characteristics of study households, South Sulawesi, March–November 2007

Characteristic		Bantaeng	Maros	Total
Households		127	115	242
Household residents	Median (range)	5 (3–10)	5 (2–12)	5 (2–12)
Respondent's age	Median (range)	27 years (18–51 years)	32 years (18–60 years)	30 years (18–60 years)
Respondent's education	No education	21%	3%	13%
	Elementary or less	60%	57%	59%
	Junior high	11%	15%	13%
	Senior high	5%	17%	10%
	Academy	2%	5%	3%
	University or higher	2%	3%	2%
Respondent's ethnicity	Makassar	98%	19%	61%
	Bugis	1%	79%	38%
	Other	1%	2%	1%
Household assets	Electricity	64%	94%	78%
	Radio/tape recorder	33%	50%	41%
	Telephone	2%	13%	7%
	Television	29%	72%	50%
	Refrigerator	2%	35%	18%
	Bicycle	5%	20%	12%
	Motorcycle	16%	28%	21%
	Car	2%	3%	3%
	Gas stove	6%	39%	21%
	Kerosene stove	28%	76%	51%
Wealth index	Poorest quintile	32%	7%	20%
	Second quintile	30%	10%	20%
	Third quintile	15%	26%	20%
	Fourth quintile	16%	24%	20%
	Wealthiest quintile	7%	33%	20%

collected the wood themselves. Kerosene was used as a fuel source by 26% of respondents.

Water testing and observations

Among 242 households, 231 (96%) source water samples and 122 (51%) stored water samples yielded *E. coli*; 59% of stored water samples in Bantaeng and 42% in Maros yielded *E. coli* (Table 4). Geometric mean *E. coli* counts were 61.3 for source water samples and 1.3 for stored water samples. Analysis of paired water samples for each household showed a 1.7 (95% confidence interval (CI) 1.4–1.9) $\log_{10}$ reduction between source and stored water samples. Stratified analysis by time of enrollment showed similar $\log_{10}$ reductions for communities in phase one (1.8, 95% CI = 1.5–2.1) and phase two (1.5, 95% CI = 1.2–1.8).

Among 240 stored water samples assessed for *E. coli* MPN, 204 (85%) came from households that reported boiling the sampled water. Among water samples that were not boiled, 89% were contaminated with *E. coli* compared with 44% among boiled samples (prevalence ratio = 2.0, 95% CI = 1.7–2.5); 14% of unboiled samples were severely contaminated (>1,000 MPN of *E. coli*) compared with 3% of boiled samples (Figure 1). The geometric mean *E. coli* count in stored water samples from households that reported not boiling was 29.9 compared with 0.8 in

Table 2 | Water sources among study households, South Sulawesi, March–November 2007

Characteristics of main water source	Bantaeng, % ($n = 127$)	Maros, % ($n = 115$)	Total, % ($n = 242$)
Improved	*93*	*87*	*90*
Piped (not municipal)	73	69	71
Public tap	13	3	8
Well water protected	2	11	7
Pump well water	2	3	2
Piped (municipal)	2	0	1
Spring water protected	1	2	1
Unimproved	*6*	*13*	*9*
Well water unprotected	4	7	5
Surface water	2	1	1
Spring water unprotected	0	3	1
Rain water	0	1	<1
Refilled water	0	1	<1
Other	*2*	*1*	*2*

households that reported boiling. Analysis of paired water samples for each household based on reported boiling of water samples demonstrated a 0.4 (95% CI = 0–0.9) $\log_{10}$ reduction among households that reported not boiling versus a 1.9 (95% CI = 1.7–2.1) $\log_{10}$ reduction among households that did boil.

The prevalence of contamination with *E. coli* in stored water was greater in wide-mouthed storage containers than narrow-mouthed storage containers (PR = 1.4, 95% CI = 1.1–1.8), in uncovered storage containers than covered storage containers (PR = 1.8, CI = 1.3–2.5), and in storage containers belonging to respondents who were observed to touch the water while collecting or serving it than in those where respondents did not touch the water (PR = 1.6, 95% CI = 1.3–2.1). Households in Bantaeng were more likely than Maros households to have stored water contaminated with *E. coli* (PR = 1.4, CI = 1.0–2.0). Respondents with less than an elementary school education had a greater tendency to have stored water contaminated with *E. coli* than more educated respondents (PR = 1.3, 95% CI = 1.0–1.6). There was no significant difference in prevalence of contaminated stored water by wealth quintile.

A multivariable model, controlling for district, education, container type and observation of respondents touching water, showed that stored water contamination was independently associated with not boiling (model-adjusted PR = 1.9, CI = 1.5–2.3).

DISCUSSION

While most POU studies are research-driven efficacy studies of novel or recently introduced interventions, this study assessed the effectiveness of boiling, an established and widely practiced intervention, as actually practiced by a vulnerable population. In this study, we found that after decades of government promotion of boiling in Indonesia, a high proportion of households in South Sulawesi boiled their water, leading to improved water quality. In the population as a whole, the reduction of *E. coli* contamination from source to stored water among paired household samples was 1.7 log. Among households that reported boiling, the log reduction was even greater at 1.9. Similar log reductions among households that reported boiling were found in three other evaluations: 2.1 in India, 1.5 in Vietnam, and 0.9 in Guatemala (Clasen *et al.* 2008a, b; Rosa *et al.* 2010). However, those other studies lacked populations of non-boiling households to evaluate and compare. Our study did include these households and determined that their log reduction was only 0.4.

In other settings, adoption of POU interventions has not been sustainable (Arnold *et al.* 2009; Musezahl *et al.* 2009). Future endeavors to implement POU interventions will benefit from understanding the potential explanations for the successful promotion of boiling in Indonesia. First, government policy regarding water treatment has been clear and consistent for many decades. At all levels of the health system, boiling water was the only practice promoted to improve water quality. Second, the practice of boiling was considered to be easy. This perception could be a result of cultural norms established in Indonesian society in response to consistent messaging from the government. Third, the population indicated that the practice was inexpensive and practical. It appears that barriers of cost and inconvenience found with boiling in other countries were not appreciable in this setting where abundant and cheap fuel was readily available. Finally, a relatively high percentage of respondents indicated that boiling killed germs, which suggests

Table 3 | Water treatment among study households, South Sulawesi, March–November 2007[a]

Characteristics of water treatment		**Bantaeng, % ($n = 127$)**	**Maros, % ($n = 115$)**	**Total, % ($n = 242$)**
Treat water		81	97	88
		$n = 103$	$n = 111$	$n = 214$
Main method	Boiling	100	97	99
	Filter	0	2	1
Reason for main activity	Kill germs	33	56	45
	To be healthy	40	38	39
	Safe	18	16	17
	Habit	8	5	7
	Easy	9	6	7
	Make water clean/sterile	7	5	6
Perceived cost	Cheap	88	86	87
	Expensive	12	14	13
Boils water		81	95	88
		$n = 103$	$n = 109$	$n = 212$
Perceived practicality	Practical	77	90	83
	Impractical	23	10	17
Perceived cost	Cheap	90	90	90
	Expensive	10	9	9
Perceived difficulty	Easy	74	72	73
	Neither easy nor difficult	20	25	23
	Difficult	6	3	4
Drinks untreated water		19	3	12
		$n = 24$	$n = 4$	$n = 28$
Reasons for not treating	Safe	25	0	21
	Habit	33	50	36
	Practical	4	25	7
	Fresher	13	0	11

[a] For some items, *n* may vary by a small number.

that awareness of health benefits of boiling were understood. Interestingly, this finding was in contrast to the perception by most that their water was 'clean'. It is possible that the perception of clean had more to do with physical appearance (i.e. clarity) than belief in the safety of water.

Despite the apparent achievement of scale and a measure of effectiveness in improving water quality through boiling, a degree of caution is warranted. Among households that reported boiling, 44% of stored water samples were contaminated by *E. coli*. Water stored in wide-mouthed containers, in uncovered containers, and water observed to have been touched while being removed from containers was more likely to be contaminated with *E. coli*. In addition, stored water in households with less educated respondents had a greater tendency to be contaminated with *E. coli*. Probably because of limited power, multivariate analysis was unable to distinguish between these factors, yet water storage and handling behaviors and education are likely to be interrelated in their role on water quality. Poorer and less educated populations have a greater burden of morbidity and mortality from diarrheal disease (Black *et al.* 2003). Yet our study suggests that boiling promotion in South Sulawesi has been less effective in the groups that would most benefit from the intervention. This finding may help explain why

Table 4 | *Escherichia coli* contamination of source and stored water among study households, South Sulawesi, March–November 2007

		Geometric mean of *E. coli* MPN (95% CI)	WHO recommended *E. coli* MPN <1 (%)	Minimal risk *E. coli* MPN 1–9.9 (%)	*E. coli* MPN 10–999.9 (%)	High risk *E. coli* MPN ≥1,000 (%)	Prevalence ratio[a] (95% CI)
Source water ($n = 241$)		61.3 (36.8–101.9)	4	17	64	15	N/A
District	Bantaeng ($n = 126$)	64.1 (29.5–139.5)	2	19	66	13	
	Maros ($n = 115$)	58.2 (30.8–110.3)	5	16	63	17	
Stored water ($n = 240$)		1.3 (0.8–2.3)	50	26	20	5	
District	Bantaeng ($n = 125$)	2.8 (1.2–6.3)	42	26	26	7	1.4 (1.0–2.0)
	Maros ($n = 115$)	0.6 (0.4–1.0)	58	30	13	2	Ref.
Boiling status	Not boiled ($n = 36$)	29.9 (9.4–94.7)	11	28	47	14	2.0 (1.7–2.5)
	Boiled ($n = 204$)	0.8 (0.5–1.2)	56	26	15	3	Ref.
Storage mouth	Wide ($n = 119$)	2.5 (1.2–5.1)	41	28	23	8	1.4 (1.1–1.8)
	Narrow ($n = 121$)	0.7 (0.4–1.3)	58	25	17	1	Ref.
Storage cover	Uncovered ($n = 8$)	15.9 (2.9–85.8)	13	25	63	0	1.8 (1.3–2.5)
	Covered ($n = 232$)	1.2 (0.7–2.1)	51	26	18	5	Ref.
Wealth	Poorest 3 quintiles ($n = 143$)	1.6 (0.8–3.1)	48	27	18	7	1.1 (0.8–1.4)
	Richest 2 quintiles ($n = 94$)	1.0 (0.5–2.0)	52	24	22	1	Ref.
Education	< Elementary ($n = 82$)	3.8 (1.4–10.0)	41	20	29	10	1.3 (1.0–1.6)
	≥ Elementary ($n = 158$)	0.8 (0.5–1.2)	54	30	15	2	Ref.
Hands touch water	Yes ($n = 29$)	12.0 (3.8–38.1)	24	24	38	14	1.6 (1.3–2.1)
	No ($n = 211$)	1.0 (0.6–1.6)	53	27	17	3	Ref.

[a] Unadjusted prevalence ratios of any *E. coli* versus <1 MPN *E. coli* in stored water.

Note: The prevalence ratio value is based on comparison with the reference ('Ref.') variable. For instance, the prevalence ratio of covered water compared with uncovered water means that the covered water is the reference variable.

Indonesia, despite its successful promotion of boiling, is still afflicted with a large number of diarrheal deaths in children under 5 years old despite recent economic development (Black *et al.* 2010).

In addition to questions of reliability of boiling as a water quality intervention, other drawbacks to the practice have been documented. These include high cost in some settings (Gilman & Skillicorn 1985), high opportunity costs of finding fuel and boiling and cooling water, the risk of burns from cooking fires among young children in developing countries (Rossi *et al.* 1998; Uygur *et al.* 2009), indoor air pollution and acute respiratory infections (Smith 2002), the contribution of black soot from cooking fires to greenhouse gases (Jacobson 2001), and lack of residual protection against recontamination of water during storage (Mintz *et al.* 1995; Reiff *et al.* 1996; Quick *et al.* 1999). Maintaining cleanliness of boiled water has been shown to be particularly challenging in focally contaminated environments (Wright *et al.* 2004), and in post-disaster situations (Gupta *et al.* 2007). Finally, in some settings, particularly in sub-Saharan Africa (Rosa *et al.* 2010), boiling is infrequently practiced, suggesting that there may be significant barriers to its use.

There were several important limitations to our study. First, our evaluation population was limited to the preselected communities of the SWASH program in South

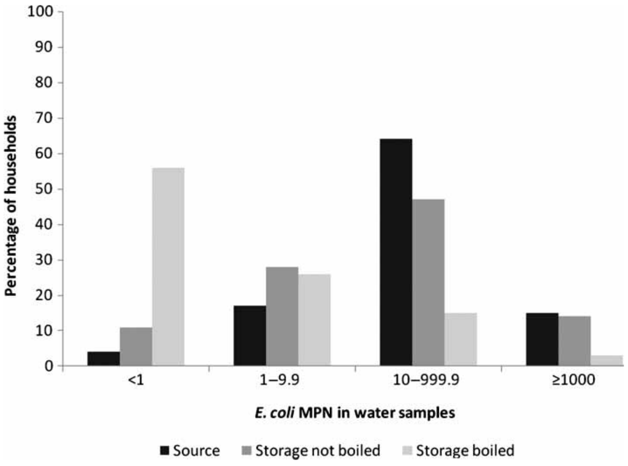

Figure 1 | Comparison of *E. coli* contamination of source water with boiled and unboiled stored water among study households, South Sulawesi, March–November 2007.

Sulawesi. As such, these communities were not representative of Indonesia as a whole. Second, evaluation communities were located in rural, wooded areas with easy access to brush and trees for fuel which would facilitate the practice of boiling. The frequency and effectiveness of boiling may differ in populations without easy and free access to fuel. Third, we were unable to observe actual boiling practices, so we could not confirm treatment status. Finally, although we translated the surveys into the national language of Bahasa Indonesia, many respondents had other local dialects as their first language. Interpretation of differences between ethnic groups should consider the role of possible misinterpretation of the Bahasa Indonesia questions.

CONCLUSION

Of all POU water treatment methods, boiling is the oldest, the most common, and arguably the only one that has reached meaningful scale in the developing world. Several studies including this one have documented that populations in developing countries that boil drinking water have reduced bacterial indicators of fecal contamination. However, a significant proportion may not boil water effectively, the practice of which includes proper storage and water handling to avoid recontamination. Further research is needed to answer three important questions regarding water treatment. First, can populations that have adopted the habit of boiling be successfully trained at scale to boil effectively and store water safely in clean and narrow-mouthed containers to maximize the benefit? Second, if practiced properly, how does the cost, ease and effectiveness of boiling compare with those of other POU technologies, such as chlorination and filtration? Third, can other POU water treatment technologies that are cheaper, easier to use, and perhaps more effective than boiling be scaled up to the same degree as boiling? The answers to these questions will help determine the progress that can be made in making household water treatment an effective intervention to protect the health of vulnerable populations until the longer term goal of providing safe water supplies for all is achieved.

ACKNOWLEDGEMENTS

This project was supported by funding from the Institute for Public Health and Water Research (IPWR). We appreciate the logistical and administrative support provided by CARE Indonesia, especially by Rieneke Rolos.

REFERENCES

Arnold, B. & Colford, J. 2007 Treating water with chlorine at point-of-use to improve water quality and reduce child diarrhea in developing countries: a systematic review and meta-analysis. *Am. J. Trop. Med. Hyg.* **76** (2), 354–364.

Arnold, B., Arana, B., Musezahl, D., Hubbard, A. & Colford, J. 2009 Evaluation of a pre-existing, 3-year household water treatment and handwashing intervention in rural Guatemala. *Int. J. Epidemiol.* **38** (6), 1651–1661.

Bieler, G., Brown, G., Williams, R. & Brogan, D. 2010 Estimating model-adjusted risks, risk differences, and risk ratios from complex survey data. *Am. J. Epidemiol.* **171** (5), 618–623.

Binder, D. 1983 On the variances of asymptotically normal estimators from complex surveys. *Int. Stat. Rev.* **51**, 279–292.

Black, R., Morris, S. & Bryce, J. 2003 Where and why are 10 million children dying every year? *Lancet* **361** (9376), 2226–2234.

Black, R., Cousens, S., Johnson, H., Lawn, J., Rudan, I., Bassani, D., Jha, P., Campbell, H., Walker, C., Cibulskis, R., Eisele, T., Liu, L., Mathers, C. & Child Health Epidemiology Reference Group of WHO and UNICEF 2010 Global, regional, and national causes of child mortality in 2008: a systematic analysis. *Lancet* **375** (9730), 1969–1987.

Boschi-Pinto, C., Velebit, L. & Shibuya, K. 2008 Estimating child mortality due to diarrhoea in developing countries. *Bull. World Health Organ.* **86** (9), 710–717.

Clasen, T., Schmidt, W., Rable, T., Roberts, I. & Calmcross, S. 2007 Interventions to improve water quality for preventing diarrhoea: systematic review and meta-analysis. *Br. Med. J.* **334** (7597), 782.

Clasen, T., McLaughlin, C., Nayaar, N., Boisson, S., Gupta, R., Desai, D. & Shah, N. 2008a Microbiological effectiveness and cost of disinfecting water by boiling in semi-urban India. *Am. J. Trop. Med. Hyg.* **79** (3), 407–413.

Clasen, T., Thao, D., Boisson, S. & Shipin, O. 2008b Microbiological effectiveness and cost of boiling to disinfect drinking water in rural Vietnam. *Environ. Sci. Technol.* **42** (12), 4255–4260.

Edberg, S., Allen, M. & Smith, D. 1988 National field evaluation of a defined substrate method for the simultaneous enumeration of total coliforms and *Escherichia coli* from drinking water: comparison with the standard multiple tube fermentation method. *Appl. Environ. Microbiol.* **54** (6), 1595–1601.

Fewtrell, L., Kaufmann, R., Kay, D., Enanoria, W., Haller, L. & Colford, J. 2005 Water, sanitation, and hygiene interventions to reduce diarrhoea in less developed countries: a systematic review and meta-analysis. *Lancet Infect. Dis.* **5** (1), 42–52.

Gilman, R. & Skillicorn, P. 1985 Boiling of drinking-water: can a fuel-scarce community afford it? *Bull. World Health Organ.* **63** (1), 157–163.

Gupta, S., Suantio, A., Gray, A., Widyastuti, E., Jain, N., Rolos, R., Hoekstra, R. & Quick, R. 2007 Factors associated with *E. coli* contamination of household drinking water among tsunami and earthquake survivors, Indonesia. *Am. J. Trop. Med. Hyg.* **76** (6), 1158–1162.

Hatcher, L. 1994 Principal component analysis. In *A Step-by-Step Approach to Using SAS for Factor Analysis and Structural Equation Modeling*. SAS Publishing, Cary, NC.

Jacobson, M. 2001 Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols. *Nature* **409** (6821), 695–697.

Luby, S., Syed, A., Atiullah, N., Faizan, M. & Fisher-Hoch, S. 2000 Limited effectiveness of home drinking water purification efforts in Karachi, Pakistan. *Int. J. Infect. Dis.* **4** (1), 3–7.

Mintz, E., Reiff, F. & Tauxe, R. 1995 Safe water treatment and storage in the home. A practical new strategy to prevent waterborne disease. *J. Am. Med. Assoc.* **273** (12), 948–953.

Musezahl, D., Christen, A., Pacheco, G., Tellez, F., Iriarte, M., Zapata, M., Cevallos, M., Hattendorf, J., Cattaneo, M., Arnold, B., Smith, T. & Colford, J. 2009 Solar drinking water disinfection (SODIS) to reduce childhood diarrhoea in rural Bolivia: a cluster-randomized, controlled trial. *PLoS Med.* **6** (8), e1000125.

Prihartono, N., Adisasmita, A., Costello, C., Damayanti, R., Prasetyo, S. & Syarif, S. 1994 Water preparation practices in south Kalimantan, Indonesia. *J. Diarrhoeal Dis. Res.* **12** (4), 279–286.

Quick, R., Venczel, L., Mintz, E., Soleto, L., Aparicio, J., Gironza, M., Hutwagner, L., Greene, K., Bopp, C., Maloney, K., Chavez, D., Sobsey, M. & Tauxe, R. 1999 Diarrhoea prevention in Bolivia through point-of-use water treatment and safe storage: a promising new strategy. *Epidemiol. Infect.* **122** (1), 83–90.

Reiff, F., Roses, M., Venczel, L., Quick, R. & Witt, V. 1996 Low-cost safe water for the world: a practical interim solution. *J. Public Health Policy* **17** (4), 389–408.

Rosa, G. & Clasen, T. 2010a Estimating the scope of household water treatment in low- and medium-income countries. *Am. J. Trop. Med. Hyg.* **82** (2), 289–300.

Rosa, G., Miller, L. & Clasen, T. 2010 Microbiological effectiveness of disinfecting water by boiling in rural Guatemala. *Am. J. Trop. Med. Hyg.* **82** (3), 473–477.

Rossi, L., Braga, E., Barruffini, R. & Carvalho, E. 1998 Childhood burn injuries: circumstances of occurrences and their prevention in Ribeirão Preto, Brazil. *Burns* **24** (5), 416–419.

Smith, K. 2002 Indoor air pollution in developing countries: recommendations for research. *Indoor Air* **12** (3), 198–207.

Sobsey, M. 2002 *Managing Water in the Home: Accelerated Health Gains from Improved Water Supply*. World Health Organization, Geneva.

Sunoto 1985 Diarrhoeal problems and infant & child mortality in Indonesia. *Paediatr. Indones.* **25** (3–4), 71–86.

Uygur, F., Sahin, C. & Duman, H. 2009 Analysis of pediatric burns in a tertiary burns center in istanbul, Turkey. *Eur. J. Pediatr. Surg.* **19** (3), 174–178.

Waddington, H., Snilstveit, B., White, H. & Fewtrell, L. 2009 *Water, Sanitation and Hygiene Interventions to Combat Childhood Diarrhoea in Developing Countries*. International Initiative for Impact Evaluation, New Delhi, India.

WHO 2008a *Progress on Drinking Water and Sanitation: Special Focus on Sanitation*. World Health Organization, Geneva, UNICEF, New York.

WHO 2008b *World Health Statistics 2008*. World Health Organization, Geneva.

Wright, J., Gundry, S. & Conroy, R. 2004 Household drinking water in developing countries: a systematic review of microbiological contamination between source and point-of-use. *Trop. Med. Int. Health* **9** (1), 106–117.

First received 8 October 2010; accepted in revised form 30 December 2010. Available online 26 April 2011