Calibrating an optimal condition model for solar water disinfection in peri-urban household water treatment in Kampala, Uganda

Kenan Okurut, Eleanor Wozei, Robinah Kulabako, Lillian Nabasirye and Joel Kinobe

ABSTRACT

In low income settlements where the quality of drinking water is highly contaminated due to poor hygienic practices at community and household levels, there is need for appropriate, simple, affordable and environmentally sustainable household water treatment technology. Solar water disinfection (SODIS) that utilizes both the thermal and ultra-violet effect of solar radiation to disinfect water can be used to treat small quantities of water at household level to improve its bacteriological quality for drinking purposes. This study investigated the efficacy of the SODIS treatment method in Uganda and determined the optimal condition for effective disinfection. Results of raw water samples from the study area showed deterioration in bacteriological quality of water moved from source to the household; from 3 to 36 cfu/100 mL for tap water and 75 to 126 cfu/100 mL for spring water, using thermotolerant coliforms (TTCs) as indicator microorganisms. SODIS experiments showed over 99.9% inactivation of TTCs in 6 h of exposure, with a threshold temperature of 39.5 ± 0.7 °C at about 12:00 noon, in the sun during a clear sunny day. A mathematical optimal condition model for effective disinfection has been calibrated to predict the decline of the number of viable microorganisms over time.

Key words | calibrating, Kampala, model, peri-urban, solar water disinfection, thermotolerant coliforms

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INTRODUCTION

Contamination of water during collection, transportation and storage between source and households has been found to be a common occurrence in most low-income settlements worldwide. Low-income urban earners tend to settle in peri-urban areas that are characterized by poor hygienic practices that impact the natural qualities of water sources (Kulabako *et al.* 2007) and re-contaminate drinking water before it is consumed at the household. A statement by the United Nations (UN) points to this fact: *'Even using an improved water source is no guarantee that the water is safe; when tested, the drinking water obtained from many improved sources has not met the microbiological standards set by WHO'* (UN 2009). Water sources used by the inhabitants in peri-urban areas may be contaminated by surface and/or sub-surface runoffs, leachate, poor solid waste management practices and lack of hygienic practices between source and point of use (Kulabako *et al.* 2007).

Due to economic and population pressures on land use activities, the urban poor tend to settle in less costly areas of land found to be low lying with a high groundwater table and prone to flooding. The predominant forms of sanitation facilities are unhygienic pit latrines that are elevated due to the high water table, thus making their accessibility difficult for children and disabled users (Kulabako 2005). The pit latrines can contaminate shallow groundwater sources used by the community and impair the proper delivery of

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safe water and sanitation services in the community. The quality of water at the household level in such settlements does not always meet acceptable standards for drinking water due to contamination and is hence unsafe for drinking (Schneider 2008).

Despite global attempts to increase improved water sources for communities, such as boreholes or standpipes, recontamination between source and household during collection, transportation and storage may still make many more people than estimated drink unsafe water from improved sources (Lantagne *et al.* 2005). Consumption of unsafe water, inadequate sanitation and poor hygiene is estimated to contribute to about 88% of diarrhoeal deaths worldwide (United Nations Children's Fund/World Health Organization (UNICEF/WHO) 2009). This calls for a household water treatment and safe storage technology (HWTS) that is affordable and adaptable to the local conditions. Due to the income status of peri-urban poor inhabitants, they may not afford the common HWTS options of boiling and use of chlorine tablets, and are left with no option than to consume the water without any household treatment. In the case of boiling, for instance, the need for about 1 kg of wood to boil 1 L of water can be unjustifiable in fuel-short regions in many parts of sub-Saharan African that are already suffering from aridity and desertification (Acra *et al.* 1984). Additionally, these parts rank last in the world in terms of safe water access with only 22–34% of the population in at least eight sub-Saharan countries having access to safe water (Tatlock 2006).

Sustainable use of natural resources as a key concept in energy management and conservation considers the utilization of solar radiation to conserve the environment and put into use the naturally available energy from the sun and is proving to be more important in the sub-Saharan countries which receive ample sunlight year-round (Acra *et al.* 1990). While the world is taking all measures to reduce the causes and effects of global warming, radiation from the sun can be utilized for disinfection and savings made on other forms of energies to conserve the environment. Solar radiation for water disinfection is an ancient practice that had been used without profound understanding of the process until the idea was presented by Aftim Acra in a booklet published by UNICEF in 1984 (Meierhofer & Wegelin 2002).

Solar water disinfection (SODIS) is a simple, environmentally sustainable, low-cost solution for drinking-water treatment at household levels (Meierhofer & Wegelin 2007). The published method involves filling transparent polyethylene terephthalate (PET) plastic bottles with water for drinking, and exposing the bottles to full sunlight for adequate duration for inactivation of bacterial cells and cysts. Pathogenic microorganisms in the water are vulnerable to effects of heat and ultra-violet radiation from the sun (UNICEF/WHO 2009). As the process uses solar energy, families are able to save on fuel that would otherwise be used to boil drinking water. Savings are made from reduced expenses on medical care and other costly methods of treating water. Also, recontamination is unlikely because, according to best practice, water is consumed directly from the small narrow-necked bottle (with caps) in which it is treated.

Studies have revealed that a 99.9% inactivation of indicator organisms is attained at 6 h of exposure to direct sunshine (Meierhofer & Wegelin 2002; Wozei *et al.* 2010; Okurut *et al.* 2011). Meyer & Reed (2001) report a 99.99% reduction in both faecal and total coliform counts within 4–6 h. Wegelin *et al.* (1994) report that water temperatures with a threshold of ~50 °C considerably increase the inactivation rate with a dose of ~5 h of mid-latitude midday summer sunshine. The work of these authors did not show a quantitative relationship between inactivation rate and duration of exposure except Okurut *et al.* (2011). Craggs *et al.* (2004) developed a model of effective disinfection from Chick's law that relates kill efficacy of microorganisms in a sample and contact time t, with a disinfecting agent to predict the decline of the number of viable microorganisms over time (American Chemistry Council (ACC) 2007). As contact time between a water sample and the disinfectant increases, the ratio of initial microorganism counts (N_0) to measured counts (N) decreases as Chick's law predicts, Equation (1).

$$\frac{\mathrm{d}N}{\mathrm{d}t} = -k(t)N \tag{1}$$

where $k(t)$ is disinfection rate (h^{-1}) which is a function of time t. N is the variable number of microorganisms (colony-forming units (cfu)/100 mL) at time t.

However, Okurut (2011) did not report on the threshold temperature over which the model works. Results of the work of Okurut *et al*. (2011) have been further developed to investigate the threshold temperature at the optimal condition of exposure for effective SODIS of drinking water in the study area. The study was conducted in Mulago III/ Kifumbira Zone – Kawempe Division in Kampala, Uganda. The area is inhabited by a transient urban poor population, as defined by the UN-Habitat (2006) who mainly depend on groundwater sources for domestic use (AquaConsult 2002). The main objective of this study was to calibrate an optimal condition model for SODIS in peri-urban household water treatment in the study area.

MATERIALS AND METHODS

Sampling strategy

Fifty households for the study were randomly selected from a population of 150 households that were identified to meet set criteria for the SODIS study. The population comprised of households that had no piped water system in their houses, and were willing to participate in the research. Water sources used by the 50 households were ranked according to number of users from the study households, and six (four standpipes and two springs) of the most commonly used sources were selected for detailed characterization from 21 sources in the study area.

Bi-weekly raw water samples from the six selected water sources were collected for water quality analysis for 3 months (December 2009 to February 2010), so as to obtain information on the baseline characteristics of the water sources. Five SODIS experiments were carried out on samples from water sources used by the study households to calibrate the optimal condition model of effective disinfection.

Analysis of water quality parameters

To ascertain the need for water treatment at household level, samples collected from both household (end-use) water storage containers and the water sources were analysed for selected physical, chemical and microbiological parameters. Water quality analysis included determination of temperature, electrical conductivity (EC), dissolved oxygen (DO), pH, total dissolved solids (TDS), turbidity, nitrates (NO_3^-), colour and thermotolerant coliforms (TTCs). TTC bacteria were used as indicator microorganisms to determine any microbiological contamination in the water samples. The reduction in TTC counts during the solar disinfection process was used to calibrate the optimal condition model. The significance of TTC is that their detection provides evidence of microorganisms of faecal origin that can even survive at temperatures above body temperature. TTC are defined as a group of coliform organisms that are able to ferment lactose at 44–45 °C (WHO 1996).

The physical parameters of source water (temperature, pH, DO, turbidity, EC and TDS) were measured *in situ* using the field meters. The temperature (°C) and pH of the water samples were measured using a HANNA, HI 991003, pH/pH-mV/ORP/Temperature meter. EC and TDS were measured using a HANNA, HI 9835, Microprocessor, Conductivity/TDS meter in μS/cm and mg/L respectively. DO content was measured in mg/L using a HANNA, HI 9146, Microprocessor, DO meter. The meters were checked and calibrated according to their operational manuals (HANNA 2010).

Water samples for laboratory analysis were collected in autoclaved-sterile plastic sample bottles and transported in an ice box (4 °C) to avoid multiplication of bacteria in the samples during collection and transportation. All samples were analysed within 3 h of collection. Turbidity, colour and nitrates were determined using a HACH DR/4000 spectrophotometer and respective methods according to procedures described in the handbook (HACH 2003).

The membrane filtration method using membrane lauryl sulphate broth growth medium with incubation at 44 ± 0.5 °C for 18–24 h was used to enumerate TTC colonies according to the *Standard Methods for Examination of Water and Wastewater* jointly prepared and published by American Public Health Association, American Water Works Association and Water Environment Federation (APHA/AWWA/WEF 1998). Pale yellow bacteria colonies of at least 1 mm diameter were counted as coliform bacteria colonies. The results were reported as colony-forming units per 100 mL of sample (cfu/100 mL).

SODIS experimental set ups

Water used in the SODIS experiments was collected from the water sources and put into transparent 1 L PET bottles as unseeded samples. Some samples from the water sources were first seeded with polluted water from a waste stabilization pond to simulate a high level of contamination. Seeding was necessary because measurements showed that the raw water had low levels of contamination and could not represent extreme conditions needed for a better generalization of the versatility of SODIS application. Unspiked controls were included in all experiments. For the SODIS experiment and the controls, samples in the PET bottles were prepared in duplicate for each time point, with one set exposed to direct sunlight and the other set kept in a dark room (controls) for 7 h between 0900 h and 1600 h. A pair of bottles was sacrificed for analysis at specific exposure time points of 1, 2, 3, 4, 5, 6 and 7 h after placing the bottles in the sun. The temperature of the water at the different time points for the control sets and SODIS experiments during solar disinfection were measured using thermometers inserted in sample filled PET bottles placed with each of the sets. The sample filled bottle with the thermometer was kept in the dark room/sun until all the bottles control/exposed during the experiment were sacrificed for analysis. The exposed samples were placed in the sunlight on a $1.2 \times 1.2\ \mathrm{m}^2$ and 1.2 m high SODIS table made of corrugated iron sheet and wooden stands.

Data analysis

Graphical plots developed with Slidewrite Plus version 6.1 (Advanced Graphics Software, Inc. 2002) were used to depict baseline water quality characteristics at water sources and in household storage containers in the study area. Statistical analysis was carried out using SPSS version 16 (SPSS Inc. 2007) to determine the arithmetic mean and standard error (SE).

An optimal condition model for effective SODIS was calibrated based on Chick's law that predicts the decline of the number of viable microorganisms over time (Equation (1)). $k(t)$ is composed of the dark disinfection rate k_d (h^{-1}) and light disinfection rate $k_\mathrm{s}G(t)$ in h^{-1}.

Separating variables and substituting for $k(t)$, Equation (1) becomes

$$\frac{\mathrm{d}N}{N} = -[k_\mathrm{d} + k_\mathrm{s}G(t)]\mathrm{d}t \tag{2}$$

G is the total solar irradiance ($\mathrm{Jm}^{-2}\,\mathrm{s}^{-1}$) incident (Craggs *et al.* 2004) upon the PET bottle. k_s is light disinfection rate coefficient ($\mathrm{MJ}^{-1}\,\mathrm{m}^2\,\mathrm{h}^{-1}$).

Integrating Equation (2) yields

$\ln(N) = –k_\mathrm{d}t–k_\mathrm{s}S(t) + C$; C is the constant of integration, $S(t) = \int_{\theta=0}^{\theta=t} G(\theta)\mathrm{d}\theta$At $t = 0$, $N = N_0$, $t = 0$; then

$$\ln(N) = \ln(N_0) - k_\mathrm{d}t - k_\mathrm{s}S(t) \tag{3}$$

where S is the total insolation ($\mathrm{MJ\,m}^{-2}$) incident upon the bottle over a specified period of time. Total insolation S, for the study area has been estimated at 5 $\mathrm{MJ\,m}^{-2}$ (Hankins 1995).

For the set of samples kept in the dark room (control), it is assumed that $G \approx 0$ and that there was no recovery of inactivated bacteria during the experimental period; Equation (3) then becomes

$$\ln(N_\mathrm{C}) = \ln(N_0) - k_\mathrm{d}t \tag{4}$$

Therefore, the slope in the linear regression fit of $\ln(N_\mathrm{C})$ against t gives the dark disinfection rate k_d (h^{-1}).

Dark disinfection rate k_d for each experiment is then substituted in Equation (3) to transform it with k_s as the only unknown as;

$$\ln(N_\mathrm{E}) + k_\mathrm{d}t = \ln(N_0) - k_\mathrm{s}S(t) \tag{5}$$

With known values of k_d, the measured TTC counts for exposed sets corrected for dark inactivation or die-off ($\ln(N_\mathrm{E}) + k_\mathrm{d}t$) is plotted against insolation and the linear regression fit of the graph estimates the light disinfection rate coefficient k_s per exposed bottle in $\mathrm{MJ}^{-1}\,\mathrm{m}^2\,\mathrm{h}^{-1}$.

The overall average k_s value for all the experiments is then the light disinfection rate coefficient for the study area to be incorporated in the mathematical model.

RESULTS AND DISCUSSION

Baseline water quality parameters

Arithmetic mean parameters of the baseline quality of raw water taken from water sources and the water storage containers at the households (Figure 1) indicate deterioration in bacteriological quality of water between sources (standpipes and unprotected springs) and the households. The values of most of the parameters measured for both water sources and household water storage containers were outside acceptable limits set by the World Health Organization (WHO).

Deterioration in water quality is a result of contamination during collection, transportation and storage from multiple factors linked to hygiene practices and circumstances at the point of supply and consumption (Clasen & Bastable 2003; Trevett *et al.* 2005). The need to maintain a safe water chain between the source and/within the households is to reduce incidences of water-borne and water-related diseases that may affect the health, social, economic and general well-being of the people (Wozei *et al.* 2010) in the community. Poor water quality at the springs could be due to contamination by unlined pit latrines constructed in flood areas and poor solid waste management practices reported by the Ministry of Water and Environment, Government of Uganda (MWE-GoU 2010) in the communities. This implies that water in household storage containers is not always safe for drinking and hence there is a need for a household water treatment technology to improve the bacteriological quality of water for drinking purposes. However, the value of some physico-chemical parameters (DO, pH and nitrates) recorded at household water storage containers may influence the rate of inactivation during a SODIS process.

Variations in water quality between source and household are presented under each parameter measured.

Temperature

The lowest temperature of water samples taken from the water sources was 20.9 °C, recorded at the unprotected

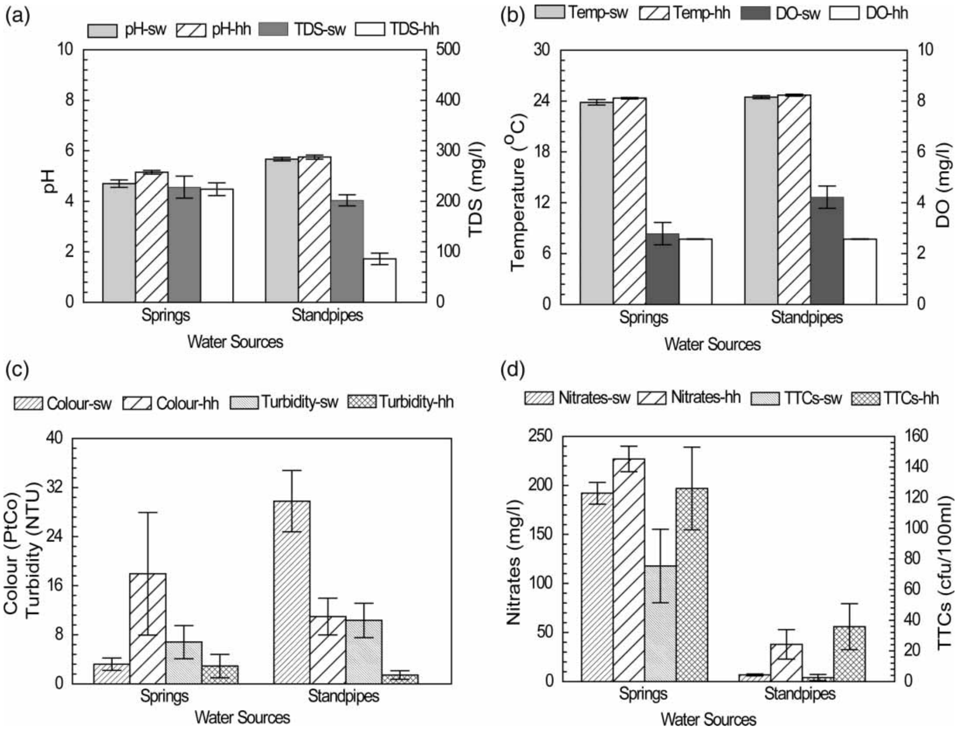

Figure 1 | Graphs of selected water quality parameters for community water sources (sw) and household water storage containers (hh) in the study area (bars represent average values ± SE, $n = 13$).

springs and the highest was 25.8 °C at the standpipes. There was some increase in mean water temperature (23.8–24.3 °C) for spring water when the water was moved from source to household water storage containers due to a change in room temperatures (~25 °C) in the households where the water storage containers are often kept.

Electrical conductivity (EC)

The arithmetic mean of EC recorded in unprotected springs was 443 ± 17.0 μS/cm, which agrees with results of other studies carried out in Kampala (Miret 2004; Haruna *et al.* 2005) that were ranging between 411–502 and 95–705 μS/cm, respectively. Standpipes show low EC (158 ± 3.6 μS/cm) which is indicative of better quality water from taps as compared with water from the springs (Hitchon *et al.* 1999).

Dissolved oxygen (DO)

The arithmetic mean value of DO was found to decrease from source to households for both tap and spring waters. Highly reactive forms of oxygen, including oxygen-free radicals and hydrogen peroxides, are formed in well-oxygenated water when exposed to sunlight (Reed 1997). These forms of oxygen inactivate microorganisms by oxidizing microbial cellular components, such as nucleic acids, enzymes, and membrane lipids and their presence accelerates the solar inactivation process (Reed 1996). The low DO content at the springs is an indication of the existence of oxidizable organic matter (Hitchon *et al.* 1999) probably coming from contamination by unlined pit latrines.

pH

The mean pH values of both source and household waters were all out of the acceptable range (6.5–8.5) for drinking water (WHO 2004b). The minimum and maximum pH of 4.7 and 5.7 recorded were in spring water at source and tap water at the household water storage containers, respectively. The arithmetic mean pH for spring water of 4.7 ± 0.1 falls within a range (4.4–4.9) reported in a study on springs in Bwaise – Kawempe Division (Miret 2004). The low pH levels recorded at both source and household storage containers can positively enhance the inactivation of some species of microorganisms by sunlight as the low pH levels present additional stress to the cell of a microorganism being inactivated, for example by requiring it to expend energy maintaining the pH (Fisher *et al.* 2008).

Total dissolved solids (TDS)

The arithmetic mean values of TDS in the study samples were lowest at the standpipes (86 mg/L) and highest (228 mg/L) at unprotected springs (Figure 1). There was no significant difference ($p < 0.01$, $n = 13$) in levels of TDS in spring water at water sources and household water storage containers. However, TDS of tap water reduced by about 57% when the water was moved from water source to household water storage containers.

Turbidity

Results of baseline water quality conditions indicate improvement in turbidity from source to household water storage containers to a level less than 5 Nepthelometric Turbidity Units (NTU); which is the acceptable limit for drinking water according to WHO guidelines (WHO 2004b). The improvement could probably be a result of settlement and tendency of some particles to stick on the inner surfaces of the storage containers when the water is left undisturbed for some time. Arithmetic mean turbidity of 6.8 ± 3 NTU was recorded for spring water at source and 2.9 ± 2 NTU for spring water at household while 10.3 ± 2 NTU and 1.4 ± 1 NTU were recorded for tap water at source and households respectively. For both water sources and household water storage containers, the arithmetic mean turbidity recorded of less than 30 NTU is desired for effective SODIS.

Nitrates

The acceptable limit of nitrate concentration in drinking water is 50 mg/L (WHO 2011). Results show a high concentration of nitrates in spring water of 192 ± 11 mg/L recorded at the water sources which is indicative of pollution of ground water by shallow and raised pit latrines constructed near the ground surface (Dzwairoa *et al.* 2006) because of high water tables, and poor solid waste management practices in the community. In the water storage containers, there is a recorded increase in nitrate concentration (227 ± 13 mg/L) which could be due to poor hygiene and sanitation practices at the households. The high nitrates recorded in the spring water can enhance the rate of inactivation of microorganisms during a SODIS process (Rincón & Pulgarin 2007).

Apparent colour

The arithmetic mean of apparent colour measurements of water recorded at the standpipe taps of 30 ± 5 PtCo units was higher than the colour of the spring water of 3 ± 1 PtCo units. Since turbidity may also cause an apparent colour in water, improvement in apparent colour of tap water at the households from 29.7 ± 5 PtCo units to 10.9 ± 3 PtCo units, could probably be a result of settlement of non-colloidal suspended particles in the water when the water is moved from the water source to the household water storage container and allowed to stand undisturbed for some time.

Bacteriological analysis

Mean TTC counts for water samples taken from household storage water containers (126 ± 27 cfu/100 mL for water collected from springs and 36 ± 15 cfu/100 mL for water collected from taps) were found to be higher than the values recorded at water sources (75 ± 24 cfu/100 mL for water at the springs and 3 ± 2 cfu/100 mL for water at the taps). The increase of TTC counts in water at the household storage containers indicate bacteriological contamination of water within the households and water storage containers, and during water movement from source to household (Lantagne *et al.* 2005).

The values of TTCs of up to 300 cfu/100 mL, recorded in the baseline water quality conditions at households provide high health risks and hence necessitate a HWTS technology that is cheap, simple and sustainable for the community.

Results of the SODIS experiments carried out on four source water samples are presented in Table 1. The raw water sample for experiment 1 was not seeded with polluted water from waste stabilization ponds so as to ascertain the difference in die-off trends for both a typical sample and one seeded to simulate to a high starting value of TTC counts.

It was observed that TTC inactivation in the seeded samples followed a different trend compared to that of the unseeded samples.

Mathematical model of optimal conditions for effective solar disinfection in the study area

Table 2 shows values of natural logarithms ($\ln(N)$) for controls ($\ln(N_C)$) and exposed ($\ln(N_E)$) calculated from the measured TTC counts (Table 1). The $\ln(N_C)$ values are

Table 1 | Results of TTC counts for analysed SODIS experimental samples

	N_1		N_2		N_3		N_4	
Sample time points	**Control**	**Exposed**	**Control**	**Exposed**	**Control**	**Exposed**	**Control**	**Exposed**
Seeded/polluted sample	–	–	100,000	100,000	238,000	238,000	100,000	100,000
9:00 h	266	266	12,100	12,100	148,000	148,000	90,000	90,000
10:00 h	264	29	11,500	63,00	162,000	22,889	70,000	10,000
11:00 h	252	1	4,700	500	146,000	19,800	60,000	1,000
12:00 h	207	0	10,800	226	10,7000	5,800	80,000	223
13:00 h	182	0	7,500	66	104,000	1,750	32,223	30
14:00 h	225	0	10,600	46	102,000	178	43,334	10
15:00 h	185	0	6,500	16	98,000	94	30,000	16
16:00 h	154	0	45,00	24	97,000	50	13,334	9

N_x = TTC counts in cfu/100 mL; where X is experiment number 1, 2, 3, 4. Laboratory experiments were done at an ambient temperature of 25 °C.

Table 2 | Natural logarithms of TTC counts for four samples experimented on SODIS at varying exposure durations

Duration of exposure, *t* (h)	**ln(N_1) ln(N_{C1})**	**ln(N_{E1})**	**ln(N_2) ln(N_{C2})**	**ln(N_{E2})**	**ln(N_3) ln(N_{C3})**	**ln(N_{E3})**	**ln(N_4) ln(N_{C4})**	**ln(N_{E4})**
0	5.58	5.58	9.40	9.40	11.90	11.90	11.41	11.41
1	5.58	3.37	9.35	8.75	12.00	10.04	11.16	9.21
2	5.53	0.00	8.46	6.21	11.89	9.89	11.00	6.91
3	5.33	–	9.29	5.42	11.58	8.67	11.29	5.41
4	5.20	–	8.92	4.19	11.55	7.47	10.38	3.40
5	5.42	–	9.27	3.83	11.53	5.18	10.68	2.30
6	5.22	–	8.78	2.77	11.49	4.54	10.31	2.77
7	5.04	–	8.41	3.18	11.48	3.91	10.19	2.20
Slope k_d in linear regression fit of ln(N_C) versus t			−0.09		−0.08		−0.18	
Overall average k_d							– 0.12 ± 0.03	

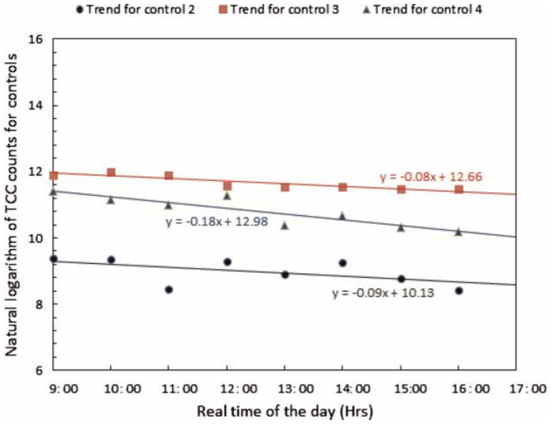

Figure 2 | Plot of ln(TTC counts) for controls against real time of the day for control set 2 on day 2, control set 3 on day 3 and control set 4 on day 4.

plotted against the duration of exposure t (Figure 2) to determine the linear regression fit as described by Equation (4) for each of the experiments.

The overall average dark disinfection rate k_d value for all the experiments is $0.12 \pm 0.03\ \mathrm{h}^{-1}$. This is the natural disinfection rate for the study area to be incorporated in the mathematical model.

Dark disinfection rate k_d for each experiment is substituted in Equation (5) and the corrected light disinfection $(\ln(N_E) + k_d t)$ shown in Table 3 is plotted against insolation. The linear regression fit of the plot (Figure 3) gives overall average light disinfection rate coefficient, k_s of $0.21 \pm 0.02\ \mathrm{MJ}^{-1}\ \mathrm{m}^2\ \mathrm{h}^{-1}$.

Table 3 | Computation of corrected light disinfection for exposed samples

		Natural logarithm of TTC counts for exposure samples					
		Uncorrected			**Corrected**		
Duration of exposure, *t* (h)	**Insolation $S = 5t$ (MJ m^{-2})**	**ln(N_{E2})**	**ln(N_{E3})**	**ln(N_{E4})**	**ln(N_{E2}) + $k_d t$**	**ln(N_{E3}) + $k_d t$**	**ln(N_{E4}) + $k_d t$**
0	0	9.40	11.90	11.41	9.40	11.90	11.41
1	5	8.75	10.04	9.21	8.84	10.12	9.39
2	10	6.21	9.89	6.91	6.39	10.05	7.26
3	15	5.42	8.67	5.41	5.70	8.91	5.94
4	20	4.19	7.47	3.40	4.56	7.79	4.10
5	25	3.83	5.18	2.30	4.29	5.58	3.18
6	30	2.77	4.54	2.77	3.32	5.01	3.82
7	35	3.18	3.91	2.20	3.82	4.46	3.43
		K_d = 0.09	K_d = 0.08	K_d = 0.18			
Slope k_s in linear regression fit of ln(N_E) + $k_d t$ versus $S(t)$					−0.19	−0.22	−0.23
Overall average k_s					– 0.21 ± 0.02		

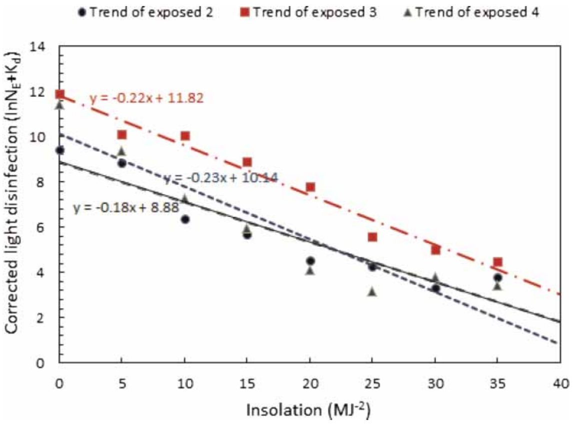

Figure 3 | Plot of ($\ln N_C + k_d t$) against $S(t)$ for the experiments of exposed set 2 on day 2, exposed set 3 on day 3 and exposed set 4 on day 4.

A summary of solar disinfection rate parameters that are incorporated in the mathematical model is shown in Table 4.

Substituting for k_d and k_s in Equation (3) gives a mathematical model for estimating the surviving TTC bacteria N after time t in water during a SODIS water treatment process:

$$\ln(N) = \ln(N_0) - (0.12 \pm 0.03)t - (0.21 \pm 0.02)S(t) \qquad (6)$$

On day 5 during experiment 5, there was cloud cover in the sky (10:00–10:40 am) which could have interrupted the inactivation trend in the exposed set. Results of experiment 5 have therefore not been used in determining the disinfection parameters in the model.

Temperatures of water in the PET bottles and efficacy of solar water disinfection

Temperatures of water in the exposed bottles were measured as each bottle was sacrificed for analysis of TTC indicator microorganisms at every time point. The temperatures in the water bottles and inactivation of TTCs were plotted against real exposure times to compare the trends for the same set of samples in Figures 4(a) and (b) respectively. The average maximum temperature of 39.5 ± 0.7 °C was recorded at 12:00 noon. By this time of the day, more than 95% of the TTC indicator microorganisms had been inactivated in the samples. The maximum temperature was recorded at midday, a time when the maximum daily mean solar radiation is experienced in the study area (Hankins 1995). This indicates that the solar inactivation rate is at a maximum in the PET bottles at the maximum daily mean solar radiation for the locality which occurs at 12:00 noon.

Results of the experiments show that a 99.9% reduction in TTC counts requires at least 6 h of direct exposure of raw water in PET bottles in the sun during a clear sunny day with a threshold temperature of 39.5 ± 0.7 °C at about 12:00 noon. The inactivation efficacy achieved in this study agrees with what has been reported by other authors (Meierhofer & Wegelin 2002; Wozei *et al.* 2010). Meyer & Reed (2001) report a 99.99% reduction in both faecal and total coliform counts within 4–6 h.

The arithmetic mean values of TTC reduction in the samples (exposed and control sets) were calculated and the mean reduction plotted against real time of exposure to direct sunlight (Figure 4(b)), to show a typical inactivation/die-off trend of TTC counts (N/N_0).

Both the ambient environment within the dark room and around the exposed bottles could have been influenced by solar irradiance and diffusion by clouds during the day as the inactivation rate declines with decreasing solar intensity towards evening.

Table 4 | Solar disinfection rate parameters

	Dark disinfection rate k_d (h^{-1})			Light disinfection rate coefficient k_s ($MJ^{-1}\ m^2\ h^{-1}$)		
	N_{C2}	N_{C3}	N_{C4}	N_{E2}	N_{E3}	N_{E4}
Parameters	**0.09**	**0.08**	**0.18**	**0.18**	**0.22**	**0.23**
Average	0.12 ± 0.03			0.21 ± 0.02		

Where N_C is number of thermotolerant coliform colonies in the control PET bottle.
N_E is number of thermotolerant coliform colonies in the exposed PET bottle.

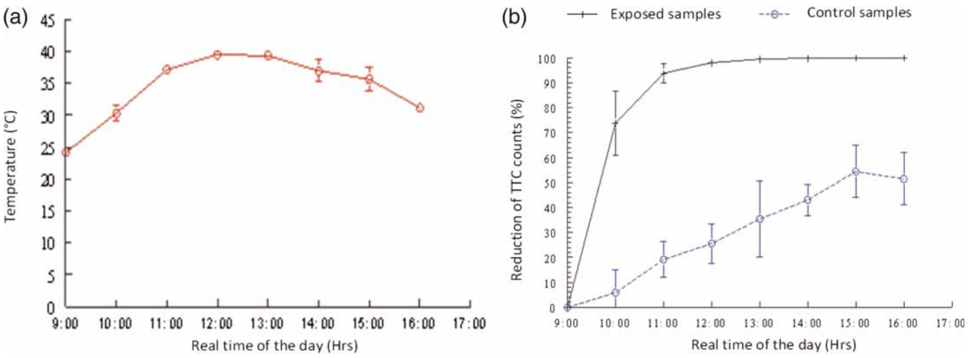

Figure 4 | Water temperature in the PET exposed bottles (a) and typical trend of TTC inactivation in control (dark room) and exposed samples, during the 7 h of SODIS experiments (mean values ± SE, $n = 3$).

Model verification

Results of the measured and calculated TTC counts of experiment 5 (Table 5) have been plotted against duration of exposure on the same axis (Figure 5) to assess the response of the model to actual die-off trend.

From Figure 5, it is noted that actual (measured) and model (calculated) die-offs follow the same trend. There are displacements of points for actual and model values at 11:00 am and 12:00 noon. These displacements could probably be a result of any or a combination of error due to model accuracy and model limitations, since there was cloud cover that diffused the sun radiation and could have affected the rate of inactivation during the experimental day.

Table 5 | Measured and calculated TTC counts for experiment 5

		N_{E1}		N_{E5}	
Time point	**Insolation $S(t) = 5$ t**	**Measured**	**Calculated**	**Measured**	**Calculated**
0	0	266	266	12,900	12,900
1	5	29	82	3,700	3,984
2	10	1	26	900	1,236
3	15	0	8	700	384
4	20	0	2	286	119
5	25	0	0	100	37
6	30	0	0	38	11
7	35	0	0	16	4

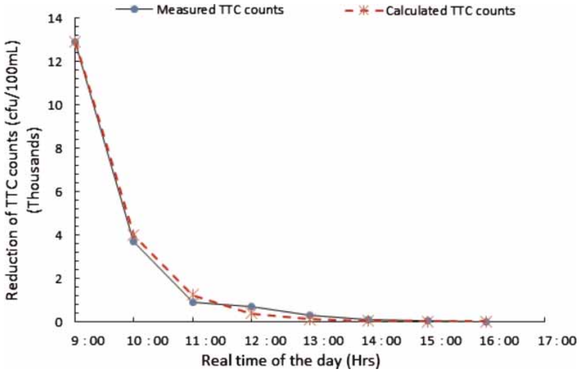

Figure 5 | Trends of TTC inactivation in the same sample for measured and calculated counts to verify the calibrated model.

The verification shows that the calibrated optimal condition model works well for various raw water qualities (Salih 2003) and therefore, a community can trust that SODIS used properly can inactivate organisms in their household water enough for use as drinking water. However, when there is cloud cover or very poor raw water SODIS has limitations so then suitable pre-treatment or an alternative treatment is advised by the Swiss Federal Institute of Environmental Science and Technology (EAWAG), Department of Water and Sanitation in Developing Countries (SANDEC) for health and safety reasons (EAWAG/SANDEC 2002).

CONCLUSIONS

Field and laboratory analysis of water samples in Mulago III/Kifumbira zone depict a deterioration in bacterial quality of water between sources and household due to contamination during collection, transportation and storage which probably explains the continual occurrence of diarrhoeal diseases (WHO 2004a) in these areas, despite increasing provision (MWE-GoU 2010) of piped and non-piped water supplies.

The optimal conditions for effective solar disinfection of spring and tap water in Mulago III/Kifumbira zone are: 6 h of exposure in transparent PET bottles of 10 cm water depths with a threshold temperature of $39.5 \pm 0.7\,^{\circ}\mathrm{C}$ at about 12:00 noon, to direct sunlight on a clear sunny day. SODIS treatment technology can reduce the bacterial counts in drinking water by up to 99.9% within 6 h of exposure, on a corrugated iron sheet, to direct sunlight (with TTC as indicator organisms measured using the membrane filtration method described in the analysis of water quality parameters) in Mulago III Parish, a peri-urban area in Uganda. When properly applied, SODIS is an effective HWTS option for peri-urban households.

The inactivation kinetics of TTCs in water during a SODIS process in the study area has been used to calibrate an optimal condition model for SODIS in peri-urban household water treatment for Kampala, Uganda, based on Chick's law. When the contamination (initial TTC counts) of a water sample is known, the reduction in the number of viable microorganisms in the sample after a specific time of exposure can be estimated using the model. This model explains the inactivation trend of TTC during the SODIS process in the study area.

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