A post-implementation evaluation of ceramic water filters distributed to tsunami-affected communities in Sri Lanka

Lisa M. Casanova, Adam Walters, Ajith Naghawatte and Mark D. Sobsey

ABSTRACT

Sri Lanka was devastated by the 2004 Indian Ocean tsunami. During recovery, the Red Cross distributed approximately 12,000 free ceramic water filters. This cross-sectional study was an independent post-implementation assessment of 452 households that received filters, to determine the proportion still using filters, household characteristics associated with use, and quality of household drinking water. The proportion of continued users was high (76%). The most common household water sources were taps or shallow wells. The majority (82%) of users used filtered water for drinking only. Mean filter flow rate was 1.12 L/hr (0.80 L/hr for households with taps and 0.71 for those with wells). Water quality varied by source; households using tap water had source water of high microbial quality. Filters improved water quality, reducing *Escherichia coli* for households (largely well users) with high levels in their source water. Households were satisfied with filters and are potentially long-term users. To promote sustained use, recovery filter distribution efforts should try to identify households at greatest long-term risk, particularly those who have not moved to safer water sources during recovery. They should be joined with long-term commitment to building supply chains and local production capacity to ensure safe water access.

Key words | ceramic water filter, disaster, point-of-use, Sri Lanka, tsunami

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INTRODUCTION

As point-of-use (POU) water treatment gains acceptance and uptake accelerates in populations needing access to safe water, there is an increasing need to examine the long-term sustainability of various POU options. While adoption may be high in the context of intensive intervention trials and implementation campaigns, rates of long-term use after initial implementation can vary greatly (Sobsey *et al.* 2008). There have been post-implementation studies examining long-term uptake and sustainability of POU technologies that were introduced in programs designed to support adoption and sustained use in people's daily lives (Brown *et al.* 2009; Liang *et al.* 2010). However, POU use and adoption results may be different if distribution and implementation are part of disaster recovery efforts (Clasen *et al.* 2006). There is some research on the effectiveness of POU technologies for meeting the immediate need for safe water in the aftermath of disasters (Dunston *et al.* 2001; Mong *et al.* 2001; Doocy & Burnham 2006). However, there are gaps in our understanding of the long-term uptake and use of POU devices distributed as part of disaster recovery and rebuilding efforts. Once disaster-affected communities begin to rebuild, re-establishing access to safe water may be a long-term process, and households may be at continued or periodic risk from unsafe water as rebuilding proceeds and displaced persons relocate and resettle into permanent homes. In this context, there is a lack of information about whether such households continue to use POU devices received during relief and recovery efforts, and what factors affect continued and effective POU use.

These issues were considered by relief and response agencies participating in the post-tsunami disaster relief in Sri Lanka over the past several years. Sri Lanka, an island nation, was one of the countries devastated by the December 2004 Indian Ocean tsunami. One of the worst natural disasters in recorded history, the tsunami killed over

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30,000 in Sri Lanka, affecting the southwestern coast most severely. Although the tsunami wave came from the east, a phenomenon called diffraction caused the wave to travel around the island, resulting in heavy damage to nearly all coastal areas of the island. In addition to water infrastructure destruction, people were at risk from surface and groundwater contamination by seawater and fecal wastes that inundated surface sources and unprotected wells, and intruded into subsurface aquifers and unprotected wells (Clasen *et al.* 2006; Villholth *et al.* 2008).

In 2007–08, Sri Lanka had begun to recover from the effects of the tsunami. As of 2008, it was classified by the World Bank as a lower middle income country. Per capita income was approximately 1,990 USD, 88% of rural residents had access to an improved water source and 92% of rural and 88% of urban residents had access to improved sanitation. However, many residents were still potentially at risk from damaged water infrastructure providing unsafe water. During this recovery and resettlement phase, the Red Cross undertook a ceramic water filter (CWF) distribution effort in the southwestern districts of Sri Lanka, distributing free CWFs to households without access to piped water sources and supplies, with accompanying instructions on filter use and maintenance and hygiene promotion training. Between February 2007 and December 2008, approximately 12,000 CWFs were distributed to households in tsunami-affected communities in the southwestern districts of Matara, Galle, Kalutara, and Gampaha.

The plan at the time of distribution was that after free distributions, sustainability of filters and growth in the number of users would follow via planned commercialization of the CWFs through the Sri Lanka Red Cross Society (SLRCS). SLRCS would market and sell the filters, creating a revenue stream to support continuing filter production and distribution and income for SLRCS. Free distribution targeted 39,220 households (196,100 individuals) in four tsunami-affected provinces in the south of Sri Lanka:

Gampaha District: 5,040 households
Matara District: 5,580 households
Galle District: 13,200 households
Kalutura District: 15,400 households.

Recipient households were selected using government data verified in the field by a Red Cross assessment team. Recipients: (1) were residents in a tsunami-affected district; (2) had no imminent access to a piped water supply; and (3) were located in a community that the local governmental unit and the SLRCS agreed to support. In communities where some households did have piped water, those households were also given CWFs to ensure equity. In addition, two local facilities capable of producing CWFs were established, and a comprehensive safe water and hygiene promotion program was implemented in areas where the filters were produced and distributed. SLRCS was trained to distribute CWFs, assess recipient satisfaction, and monitor quality control. At conclusion, the filter program reached 60,235 individuals, distributed 12,047 free filters, sold an additional 4,921 filters, and conducted 247 hygiene promotion activities in affected areas.

Some CWFs in the free distribution originated from Cambodia; most were made locally in Sri Lanka. Initially the Red Cross imported CWFs from Cambodia (500–800 filters distributed starting February 2007). A first in-country filter production facility started making filters in February 2007, and a second in-country filter factory began making filters in October 2008, producing filters painted with colloidal silver. Free distribution was halted in November 2008.

This study was undertaken as an independent post-implementation assessment of tsunami-affected households in Sri Lanka that received CWFs during the Red Cross distribution program. It consisted of a cross-sectional survey with accompanying water sampling and analysis. Study objectives were to determine the proportion of households still using filters, household use patterns, and the continued effectiveness of filters for improving household drinking water quality.

METHODS

The study was a cross-sectional survey administered by in-person oral interview. Study protocols and materials were approved by the UNC Biomedical IRB (#09-1,453), University of North Carolina Chapel Hill, USA, and the Ethical Review Committee of the Faculty of Medicine, University of Ruhuna, Sri Lanka. From the original distribution of approximately 12,000 filters, records were available from the Red Cross for about 9,000 households. Assuming only one filter was distributed per household, the target population for the study was these 9,000 households. A target sample size of 5% of the total study population, or 450 households, was used.

Study communities to be sampled were located in the Galle, Kalutara, and Matara districts. For logistical practicality in conducting the survey, study households were chosen from communities where >20 households received filters. After exclusion of known resettlement villages, the eligible household totals per district were: Galle = 1,581, Kalutara = 2,727 and Matara = 2,626 households. The unit of randomization for sampling was the community. Each district was weighted according to its relative contribution to the total number of households in order to determine how many communities from each district to sample. Communities were selected using a random number generator. Enumerators then went from door to door requesting household participation. After the minimum number of communities had been sampled in each district, if the sample size had not reached 450, additional communities were selected using a random number generator and sampled until a sample size of 450 households was reached.

Inclusion criteria were: the family or other household communal unit received a CWF through the implementation program, the family or other household communal unit was still living at the same location where they received the filter, and the household was willing to participate in the survey. Exclusion criteria were: the family or other household communal living unit no longer lived at the original location where they received the filter, including households in the selected communities that were found upon community visit to be resettlement villages, and unwillingness to participate in the survey.

Survey questions that had been validated in previous studies for collecting data on household water use practices and POU use were used with minor modifications for the Sri Lankan context and the filter distribution program (Stauber *et al.* 2009). Surveys and informed consent materials were translated into Sinhala by native speakers and back-translated into English for quality control. The survey instrument was piloted with field staff for suitability of content and structure, reliability, and consistency. Data were collected from September to December 2009. Once eligible households were identified, a data collection field team consisting of native Sinhala speaking medical graduates pre-trained to administer surveys went door to door. Each study household received two visits. At the first household visit, they obtained informed consent and took water samples for analysis. At the second visit, the survey was administered by field staff members. The female in charge of the household, defined as the primary caregiver for the children, responsible for household work, and either responsible for or knowledgeable of household water management practices, was identified. This individual gave informed consent and responded to the survey on behalf of all household members. Data were collected on water sources, water treatment practices, filter use, and household and demographic variables thought to influence filter use, using predominantly closed-ended questions. Survey responses were recorded on paper surveys and entered into an EpiInfo database.

In a household with a filter, the respondent was asked to show the enumerators the water they used to put through the filter. A sample was taken from this water. If water that had been put through the filter was available in the household, this water was also sampled. In households without filters, a sample was taken from whatever water the household used for drinking. At the second visit, water samples were taken in the manner described above. During the time the survey was being administered, the respondent was asked to place water in the filter and allow it to run. The filter flow rate was measured using this water. If a filter was present in the household, the enumerator also made observations of the filter itself to determine if it was being used. *Escherichia coli* in water was measured using the IDEXX Quantitray system with Colilert medium, and results were expressed as most probable number (MPN) of *E. coli* per 100 mL. The upper limit of *E. coli* that can be measured by the Quantitray is 2,419 MPN/100 mL. Survey responses were recorded on paper surveys and entered into an EpiInfo database.

RESULTS

A total of 452 households gave informed consent, completed surveys, and provided water samples for analysis. The distribution of survey households by district was 58 from Galle, 204 from Kalutara, and 190 from Matara. It was found during the data collection phase that Galle had a larger proportion of communities that were not identified in Red Cross records as resettlement villages. These resettlement communities were excluded, resulting in a smaller proportion of study households from Galle. The total number of individuals in survey households was 2,041, with a mean number of 4.5 individuals per household and an average age of 33.5 years.

Self-reported use was ascertained by asking the respondent when was the last time that they had used the filter: 71% of households reported having used the filter on the day of survey or the day before, 5% within the last month, and 24% more than 1 month ago. Filter use was validated by having the enumerator observe the filter itself: whether there was water in the ceramic filter storage vessel, whether there was water in the filter element, and having the respondent demonstrate to the enumerator that the filter was working by pouring water through it. Results of observation and self-reported last filter use are shown in Table 1.

Twenty-two households (5%) reported use within the last month. All of these households still had the filter present; 95% of filters were observed to be working. Because filters in these households appear to have been in recent use, for subsequent analyses, households were classified as filter users if they reported using the filter within the last month and as filter non-users if they reported last using the filter more than 1 month ago. Using this classification, 76% of households (345/452) were filter users at the time of survey.

Respondents who were classified as filter users were asked where they obtained water for the household; they could choose more than one option. Water sources are shown in Table 2. The most frequent response was tap inside or outside the house, or both (56% in filter user households), though wells (mostly shallow hand-dug) were also common (54% in filter user households. About 5% of households reported using surface water sources. Water from piped systems in this area is largely treated surface (river) water.

A number of households reported having both taps and wells, although it is not clear whether they have taps attached to pipes that run to their private wells, or are connected to piped water while also having a private well. Of 38 filter households that reported having both a tap and a well, 38% put water through the filter from an inside tap, 36% from an outside tap, and 40% from a well.

Households were asked if they used any methods of water treatment (Table 3). A list of options to choose from was provided. Ceramic filters, boiling, and having tap water that was already treated were the most frequent responses; other methods were rare. Only 25% of filter users reported that their tap water was already treated. However, 55% of households that report having tap water that is already treated still report using the filter.

Households boiled water even if they used other treatment methods or had water that was already treated. About 1/3 of households that used the CWF still reported boiling their water (113/345). Respondents were not asked whether they boiled water before or after filtration. Many people report using filtered water for 'making tea', a use of filtered water that was often reported by respondents

Table 1 | Self-reported last filter use and enumerator observations of filter if present in household ($n = 452$)

	Self-reported last filter use					
	Today or yesterday		**Within last month**		**>1 month ago**	
Total	323		22		107	
Water in the filter	285	88%	9	41%	1	1%
Water in the storage vessel	314	97%	16	73%	2	2%
Filter is working	317	98%	21	95%	37	35%

Table 2 | Household water sources in filter user households ($n = 345$)

	No. (%)
Tap inside the house	72 (21)
Tap outside the house	76 (22)
Tap inside and outside	44 (13)
Shallow (hand-dug) well, lined	156 (45)
Shallow (hand-dug) well unlined	16 (5)
Deep (drilled) well	26 (8)
Lake or pond	16 (5)
River, stream, or canal	0 (0)
Rainwater	5 (1)
Purchased water	0 (0)
Other	3 (1)

separately from using filtered water for drinking. This suggests that water may be put to uses for which it is boiled after it has been filtered.

Households that reported filter use were asked a series of closed-end questions about use of the filter and use of the filtered water (Figure 1).

The majority (82%) of filter households reported that they used filtered water for drinking only. The responses suggest that putting water through the filter once or less than once a day supplies 'most' of the drinking water that members of the family consume. When asked if the filter provides enough drinking water to the family each day, 75% (259/345) of filter households responded 'always' and 16% (55/345) responded 'most of the time'. Respondents were also asked whether they used water for specific tasks. It does not appear that filtered water is routinely put to uses other than drinking in the household; other uses of filtered water, including preparing infant formula, washing vegetables, handwashing, and bathing, were reported by <5% of respondents. Overall, the patterns of water use suggest that filter user households use water that has undergone treatment mainly for drinking, not for other household purposes.

Table 3 | Treatment methods reported by filter user households ($n = 345$)

	No. (%)
Boiling	113 (33)
Chlorination with bleach	7 (2)
Other chemical	0 (0)
Ceramic water filter	345 (100)
Biosand filter	0 (0)
Other sand/granular medium filter	0 (0)
Letting water 'settle' in container	4 (1)
Coagulation	0 (0)
Tap water is already treated	85 (25)
Don't treat water	1 (0)
Other treatment	1 (0)

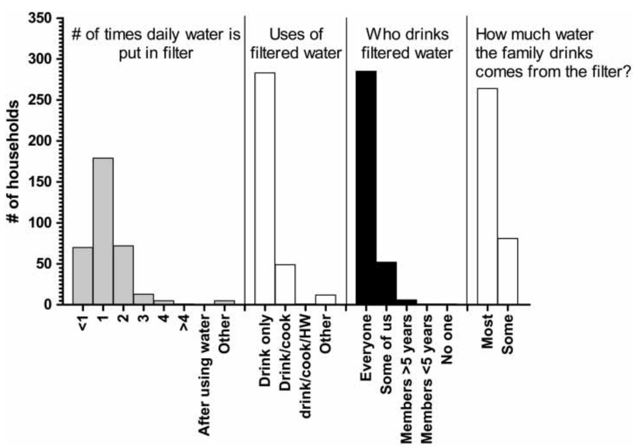

Figure 1 | Patterns of filter use among user households ($n = 345$).

All filter households reported using the ceramic filter storage vessel to store treated water. Some households reported also using jerricans (5%); households in Sri Lanka sometimes store tap water due to intermittent piped water service (Palmer 2005a). Most households (339/345) reported cleaning filtered water storage containers. The most frequently used agents were soap and water, though households also used water only, bleach solution, Teepol, and Vim (household cleaning products sold in Sri Lanka). Only 22% of households reported cleaning the container each time water was gathered; when asked to estimate cleaning frequency, 67% of user households reported cleaning once or more per week, 19% every 2 weeks, and 14% cleaned once a month or less.

Water was available to measure flow rates at the study visit for 343/345 filter households. The mean filter flow rate was 1.12 L/hr (range 0–5.9); median flow rate was 0.80 L/hr for households reporting taps only, 0.71 for those reporting wells only, and 0.80 for those reporting taps and wells. There was no significant difference in flow rates among households that reported the household water source as well water, tap water, or both tap and well water ($P = 0.19$). The distribution of flow rates for all filters where flow was measured is shown in Figure 2. At the time of survey 31% (108/345) of filters fell within recommended ceramic filter manufacturing quality control guidelines of flow rate of 1–3 L/hr (Brown & Sobsey 2007) 61% (210/345) fell under 1 L/hr, and the remaining 8% were greater than 3 L/hr.

Filter user households were queried about problems experienced with the filter (Figure 3). The most frequent response (14% of households who were users at the time of the survey) was that the flow rate was too slow. There was also a low rate of spigot breakage or other technical

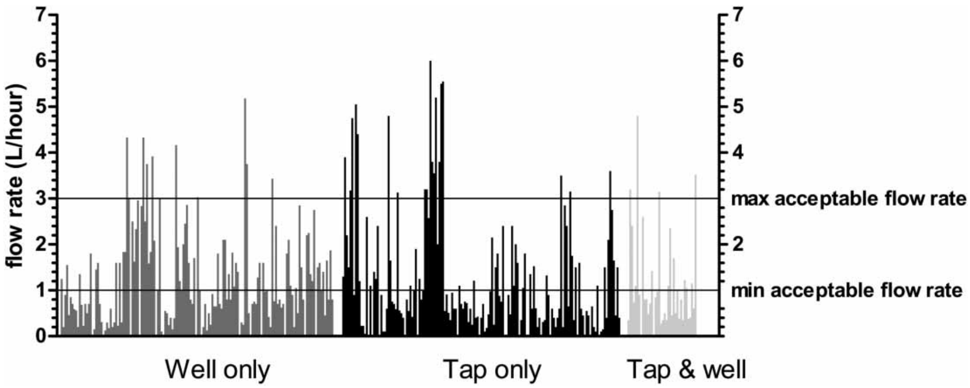

Figure 2 | Ceramic filter flow rates for all measured filters.

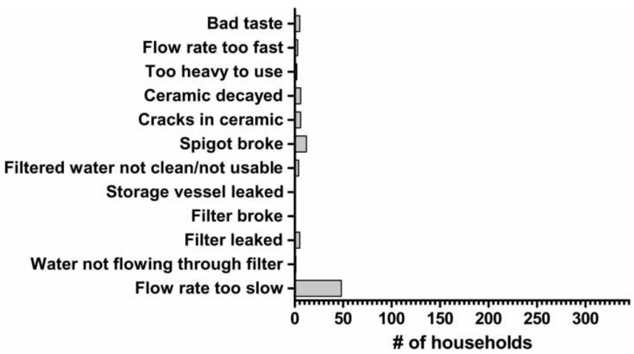

Figure 3 | Reported problems with filter in user households.

malfunctions such a leaky storage vessel, filter cracks, or other filter defects. No households selected the 'filter broke' option, but households reported that they used the filter even though the ceramic vessel had cracked, which may be a reason for some of the filters with high flow rates. Some responses indicated that filter was undergoing 'decay'. Enumerator observation indicated that this was a sloughing off of ceramic material into the water, probably due to problems with the filter manufacturing process.

When asked if they could get a new filter in their area, most user households believed they could not (216/345) or did not know (124/345); 338/345 respondents reported that they did not know of a place where they could get a new filter or replacement parts. Only one household reported having bought a new filter. Purchase of spare parts was more common but still infrequent (7%). However, there was a high level of willingness to buy replacements; 88% (305/345) said they would buy a new filter or spare parts if needed. To elicit some information about willingness to pay, respondents who were filter users at the time of the survey were asked an open-ended question: 'How much would you be willing to pay to buy a whole new filter?', and the amount was recorded. Responses ranged from 0 to 5,000 Sri Lankan rupees (mean 750 rupees). Responses clustered at 500 rupees (4.50 USD; 28% of households), and 1,000 rupees (9.00 USD; 15% of households).

The effect of filters on household water quality was also measured, using *E. coli* as an indicator of the microbiological quality of water. *E. coli* levels were compared between the main water sources reported by households, taps and wells. 'Tap and well' was included as an additional category since a number of households reported both. *E. coli* in household source water is shown in Figure 4.

Many households in the study population had good quality source water, but quality differed by water source. *E. coli* levels in source water were significantly higher in households reporting wells as their water source compared to households reporting taps ($P < 0.0001$). Of households reporting taps only, there was no significant difference in

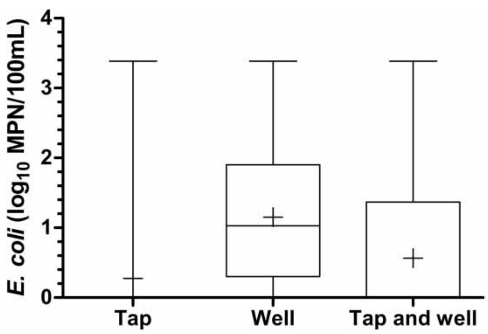

Figure 4 | *E. coli* in source water of filter user households ($n = 345$).

source water *E. coli* between houses that reported having taps inside and those that reported taps outside ($P = 0.27$). Turbidity in source water was significantly higher in households reporting wells as their water source compared to households reporting taps ($P < 0.0001$); mean turbidity in households reporting taps only was 0.8 NTU, in households reporting wells only it was 1.5 NTU. This was influenced by outliers; in households reporting wells only median turbidity was 0.9 NTU (Figure 5).

Since water samples in filter user households were not necessarily taken from the same household water before and after filtration, it was not possible to calculate $\log_{10}$ reduction values for each household. Therefore, *E. coli* levels in filter user household source water and water that had been put through the filter were compared statistically across all households without calculating $\log_{10}$ reductions for individual households (Figure 6).

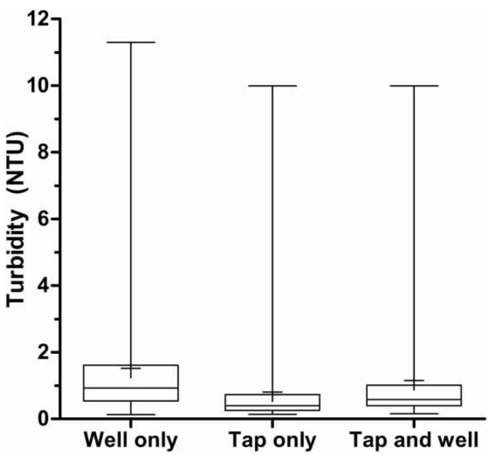

Figure 5 | Turbidity source water of filter user households ($n = 345$).

Although *E. coli* in source water from taps was lowest to begin with (mean 0.27 $\log_{10}$ MPN/100 mL), *E. coli* was significantly lower in filtered water compared to source water ($P = 0.007$). Well water had the highest levels in source water (mean 1.15 $\log_{10}$ MPN/100 mL), but *E. coli* in filtered well water was also significantly lower than in the source water ($P < 0.0001$). Levels of *E. coli* in filtered water were similar for all sources (0.13 $\log_{10}$ in filtered tap water, 0.11 $\log_{10}$ in filtered well water, 0.06 $\log_{10}$ for households reporting both tap and well). Filtration also significantly reduced turbidity for tap ($P = 0.0001$) and well ($P = 0.0001$) water (Figure 7).

Levels of *E. coli* in source and filtered water were also categorized using the WHO classification for drinking water quality. The households with source water falling into the 'very high risk' category (>1,000 *E. coli*/100 mL) were largely households that reported wells as a water source (Figure 8). Use of this classification shows that the majority of households had very good quality source water; almost 80% of households reporting tap water only were in the lowest risk category (<1/100 mL); 25% of households reporting well water only were in this category. Overall, untreated well water is higher risk than tap water using the WHO classifications as a guide. However, *E. coli* is still found in tap water in study households; 78/281 (28%) households that reported having a tap inside or outside as one of the household water sources had *E. coli* in the source water. After filtration, a greater proportion of households in each water source group had water falling into the <1 *E. coli*/100 mL after filtration. The largest change was seen among households with well water, since well water was the source water with the highest levels of

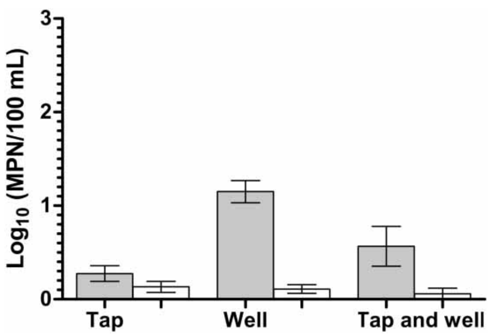

Figure 6 | *E. coli* in source and filtered water in filter user households (gray = source; white = filtered; bars = 95% CI) ($n = 345$).

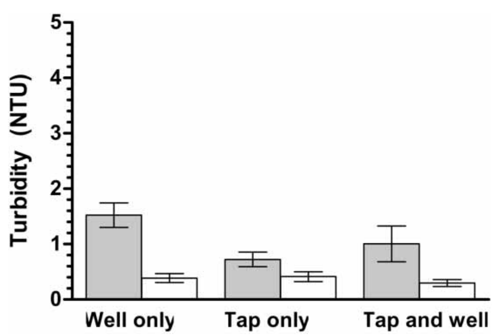

Figure 7 | Turbidity in source and filtered water in filter user households (gray = source; white = filtered; bars = 95% CI) ($n = 345$).

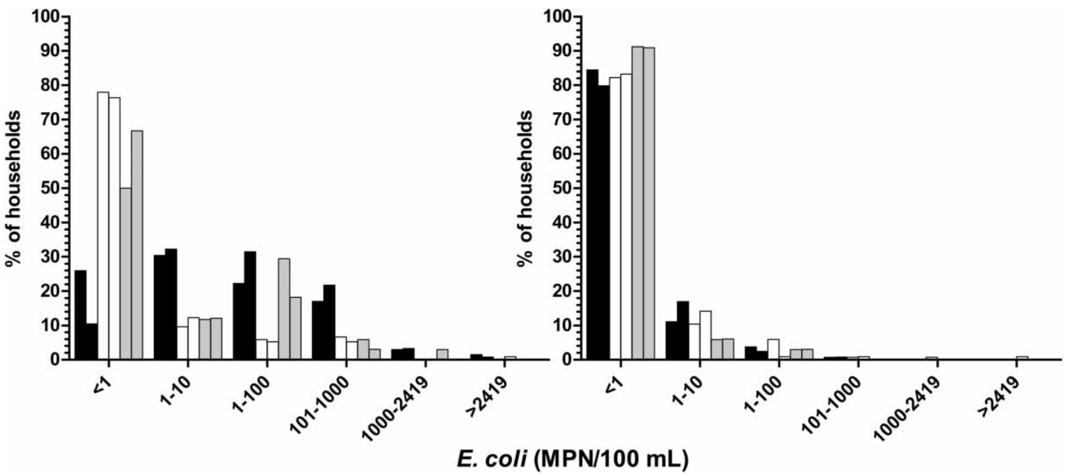

Figure 8 | *E. coli* in source (left) and filtered (right) water, using WHO risk classification. Side-by-side bars = first and second household visits (well = black; tap = white; tap and well = gray; 2,419 = upper detection limit of method).

E. coli. In this group, the number of households whose water met WHO standards of <1 *E. coli*/100 mL increased by approximately 50%.

To take into account the differing quality of source water, households were stratified by which WHO risk category their source water fell into. The quality of filtered and unfiltered water was then compared across all households falling into each category. The levels of *E. coli* in source and filtered water for filter user households stratified by WHO categorization of source water quality are shown in Figure 9.

The greatest reductions are seen in households with the highest levels of *E. coli* in source water. The greatest benefit from filtration appears to accrue to households with wells as their main water source; tap water households experience less benefit in terms of reduced levels of *E. coli* because their water is has low or no *E. coli* to begin with.

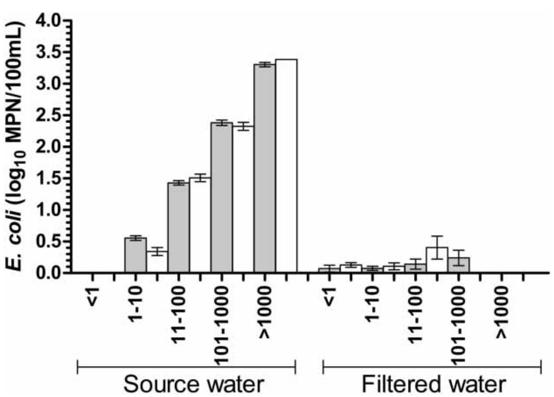

Figure 9 | *E. coli* in source and unfiltered water, stratified by WHO risk category of source water (gray = well; white = tap; bars = 95% CI).

DISCUSSION

Approximately 2 years after a CWF distribution program to tsunami-affected communities in southern Sri Lanka, 76% of recipient households were still using their filters. The majority of filter users report that the filter produces enough water for their family's needs; the perception of the filter producing enough water was also observed in a study of ceramic candle filters used in disaster relief in the Dominican Republic (Clasen & Boisson 2006). In both that study and this one, users reported putting water through the filter once or less than once per day. Since filtering habits as reported by respondents in this study would not produce large quantities of water per day, it is not surprising that filter user households report using filtered water mainly for drinking. Filtered water was infrequently applied to other household uses such as bathing, cooking, or handwashing. This finding is similar to previous findings for ceramic filter users. In Cambodia, a post-implementation study found that 86% of households using ceramic pot filters reported using the filter for drinking water only (Brown *et al.* 2009); in the Dominican Republic, 73% used filtered water for drinking only (Clasen & Boisson 2006). Together, these data suggest that households using CWFs view filtered water as water for drinking, not necessarily as water to be applied to all household needs. This may be because the filter only provides enough water for drinking, but people may also not perceive it as necessary to use treated water for other household applications such as handwashing, bathing, or cooking. In an evaluation of CWFs distributed by the Red Cross in a different region of Sri Lanka 6 months after the tsunami, it was found that 'drinking water was treated only for those household members perceived to be more vulnerable to unsafe water' (Palmer 2005a). If this is the case, additional educational efforts may be needed to encourage households to apply treated water to all or most of their most hygienically critical household needs to maximize protection from waterborne disease (Sobsey 2002).

Boiling is still common in the study population, and households reported boiling water regardless of their water source. This is not surprising; boiling is the most commonly used method of POU water treatment worldwide (Clasen *et al.* 2008). This suggests that boiling is an ingrained or habitual practice that continues even after another POU treatment method is introduced or there is piped water access. Households that report their tap water is already treated also still report filtering water. Most survey households drew water from taps or wells, with some reporting both sources. Although well water was more contaminated, *E. coli* was still detected in source water from households with taps. A limitation of the survey is that the questions were not designed to determine whether people who reported both well and tap as sources had tap water and well water as separate sources, or whether they had a tap connected to a well. For both *E. coli* and turbidity, the mean values for household reporting both taps and wells were in between the mean values for taps and the mean values for wells. This *may* suggest that households reporting both sources have both a connection to piped water and a well on the property, and the water they use is a mixture of both sources. The possibility of multiple sources, as well as the detection of *E. coli* in tap water, suggest that households connected to piped supplies should not be ignored in filter distribution efforts on the assumption that their water is microbiologically safe.

Perceptions of the filters were generally positive; users both know that water filtration can prevent diseases acquired from water and believe the filter has done so for their family. Questions about experiences and attitudes toward the filter indicated high satisfaction despite problems; 99% of households reported they planned to continue using the filter and 95% of filter households said they would recommend the filter to others. Use and satisfaction data indicate that there is an opportunity to support continued filter use and expanded marketing and distribution over the long term. However, the resources for and commitment to such a program need to be available. In this study, there was a high level of interest in and satisfaction with the filter, but a low level of knowledge about and availability of replacement filters and their parts. Households indicate willingness to acquire and pay for new filters, but most do not know of a place to obtain one.

Analysis of source water quality shows that many households had access to water that meets WHO standards for drinking water quality, but there were still households that fell into high risk categories based on the levels of *E. coli* in their source water. The microbiological quality of tap water overall was better than the quality of well water. There are few long-term follow-up studies of the microbiological performance of ceramic filters that have been in use in households. Laboratory studies have shown that ceramic filters can reduce *E. coli* in water by 1–2 $\log_{10}$ (Brown & Sobsey 2010). Field trials have demonstrated that these reductions can also be seen in household use; ceramic filters in use by households have been shown to reduce *E. coli* in drinking water by an average of 1.4 $\log_{10}$ in Cambodia (Brown *et al.* 2008) and 80–90% in Guatemala (Kallman *et al.* 2011). One Cambodian study showed that ceramic filters were still reducing levels of *E. coli* in drinking water after up to 44 months in use. There did not appear to be a relationship between *E. coli* reductions and time in use (Brown *et al.* 2009).

It is important to note that the quality of source water in Cambodian households was poorer than in this study (averaging 3 $\log_{10}$ *E. coli*/100 mL), probably due to their use of highly contaminated surface waters. Although absolute reductions in *E. coli* levels are important, they depend on the starting levels of *E. coli* in source water. In this study, filtration increased the number of households in the lowest risk WHO category for drinking water quality (<1 *E. coli*/100 mL), especially in households reporting wells, which had the highest levels of source water *E. coli*. Greater than 20% increases in the number of households in compliance with *E. coli* guidelines have also been observed in Cambodia (Brown *et al.* 2008), Zimbabwe, and South Africa after introduction of ceramic filters (Du Preez *et al.* 2008).

In this study, reductions of *E. coli* by filtration were also compared across WHO categories of source water quality; the greatest reduction is seen in households with >10 *E. coli*/100 mL. Most of these households reported well water as their primary water source. At almost 5 years post-disaster approximately 50% of households reported some type of tap water connection. Based on microbial reductions, it appears that much of the benefit of using filters accrues to households with the highest levels of *E. coli* in their source water, which in this study population were households using well water. For households that have established access to tap water, the benefits of continued filter use may be marginal. Although assessment of drinking water sources post-tsunami have examined the problems of seawater intrusion into wells (Villholth *et al.* 2008), there were not widespread efforts to monitor microbial quality of water sources in the immediate aftermath of the disaster despite intensive efforts to provide safe drinking water (Clasen *et al.* 2006). Recipients in this study were targeted based on having been affected by the disaster, not on measurements of the quality of their drinking water. Households that already had safe sources or were being reconnected to safe sources may have been included. Without follow-up testing of water quality and assessment of whether households are changing sources as time passes, households themselves are unlikely to know whether continued filter use is useful and beneficial.

There are still few data on whether adoption of POU technologies in the aftermath of disasters facilitates long-term adoption. It has been suggested that uptake of POU treatment after a disaster may not result in habitual long-term use (Clasen *et al.* 2006). This study provides some of the first evidence of long-term use of CWFs distributed as part of disaster recovery efforts. The results suggest that use of CWFs remains high among households that received them for free as part of a disaster recovery effort.

There are limitations of the cross-sectional survey design for ascertaining continued use (is the filter in use or not at the time of follow-up?) and consistent use (is the filter used consistently over time for all household water needs?). Observation of the filter itself at time of follow-up is a way to confirm household reports of continued use (filter is in use or not). However, using this classification may capture households that used the filter recently (within a few days), but are not using it every day for all their water needs. One study that classified households as users if the filter 'contained water or was damp from recent use', noted that filters can take three or more days to dry completely (Brown & Sobsey 2007). In the cross-sectional design, using a measure that captures those who put water in the filter within the past few days means that which category households fall into depends partly on the timing of the cross-sectional interview. Therefore, it is possible for households that used the filter a few days before observation to be included as users. Because there are no repeated observations of the filters themselves, cross-sectional design is not ideal to ascertain patterns of filter use over time, identify intermittent use, or observe variable patterns of use (such as use on some days but not others or variation in number of times water is put through the filter per day) that might be difficult for users to recall precisely. It may also capture households that are continued users but not consistent users. However, a study in Cambodia that used this classification of continued use to enroll participants in a longitudinal study of filter use and diarrheal disease showed health benefits in the user group (Brown *et al.* 2009), suggesting that even a classification of use that may capture some households that are not consistent users can have health benefits.

Although a variety of implementation models are still needed to suit individual communities and situations, disaster relief programs may present one opportunity to facilitate adoption of CWFs among users who may or may not be connected to piped water supplies during recovery and rebuilding. It has been observed in responses to a previous flooding disaster in Sri Lanka that displaced people tended to begin returning to their homes soon after the disaster, perhaps after 1–2 weeks. Assessments immediately after the tsunami suggest that people who received filters after resettling were more likely to adopt them than people who received them while living in temporary emergency shelter (Palmer 2005a, b). Immediate post-disaster needs for clean water for displaced people may be served by tanker trucks or other prepackaged large volume sources. But displaced people who are returning to their homes and previous, possibly contaminated, water sources can be targeted for CWF distribution even shortly after a disaster has taken place.

A growing body of literature on post-implementation assessments ranging from Cambodia (Brown *et al.* 2009) to Guatemala (Kallman *et al.* 2011) indicates that ceramic filters improve water quality over long-term use in the field, and that there is continued user satisfaction with filters. In these tsunami-affected Sri Lankan communities, people who received filters were still using them 1–2 years later. These filters were still effective in improving the microbiological quality of their drinking water, and increasing the number of households whose drinking water met WHO standards for drinking water quality. These households expressed satisfaction with their filters and perceived their water as needing treatment, and their source water, particularly well water, is contaminated with *E. coli*. They could potentially develop into long-term users of POUs even after their communities have begun to recover from the initial disaster.

The greatest benefits in water quality improvement occurred in households where the microbial quality of source water was poor. A number of households surveyed had source water that placed their drinking water in the lowest risk categories (1 *E. coli*/100 mL) according to the WHO classification. In this particular setting, continued use of filters may be happening both in households that benefit from water quality improvement (poor source quality, largely well water) and households where the benefit is marginal (largely tap water connections). Without follow-up of disaster-relief POU implementations, it may not be possible to know if this is the case, further emphasizing the need for continued monitoring of implementation programs. If households receiving filters post-disaster later move to safer sources (such as being reconnected to piped water systems), filter use may have diminishing benefits over time, a very different situation from a country like Cambodia, where implementation is targeted at populations who are unlikely to have access to improved sources in the foreseeable future.

These data indicate that continued sustained filter use can potentially be encouraged and supported by establishing a continuing supply chain for replacement filters and spare parts, as well as expanding to new customers. Large free distributions of filters to households can serve an important need in the immediate aftermath of a disaster. But to ensure that effective use of filters is possible and has continued benefits over the long term, implementers of disaster relief efforts involving filters and other POUs need to consider the long-term sustainability of these projects by planning for continued production, supply chains, and monitoring to support communities' adoption of POU technology.

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