Kenya: Potential Health Impact of Household Water Treatment Technologies

Highlights

- All the assessed HWT methods reduced users’ exposure to *E. coli* and probability of infection, in spite of the unhygienic water and sanitation conditions and poor user knowledge and behaviour.
- The degree of reduction in risk was higher with consumption of treated unimproved water sources than from improved sources. Suggesting that the health benefit of household water treatment may be higher in water sources that have higher levels of microbial contamination before treatment.
- The risk to the user after treatment with each of the HWT products was still much higher than the acceptable annual risk of enteric diseases stipulated by the United States Environmental Protection Agency (USEPA).

Household water treatment technologies are used by only about 18 million of the 884 million people without adequate access to safe water in spite of the efforts of donor agencies to support the scaling up and large-scale promotion of household water treatment and storage (HWTS) methods (Clasen, 2008).

Wide spread promotion can only happen if governments adopt and institutionalise these methods as part of their national development plans. However efforts to promote their large-scale adoption are hindered by dissenting opinions within the sector about the health benefits of household water treatment methods.

Some of the HWT methods that have been shown to improve microbial efficacy either in the laboratory or during small-scale trials include sodium hypochlorite (Lantagne, 2006); PUR (Crump *et al.*, 2004; Albert *et al.*, 2010); Ceramic filters (Biefeldt *et al.*, 2009; Brown *et al.*, 2008) and Aquatab (Clasen and Edmonson, 2005).

However, the reported improvement in quality and its impact on health has generated some points of debate.

The first is the observation that none of the HWT technologies have shown consistency in their ability to reduce contamination to levels that comply with sector standards.

Secondly, because these observations have been made during small-scale or short-lived interventions, the actual effectiveness of the technologies under typical-use conditions is not well known (Sobsey *et al.*, 2008, Luby *et al.*, 2008; Mclaughlin *et al.*, 2009).

Thirdly, bias has been cited as the reason for the reported health benefits of HWT and for the reported differences in microbial water quality between treatment and non-treatment households) (Schmidt and Cairncross, 2008; Mclaughlin *et al.*, 2009).
In light of the above, it is necessary to assess the ability of HWT technologies to reduce the risk of water-borne infections, post-implementation, under typical-use situations by using a method that eliminates the types of bias alluded to by these authors.

Methods
Quantitative Microbial Risk Assessment (QMRA) was carried out in 37 households in five villages in the Nyanza province of Western Kenya. The microbial quality of 107 water samples from household collection containers and 107 samples from storage containers from 11 water sources was used to determine the potential health impact of selected household water treatment technologies.

Choice of reference pathogen

*E. coli* was used as proxy indicator for faecal pathogens. The study used the concentrations of *E. coli* in the household drinking water of the study population to estimate the probability of exposure and risk of infection from faecal pathogens using a dose-response model for enterovirus (van Lieverloo *et al.*, 2007).

*E. coli* was chosen as the reference pathogen based on its use as an indicator of the presence of pathogens which are spread through faeces of warm blooded animals and some reptiles.

Enterovirus was selected because they are water-borne pathogens which are more resistant to water treatment processes than *E. coli*, and are therefore a more reliable indicator of the risk of infection from water-borne pathogens.

The assumption made is that the presence or absence of *E. coli* is suggestive of the presence or absence of other water-borne pathogens, though the absence of *E. coli* in treated water does not rule out the presence of cysts of protozoa such as *Giardia lamblia* or *Cryptosporidium* spp, which are more resistant to chlorination.

Nevertheless, the choice of *E. coli* as the reference pathogen and enterovirus as the faecal pathogen is appropriate for this study's objective of assessing whether the selected HWT technologies are able to reduce exposure and probability of infection with water-borne pathogens.

These risk measurements are used as proxy indicators for the health benefits of HWT technologies. This is based on the premise that when water is a major source of exposure to pathogens, a reduction in exposure to the pathogens will lead to improved health (Brown and Clasen, 2012).

The exposure assessment

*E. coli* concentrations were determined by:

- Quantifying the *E. coli* concentration of 107 water samples from the collection containers and 107 water samples from the drinking water storage containers of the 37 households using the HWT technologies (Table 1)
- Quantifying the volume of untreated and treated water consumed by the adult respondent using the adoption and survey KAP results. A single estimate of the average quantity of water consumed per person per day (1,025 ml) was calculated from the daily consumption per respondent in each of the five villages.
- Determination of dose before and after treatment by multiplying the average quantity of water (1,025 ml) consumed with the *E. coli* concentration in drinking water at collection and storage.

Problem formulation and hazard identification

Hazards were identified by:

- Conducting a KAP study in the fifteen villages from which the five villages used for the QMRA were selected.
- Analysing of the drinking water sources used

Hazards that increased the study population’s exposure to enteric pathogens include:

- Poor water sanitation and hygiene, with only one in two households using *improved* water sources and only one in twelve using *improved* sanitation.
- Poor knowledge of the critical steps for effective use of the four HWT methods.
- High fecal counts of the drinking water sources.
Calculation of the exposure per person per day to pathogens in drinking water, before and after treatment with selected HWT technologies

Pathogen exposure per person per day was determined using the following formula (van Lieverloo et al., 2007):

\[ P_{\exp.d} = P_{E.d} P_{R} P_{Cd} \]  

Equation 1

Where:
- \( P_{\exp.d} \) = the daily probability density function (PDF) of an inhabitant of the study area being exposed to a pathogen or (when the probability is higher than 1) the expected number of pathogens consumed per person per day
- \( P_{E.d} \) = the empirical probability distribution function (PDF) of all \( E. coli \) or TTC concentrations in drinking water during the day
- \( P_{R} \) = empirical PDF of the pathogen to \( E. coli \) ratios in the contamination source
- \( P_{Cd} \) = PDF of daily consumption of untreated water fitted to a Poisson distribution

The difference in exposure per person per day to faecal pathogens when untreated water and treated water was consumed represented the effect of each HWT technology on user-exposure to faecal pathogens.

Table 1 Water samples used to assess potential health impact of household water treatment methods

<table>
<thead>
<tr>
<th>Technology</th>
<th>Village</th>
<th>Type of source</th>
<th>Category of source</th>
<th>At source</th>
<th>At collection</th>
<th>At storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquatab</td>
<td>Angenyoni and Akado</td>
<td>Unprotected handdug well</td>
<td>Unimproved</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Borehole with handpump &amp; rain water</td>
<td>Improved</td>
<td>16</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>PUR</td>
<td>Kinasia</td>
<td>Surface water</td>
<td>Unimproved</td>
<td>22</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Waterguard</td>
<td>Kokul</td>
<td>Surface water</td>
<td>Unimproved</td>
<td>29</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rainwater</td>
<td>Improved</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Ceramic filters</td>
<td>Tito</td>
<td>Surface water</td>
<td>Unimproved</td>
<td>16</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rainwater</td>
<td>Improved</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Grand Total</td>
<td></td>
<td>Total</td>
<td>107</td>
<td>107</td>
<td>107</td>
<td></td>
</tr>
</tbody>
</table>

Assumptions made in the calculation of the expected number of pathogens consumed per person per day are:
1) That the respondents are exposed to either treated or untreated water whether from an unimproved or improved source.
2) The use of \( E. coli \) as the reference pathogen, assumes that every \( E. coli \) ingested through drinking water constitutes an exposure, irrespective of the virulence of the strain of pathogen and that \( E. coli \) resistance and infectivity rates are similar to that of all other faecal pathogens including enteroviruses.

The first assumption is acceptable within the objective of this study because the study makes use of the actual \( E. coli \) concentrations of the drinking water samples from the study households to assess exposure before and after treatment with selected technologies.

The second assumption is justifiable on the basis that the study’s objective is not the prediction of the risk from a specific pathogen, but the estimation of the reduction in risk before and after treatment with a technology. This is based on the premise that a reduction in exposure translates into a reduction in risk (Brown and Clasen, 2012).

Calculation of the probability of infection before and after treatment with selected HWT technologies

This study calculated individual risks of infection per contamination event (van Lieverloo et al., 2007) and not a yearly event level of risk in order to minimize the effect of uncertainties related to changes in pattern of consumption, pathogen occurrence, and household treatment methods over a longer time frame.

The \( E. coli \) concentration in drinking water collection and storage containers were taken as detected contamination events.

Each value in the PDF of daily exposures was used to calculate the daily probability of infection i.e. the probability that a single exposure to \( E. coli \) from drinking water consumption will result in infection using the following formula (Abongo et al., 2008; van Lieverloo et al., 2007).  

\[ P_{\text{inf.d}} = 1 - (1 + \frac{d}{\beta})^{-\alpha} \]  

Equation 2

Where:
- \( P_{\text{inf.d}} \) = probability of infection risks per person per day
- \( d = \) infectious dose = CFU x g capita$^{-1}$ day$^{-1}$ or 1 025 ml person$^{-1}$ day$^{-1}$ based on the average daily intake of water of the study population
- \( \beta = \) Beta model parameter (0.422)
- \( \alpha = \) alpha model parameter (0.253)

The alpha and beta values were adopted from van Lieverloo et al. (2007) using the following dose-response model for enterovirus:

\[ P_{\text{inf.d}} = 1 - (1 + d/0.422)^{-0.253} \]

The difference in probability of infection before and after treatment was then quantified for each of the four selected HWT technologies, to represent the effect of each technology.
The assumptions made in determining the probability of risk of infection are that the risk of infection is dependent on the exposure to the reference pathogen, irrespective of individual immunity, prior exposure to the pathogen or virulence of the pathogen.

These assumptions are justified because the purpose of the assessment was to assess the potential of HWT to reduce health risks associated with the consumption of microbiologically polluted water by reducing exposure and probability of infection of HWT users to E. coli.

This approach conforms to the use of a prevention of infection approach strategy by the United States Environmental protection agency to reduce risks of enteric diseases associated with water-borne microbial pathogens (USEPA, 1992)

**Results**

*Escherichia coli* exposure per person per day before and after treatment with selected household water treatment technologies

The technologies did not differ significantly in exposure of their users to *E. coli* before water treatment with the HWT technologies, thus providing a basis for comparing the probability of infection after household water treatment.

Before treatment with Aquatab, PUR, Waterguard and ceramic filters did not differ statistically in user-exposure to water-borne pathogens if they consumed 1 025 ml of untreated water per person per day from *improved* sources (p = 0.41).

Before treatment with Aquatab, PUR and Waterguard, users were similar in exposure to water-borne pathogens if they ingested water from *unimproved* sources but differed significantly from ceramic filters users in exposure (p < 0.04).

When water from unimproved sources was treated, the four assessed technologies showed a reduction in user exposure to water-borne pathogens. This was demonstrated by comparing the user exposure before and after treatment with the selected technologies, based on the exposure to *E. coli* per person per day of an adult consuming an average of 1 025 ml of water per day from *unimproved* sources (Figure 1).

Figure 1 shows that ceramic filters had the highest reduction in user-exposure, even though the users had significantly higher exposure before treatment. In descending order, the mean log₁₀ reduction in exposure to *E. coli* (log₁₀ cfu/1025 ml per person per day) was ceramic filter (log₁₀ 2.1), Aquatab (log₁₀ 1.9), PUR (log₁₀ 1.5) and Waterguard (log₁₀ 0.9). The technologies did not differ significantly in difference in user-exposure after treatment (p = 0.80; not shown).

When water collected from *improved* sources was treated by households, the HWT technologies did not differ significantly in reduction in user exposure after treatment (p = 0.62).

**Table 2** Test of significance of difference in user–exposure between water sources used to test HWT technologies before and after treatment

<table>
<thead>
<tr>
<th>Water source category</th>
<th>Technology</th>
<th>Summary p - value between technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aquatab</td>
<td>PUR</td>
</tr>
<tr>
<td>Collection unimproved</td>
<td>2.4a</td>
<td>3.6a</td>
</tr>
<tr>
<td>Collection improved</td>
<td>3</td>
<td>3.5</td>
</tr>
<tr>
<td>Storage unimproved</td>
<td>0.5</td>
<td>2.1</td>
</tr>
<tr>
<td>Storage improved</td>
<td>0.8</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Similar Superscript letters denote no significant difference between technologies
When drinking water from improved sources was consumed, the mean difference in exposure to *E. coli* (log_{10} *E. coli* cfu/1025 ml of water per person per day) after treatment was: Aquatab (log_{10} 2.2), PUR (log_{10} 1.0), Waterguard (log_{10} 0.5) and ceramic filter (log_{10} 0.1; Figure 2).

**Average probability of infection with *Escherichia coli* per person per day before and after treatment with selected household water treatment technologies**

The technologies did not differ significantly in their users’ average probability of infection with *E. coli* per person per day before water treatment with the HWT technologies, thus providing a basis for comparing the probability of infection after household water treatment. This was the case whether the different HWT user households had been exposed to water collected from unimproved (0.11) or improved (0.12) sources (Table 3).

**Table 3** Test of significance of probability of infection of HWT user before and after water treatment

<table>
<thead>
<tr>
<th>Water source</th>
<th>Technology</th>
<th>p-value between technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aquatab</td>
<td>PUR Waterguard Ceramic filter</td>
</tr>
<tr>
<td>Collection</td>
<td>0.46±0.18</td>
<td>0.63±0.29 0.81±0.10 0.86±0.13</td>
</tr>
<tr>
<td>Collection</td>
<td>0.42±0.27</td>
<td>0.88±0.07 0.92 0.36±0.16</td>
</tr>
<tr>
<td>Storage</td>
<td>0.08±0.14</td>
<td>0.41±0.38 0.48±0.19 0.15±0.16</td>
</tr>
<tr>
<td>Storage</td>
<td>0.14±0.23</td>
<td>0.81±0.08 0.89 0.20±0.14</td>
</tr>
</tbody>
</table>

All the HWT technologies reduced the probability of infection in their users when the average probability of infection of an individual consuming untreated and treated water from improved and unimproved sources was compared.

When the average probability of infection with *E. coli* per day of an adult consuming an average of 1 025 ml of water per day from unimproved sources was compared before and after treatment with the selected technologies, the mean difference in probability of infection per person per day was: ceramic filter (0.71), Aquatab (0.38), Waterguard (0.33), PUR (0.22: p = 0.22; Figure 3).

In descending order, the mean difference in probability of infection with *E. coli* per person per day in an adult consuming 1 025 ml of treated water per day from improved sources, was: Aquatab (0.29), ceramic filter (0.16), PUR (0.08) and Waterguard (0.03: Figure 4).

**Figure 3.** Mean probability of infection per person per day with *Escherichia coli* before and after treatment of unimproved drinking water sources.

There was no statistical significance to the difference observed between technologies in the average probability of infection with *E. coli* of individual users after consuming treated water from unimproved (0.22) and improved sources (0.60).
Implications

In spite of the inability of the four HWT technologies to consistently reduce microbial concentrations in treated water to drinking water quality standards, this study showed that all the assessed HWT technologies reduced exposure to *Escherichia coli* and probability of infection in users after drinking water treatment.

The reduction in exposure to *E. coli* in users of the four technologies ranged from $\log_{10} 0.9$ to $\log_{10} 2.1$, when they consumed treated water from *unimproved* water sources and $\log_{10} 0.1$ to $\log_{10} 2.2$ when water from *improved* sources was treated and consumed. This translates to a reduction in average probability of infection per day with *E. coli* per individual ranging from 0.22–0.71 when water from *unimproved* sources was treated and consumed and 0.03–0.29 when treated water from *improved* sources was consumed.

Therefore the study observations do not support the school of thought that current evidence pointing to the health-related effects of HWT technologies is entirely due to bias.

Comparison of the household water treatment technologies’ effect on *Escherichia coli* exposure and probability of infection in unimproved water sources

In recognition of the dependence of these study communities and others on unimproved water sources, the HWT technologies were compared on the basis of the magnitude of reduction in exposure and risk to *E. coli* they achieved after users consumed untreated and treated water from unimproved sources.

Ceramic filters had the highest effect and reduced exposure by 57% and the average probability of infection from 8 600 per 10 000 to 1 500 per 10 000.

Waterguard had the lowest reduction of exposure in users of 23% and reduced average probability of infection from 8 100 per 10 000 to 4 800 per 10 000.

Given that the majority of these unimproved drinking water sources were highly turbid (mean 210.33 NTU±189.30), these findings reinforce the warning by Sobsey *et al.* (2009) that hypochlorite based water treatment methods should not be promoted without adequate measures to ensure that users can reduce the turbidity of the water before disinfection.

In contrast, Aquatab, though a hypochlorite based method, was second highest after ceramic filters amongst the four HWT technologies in reducing both risk parameters when water from *unimproved* sources was treated and consumed.

PUR acts as both a flocculant and a disinfectant (Lantagne *et al.*, 2006); it was therefore expected that the reduced turbidity before treatment, would lead to a higher reduction in exposure to *E. coli* and the probability of infection in a user of PUR compared to a Waterguard user. This expectation was confirmed concerning reduction in exposure with both *unimproved* and *improved* water sources.

However, Waterguard had a higher reduction in average probability of infection (0.33) than PUR (0.22) when *unimproved* water sources were treated and consumed but PUR had a higher reduction in average probability of infection in users (0.08) than Waterguard (0.03), when *improved* sources were treated.

The lack of consistency and closeness in the magnitude of risk reduction (probability of infection) is consistent with the observation by Sobsey *et al.* (2009) that turbidity might mask the actual efficacy of a water treatment method.

Comparison of the effect of household water treatment technologies on *Escherichia coli* exposure and average probability of infection in unimproved and improved water sources

Consumers of HWT-treated water collected from improved sources had a lower reduction in exposure to *E. coli* and the average probability of infection with *E. coli* than consumers of HWT treated water from *unimproved* sources.

For instance, the combined average reduction in the daily exposure to *E. coli* from treated *unimproved* water sources was $\log_{10} 1.6$ in comparison to $\log_{10} 1.2$ in the *improved* water sources, while the combined average after the consumption of treated water from *unimproved* water sources was 0.41 compared to 0.14 after consuming treated water from *improved* sources.

This is consistent with the observations from another study by same author that though the *improved* sources show a much higher deterioration in quality after the source than the *unimproved*, the *improved* sources were less contaminated at every stage than the *unimproved* sources.

It is therefore expected that higher quality water will result in a lower reduction in risk of exposure and infection. This is consistent with the report by Brown and Clasen (2012) that lower quality water has a higher health risk than water of higher quality and the health impact of HWT is greater where poorer quality water is used.

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1 Field note, November 2012*
In terms of individual technologies, ceramic filters showed the greatest contrast between improved and unimproved sources with the highest reduction in exposure to *E. coli* \((\log_{10} 2.1)\) of the four technologies, when treated water from unimproved water sources was consumed, but the lowest \((\log_{10} 0.1)\) when water from improved water sources was treated and consumed.

Similarly, the reduction in average probability of infection when a ceramic filter user consumed treated water from unimproved sources was almost four and a half times the reduction in average probability of infection when the consumed treated water was from improved water sources.

It is expected that the reduction in exposure and risk of infection of consumers of improved water will be lower because of its higher quality. This study’s findings can also be attributed to consumers of water from improved sources engaging in risky behavior by omitting to take the necessary steps to protect their drinking water (Wright et al., 2004), while those who take water from unimproved water sources may take more precautions (Brown and Clasen, 2012).

Brown and Clasen (2012) queried the role perception of water safety plays in user adherence and health risk, the KAP study conducted as part of this study found that households perceived rainwater as an improved source which did not require treatment, though rainwater used by the study households was found to be contaminated with *E. coli*.

**Conclusion**

This study found that in a post-implementation and typical-use setting, the HWT technologies reduced the user’s exposure to pathogens (*E. coli* as indicator) and probability of infection when unimproved and improved water sources were treated and consumed.

This suggests that though they were unable to consistently meet stipulated drinking water standards, the technologies provide some level of protection to the consumer even post-implementation when external support had been withdrawn from the users.

Though the four HWT products, reduced the probability of infection with *E. coli*, the risk to the user after treatment with each of the HWT products was still much higher than the acceptable annual risk stipulated by the USEPA. This is not surprising because though the study households generally perceived the HWT technologies as high value products, they were unable to use them correctly.

**Lessons Learned**

The experience of HWT as practiced post-implementation in the Western and Nyanza provinces of Kenya, have demonstrated the HWT technologies’ ability to reduce health risks in a real-world high risk setting of poor water quality, inadequate sanitation and unhygienic user behaviour. The following are the main lessons learned from this study:

1. Though the assessed HWT technologies did not achieve the expected baseline log reduction in microbial concentration, all the technologies were able to reduce the HWT user’s risk of exposure to and infection with *E. coli*.
2. Consumers of HWT-treated water collected from improved sources had a lower reduction in exposure to *E. coli* and the average probability of infection with *E. coli* than consumers of HWT treated water from unimproved sources.
3. The health impact of HWT is greater where poorer quality water is used because lower quality water has a higher health risk than water of higher quality.

**Next Steps**

While it is recognised that many classes of pathogens found in faeces are able to cause waterborne infections (Leclerc et al., 2002) and that apart from exposure, other factors such as virulence, infectivity, individual immunity determine the probability of infection with water-borne diseases (WHO, 2008), this study’s findings provide a preliminary basis for decision-making about the promotion of HWT technologies.

The study findings lend support to two alternate scenarios: The first is discontinuing the large-scale HWT technology promotion based on the observation that though HWT technologies reduce the risks of infection, they do not consistently do so to a point where HWT-treated water can be considered as holding negligible risks of exposure and infection to the consumer.

The second is continuing HWT promotion, based on the study’s observation of reduced risk of exposure to and with infection by water-borne pathogens in consumers of HWT-treated water. Since these users would otherwise be fully exposed to the health risks of consuming untreated water from polluted sources.

This author supports a third scenario, suggested by Sobsey et al. (2009), that HWT technologies should be promoted with an urgent call for the appropriate guidelines and appropriate supportive technology to help the users of HWT improve the effectiveness of HWT technologies.
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