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Effectiveness and health risk assessment of drinking water from different sources treated by local household water treatment methods in Bamenda, Cameroon

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ABSTRACT

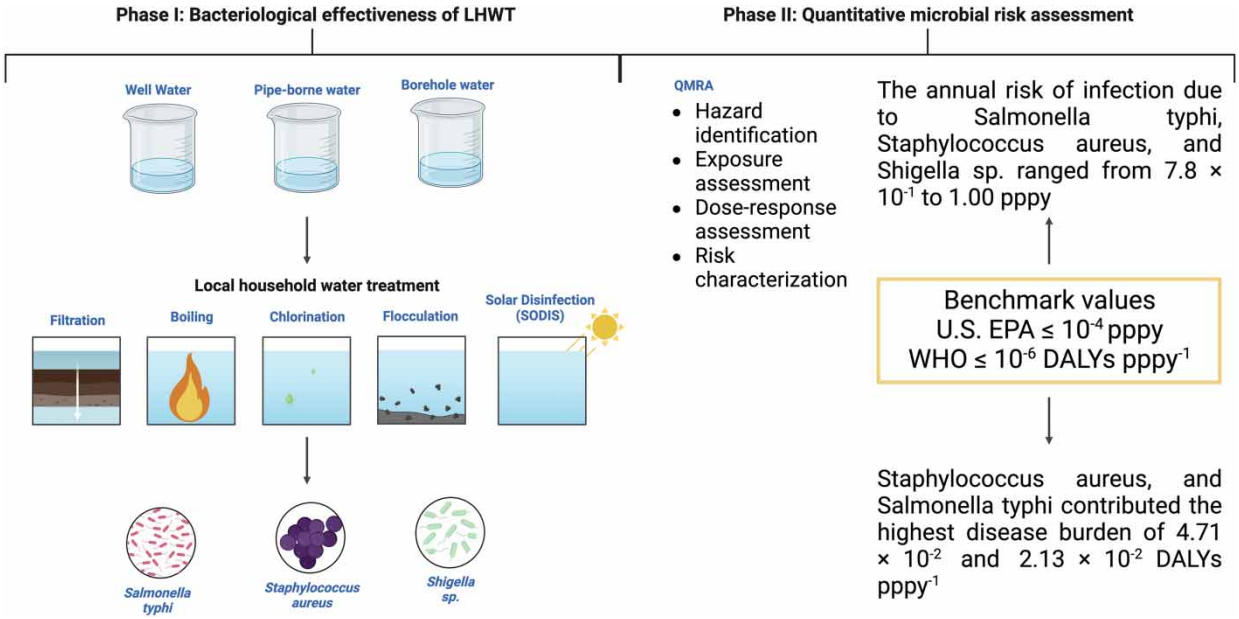
This study accessed the efficiency and health risks of drinking water from different sources treated by filtration, boiling, chlorination, flocculation, and solar disinfection. The microbial quality of 45 treated water samples from boreholes, wells, and pipe-borne water was analyzed to determine treatment effectiveness and to quantify risk using quantitative microbial risk assessment. The effectiveness of each treatment method was a function of sampling sources ($p < 0.05$) and location ($p < 0.10$), chlorination and boiling being the most efficient methods (100%). *Shiegella* in well water samples treated by filtration and flocculation had the highest daily infection risk of 69.5×10^{-1} and 67.5×10^{-1} pppd. The annual risk of infection from *Salmonella*, *Shigella*, and *Staphylococcus* ranged from 7.8×10^{-1} to 1.00 pppy, exceeding the U.S. EPA annual infection benchmark ($\leq 10^{-4}$ pppy). *Salmonella*, *Shigella*, and *Staphylococcus* had the highest risk of illness of 4.50×10^{-1}, 3.30×10^{-1}, and 9.80×10^{-1}, respectively. All disease burden values exceeded the WHO disease burden benchmark ($\leq 10^{-6}$ DALYs/pppy), with *Staphylococcus* and *Salmonella* contributing the highest disease burden of 4.71×10^{-2} and 2.13×10^{-2}, DALYs/pppy. Therefore, boiling and chlorination are the best disinfection methods for the pathogens tested.

Key words: disease burden, pathogens infection risk, quantitative microbial risk assessment, risk of illness, water treatment

HIGHLIGHTS

- WHO recommended several local household water treatment (LHWT) methods.
- Despite this, 2.3 billion people suffer from water-borne diseases and 1.8 million die because of contaminated water and sanitation.
- Current water stress is increasing water-borne diseases and the microbial risks of recommended LHWT have not been quantified.
- Boiling and chlorination are the best disinfection methods for the pathogen tested.

GRAPHICAL ABSTRACT



INTRODUCTION

Access to safe drinking water and basic sanitation by 2030 is the core of the United Nations 2015 Sustainable Development Goal (SDG-6). However, 2.6 billion people lack access to improved water sources, and in Africa, less than 50% of the population has improved sanitation, and about 70% of those lacking improved water sources do not drink treated mineral water (WHO/UNICEF 2018). Globally many countries are experiencing water stress due to pressure on water resources, and approximately 2.3 billion people are suffering from water-related diseases (Sauer *et al.* 2016). Annually, about 1.8 million people die because of poor sanitation and the consumption of contaminated drinking water, with children under 5 years old constituting 90% (Ahmed *et al.* 2020). Drinking water is a reservoir of water-borne pathogens that may pose devastating health risks after consumption (WHO/UNICEF 2018).

However, simple local household water treatment (LHWT) and good storage methods can considerably reduce health risks by improving the microbial quality of drinking water. Globally, approximately 1.8 billion people use household water treatment to improve drinking water quality and thus prevent water-borne diseases (Rosa *et al.* 2016). In developing countries, biosand filters, ceramic water filters, boiling, solar disinfection (SODIS), and chemical treatment (chlorination) are the common LHWT methods (Rosa *et al.* 2014). Treated drinking water can be considered safe, but it may be a source of water-borne infections if not treated properly (Saturday 2016). The microbial quality of treated water can be used to determine the effectiveness of the LHWT method and the quantitative microbial risk assessment (QMRA) due to the consumption of drinking water treated by various LHWT methods.

QMRA is a tool for estimating the risks of an adverse effect of infection, illness, and /or death due to exposure to various doses of water-borne pathogens (NRC 1983). So far, the QMRA model has been recently used to assess the microbial risk of wastewater, surface water, drinking water, food, and recreational water (Howard *et al.* 2006; Enger *et al.* 2012; Membré *et al.* 2015; Abia *et al.* 2016; Kouamé *et al.* 2017; Ahmed *et al.* 2018). Recent studies on the QMRA of drinking water treated by various LHWT methods are, however, limited. For instance, Sari *et al.* (2019) used the QMRA model to compare the annual infection risk of drinking water after boiling, filtration, and water-refill methods in urban–slum areas. However, their study was limited only to annual infection risks of Coliforms and *Escherichia coli* from one water source. The prevalence of water-borne diseases is continuously rising even though LHWT methods are used by many to improve drinking water quality from various sources, especially in countries experiencing water stress such as Cameroon. This shows the need for a detailed QMRA study to determine the health risks associated with the consumption of drinking water from different sources treated by various LHWT methods.

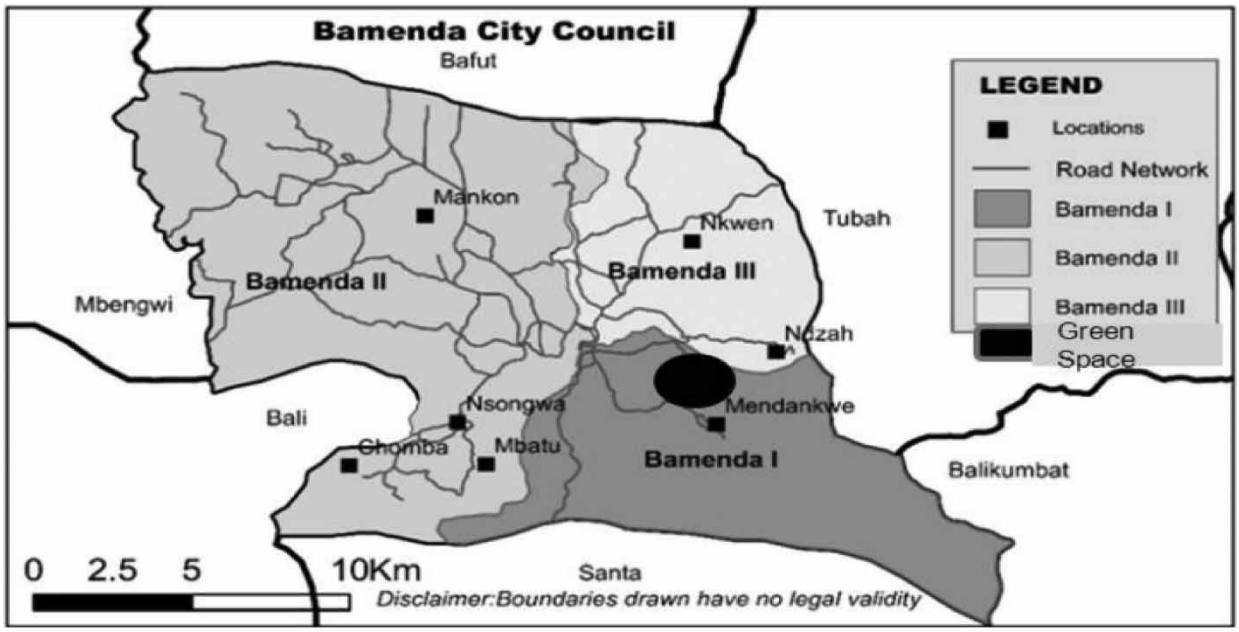


Figure 1 | Map of Bamenda urban area in North West Cameroon (*Source:* BCC 2016).

Currently, rapid population growth and high rates of urbanization in Bamenda have increased water stress and the dependency on alternative drinking water sources such as boreholes, springs, rivers, rainwater, and locally dug wells. These water sources in Bamenda have been shown to have high concentrations of pathogenic contaminants (Abendong *et al.* 2019; Anyang 2021; Mufur *et al.* 2021). Water-borne illnesses are also common though the inhabitants use ceramic filters, boiling, chlorination, or SODIS to treat drinking water (Nde 2017). These factors show the need of assessing the microbial quality and health risks of treated drinking water to recommend the best LHWT methods for the inhabitants in Bamenda. Therefore, the current study aimed to compare the bacteriological quality and QMRA of drinking water from different sources treated by various LHWT methods.

MATERIALS AND METHODS

Study area

The Bamenda Town, found in the North West region of Cameroon, lies between latitude 5°43′ to 7°10′ north and longitude 9°35′ to 11°12′ east and at an altitudinal range of 1,200 to 1,865 m above sea level (Mufur *et al.* 2021). The town has a surface area of about 3,125 ha (AchoChi 1998) and is characterized by very steep slopes (Ndenecho 2004). The climate is equatorial, characterized by a rainy season that lasts for 7 months (from April to October) and a short dry season that lasts for 5 months (November to March) (Mufur *et al.* 2021). The average annual rainfall is 2,670 mm, and the mean annual temperature is 25°C. The population of the town has been on the rise for several decades now, making it the third-largest city in Cameroon (Wirba 2020). Presently town has a population of over 600,000 inhabitants and is divided into three subdivisions (Bamenda I, II, and III) with city councils that manage local developments. The water consumption rate per household is mostly below 50 l/day, with very few households using up to 200 l/day. Pipe-borne water is the main source of water (65%), boreholes 18.2%, wells 8.3%, and streams/rivers 8.3% (Wirba 2020). Because of the inconsistency and unreliability of the pipe-borne water supply, coupled with water stress, the population uses these other sources as coping strategies (Chiaga 2019).

Sample collection

Water samples were obtained from field sites by stratified random sampling. The three subdivisions of Bamenda were used as a basis for stratification into Bamenda I (Up-station), Bamenda II (Old-town), and Bamenda III (Nkwen). Forty-five water samples were collected randomly from wells, taps, and boreholes into labeled 1-l sterile bottles. The water samples were

put in a cooling flask and transferred to the Science Laboratory of the Catholic University of Cameroon for bacteriological analysis. The physical properties of water were measured on-site.

Household water treatment methods

The collected water samples were independently treated with the following methods to determine the effectiveness of each treatment method.

Filtration method: A popular and commonly used ceramic water filter was used in the filtration process, after which bacteriological tests were conducted. The pore size of the ceramic filter was between 0.3 and 3 μm. For each filtered sample, 0.25 l was used for the microbiological tests to identify bacteria that were not removed by filtration (Sari *et al.* 2019).

Boiling method: One liter of each water sample was boiled at 100°C in a stainless-steel pot for 30 min. After cooling, the samples were tested for microbes that were not destroyed by heat treatment (Sari *et al.* 2019).

Chlorination: Two drops (0.1 ml) of 10% sodium hypochlorite solution (commercial liquid laundry bleach solutions; 'Eau de javel'), NaClO were put into 1 l water samples, swirled, covered, and allowed to stand for 30 min–time allowed before drinking (Lantagne *et al.* 2006). As it dissolves in water, hypochlorous acid (HClO) was formed, which diffuses through the bacterial cell wall destroying the membrane proteins. The samples were then tested for any residual pathogen.

Flocculation method: Five gram of alum, $Al_2(SO_4)_3{\cdot}14H_2O$, were put into 1 l water samples and vigorously mixed to dissolve thoroughly. It was then swirled (slow mixed) and allowed to stand for 30 min to form a coagulum, and sediment negatively charged the microorganisms to collide and clump together into larger, more easily removable clots or 'flocs'.

SODIS: Labeled sterilized transparent plastic bottles were filled with 1 l of each water sample and kept on a zinc rooftop to expose it to full sunlight for 5–6 h. That is, from 9 am to 3 pm on a sunny day (CDC 2008). This exposure allows the bottled water to receive solar radiation intensity of 500 W/m^2 (equivalent to 5 h of mid-latitude sunshine in summer). The water samples were later tested for the presence of pathogenic water-borne bacteria.

Isolation and identification of bacteria in drinking water before and after treatment

Nutrient agar was prepared for bacteria culture using the manufacturer's instructions. It was then sterilized in an autoclave at 121°C for 15 min and allowed to cool before use. The cool agar was then poured into Petri dishes for inoculation of the samples. The surface viable count of bacteria colonies was done using the drop plate method by Miles and Misra (Miles *et al.* 1938). One milliliter of the water sample was transferred to 9 ml of normal saline to make four serial dilutions. The sterilized nutrient agar sterilized in each Petri dish was allowed to dry. The plates were divided into four sectors and labeled according to the different dilutions. Twenty milliliter of each dilution from each sample, before treatment and after treatment, was inoculated onto the corresponding sector of the agar using the spread technique. This was done in triplicates and plates were then incubated at 35°C for 18–24 h in an inverted position. The resulting observed bacteria colonies were counted and recorded for each sector. The limit of detection was determined by serial dilution to be 0–1,000 CFU/ml. The number of colonies forming units per milliliter of the original sample was determined using the following formula:

$$\frac{\text{CFU}}{\text{ml}} = \text{Average number of colonies on the three plates} \times \text{Dillution factor} \times 50 \quad (1)$$

The Gram stain test was used to identify the Gram-positive bacteria from the Gram-negative bacteria. After Gram staining, the Gram-positive cocci were tested for catalase and coagulase production. This test separated pathogenic *Staphylococcus aureus* from other non-pathogenic *Staphylococci* species. The sulfide indole motility (SIM) medium test was used to identify Gram-negative bacteria. SIM differentiates Gram-negative members of Enterobacteriaceae by their ability to reduce sulfur, produce indole, or move.

Procedure to determine the effectiveness of treatment

The bacterial reduction effectiveness of the treatment method was determined using the following formula (Mahmoud *et al.* 2013);

$$\text{Effectiveness } (E) = \frac{(\text{LCBT} - \text{LCAT})}{\text{LCBT}} \times 100 \quad (2)$$

where LCBT is the level of contamination before treatment (influent/untreated water) and LCAT is the level of contamination after treatment (effluent/treated water).

Quantitative microbial risk assessment

The QMRA was used to determine the annual infection or disease risk resulting from exposure to pathogens in treated water samples (NRC 1983; Haas 2014). The identified bacteria in water samples treated by various local household methods were considered for the QMRA. The QMRA comprises four steps: hazard identification, exposure assessment, dose–response assessment, and risk characterization (Rose & Haas 1999; Medema & Ashbolt 2006) as described below.

Hazard identification

This step identifies the microbial agent and its associated adverse health effects on a given population. In the current study, *Salmonella typhi*, *Shigella*, and *S. aureus* were identified and used in estimating the exposure of the inhabitants to these pathogens after consuming locally treated water. These bacteria were selected because, in Bamenda, the prevalence of typhoid fever, dysentery, pneumonia, and skin infections is high, and they are the causative infectious agents (Fonyuy 2014; Biosengazeh *et al.* 2020).

Exposure assessment through locally treated drinking water

The exposure assessment estimated the dose of pathogens in treated water samples following ingestion in a day and a year. The exposure dose of pathogens was determined as follows (Kouamé *et al.* 2017):

$$D = \mathrm{Iv} \times \mathrm{Mc} \tag{3}$$

where D is the exposure dose expressed in pathogens day^{-1}, Mc is the mean concentrations of the targeted pathogens (CFU/ml), and Iv is the ingested volume of treated water; based on the assumption that children and adults drink 1,000 and 2,000 ml of treated water per day (USEPA 2000; WHO 2011), These values are the default rate of daily drinking water intake for children and adults used by many countries and international organizations in exposure assessment.

Dose–response assessment

The probability of water-borne illnesses from the intake of *S. aureus* in treated water was estimated by the exponential dose–response model developed by Rose & Haas (1999), given as follows:

$$P\ (\mathrm{inf}) = 1 - e^{-\mathrm{rd}} \tag{4}$$

where P(inf) is the probability of being infected after daily exposure (per person per day), r is the pathogen infectivity constant for *S. aureus*, and d is the exposure dose calculated in Equation (3) (pathogens day^{-1}).

For *Salmonella typhi* and *Shigella*, the beta-Poisson dose–response model was used to calculate the infection as shown below (NRC 1983; Haas 2014):

$$P(\mathrm{inf}) = 1 - \left[1 + \left(\frac{d}{N_{50}}\right)\left(2^{\frac{1}{\alpha}} - 1\right)\right]^{-\alpha} \tag{4}$$

where P(inf) is the probability of infection from a single exposure, d is the exposure dose of the microorganism, N_{50} is the median infectious dosage, and α is the distribution parameter. For multiple exposures to pathogens within a year, the individual probabilities were summed over a specified period of the year (Busgang *et al.* 2015). Thus, the likelihood of annual infection was calculated as follows:

$$P(\mathrm{inf})\ \mathrm{annual} = 1 - \left[1 - \frac{P(\mathrm{inf})}{\mathrm{day}}\right]^{n} \tag{5}$$

where the probability of infection per day (P(inf)/day) was obtained from Equation (4) above and n is the number of exposure days in a year (365 days). The probability of illness was calculated as follows:

$$P(\text{ill}) = P(\text{inf})\text{annual} \times P(\text{ill/inf}) \quad (6)$$

where P(ill/inf) is the likelihood of illness per infection, and P(inf) annual is defined in equation (5b). Table 1 shows the model parameters related to all models used in the QMRA.

Risk characterization

Results from hazard identification, exposure assessment, and dose–response assessment were used in characterizing the risk of infection/illness after consuming treated water. The annual infection risks and disease burden resulting from the consumption of water treated by each local water household treatment method was estimated based on the U.S. EPA annual probability risks benchmark ($\leq 10^{-4}$ pppy) and the World Health Organization (WHO) disease burden benchmark ($\leq 10^{-6}$ DALYs/pppy) (EPA 2005; World Health 2008). The disease burden was determined as follows (Hadi *et al.* 2019):

$$\text{DB} = P(\text{inf})\text{annual} \times P(\text{ill/inf}) \times B \times \text{Sf} \quad (6)$$

where DB is the disease burden expressed in DALYs per person per year (DALYs/pppy). P(inf) annual is the annual infection risk (pppy), P(ill/inf) is the probability of illness to infection ratio, B is the pathogen-specific disease burden, and Sf is the susceptible fraction of the population which is assumed to be 1 (Sf = 1) (Busgang *et al.* 2015). The study assumed that the whole population was susceptible to infection caused by all pathogens in treated water, there was no immunity development, and the concentration of pathogens in treated water was constant (Busgang *et al.* 2015). However, elderly adults, young children, and immunocompromised individuals have the highest risks of infection and severe illness (Wibuloutai *et al.* 2019).

Data analysis

Data for evaluating the efficiency of the various LHWT methods were analyzed using the IBM Statistics SPSS version 21.0 (SPSS, Chicago, USA). A one-way analysis of variance was used to compare the means at a significant level of $p < 0.05$. Microsoft Excel, version 2013, was used to plot graphs and to determine the efficiency of treatment methods.

RESULTS

Physical properties

Table 2 shows the physical properties of the 45 water samples measured during collection. The temperature ranged from 22.3 to 24.2°C. Nkwen well water had a brown color and was highly turbid.

Table 1 | Dose–response parameter for all bacteria investigated

Organism	Parameter	Type of model	Reference
Dose–response model			
Salmonella typhi	$\alpha = 1.75 \times 10^{-1}$ $N_{50} = 1.11 \times 10^{6}$ PDi = 0.45	beta-Poisson	Hornick *et al.* (1970); Abia *et al.* (2016)
Shigella sp.	$\alpha = 0.162$; $N_{50} = 1.127 \times 10^{3}$ PDi = 0.35	beta-Poisson	Haas *et al.* (1999); Van Lier *et al.* (2016)
S. aureus	$r = 7.64\text{E-}08$ PDi = 1	Exponential	Rose & Haas (1999); Busgang *et al.* (2018)
Disease burden			
Salmonella typhi	49×10^{-3}		Havelaar *et al.* (2012)
Shigella sp.	26×10^{-3}		Van Lier *et al.* (2016)
S. aureus	49×10^{-3}		Havelaar *et al.* (2012)

Table 2 | Physical properties of water samples at point-source

Location	Source	Color	Odor	Mean turbidity (NTU)	Mean temperature (°C)	Mean pH
Up-station (Bamenda I)	Pipe-borne	Colorless	Odorless	1.7	23.5	6.2
	Covered-well	Colorless	Odorless	1.5	24.1	5.5
	Borehole	Colorless	Odorless	0.6	23.9	6.2
Old-town (Bamenda)	Pipe-borne	Colorless	Odorless	2.1	22.3	6.2
	Covered-well	Colorless	Yes	1.5	23.5	5.1
	Borehole	Colorless	Odorless	0.4	23.8	5.8
Nkwen–Bamenda III	Pipe-borne	Colorless	Odorless	1.7	22.7	6.2
	Uncovered-well	Brown	Yes	2.1	23.4	5.6
	Borehole	Colorless	Odorless	0.5	24.2	5.5

The number of colony-forming units counted

Table 3 shows the data obtained from bacteria viable plate count, where LCBT is the level of contamination before treatment and LCAT is the level of contamination after treatment. Twenty-five out of the 45 (55.56%) water samples collected for the studies before treatment were seen to be contaminated. Only 20 water samples (44.44%) were free of pathogens and suitable for drinking as they met the WHO guidelines for quality drinking water (Table 3). Water samples from wells were the most contaminated, with samples from Nkwen having the highest bacteria load (298 CFU/ml). Water samples from boreholes had the lowest level of contamination, with the highest bacterial load of 4 CFU/ml before treatment (4 CFU/ml) (Table 3). After disinfection, 86.67% of the 45 treated samples met the WHO drinking water standard, and 13.33% remained contaminated (not safe for drinking). Well water samples treated by filtration were the most highly contaminated (66.67%) (Table 3).

There was a complete absence of pathogens of interest in borehole water sources following treatment with different LHWT methods. However, these methods partially disinfected water from well and pipe-borne sources (Figure 2). No bacteria growth was observed in boiled and chlorinated water samples (Figure 2). There was a significant difference ($p < 0.01$) between the source of water and the method of disinfection, implying that the effectiveness of each water treatment method depends on the water source. However, there was no significant difference between the effect of various treatment methods on disinfection ($p > 0.05$).

Amongst the three locations, water sources from Nkwen had the highest level of contamination before and after treatment. Well water samples from Nkwen had the highest bacteria load, followed by well and pipe-borne water samples from Old-town and well water samples from Up-station (Figure 3). There was a significant difference ($\alpha = 0.05$; $p < 0.10$) between the effectiveness of various treatment methods and the location of sources of water, indicating that the location of the source of water determines the effectiveness of the treatment method.

Table 3 | Average bacterial colonies counted before and after treatment

			LCAT/(CFU/ml)				
Source	Site (5 samples per site)	LCBT/(CFU/ml)	Filtering	Boiling	Chlorine	Flocculation	SODIS
Pipe-borne	Up-station	0	0	0	0	0	0
	Nkwen	0	0	0	0	0	0
	Old-town	57	17	0	0	0	0
Well	Up-station	31	7	0	0	0	0
	Nkwen	298	145	0	0	8	73
	Old-town	109	13	0	0	0	0
Borehole	Up-station	4	0	0	0	0	0
	Nkwen	0	0	0	0	0	0
	Old-town	0	0	0	0	0	0
WHO standard		≤ 0.01 CFU/ml (1 CFU/100 ml)					

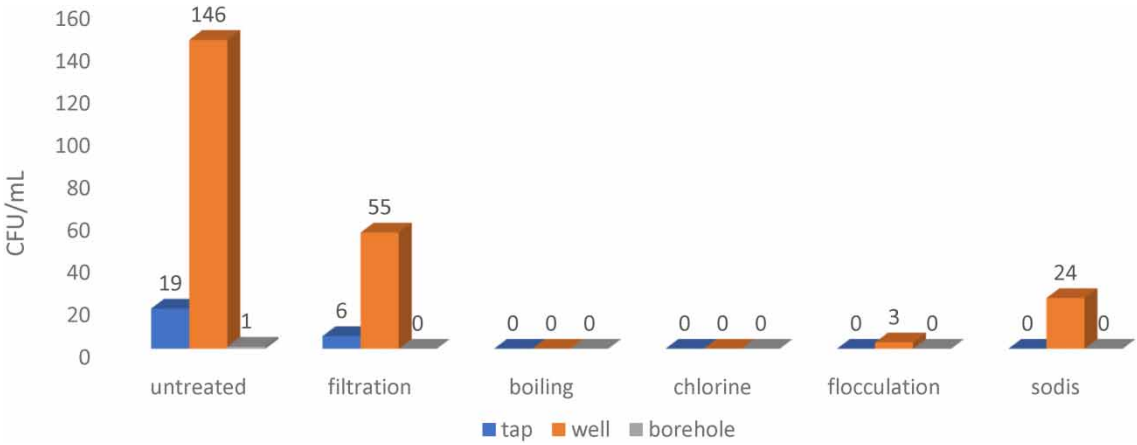


Figure 2 | Effects of the treatment method of disinfection on water source.

Effectiveness of disinfection methods

All five household water treatment methods were 100% effective in treating borehole water (Figure 4). The most effective method of treatment for well water was boiling (100%) and chlorination (100%) and followed by flocculation (98.25%), SODIS (85.96%), and filtration (62.33%), respectively (Figure 4).

Risk of pathogenic infection

The concentration of *Salmonella typhi*, *Shigella* sp., and *S. aureus* was highest in well water samples from Nkwen, disinfected by filtration, flocculation, and SODIS, and maximum concentration values were 87.1, 56.2, and 76.3 CFU/100 ml, respectively (Table 4). Filtered water samples had the highest risk of infection. However, infection risk per day varied with the source of drinking water. The risk of infection per day due to *Shigella* sp. in well water was high with maximum values of 6.95×10^{-1} and 6.75×10^{-1} pppd in filtered and flocculated water samples, while *Salmonella typhi and S. aureus* had a low infection risk, with maximum values of 1.55×10^{-1} and 1.16×10^{-2} pppd, respectively (Table 4). The infection risk of pathogens per day for children was not significantly different from the infection risk of pathogens per day for adults.

Disease burden

The risk of infection per day due to *Shigella* sp. in well water was high, with maximum values of 6.96×10^{-1} and 6.75×10^{-1} pppd in filtered and flocculated water samples (Table 5). The annual risk of infection due to *Salmonella typhi*,

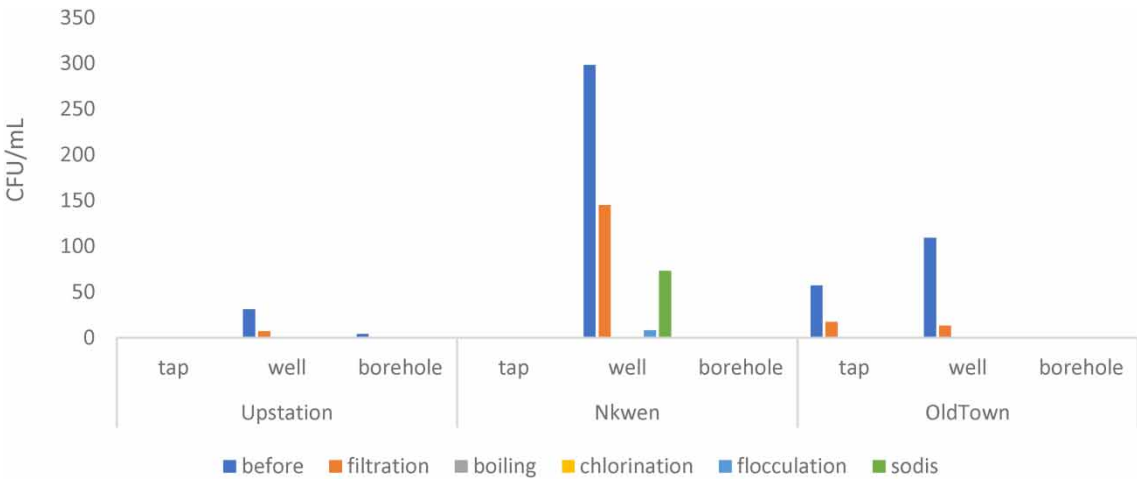


Figure 3 | Effect of the method of disinfection on the location of water source.

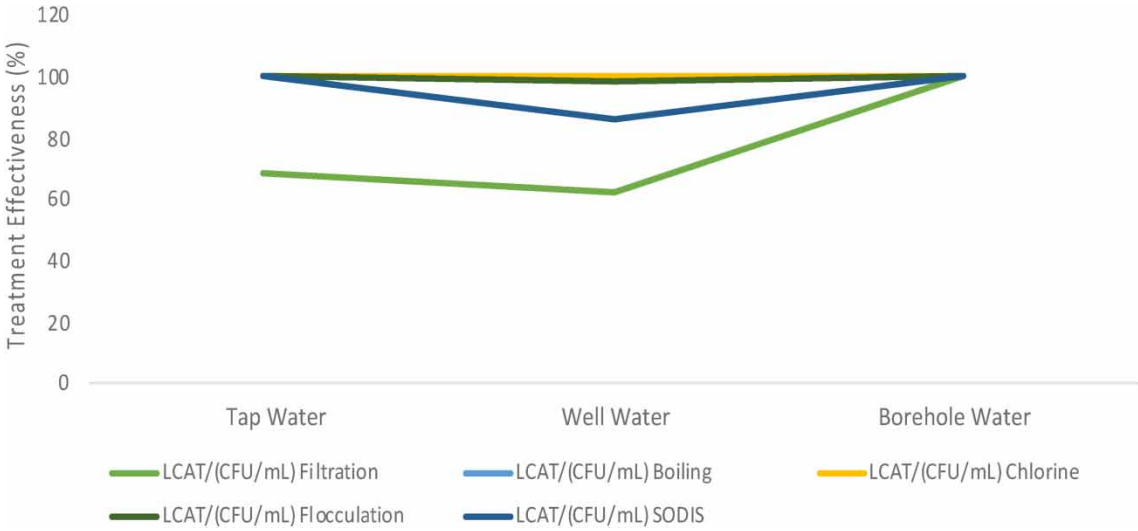


Figure 4 | Effectiveness of each method of treatment on different water sources.

Shigella sp., and *S. aureus* ranged from 7.80×10^{-1} to 1.00 pppy. The maximum risk of illness was 4.50×10^{-1}, 3.30×10^{-1}, and 9.80×10^{-1} for *Salmonella typhi*, *Shigella* sp., and *S. aureus*, respectively (Table 5). *S. aureus* and *Salmonella typhi* contributed the highest disease burden with a maximum value of 4.71×10^{-2} and 2.13×10^{-2} DALYs/pppy (Table 5). The annual infectious risk and disease burden of *S. aureus* and *Salmonella typhi* in water samples treated by filtration, flocculation, and SODIS exceeded the U.S. EPA annual infection benchmark ($\leq 10^{-4}$ $pppy^{-1}$) and the WHO disease burden benchmark ($\leq 10^{-6}$ DALYs/pppy) (U.S. EPA 2005; WHO 2008) (Table 5). There was no significant difference between the annual risk of infection, risk of illness, and disease burden values for adults and children. *S. aureus* had the highest probability of the infection developing into a symptomatic illness (9.8×10^{-1}), while *Shigella* sp. had the lowest probability of symptomatic infection (3.0×10^{-1}) (Table 5).

DISCUSSION

Bacteriological quality of water treated by LHWT methods

According to the WHO guidelines, safe drinking water should contain no pathogens to avoid water-borne diseases, and pathogenic safety levels should be less than 1 CFU/100 ml of water (WHO 2006). In this study, less than half of the drinking

Table 4 | Probability of infection per child/adult per day exposed to pathogens in treated water under the dose–response model

Treatment method	Water source	Mean concentration of Bacteria CFU/100 ml	Quantity of water consumed/ children (ml)	Quantity of water consumed/ adult (ml)	Exposure dose/ children	Exposure dose/adult	*P*(inf)/ children (pppd)	*Pinf*/adult (pppd)
Filtration	*Salmonella typhi*							
	Pipe-borne water Old-town	17.2	1,000	2,000	17,200	34,400	1.55×10^{-1}	2.43×10^{-2}
	Well water Nkwen	89.1	1,000	2,000	89,100	178,200	6.16×10^{-1}	1.19×10^{-1}
	Shigella sp.							
	Well water Up-station	7.3	1,000	2,000	7,300	14,600	6.29×10^{-1}	6.69×10^{-1}
	Well water Old-town	13.2	1,000	2,000	13,200	26,400	6.64×10^{-1}	6.99×10^{-1}
	S. aureus							
	Well water Nkwen	56.2	1,000	2,000	56,200	112,400	4.30×10^{-3}	8.60×10^{-1}
Flocculation	*Shigella* sp.							
	Well water Nkwen	8.1.	1,000	2,000	8,100	16,200	6.36×10^{-1}	6.75×10^{-1}
SODIS	*S. aureus*							
	Well water Nkwen	76.3	1,000	2,000	76,300	152,600	5.80×10^{-3}	1.16×10^{-2}

Table 5 | Probability of illness per child/adult per day and disease burden due to exposure to the pathogen in treated water

Treatment method	Water source	*P*(inf)/ children	*P*(inf)/adult	Pa(inf)/ children (pppy^{-1})	Pa (inf)/adult (pppy)	*P*(ill)/children	*P*(ill)/adult	DB/children (DALYs/pppy)	DB/adults (DALYs/pppy)
Filtration	*Salmonella typhi*								
	Pipe-borne water –Old-town	1.55×10^{-1}	2.43×10^{-2}	1.00	9.90×10^{-1}	4.50×10^{-1}	4.40×10^{-1}	2.07×10^{-2}	2.13×10^{-2}
	Well water Nkwen	6.16×10^{-2}	1.19×10^{-1}	1.00	1.00	4.50×10^{-1}	4.50×10^{-1}	2.07×10^{-2}	2.07×10^{-2}
	Shigella sp.								
	Well water Up-station	6.29×10^{-1}	6.69×10^{-1}	1.00	1.00	3.50×10^{-1}	3.30×10^{-1}	9.10×10^{-3}	8.58×10^{-3}
	Well water Old-town	6.64×10^{-1}	6.99×10^{-1}	1.00	1.00	3.50×10^{-1}	3.00×10^{-1}	9.10×10^{-3}	7.80×10^{-3}
	S. aureus								
	Well water Nkwen	4.50×10^{-3}	8.60×10^{-3}	7.90×10^{-1}	9.60×10^{-1}	7.90×10^{-1}	9.60×10^{-1}	2.87×10^{-3}	4.52×10^{-2}
Flocculation	*Shigella* sp.								
	Well water Nkwen	6.36×10^{-1}	6.75×10^{-1}	1.00	1.00	3.50×10^{-1}	3.30×10^{-1}	9.10×10^{-3}	8.58×10^{-3}
SODIS	*S. aureus*								
	Well water Nkwen	5.80×10^{-3}	1.16×10^{-2}	8.8×10^{-1}	9.8×10^{-1}	8.8×10^{-1}	9.8×10^{-1}	3.65×10^{-2}	4.71×10^{-2}

water samples met these criteria (Table 3), underpinning the need for a household treatment of drinking water in Bamenda. However, the choice of an appropriate LHWT method depends on the source of water since the bacteria load in the current study varied with treatment method and water source (Table 3). The significant difference ($p \leq 0.05$) between the effectiveness of LHWT methods in the current study was probably due to the different levels of exposure of water sources to microbes (Rosa *et al.* 2014). Pipe-borne water may not be considered safe for consumption since samples from Old-town had low microbial concentrations (Table 3), probably due to the presence of contaminants in storage tanks or pipes during transportation (Katukiza *et al.* 2014). Borehole sources had the lowest contamination levels (Table 3), confirming findings by Njunda and colleagues at the Cameroon Development Corporation (Njunda 2013). Contrarily, locally dug well water sources were the most contaminated (Table 3), aligning with the results of Magha (2021) in Bamenda. The high contamination of exposed well water sources may be attributed to possible wash-off from fecal contaminants from neighboring toilets or sewage from poor sewer systems. Treatment methods differ in their effectiveness in preventing water-borne pathogens (Figure 4). For instance, chemical treatment with sodium hypochlorite and heat treatment by boiling showed no bacteria prevalence for tested pathogens, indicating their high effectiveness (100%) for use in treating water unless resources are unavailable. This result corroborates findings established by Okwadha & Ahmed (2017). However, chlorination may be more cost-effective for poor households. According to Mohamed *et al.* (2016), decisions related to scaling up LHWT practices are affected by factors such as effectiveness, adherence (correct, consistent, and sustained use), and the cost of achieving the desired aim of reducing pathogens.

SODIS was ineffective in disinfecting well water samples from Nkwen (Table 3), probably due to high bacteria load, high turbidity, and high concentration of dissolved organic matter. Normally, for solar treatment to be efficient, turbid water must be made clear by filtration or sedimentation. Little to no sunlight on rainy days also reduces the effectiveness of SODIS and prolongs disinfection time, making disinfection by solarization difficult for consistent use in the rainy season. Moreover, ultraviolet radiation catalysis the degradation of plastics to Bisphenol-A (BPA), which can diffuse into treated water in plastic bottles to pose a carcinogenic risk (Seachrist *et al.* 2016). Furthermore, recent research findings have proven the occurrence of carcinogenic microplastics, phthalates, and alkylphenol in plastic bottled water (Amiridou & Voutsa 2011; Gambino *et al.*

2022). These factors greatly limit or discourage the use of solarization method of disinfection. In the current study, filtration had the lowest effectivity (Figure 4), though the effectiveness of filtration may depend on the filtering apparatus. The current study used ceramic filters with pore sizes of 0.3–3 μm, commonly and frequently used in treating water locally by most households in Bamenda.

Health risk assessment of treated water

The approach of QMRA is a comparatively new approach in identifying health risks associated with pathogens in drinking water (Bentham & Whiley 2018). In the current study, the overall health risks (Tables 4 and 5) due to *Salmonella typhi*, *Shigella* sp., and *S. aureus* in locally treated water may be ascribed to the low infectious dose of pathogens (Katukiza *et al.* 2014), since all pathogenic concentrations above the WHO benchmark ($\leq$1 CFU/100 ml) posed a high annual risk of infection (Table 4). The overall high risks of illness due to *S. aureus*, *Shigella* sp., and *Salmonella* in the current study are congruent with other studies on drinking water (Busgang *et al.* 2015; Ahmed *et al.* 2020). However, these findings were based on untreated water samples. Water samples treated by filtration contributed the highest overall risks due to the presence of all three pathogens, indicating that health risks may also vary with local household treatment methods.

Disease burden of pathogens in treated water

Diseases related to inadequate water, sanitation, and hygiene contribute to a huge burden of disease in low-income countries (Ahmed *et al.* 2020). The disease burden of all three pathogens in treated water samples exceeded the WHO disease burden benchmark. Katukiza *et al.* (2014) also found a high burden of water-borne diseases in a low-income population who use surface water as the main source of drinking. Filtered well water samples contributed to the highest disease burden (Table 5), probably due to the high prevalence of all three pathogens, putting the proportion of the population that depends on well water as a drinking source and the use of artificial filters at risk of water-borne disease. Thus, to minimize the overall risk of illness from infection by tested pathogens, users should treat well water by boiling or chlorination. However, filtration, solarization, and flocculation can be effective if combined with other treatment methods. *Salmonella typhi* was present in both well and pipe-borne water sources and contributed to the highest proportion of disease burden (Table 5). Globally, about 212 million cases of typhoid, with 129,000 deaths, are reported yearly, with children and young adults being the vulnerable groups (Steele *et al.* 2016). Several studies in Cameroon have reported a high prevalence of typhoid fever due to *Salmonella* sp infection (Njoya *et al.* 2021; Ndip *et al.* 2022). The global burden of *Shigella* and other water-borne illnesses is mostly unknown because most of the cases go unreported (Zahid 2018).

The current study is, however, limited because it did not consider the uncertainty of risk estimates as in the case of Monte Carlo risk analysis. Also, the prevalence of *Salmonella* sp. in treated water samples suggests fecal contamination and, therefore, the possibility of contamination by other fecal pathogens such as *Vibro cholerae*, *E. coli*, *Campylobacter*, and *Cryptosporidium* bacteria with time and availability. However, based on available resources, the current study investigated only three water-borne pathogens. Also, previous studies by Fonyuy (2014) and Biosengazeh *et al.* (2020) show high prevalence of illnesses such as typhoid fever, dysentery, pneumonia, and skin infections caused by *Salmonella typhi*, *Shigella* sp., and *S. aureus* in Bamenda probably due to contaminated water, since most households used local water treatment methods to reduce disease risk especially during water stress, when water supply is unreliable or scarce.

CONCLUSION

For the pathogen tested, chlorination and boiling were the most efficient disinfection methods, regardless of the water source. The overall health risks for both children and adults were not significantly different. Drinking water from well sources treated by filtration with a ceramic filter of pore size 0.3–3 μm contributed to the highest health risks. *Salmonella typhi* and *Shigella* sp. had approximately 1.00 annual probability risk of infection. *S. aureus* had the highest probability risk of developing into illness (9.80×10^{-1}), while *Salmonella typhi* had the lowest (4.50×10^{-1}). The overall probability risk of infection and disease burden exceeded the U.S. EPA annual infection and the WHO disease burden benchmark. The filtration, flocculation, and SODIS did not reduce pathogenic concentrations below risk levels. Although the boiling and chlorination methods did not pose risks for the pathogens tested, the study did not address a wide range of pathogens.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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