An assessment of boiling as a method of household water treatment in South India

Luke Juran and Morgan C. MacDonald

ABSTRACT

This article scrutinizes the boiling of water in Tamil Nadu and Puducherry, India. Boiling, as it is commonly practiced, improves water quality, but its full potential is not being realized. Thus, the objective is to refine the method in practice, promote acceptability, and foster the scalability of boiling and household water treatment (HWT) writ large. The study is based on bacteriological samples from 300 households and 80 public standposts, 14 focus group discussions (FGDs), and 74 household interviews. Collectively, the data fashion both an empirical and ethnographic understanding of boiling. The rate and efficacy of boiling, barriers to and caveats of its adoption, and recommendations for augmenting its practice are detailed. While boiling is scientifically proven to eliminate bacteria, data demonstrate that pragmatics inhibit their total destruction. Furthermore, data and the literature indicate that a range of cultural, economic, and ancillary health factors challenge the uptake of boiling. Fieldwork and resultant knowledge arrive at strategies for overcoming these impediments. The article concludes with recommendations for selecting, introducing, and scaling up HWT mechanisms. A place-based approach that can be sustained over the long-term is espoused, and prolonged exposure by the interveners coupled with meaningful participation of the target population is essential.

Key words | boiling, household water treatment, India, point-of-use treatment, public health interventions, water

Luke Juran (corresponding author)
Department of Geography and Virginia Water Resources Research Center,
Virginia Tech,
125 Major Williams Hall,
Blacksburg,
VA 24061,
USA
E-mail: *ljuran@vt.edu*

Morgan C. MacDonald
Australian Rivers Institute and Griffith School of Environment,
Griffith University,
Nathan Campus,
Sir Samuel Griffith Centre,
Office 4.11NATHAN QLD 4111 Brisbane,
Australia

INTRODUCTION

Poor and marginalized households in Nagapattinam District, Tamil Nadu and Karaikal District, Puducherry, located in South India, are routinely subjected to drinking water unfit for human consumption (see Table 1). In general, government-provided piped water is laden with fecal coliform and fails to meet standards set by the Bureau of Indian Standards and the World Health Organization (WHO) (see Table 2). Moreover, quality further deteriorates as a result of retrieval, storage, and serving processes. In cases such as this, household water treatment (HWT) – promoted by bodies such as the WHO's International Network on HWT and Safe Storage – has been touted as a method for ensuring potable water among at-risk populations. Boiling is the most common method of HWT, practiced by 21% of households in low- and middle-income countries, including 10.4% of households in India (Rosa & Clasen 2010). Clasen, a professor of water, sanitation, and health at the London School of Hygiene and Tropical Medicine, comments on the comprehensiveness of such a procedure.

> *'Boiling or heating with fuel is perhaps the oldest means of disinfecting water at the household level. If practised correctly, boiling is also one of the most effective [methods], killing or inactivating all classes of waterborne pathogens, including bacterial spores and protozoan cysts that have shown resistance to chemical disinfection and viruses that are too small to be mechanically removed by microfiltration … Moreover, while chemical disinfectants and filters are challenged by turbidity and certain dissolved constituents, boiling can be used effectively*

doi: 10.2166/wh.2014.010

Table 1 | Water quality at household scale

	No. of samples	Samples – fecal coliform absent	Fecal coliform absent (%)
Nagapattinam			
Akkaraipettai	21	5	23.81
Andana Pettai	21	7	33.33
New Nambiyar Nagar	37	4	10.81
Samanthanpettai	26	4	15.38
Saveriyarkovil	26	1	3.85
Theti	23	7	30.43
Uzhuvar Nagar	15	1	6.67
Total Nagapattinam	n = *169*	*29*	*17.16*
Karaikal			
Akkam Pettai	18	1	5.56
Amman Kovil Pathu	19	6	31.58
Kilinjilmedu	24	5	20.83
Kizhakasakudimedu	21	6	28.57
Mandapathur	18	2	11.11
Paravaipettai	15	7	46.67
Vettakaramedu	16	5	31.25
Total Karaikal	n = *131*	*32*	*24.43*
Total	**n = *300***	***61***	***20.33***

> *across a wide range of physical and chemical characteristics'* (Clasen 2009).

Households in the study area of Nagapattinam and Karaikal practice HWT to some extent, with boiling representing the primary method. Thus, this article examines the rate and results of boiling in the study area, followed by the efficacy, barriers to, and caveats of its practice. The article ends with recommendations for improving and scaling up boiling as well as other methods of HWT.

METHODS

This study randomly selected seven housing settlements each in Nagapattinam and Karaikal Districts; eight of the 14 settlements are urban and six are rural. The settlements range in size from 22 to 892 houses, with an average of approximately 200. The bacterial quality of water was tested at 300 randomly selected houses (minimum 15 at each site) with a sterilized H_2S test that detects the presence–absence of bacteria of fecal origin (see Table 1). The H_2S method was best suited for this study. Water quality tests were conducted a full day from a laboratory, rendering more rigorous methods infeasible. While H_2S tests merely determine the presence–absence of hydrogen sulfide-producing agents (i.e. enteric bacteria, of which *Escherichia coli* is most common), it has been demonstrated that the method 'detects fecally contaminated water with about the same frequency and magnitude' as other traditional methods (Sobsey & Pfaender 2002). Thus, the H_2S method was appropriate for the rural context and accurate enough for analysis despite limitations in parametric detection. It must be mentioned that samples free of fecal coliform may contain other hazards (e.g. protozoa), and that samples with a presence of fecal coliform may not lead to sickness (i.e. incidence is a probability). Chemical tests comprising eight parameters were also conducted at access points, but the data will not be analyzed in this article. Common results include: high pH, hardness, chlorides, and alkalinity; absence of residual chlorine; and occasionally high levels of fluoride and iron. All tests were conducted in August–September 2012 on water being consumed by each household using standard methods of the US Environmental Protection Agency. Furthermore, because households obtain drinking water from communal sources, a total of 80 access points (minimum five at each site) were tested (see Table 2). These tests revealed the initial quality of water, buttressed the relevance and urgency of HWT, and established occurrences of post-point contamination (see Table 3). Focus group discussions (FGDs) were organized at each site. The 14 FGDs included all 300 subjects and 67 additional residents of the study sites who wished to participate ($n = 367$). The FGDs probed water quality issues, coping with such issues via HWT, and individuals' decisions to boil or not boil. FGDs were instrumental in pinpointing areas of broad consensus and disagreement, and served as a means to verify data from household interviews and validate external observations. Purposefully sampled semi-structured interviews lasting 1–2 hours each were conducted with a subset ($n = 74$) of the subjects (minimum five at each site) in order to further investigate the rationale for boiling or not boiling and as media to observe how individuals boil, manage, and

Table 2 | Water quality at access points

	Govt taps sampled	Govt taps – fecal coliform absent	Fecal coliform absent (%)	Other samples (# fecal coliform absent/# sampled)[a]
Nagapattinam				
Akkaraipettai	5	2	40.00	–
Andana Pettai	5	4	80.00	1/1
New Nambiyar Nagar	9	0	0.00	–
Samanthanpettai	6	1	16.67	–
Saveriyarkovil	6	0	0.00	–
Theti	5	2	40.00	–
Uzhuvar Nagar[b]	4	0	0.00	0/1
Total Nagapattinam	n = *40*	*9*	*22.50*	–
Karaikal				
Akkam Pettai	5	0	0.00	0/1
Amman Kovil Pathu	5	3	60.00	–
Kilinjilmedu	5	2	40.00	–
Kizhakasakudimedu	5	0	0.00	1/1
Mandapathur	5	0	0.00	1/1
Paravaipettai	5	5	100.00	–
Vettakaramedu	5	2	40.00	–
Total Karaikal	n = *35*	*12*	*34.29*	–
Total	n = *75*	*21*	*28.00*	*3/5*

[a] Non-government sources: treatment centers at Andana Pettai and Kizhakasakudimedu, hand-pump in Uzhuvar Nagar, and borewells in Akkam Pettai and Mandapathur.

[b] A minimum of five taps were tested, but Uzhuvar Nagar has only four taps in total.

Table 3 | Post-point contamination

	Household samples traced to source with absence of fecal coliform	Household samples that maintained absence of fecal coliform	Households that maintained absence of fecal coliform (%)
Source – treatment center	22	9	40.91
Source – govt tap	16	7	43.75
Total	n = *38*	*16*	*42.11*

serve water. Purposive sampling seeks to capture rich data and its variability in an efficient manner, the objective being to uncover breadth and reach data saturation given logistical and time constraints. Lastly, this study is informed by an ethnographic approach that pursues Geertz's (1973) goal of 'thick description'. Thus, a longitudinal frame of reference was generated by conducting four visits to the field over a four-year period. The visits encompassed all of the climatic seasons (e.g. monsoon and dry), which necessarily perturb water quality, quantity, and social systems related to water. Ultimately, culture, economics, and larger issues of coupled water-society constructs are linked to produce a case study that provides insight in both the South Indian and global contexts.

RESULTS

A sample of 300 households revealed that 20.7% of households in Nagapattinam and 22.9% in Karaikal practice HWT, resulting in a total of 21.7% (see Table 4), all but one of the houses engaged in HWT boiling practice. Moreover, the outcomes of HWT are alarming: of the 35 households that practiced HWT in Nagapattinam, 19

Table 4 | Results of household water treatment

	Nagapattinam	Karaikal	Total	Total (%)
Households practicing HWT	35/169	30/131	65/300	21.67
Households practicing HWT–fecal coliform absent	16/35	10/30	26/65	40
Households not practicing HWT–fecal coliform absent	13/134	22/101	25/135	14.89
HWT	$n\ max = 169$	$n\ max = 131$	$n\ max = 300$	

HWT = household water treatment.

Note that HWT households exhibited water with an absence of fecal coliform only 40% of the time, yet were more than two and a half times likely to exhibit such water.

Note that all but one of the HWT households boiled, and it revealed an absence of fecal coliform.

samples tested positive for bacteria of fecal origin. Likewise, 20 of 30 samples tested positive in Karaikal. The aggregate is that only 26 of 65 (40%) households that practiced HWT generated water free of enteric bacteria; this mirrors a study in Vietnam in which the presence of fecal coliform was detected in 37% of households that boiled (Clasen *et al*. 2008). While the outcome should theoretically be 100%, study households engaging in HWT were more likely to consume potable water than those that drank untreated water: 40% of households that practiced HWT exhibited potable water compared to only 14.9% among their counterparts; and only 21.7% of households practiced HWT, yet they comprised 42.6% of tests negative for bacteria of fecal origin. Thus, while HWT delivered improved, albeit lackluster, results, issues of efficacy emerge, particularly when considering a method that can guarantee water free of bacteria. Therefore, the subsequent section will examine pretexts for the lower than expected proportion of safe water as well as barriers to and caveats of HWT in practice.

EFFICACY, BARRIERS, AND CAVEATS

This section begins by deconstructing the efficacy of boiling in the study area (i.e. why much boiled water fails to reach a safe standard). Next, several barriers to and the rationale for not boiling will be posited, which will be supplemented by caveats that accompany the process. The portion on barriers and caveats resembles Wellin's (1955) classic case study 'Water Boiling in a Peruvian Town', in which socio-cultural justifications for boiling or not boiling were teased out through methods of observation and ethnography.

Beginning with efficacy, there are two hypotheses for why boiling failed to fully eliminate bacteria of fecal origin. Excluding the single household that filtered (at which fecal coliform was not detected), 25 of 64 (39.1%) households that boiled were able to produce water free of fecal coliform. Informed by much observation and FGD dialogues, the principal factor impeding higher rates of bacterial elimination pertains to the execution of boiling in practice. After observing numerous individuals boil water in their home (without cueing), it became apparent that they did not actually boil the water. Rather, individuals simply heated the water, which they reported as *sooru thanni* ('boiled water' in Tamil). Households tend to 'boil', at one time, enough drinking water for the day (10–15 liters). The time taken to boil this volume is considerable, often exceeding 15 minutes. Water boilers, generally female heads of household, have multiple tasks to undertake including cooking, which requires the same stove or hearth space used to heat the water, engendering boilers to remove water from the heat source as soon as it is subjectively deemed hot enough (i.e. often before disinfection). Consequently, the water rarely reaches boiling point, which further precludes a rapid boil for several minutes as recommended by experts (CDC 2005). While simply heating water can kill microorganisms, elimination is not guaranteed unless water is brought to a sustained rolling boil. Second, based on observations and water quality testing at public taps and in the households, efficacy is compounded by storage and serving processes. Whether boiled properly or not, water stored in containers that may be contaminated (especially in episodes of prolonged storage, which is common) and served by dipping hands and cups, which likewise may be unclean, into the container present hazards for post-treatment contamination. Collectively, insufficient boiling combined with unsanitary methods of storage and serving render boiling less efficient than it otherwise should be.

Assuming issues of efficacy can be surmounted, several barriers exist for households taking up boiling. First, interviews and FGDs uncovered that many households not engaged in boiling presume that government-provided water is automatically 'good water': if it comes from a pipe and has been treated then it must be safe. Furthermore, individuals often subscribe to the argument that nobody in their household is sick, so the water must be safe. In other words, if the water was contaminated then, using syllogism, members of the household would be ill. This assumption is best illuminated by Rekha of Akkaraipettai:

> *'You do not know what you are talking about [in response claiming that her water is contaminated]. Piped water is good, very good. It's super. If there are* krimi *['bacteria' or 'germs' in Tamil] then I would be sick right now. I'm not sick, so the water is safe. There are no* krimi*, you are wrong!'* [said chuckling]

Contentions of this nature are not restricted to the study sites, as Wellin (1955) reported analogous responses in Peru. In a similar vein, knowledge on the benefits of boiling appear to be absent among some residents of the study sites. For example, Priya, a subject from Kizhakasakudimedu, declares:

> *'I boil my water every day, but some people do not believe that it's healthy. They say people who boil water get sick more often and people who drink water directly stay healthier. I tell them they're wrong, but they don't believe me and they'll never change. I am the leader of 37 women in a microcredit group in this area. I always tell them to boil; some listen and some don't. Even if they know that it's healthier many still won't do it. What to do?'*

Not only does Priya's quote correspond with Wellin's observation that 'the people of Los Molinos equate health with unboiled water' and infirmity with boiled water (Wellin 1955), but it surfaces instances of resistance even when the benefits are known. This assertion of informed opposition is reinforced by Malathi, a subject from Kilinjilmedu who refuses to boil despite her spouse's death from cholera. The contention is further upheld by numerous households that were shown (colorfully and odorously with black, sulfur-laden vials of H_2S media) that their water tested positive for enteric bacteria, yet stated vehemently that they do not intend to boil or practice any form of HWT.

Assuming residents of the study sites can be persuaded of the health benefits of boiling, are willing to embrace the method, and its efficacy can be improved, several barriers to adoption still exist. When such hitches are removed, barriers in the form of time, monetary costs, and consumption preferences still reign formidable. Beginning with time, it was already cited that boiling, especially in large single batches, requires considerable time, an argument also remarked by Wellin (1955) in Peru, Clasen *et al*. (2008) in Vietnam, and Adair-Rohani (2011) in Uganda. Moreover, Poulos *et al*. (2012), in Andhra Pradesh, India (the state that borders the study area), report that time required to treat water was a major factor in households determining whether an HWT intervention was worthwhile. Furthermore, peer debriefing sessions with scholars who study participatory HWT interventions revealed that residents of a target population in Chennai, Tamil Nadu, voiced a preference for quicker methods of HWT. Observed pragmatically at the study sites, the burden of boiling, a profoundly gendered chore, competes with myriad tasks that must be managed concurrently: gathering water, cooking breakfast, feeding children, getting family members ready for school/work, cooking and packing lunch for those going to school/work, washing dishes and laundry, bathing, and the list continues. Without allotting time for relaxation, the list of 'duties' performed by women permits little time for boiling, particularly when considering that boiling takes up all or half of the stove/hearth space, thereby restricting space available for conducting other tasks. Thus, it is no wonder why the time and opportunity costs led Suneetha of Paravaipettai to cease the practice in less than 1 week: 'It [boiling] became too troublesome and took too much time. I have other things to do. Who has such free time?' Lastly, a majority of the study population uses biomass fuel for cooking, which translates to supplemental stores of fuel if households opt to boil. Thus, the chore of gathering biomass imposes additional time and opportunity costs, especially during the monsoon when dry brush is scarce.

The monetary costs of boiling also present a significant obstacle, a liability attested to by Wellin (1955) in Peru, Gilman & Skillicorn (1985) in Bangladesh, and Clasen *et al*. (2008) in Vietnam. In fact, in neighboring Bangladesh, it was demonstrated that families in the lowest income quartile that boil are forced to exploit 22% of their fuel for boiling, and that boiling increased household expenditures by 11%, a price few can afford (Gilman & Skillicorn 1985). Echoing the data, it is estimated that '1/5 of the total end-use of energy for households in developing regions' is for heating water (Adair-Rohani 2011). At the study sites, electing to boil either entails searching for biomass more frequently and for longer durations, or the purchase of greater quantities of propane or kerosene. At the last check (January 2013), propane was available from private vendors at the rate of 420 Indian rupees for a 14.2 kilogram tank. Additionally, vendors levy a deposit amounting to several hundred Indian rupees and the use of propane also requires a stove, costing roughly 600–900 Indian rupees. Collectively, the expenses often price out the study population. Furthermore, propane is in high demand, meaning that many vendors will not entertain new orders and that there is often a 1–2 week delay in empty tank replacement. Kerosene is used by some households, although propane, when economically feasible, is preferred and biomass is unequivocally the most dominant fuel source. Kerosene is only available at government ration shops at the rate (January 2013) of 15.5 Indian Rupees per liter, and its use also requires the purchase of a stove. Thus, the costs of boiling, namely opportunity and economic, often render the practice burdensome and costly.

Finally, preferences associated with the physical properties of water further inhibit the operationalization of boiling. FGD participants, as did the subjects of Wellin's (1955) study, pronounced that they dislike drinking boiled water. Participants complained that the temperature both outside and inside the home is generally hot, and that consuming hot water is inimical to natural cooling processes: 'Why would I want to drink hot water when it's [the weather] hot?' complained Muthu of Saveriyarkovil, earning the consensus approval of FGD participants. While boiled water can be left to cool, this requires approximately 2 hours given 10–15 liter batches. Thus, the time when water arrives to taps (once daily between 6 and 8 am) does not allow for water to be boiled, cooled, and subsequently consumed at the beginning of the day, not to mention that water cannot be cooled to a point that household members can take it to school and work. Additionally, interlocutors object to the aesthetics of boiled water, with Jancy of Samanthanpettai voicing, 'I don't want to boil my water. I don't like boiled water, I just don't like it. It tastes bad.' Jancy's opinion, shared by many at FGDs, is the joint result of the de-oxygenation of water that occurs during the boiling process and the condition of the pots used. The pots harnessed for boiling have typically suffered heavy usage, leach a metallic flavor, and contain food films or particulates (from cooking) that sully the taste of the water. Even when a pot is employed exclusively for boiling, individuals claim that a metallic tincture is palpable and that the taste is aesthetically unpleasant or 'not pure tasting', layered on the fact that many remain adverse to consuming hot water to begin with.

In addition to the efficacy of boiling and barriers to its employment, several caveats must be inventoried. A chief caveat is of temporal nature: few households that self-report as boilers exercise the practice consistently. Rather, while a minority boil uninterruptedly, the majority boil only during the monsoon season or when a household member is ill. Just as certain foods, such as mangoes and jackfruit, produce heat, while others, such as bananas and curd, cool the body, hot water is accepted as a heating agent during the relatively chilly monsoon season, thereby generating a temporal spike in the number of boilers. The concept of 'hot' and 'cold' foods is both a cultural convention and practiced clinically in *ayurveda*, a traditional medicinal system rooted in Hinduism. During interviews, the common response was affirmative when households were asked if they boil. However, when a sample of boiled water was requested for testing, more often than not, there was none to be found. This was perpetually qualified through an explanation that 'We do boil our water, but only during the monsoon,' as told by Sweta of Theti. Interlocutors commented that, during the monsoon, temperatures plummet, winds increase, rain prevails, and the interior of their homes is cool and moist, all of which are abated by consuming hot water.

Similarly, the consumption of boiled water is reserved situationally for the ill, an exercise that was also unearthed by Wellin (1955) in Peru. Individuals who boil water for the ill acknowledge its safety relative to unboiled water, and both *ayurvedic* praxes and allopathic doctors instruct parents to boil water for children in times of sickness.

Consequently, what transpires is that water is boiled only while individuals are ill, and the practice is terminated once individuals recover. Thus, rather than boiling daily, which would decrease disease incidence rates overall and prevent cases that trigger episodes of boiling to begin with, households engage in routinized cycles of boiling and not boiling as a function of real or perceived illness. Therefore, the temporality of boiling, whether observed during the monsoon or in episodes of sickness, lacks a preventive component and is demoted primarily to a reactive procedure.

The consumption of boiled water also demonstrates a selective dimension. Among households that boil, it is common for only a portion of the household to consume the water. For example, water is typically boiled solely for children, while the remainder of the household consumes untreated water. Interestingly enough, while such boilers acknowledge that their water may be contaminated and that heat kills germs, they opt not to compel the entire household to consume the very water that they appraise as relatively safer. This point is aptly illustrated by Swati of Andana Pettai: ‘I boil water for my children because it’s good for them, but we [rest of household] don’t like boiled water.’ Likewise, it is common for only elderly members of the household to drink boiled water. This is principally founded on the premise that exposure to cold airs and the consumption of cold items, such as ice cream, items stored in a refrigerator, and chilled beverages, propagate illness. For example, if an individual is observed drinking cold water today and is infirm tomorrow, the etiology, according to many (particularly the elderly), was the consumption of chilled water. This dichotomy of hot and cold water is not based on microbes, but on traditionally held beliefs rooted in popular conventions and *ayurveda*. Thus, predicated on relative interpretations of disease origins, the elderly are more likely to consume boiled water, while the remainder of the household tends to consume unboiled water. Vikas, a 73-year old subject from Vettakaramedu, upholds this claim: ‘I drink hot water. Cool drinks cause *joram* [‘fever’ in Tamil]. My daughter-in-law boils water daily for me. I drink boiled water, but only me in this house.’ Therefore, substantiated in observations, FGDs, and interviews, it is evident that a household that reports as boiling does not translate to all members consuming the water. Rather, the treated water is likely consumed only by a subset of the household, typically the children or elderly. Furthermore, while the rationale stems from philosophies of health understanding, the reasoning derives from two camps: the germ theory and a cold-hot binary.

A final caveat concerns the ancillary health impacts of boiling. At the study sites, most cooking, and thus boiling, is fueled by biomass (e.g. wood, shrubs, and dung). Propane is generally cost-prohibitive and kerosene, while cheaper, still costs more than freely available biomass; hence the proclivity of harnessing biomass for fuel. Unfortunately, the use of biomass is associated with increased exposure to air pollution, formaldehyde, acrolein, benzene, toluene, and particulates comprising some of the injurious constituents (Smith 2002; Shaheed & Bruce 2011). Furthermore, air pollution from biomass fuel has been correlated with, *inter alia*, low birth weight, acute respiratory infection, cataracts, chronic obstructive pulmonary disease, asthma, and lung cancer (Smith 2002; Shaheed & Bruce 2011). Since boiling increases the quantity of biomass combusted, it surfaces a notable drawback and it is therefore contended that boiling, while beneficial, may not be as cumulatively healthy as proponents suggest.

Boiling is also associated with increases in burns and scalds, especially among children (Clasen *et al.* 2008; Adair-Rohani 2011). In fact, in a slum in São Paulo, Brazil, it was found that the heating of liquids, water the most frequent, accounted for 50% of all reported burns (Rossi *et al.* 1998). Furthermore, 85.6% of burn accidents took place in the home, 50% of cases were among children, and 80.7% occurred with at least one parent present (Rossi *et al.* 1998). Therefore, prescriptions to increase boiling would likely be matched with escalations in burn risk, with children, even with parents present, acutely affected. Lastly, in this era of deforestation, desertification, and climate change, it is recognized that increases in boiling amplify both greenhouse gas emissions and unsustainable practices that reduce vegetation cover. However, while this argument is valid, we refuse to hold subaltern populations responsible for processes to which they have either contributed minimally or possess few methods for moderating.

DISCUSSION

This section mirrors Wellin’s (1955) structure by providing recommendations for increasing the efficacy of boiling and scaling up boiling and HWT in the study area. Given data in the previous section, it has been established that boiling as it is commonly practiced is not realizing its full potential in augmenting water at point-of-use. While boiling improves water quality, the full risk to pathogens is not eliminated and drawbacks emerge, such as opportunity and monetary costs, popular resistance, manifestations of non-continuous and selective boiling practices, and indirect health impacts. Thus, the evidence coalesces to classify boiling in practice as a quasi-effective method that can be considerably improved with the incorporation of grounded, culturally sensitive knowledge.

Several insights have been garnered for improving the effectiveness of boiling. First, proper methods must be relayed in order to increase the elimination of bacteria. Households tend to only heat their water, presuming that it has boiled and microbes have been destroyed. However, while some microbes are killed by heating to 55 °C, bringing water to a rapid boil (i.e. 100 °C), preferably for several minutes, is the only surefire way to eliminate the full risk (Clasen 2009; Rosa & Clasen 2010). Thus, instructions on what constitutes boiling must be imparted, with clear guidelines on producing 'bubbles' for several minutes as both a visible and auditory cue that water has been boiled. Furthermore, it is suggested that households use pressure cookers to enhance the efficacy of boiling. Pressure cookers, used for cooking rice, meats, and other foodstuffs, are a common kitchenware in India. Not only would the device's pressure better ensure the destruction of bacteria (e.g. pressure is used in health settings to sterilize medical instruments), but it would also provide sensory clues (through the 'whistle' sounds emitted) that water has been boiled. Furthermore, pressure cookers would reduce the time required to boil, an opportunity cost identified in FGDs and interviews as a major barrier. Lastly, the caveat of burns would be diminished because pressure cookers contain their contents with sealed lids.

Turning to barriers, which pressure cookers tangentially address, changing the time of boiling may prove helpful. Given that women, the primary handlers of water, are busy in the morning (when water arrives), and in an effort to circumvent the preference of many not to consume hot water, it is recommended that water be boiled in the evening. Water boiled in the evening would be cooled by morning, facilitating the consumption of treated water throughout the day and enabling household members to carry it to school and work. Furthermore, it is likely that more adults are present in the household in the evening, permitting the boiler to fulfill the task while others watch over the children, which would reduce opportunities for burns. Next, in an attempt to mask the undesirable flavor of boiled water, to which subjects expressed opposition, it is posited that additives be introduced during the boiling process. For example, in the study area, it is common to add cumin, bark from *Caesalpenia sappan* (a tree with *ayurvedic* properties), and herbs to water. Additives would render the water more palatable, thus increasing the likelihood of consumption among those who remain adverse to the aesthetics of raw boiled water.

In terms of caveats, while the use of pressure cookers would diminish the hazard of tipping, thereby reducing the risk of burns, other caveats can be addressed. First, the temporality of boiling, particularly during the monsoon and in bouts of illness, must be expanded. The benefits of boiling for epidemiological bases, that is its capacity to prevent would-be diseases which are commonly conceptualized as 'non-events', must be articulated to at-risk populations. Boiling during the monsoon is a prudent practice, not because the air temperature is relatively cold, but because water quality decreases with the deluge of floodwaters and saturated soils enveloping shoddy underground pipes and public standposts. However, while differential health results would be attained, continuing the practice year-round must be distinguished as a mechanism for maintaining health throughout the year. Furthermore, communicating that numerous illnesses, which serve to spawn temporary episodes of boiling, are progenies of poor water quality (*prima facie*) is warranted. Thus, knowledge on waterborne diseases and their manifestations, combined with evidence that continuous boiling can mitigate incidents of disease from occurring in the first place, is a step towards increasing the scope of boiling. Moreover, since the opportunity costs of boiling embody a significant barrier, it may prove useful to couch incidences of disease as opportunity costs themselves: they keep adults from work, children from school, make domestic tasks difficult, and bring hardships. Thus, conveying that opportunity costs of boiling in the present will be rewarded with fewer cases of sickness in the future may gain traction, in effect adding value to the 'non-events'.

Last is the caveat of pollutant exposure from biomass combustion. While propane, a less hazardous fuel in terms of pollutants, is the preferred method for cooking, it remains cost-prohibitive for most of the study population, not to mention its limited availability. Kerosene is more injurious than propane and also costly, and biomass is both the most dominant and dangerous (in terms of pollutants) of the three fuels. Thus, there are efforts to introduce solar cookers to villages in India and globally, which elides issues of electricity, cost, air pollution, deforestation, and climate change (Pohekar & Ramachandran 2004). While the prospect of solar cookers is gaining a foothold, impediments remain in design, capacity of energy storage, and popular acceptance. Nonetheless, solar cookers are an avenue being explored, and their contribution to reducing exposure to air pollution (e.g. while boiling) merits attention.

Scalability is a sphere much researched in the arenas of health intervention, technological dissemination, and HWT. Scholars agree that education, sensitization, or advocacy campaigns are crucial components of introducing technologies and sanitary practices, but that such interventions often fail to penetrate or peter out over time. Thus, Lantagne (2011) argues that scaling up HWT requires the selection of a culturally and geographically appropriate method vis-à-vis the target population. Lantagne (2011) also contends that knowledge be disseminated to ensure correct and consistent use of the method, and that it be available on a long-term, sustainable basis. Furthermore, scholars suggest holding workshops in the target community, working through local health clinics, performing continued monitoring and evaluation, and that interveners exercise prolonged exposure, not one-off sessions (Schmidt & Cairncross 2009). Through these approaches, target populations are more willing to modify their behaviors, especially when the method is easy to perform and materials are locally sourced. Furthermore, interveners can oversee the practice of HWT, evaluate its efficacy, gain acceptance (through repeated visits), and incorporate user feedback. Thus, the patronizing approach of ‘provision and adoption’ is evaded by building rapport, cultivating participation, and instilling value and ownership, which collectively enhance project performance and user acceptability.

While the approaches outlined above are widely accepted and practiced to some extent by health professionals and non-governmental organizations, the format for conducting such activities must be iterated. First, a survey or pilot study should be conducted in order to identify the best method for HWT given the initial quality of water, demographics of the target population, and practices that will be sustainable and minimally intrusive for the end users. Pre-intervention field visits also allow for inputs from the target population to influence HWT design, with FGDs representing a possible medium. After an appropriate method is chosen, information on waterborne diseases and their manifestations, the benefits of HWT, and demonstration of the selected HWT strategy should be delivered via interactive workshops. To bolster authenticity and legitimacy, workshops should be performed in coordination with or after receiving approval from village leaders or respected members of the community. For visible effects at workshops, the authors recommend using H_2S strip tests (as well as titration methods) to visualize the difference between contaminated, untreated water (jet-black) and that which has undergone treatment (clear), thereby ‘showing’ the benefits of HWT. Throughout the process, members of the community should partake in demonstrations and be invited to extend improvements and feedback, which can help foster voluntary operationalization of the selected method. Proper HWT strategies should be presented in simple text and graphics based on local language and customs, perhaps on placards or posters that can be hung in the home. This enables consistent public health messaging and strategy retention among the target population. For example, with reference to boiling, placards should display bubbles rolling in the water along with a note stating that the bubbles should be sustained for 3 minutes (this duration could also be expressed in cultural or domestic terms, such as the length of time taken to perform a common task). After the HWT intervention has been implemented, weekly check-ups at the household scale, tapered off to monthly and yearly visits, should be executed; such visits can be aided by representatives of the target population. Regular checks can galvanize fellowship among all members of the venture and assist in solidifying HWT as a long-term, and hopefully permanent, practice. It may be appropriate to have the target community elect representatives or form an ‘HWT Committee’. These bodies can record suggestions and complaints, report to intervenors, implement surveys, and execute other functions. Furthermore, such bodies may serve to instill ownership of and control over HWT processes, as well as popularize HWT and promote its scalability. Finally, the doling of rewards for adhering to learned behaviors is sometimes applied. However, this can backfire, thereby threatening to create conflict and division among the target population. If a reward system is activated, then consider a communal reward for the entire population, such as a community-owned well. This may prove more appropriate and less divisive than individual rewards.

In addition to demonstrations, cueing materials, and follow-ups, education on hygiene and sanitation practices, which secondarily deteriorate water quality, must be imparted (see Table 3). Topics for education include: keeping public taps and their environs clean and dry; washing collection vessels with soap; the mal-effects of storage; proper serving procedures; and not reusing plastic beverage bottles (which are difficult to clean given their narrow necks and may leach chemicals over time). Information dissemination on the benefits of such practices will both maintain the initial quality of water, thereby reducing the quantity of microbes that must be removed by HWT, and curb incidents of post-HWT contamination.

As for selecting an HWT technology, no universally optimal choice exists considering variability in target populations, local resource availability, and consumer preferences. When performed properly, boiling completely eliminates pathogens, yet its efficacy (39.1%) and limitations in the study area have been underscored. Turning to other approaches, Hunter (2009) demonstrated in a meta-analysis that chlorine tablets were less effective in destroying microorganisms than other methods (boiling was not considered). Additionally, shock chlorination is hindered by dissolved solids and turbidity, so water chemistry must be ascertained beforehand. Furthermore, disinfection byproducts can be generated, which are a known hazard. Moreover, consumers, including the study participants, often find the taste of chemically treated water undesirable, which impedes user compliance (Crump *et al.* 2004). Thus, there is a proclivity to resist consumption of chemically treated water on aesthetic grounds, as lamented by Raj of Mandapathur: ‘I will not drink water with bleaching powder [chlorine]. It doesn’t taste good. It tastes like chemicals, it tastes unnatural.’ Hunter (2009) also established that solar disinfection is less effective than other strategies, not to mention that it entails several hours to perform (time already recognized as a major barrier). Hunter’s study revealed that ceramic filters, followed by biosand filters, were the most effective means for removing bacteria, and Mwabi *et al.* (2011) demonstrated in a comparative study of four methods that silver-impregnated ceramic filters were the most effective (neither study considered boiling). However, ceramic filters are easily broken, and both ceramic and biosand filters can occupy considerable space in the home (space is frequently scarce in low-income settlements). Furthermore, peer debriefing sessions indicate that households in a Chennai slum were averse to biosand filters. At the implementation stage, households resisted usage because the biofilm layer, the principle component for removing pathogens, emitted a foul odor (MacDonald *et al.* 2013). Taken collectively, while methods of HWT eliminate microorganisms, they do so at different rates and may be opposed by populations for reasons manifold. Therefore, just as boiling exhibits room for improvement, so do alternative methods of HWT. Ultimately, pilot studies must be conducted in order to isolate the most effective, culturally acceptable method that can be sustained over the long-term.

Finally, narrowing to the study area, the governments of Nagapattinam and Karaikal warrant criticism for their role in water quality. HWT would not be required, or would at least be less prominent an issue, if the governments provided safe water from the outset. In Nagapattinam, water directly from government taps tested positive for bacteria of fecal origin 77.5% of the time; in Karaikal, 65.7% of samples tested positive (see Table 2). The aggregate is that 72% (54 of 75 samples) of water supplied to the study sites was tainted with enteric bacteria before it reached the household, with quality deteriorating *post facto* from retrieval, storage, and serving processes (see Table 3). Thus, informed by dialogues with government officials and the totality of fieldwork, it is recommended that the governments: improve existing disinfection methods; repair aged supply infrastructure and broken pipelines; clean sediment-laden water towers more frequently; ensure a continuous supply of piped water (to maintain in-pipe pressure and prevent groundwater inflow); and imbue water with residual chlorine. While HWT can counteract deficiencies in government treatment and supply, the extent required is a function of the initial quality, and risks should be mitigated as one cannot expect or demand all households to practice HWT. Moreover, the necessity of HWT is chiefly an artifact of inadequate government supplies to begin with. If improved, the urgency of HWT would be diminished, households could save time and resources, and the disease burden would be reduced.

CONCLUSION

This article examined boiling as a method of HWT. The rate and efficacy of boiling, barriers to and caveats of adoption, and recommendations for improving and scaling up its practice (as well as the trajectory of other methods) have been detailed, though non-exhaustively. While boiling is scientifically proven to eliminate fecal coliform, data demonstrate that pragmatics problematize their destruction. Furthermore, data indicate that an array of cultural, economic, and health-based factors impinge the acceptability and scalability of boiling. For these reasons, prescribing populations to simply 'boil their water' may be accompanied by several hitches. Rather, in order to reach its full potential, boiling should be perceived as an effective method that must be introduced in line with local socioeconomics, natural environments, and cultural preferences.

No method of HWT represents a silver bullet. Thus, confronted with limitations, actors have turned to full-fledged campaigns seeking to better operationalize and increase the practice of boiling and other methods of HWT. If interventions are conducted, prior exposure to the target population (e.g. observations, FGDs, and surveys or pilot studies) is vital. Pre-intervention exposure facilitates problem identification, water quality testing across competing HWT approaches, rapport building, popular input, and ultimately a more culturally and geographically nuanced method. Just as boiling exhibits limitations, other methods of HWT may also underperform and/or be resisted by the community. Therefore, selection of the most effective method that is contextually appropriate and sustainable over the long-term is imperative. Furthermore, presence in the target population post-intervention is crucial for monitoring, evaluation, and verifying adherence to the HWT method. Lastly, while professionals possess engineering knowledge on HWT, success is contingent upon the heterogeneous bloc of water treaters and consumers that must adopt and adapt to HWT processes. Therefore, a place-based participatory approach (enacted at the earliest possible stage) is fundamental, especially when foreign or 'outside' populations are leading the intervention. The introduction of HWT methods is best perceived as a collaborative venture with all participants possessing valuable knowledge.

ETHICS STATEMENT

Free and informed consent of the participants was obtained via a waiver of informed consent (provided by the ethics committee) and the study protocol was approved by the University of Iowa Human Subjects Office/Institutional Review Board (IRB-02, DHHS Registration # IRB00000100, IRB Chair Elona McLees), State of Iowa, USA, DHHS Federal-wide Assurance #FWA00003007, 12/02/2010.

REFERENCES

Adair-Rohani, H. 2011 Status of stoves, health & global guidance. In Workshop on Household Water Treatment and Safe Storage Strategies and Integrated Household Environmental Health Interventions, June 27–29. WHO, UNICEF & UNC Water Institute, Entebbe.

CDC 2005 *Emergency Preparedness & Response: Emergency Water Storage and Purification*. CDC, Atlanta.

Clasen, T. 2009 *Scaling up Household Water Treatment among Low-Income Populations*. WHO, Geneva.

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

Crump, J. A., Okoth, G. O., Slutsker, L., Ogaja, D. O., Keswick, B. H. & Luby, S. P. 2004 Effect of point-of-use disinfection, flocculation and combined flocculation-disinfection on drinking water quality in western Kenya. *J. Appl. Microbiol.* **97** (1), 225–231.

Geertz, C. 1973 Thick description: toward and interpretive theory of culture. In: *The Interpretation of Cultures: Selected Essays* (C. Geertz, ed.). Basic Books, New York, pp. 3–32.

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

Hunter, P. B. 2009 Household water treatment in developing countries: comparing different intervention types using meta-regression. *Environ. Sci. Tech.* **43** (23), 8991–8997.

Lantagne, D. 2011 Evaluating HWTS: from evidence to action. In HWTS Network Webinar on Evaluating HWTS, April 27. WHO, UNICEF & UNC Water Institute.

MacDonald, M. C., Ali, S. I. & Hall, K. 2013 Collaborative innovation for the development of contextually appropriate water treatment technology in a marginalized, low-income South Asian community. *Int. J. Tech. Knowl. Soc.* **8** (3), 105–120.

Mwabi, J. K., Adeyemo, F. E., Mahlangu, T. O., Mamba, B. B., Brouckaert, B. M., Swartz, C. D., Offringa, G., Mpenyana-Monyatsi, L. & Momba, M. N. B. 2011 Household water treatment systems: a solution to the production of safe drinking water by the low-income communities of Southern Africa. *Phys. Chem. Earth* **36** (14), 1120–1128.

Pohekar, S. D. & Ramachandran, M. 2004 Multi-criteria evaluation of cooking energy alternatives for promoting parabolic solar cooker in India. *Renew. Energy* **29** (9), 1449–1460.

Poulos, C., Yang, J., Patil, S. R., Pattanayak, S., Wood, S., Goodyear, L. & Gonzalez, J. M. 2012 Consumer preferences for household water treatment products in Andhra Pradesh, India. *Soc. Sci. Med.* **75** (4), 738–746.

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

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

Schmidt, W. P. & Cairncross, S. 2009 Household water treatment in poor populations: is there enough evidence for scaling up now? *Environ. Sci. Tech.* **43** (4), 986–992.

Shaheed, A. & Bruce, N. 2011 *Combined Household Water Treatment and Indoor Air Pollution Projects in Urban Mambanda, Cameroon and Rural Nyanza, Kenya*. WHO, Geneva.

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

Sobsey, M. D. & Pfaender, F. K. 2002 *Evaluation of the H_2S Method for Detection of Fecal Contamination of Drinking Water*. WHO, Geneva.

Wellin, E. 1955 Water boiling in a Peruvian town. In: *Health, Culture, and Community: Case Studies of Public Reactions to Health Programs* (B. D. Paul, ed.). Russell Sage Foundation, New York, pp. 71–103.

First received 13 January 2013; accepted in revised form 13 March 2014. Available online 5 April 2014