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Evidence-based chlorination targets for household water safety in humanitarian settings: Recommendations from a multi-site study in refugee camps in South Sudan, Jordan, and Rwanda

Syed Imran Ali[a,b,c,*], Syed Saad Ali[a], Jean-Francois Fesselet[b]

[a] Dahdaleh Institute for Global Health Research, York University, 88 The Pond Road, M3J 1P3, Toronto, Canada
[b] Médecins sans Frontières, Plantage Middenlaan 14, 1018 DD Amsterdam, Netherlands
[c] Development Impact Lab, University of California, Berkeley, Blum Hall #5570, Berkeley, CA, USA

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Abbreviations
CDC, Centers for Disease Control
DBP, Disinfection By-product
FRC, Free residual chlorine
GDWQ, Guidelines for Drinking-Water Quality
IDP, Internally displaced person
LMIC, Low- and middle-income country
MSF, Médecins Sans Frontières
NTU, Nephelometric turbidity units
UNHCR, United Nations High Commissioner for Refugees
WASH, Water, sanitation, and hygiene
WHO, World Health Organization

ABSTRACT

The current Sphere guideline for water chlorination in humanitarian emergencies fails to reliably ensure household water safety in refugee camps. We investigated post-distribution chlorine decay and household water safety in refugee camps in South Sudan, Jordan, and Rwanda between 2013-2015 with the goal of demonstrating an approach for generating site-specific and evidence-based chlorination targets that better ensure household water safety than the status quo Sphere guideline. In each of four field studies we conducted, we observed how water quality changed between distribution and point of consumption. We implemented a nonlinear optimization approach for the novel technical challenge of modelling post-distribution chlorine decay in order to generate estimates on what free residual chlorine (FRC) levels must be at water distribution points, in order to provide adequate FRC protection up to the point of consumption in households many hours later at each site. The site-specific FRC targets developed through this modelling approach improved the proportion of households having sufficient chlorine residual (i.e., ≥0.2 mg/L FRC) at the point of consumption in three out of four field studies (South Sudan 2013, Jordan 2014, and Rwanda 2015). These sites tended to be hotter (i.e., average mid-afternoon air temperatures >30°C) and/or had poorer water, sanitation, and hygiene (WASH) conditions, contributing to considerable chlorine decay between distribution and consumption. Our modelling approach did not work as well where chlorine decay was small in absolute terms (Jordan 2015). In such settings, which were cooler (20 to 30°C) and had better WASH conditions, we found that the upper range of the current Sphere chlorination guideline (i.e., 0.5 mg/L FRC) provided sufficient residual chlorine for ensuring household water safety up to 24 hours post-distribution. Site-specific and evidence-based chlorination targets generated from post-distribution chlorine decay modelling could help improve household water safety and public health outcomes in refugee camp settings where the current Sphere chlorination guideline does not provide adequate residual protection. Water quality monitoring in refugee/IDP camps should shift focus from distribution points to household points of consumption in order to monitor if the intended public health goal of safe water at the point of consumption is being achieved.

1. Introduction

Provision of safe water is essential for preventing waterborne diseases in refugee and internally displaced persons (IDP) camps during humanitarian emergencies (Connolly et al., 2004; Salama et al., 2004). Chlorination is the most widely used method of water treatment in humanitarian operations because of its low cost, ease of use, and, importantly, the residual protection it provides against microbiological contamination. Humanitarian responders implement a range of interventions for delivering safe chlorinated water to people living through crises—from manual bucket chlorination to centralized chlorination in piped water systems—that are appropriate at different points along the acute-transitional-post/protracted emergency continuum (Sikder et al., 2020). For all chlorination interventions, it is essential to ensure sufficient chlorine residual to protect water against microbiological contamination up to the point of consumption, while keeping chlo-

* Corresponding author.
E-mail address: siali@yorku.ca (S.I. Ali).

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rination levels within acceptable limits so as to not engender taste- and odour-driven rejection of treated water. The Sphere Handbook (2018) sets forth minimum standards for humanitarian response including standards for chlorinated water supplies. Sphere's *Water supply standard 2.2: Water quality* specifies that free residual chlorine (FRC) levels in chlorinated water supplies should be 0.2–0.5 mg/L at the point of distribution, with turbidity less than 5 NTU. This is a universal FRC standard that is widely used in refugee/IDP camp water systems globally.

The Sphere FRC target however comes from the WHO Guidelines for Drinking-Water Quality (GDWQ), which are based on conventions from the routine operation of municipal piped water systems in cities (WHO, 2017). As the US CDC (2014) observe, the GDWQ FRC target is appropriate only when users drink water directly from the flowing taps of a piped system. It is unlikely to provide sufficient residual protection in situations where the point of consumption is spatially and temporally distant from the point of distribution, something which is commonly the case in refugee/IDP camps. In these settings, people must collect water from public distribution points (known as "tapstands"), transport it in containers back to their shelters, and then store and use that water for up to 24 hours or longer. Multiple studies in refugee/IDP camps have shown that pathogenic recontamination of water can occur during collection and transport from distribution points, as well as during storage and use in camp households, and that these are linked to the spread of waterborne diseases among camp populations (Mahamud et al., 2012; Roberts et al., 2001; Shultz et al., 2009; Steele et al., 2008; Swerdlow et al., 1997; Walden et al., 2005). Sikder et al. (2020) found that maintaining ≥0.2 mg/L FRC in households was necessary for preventing *E. coli* contamination of stored water in refugee camp households in Bangladesh, corroborating a long-standing convention that at least 0.2 mg/L FRC is needed to ensure microbiological water safety (Lantagne, 2008). In an earlier study, the authors found that implementing the Sphere FRC target at water distribution points in refugee camps in South Sudan failed to reliably ensure sufficient FRC protection up to the point of consumption in refugees' shelters (Ali et al., 2015). These findings signify that the 0.2–0.5 mg/L FRC target range prescribed by Sphere is indeed protective *if* it is implemented at the point of consumption, rather than at the point of distribution. This raises the question then: *What must FRC be at water distribution points in order to ensure that at least 0.2 mg/L remains at the point of consumption many hours later?* This question has public health implications wherever people do not drink water directly from the tap and must store and use water for many hours, such as in refugee and IDP camps during humanitarian emergencies, or in intermittent water systems in low- and middle-income countries (LMICs) (Elala et al., 2011).

In response to these water safety concerns, we launched a multi-site study to investigate post-distribution chlorine decay and household water safety in refugee and IDP camps. In field studies conducted between 2013-2015 in refugee camps in South Sudan, Jordan, and Rwanda, we observed how water quality changed in chlorinated water supplies between distribution and consumption. We implemented a nonlinear optimization approach for the novel technical challenge of modelling post-distribution chlorine decay in order to generate estimates on what FRC must be at water distribution points in order to provide adequate FRC protection up to the point of consumption in households many hours later. The objective of our research was to demonstrate this approach for generating site-specific and evidence-based chlorination targets for refugee/IDP camp water systems, and evaluate whether these site-specific FRC targets could increase the proportion of households having safe water at the point of consumption compared to the status quo Sphere FRC target. The approach developed here forms the basis of an operational support tool that assists refugee/IDP camp water system operators in generating site-specific chlorination targets to keep water safe to drink for the entire duration of household storage and use.

2. Materials and Methods

2.1. Study Sites

We carried out four field studies at refugee camps with different temperature and environmental conditions in South Sudan, Jordan, and Rwanda (Table 1). Our first site, the Maban County Refugee Camps in South Sudan (March 20–April 18, 2013), was located in a hot semi-arid setting and had poor water, sanitation, and hygiene (WASH) conditions. This site sheltered refugees from

Table 1
Summary of temperature and environmental conditions at study sites. * *indicates that WASH coverage failed to meet Sphere minimum standards.*

						WASH Indicator Coverage[1]			
Country	Camp (Phase)	Köppen-Geiger Climate Classification	Local Terrain	Ambient Air Temperature (Mid-afternoon)	Population	Water Supply (L/p/d)	Water Access (# of users per tapstand)	Sanitation Access (# of persons per latrine)	Reporting Period
South Sudan	Jamam	Hot semi-arid climate (BSh)	Floodplain (Nile basin)	35.3°C, (Min: 28.3°C; Max: 45.7°C)	15,670	18.9	97	20*	Mar 2013[2]
	Gendrassa				15,810	25.6	88	14	
	Batil				37,199	19.3	84	19	
Jordan	Azraq (Summer)	Hot desert climate (BWh)	Stony desert with shallow rolling hills	32.7°C, (Min: 27.1°C; Max: 43.3°C)	7,470	36.9	63	4.5	Jul-Aug 2014[3]
	Azraq (Winter)			21.7°C, (Min: 14.5°C; Max: 29.3°C)	14,797	21.6	123	8.8	Mar-Apr 2015[3]
Rwanda	Kigeme	Tropical savannah climate (Aw)	Forested highlands	22.2°C, (Min: 18.3°C; Max: 31.0°C)	18,569	13.6*	135	33*	Jun 2015[4]
		Sphere Handbook Minimum Humanitarian Standard (2018):				>15	<250	<20	

Source: *Médecins Sans Frontières, Maban County, South Sudan WASH Coordination Report (Weeks 11 and 12, 2013).*Source: *UNICEF, Azraq, Jordan WASH Monitoring Reports (2014 & 2015).*Source: *PAJER, Kigeme, Rwanda WASH Monthly Updates (June-July 2015).*

[1] Indicator values are averages for the whole camp during the reporting period.
[2] Source: *Médecins Sans Frontières, Maban County, South Sudan WASH Coordination Report (Weeks 11 and 12, 2013).*
[3] Source: *UNICEF, Azraq, Jordan WASH Monitoring Reports (2014 & 2015).*
[4] Source: *PAJER, Kigeme, Rwanda WASH Monthly Updates (June-July 2015).*

Fig. 1. Typical water distribution points at study sites: (a) Batil Refugee Camp, Maban County, South Sudan, April 2013; (b) Kigeme Refugee Camp, Rwanda, July 2015; and (c) data collection at Azraq Refugee Camp, Jordan, April 2015 (All photos: Syed Imran Ali).

Sudan and was composed of three sub-camps (Jamam, Batil, and Gendrassa) that were geographically close to one another and had similar conditions. Located in the Nile basin floodplain, the local terrain was characterized by thick strata of heavy clay-rich soil that is prone to waterlogging and has low groundwater productivity. During the 2012 rainy season, the camps suffered widespread flooding resulting in multiple outbreaks of waterborne diseases, including hepatitis E, the severity and persistence of which was exacerbated by the poor WASH conditions. Shelters at this site were predominantly standard-issue United Nations High Commissioner for Refugees (UNHCR) canvas tents. Our second site, the Azraq Refugee Camp in Jordan, sheltered Syrian refugees and was located in an arid desert setting. In contrast to the South Sudan site, the Azraq Refugee Camp was a fully planned site with water and sanitation infrastructure exceeding humanitarian standards. We carried out two phases of data collection at Azraq in order to control for site-related factors and observe how temperature may affect chlorine decay. The first Jordan study phase took place during the summer (July 13–August 20, 2014) and the second during late winter/early spring (March 17–April 13, 2015). Shelters at this site were semi-permanent sheet metal structures with either plastic tarp or poured concrete floors. Our final site, the Kigeme Refugee Camp in Rwanda (June 23–July 15, 2015), sheltered refugees from the Democratic Republic of the Congo. Located in the forested highlands of western Rwanda, Kigeme had a relatively cool climate. WASH conditions at Kigeme were poor and similar to the South Sudan camps. Sanitation at Kigeme took the form of communal dischargeable latrine blocks that drained via surface channels, which exposed sewage effluent to the ambient environment. Kigeme Camp was built on two hills improved by terracing on which densely crowded shelters where constructed from mud, wood, and plastic sheeting by the refugee population.

All study sites had centrally chlorinated piped water supply infrastructure typical in refugee/IDP camps during the stabilized emergency phase. In these water systems, abstracted groundwater from boreholes (South Sudan, Jordan) or clarified surface water (Rwanda) was treated immediately after abstraction or clarification by automatic in-line chlorine dosers, which dispensed either chlorine solution prepared from calcium hypochlorite powder (South Sudan, Rwanda) or chlorine gas (Jordan). Water was chlorinated to, in principle, satisfy the inherent chlorine demand of the water and achieve breakpoint chlorination in retention tanks (with at least one hour of contact time), before being delivered to public water distribution points with the specified target FRC. Images of public water distribution points from each site are presented in Fig. 1.

2.2. Field Data Collection

At each site, we observed how water quality changed between distribution and consumption by measuring water quality in the same parcel of water at multiple points along the water supply chain:

1. Directly from the tap at the public water distribution point;
2. From the container after it was filled at the distribution point;
3. From the same container, after being carried back to the water-user's shelter; and
4. From the same container, after several hours of household storage and use (i.e., the *point of consumption*).

Each sample collected therefore consisted of a time-series of four consecutive water quality observations taken from the same water. We measured free residual chlorine (FRC), total residual chlorine (TRC), turbidity, pH, electrical conductivity (EC), and water temperature. FRC and TRC were analysed via the colorimetric method using a Palintest PTH 7091 compact chlorometer and Wagtech 7100 photometer with Palintest DPD1/DPD3 reagents (Palintest Ltd., Tyne & Wear, UK). Turbidity was measured using a Palintest PTH 090 compact turbimeter (Palintest Ltd., Tyne & Wear, UK). pH, EC, air and water temperature were measured via the potentiometric method using an Eijkelkamp 18.21 multimeter (Eijkelkamp Agrisearch Equipment, Giesbeek, Netherlands), Hanna Instruments HI 98311 EC/TDS/temperature multi-meter (HANNA Instruments, Woonsocket, RI, USA), or a Hach sensION+ multi-meter (Hach Instruments, Loveland, CO, USA). Analytical equipment was calibrated using non-expired manufacturer standards every one to two days of consecutive field use. We also collected data on water handling practices via spot observations or respondent self-report including on container type, container covering, container cleanliness, sun exposure, and method of drawing water. At each site, members of the local refugee population were recruited and trained as field data collectors. The primary investigator accompanied field teams over the course of data collection at each site in order to ensure procedural adherence.

2.2.1. Timing of household follow-up visits

During the South Sudan 2013 study, overall water supply was limited in the camps, so water was commonly consumed the same day it was collected. We therefore initiated samples in the morning and returned to households for follow-up in the afternoon, representing approximately a 6 to 9 hour interval between distribution and consumption. In the Jordan and Rwanda studies, water supply was more plentiful, so people collected more water and stored and used it in their households for longer (up to 24 hours). At these sites, we varied the timing of household follow-up visits in order to collect data representing different durations of household storage and use. We alternately initiated samples in the morning and returned to households for follow-up either the same day afternoon (approximately 6 to 9 hours interval) or the next morning (approximately 24 hours interval), or we started samples in the afternoon and returned for follow-up the next morning (approximately 18 hours interval). For the final phase in Rwanda, we followed up at households twice in order to gather an additional time-series data point (for a total of five) with which to better constrain subsequent chlorine decay modelling.

2.2.2. Sample sizes and site representativeness

To determine the number of samples for the initial study in South Sudan, we looked to previous work characterizing water quality changes between source and consumption in LMIC settings (e.g., Levy et al., 2008; Trevett et al., 2004). These studies typically had 50 to 150 samples (where each sample consisted of two paired measurements at source and at point of consumption), so we collected approximately 70 samples at each of the three sub-camps for a total of 220 samples across the South Sudan site. As each sample consisted of a time-series of four water quality measurements, this represented approximately 880 FRC-time data points. For the first phase in Jordan, we similarly collected 199 unique samples, representing approximately 796 FRC-time data points. For the second phase in Jordan, we used the first Jordan dataset to determine the number of samples to collect by evaluating how variance in distribution point FRC data decreased as the number of samples increased. We found that variance stabilized at the same level as for 199 samples at just 120 samples, so for the second phase in Jordan we collected 120 unique samples, representing approximately 480 FRC-time data points. For the final study phase in Rwanda, we similarly collected 134 unique samples. In Rwanda, as each sample consisted of a time-series of five water quality measurements, this represented approximately 670 FRC-time data points.

We sought to systematically sample all water distribution points in each camp, however, this was not always possible due to inconsistent service levels in some camps or the size of the water systems in others. In South Sudan, because of persistent water supply shortages and inconsistent chlorination management, water distribution points were often dry or unchlorinated. We therefore adopted a convenience sampling approach wherein we sampled distribution points attached to boreholes that were flowing and chlorinated each day of data collection. We sought spatial representativeness by: (i) collecting an equal number of samples in each sub-camp; (ii) visiting different distribution points in different areas of each sub-camp each day; and (iii) sampling distribution points attached to different boreholes in each sub-camp each day. A majority of borehole sources in each sub-camp in South Sudan were ultimately sampled and there was no apparent bias toward specific distribution points or boreholes. In Jordan, we systematically sampled every distribution point in the populated sectors of the camp during the 2014 and 2015 studies. In Rwanda, there were more distribution points than the number of samples we sought to collect, so we utilized a random number generator to randomly select an equal number of distribution points from the two hill sectors that constituted the camp. Through this approach, we were able to collect a representative, randomized distribution of samples across the Rwanda site area.

2.3. Ethics

The initial field work in South Sudan received exemption from full ethics review by the Medical Director of Médecins Sans Frontières (MSF) (Operational Centre Amsterdam) as we were collecting routine data in the midst of an on-going water supply intervention. For subsequent field studies in Jordan and Rwanda, we received ethics approval from the Committee for Protection of Human Subjects (CPHS) of the Institutional Review Board at the University of California, Berkeley (CPHS Protocol Number: 2014-05-6326).

2.4. Data Analysis

Our analytical objective was to model post-distribution chlorine decay as a function of time using only the water quality data that is routinely available in refugee/IDP camps. Developing site-specific models of post-distribution chlorine decay enables us to design distribution point FRC targets that provide sufficient residual protection for the typical duration that water is stored and used in camp households at a given site. Our goal was to evaluate whether the site-specific and evidence-based FRC targets generated through this modelling approach could improve household water safety outcomes compared to the status quo Sphere FRC target.

2.4.1. Post-distribution chlorine decay modelling

While chlorine decay in distribution systems is well understood, post-distribution chlorine decay has not, to our knowledge, been subject to modelling efforts (c.f., the Grayman, 2018 review of the drinking water quality modelling sector). We therefore devised a nonlinear optimization approach for the novel technical challenge of modelling post-distribution chlorine decay in refugee/IDP camps by drawing on concepts from water quality modelling in distribution systems and modifying some of its assumptions.

Chlorine residuals in municipal water distribution systems are typically modelled by coupling hydraulic mass transport and kinetic decay models in order to represent advective and diffusive mass transport in piped networks and the consumption of chlorine due to reactions in the bulk fluid phase and along the pipe wall, characterized respectively by first- or second-order reaction kinetics, and zero- or first-order kinetics (Biswas et al., 1993; Clark and Sivaganesan, 2002; Rossman et al., 1994; Vasconcelos et al., 1997). While mass transport is important in distribution systems, it is less relevant and likely represents a minor component during the post-distribution period where water is stored in containers. Moreover, while water quality modelling in distribution systems is based on the premise of a closed system, this does not hold once water exits the piped network. The post-distribution system can be better understood as an open system influenced by multiple known and unknown factors, which could include biofilms on storage containers, temperature, exposure to ultraviolet light, or discrete contamination events linked to unhygienic water handling in which new organic material is introduced to water. Given the complexity of the multiple reactions that could take place between chlorine and various organic and inorganic constituents, as well as the influence of known and unknown external mediating factors, analytical-mechanistic models of post-distribution chlorine decay may not be feasible. Therefore, recourse to empirical reaction kinetic models is justified, in a similar vein to early modelling efforts on trihalomethane formation kinetics (c.f., Vasconcelos et al., 1996).

An overall empirical kinetic model provides a way to represent the combined effects of all factors influencing post-distribution chlorine decay at a given site, such as source water quality, environmental factors such as ambient air temperature, or, importantly, the diverse range of water handling practices that will inevitably prevail among a large number of water-users in a real-world refugee/IDP camp setting. The impact of these decay-influencing factors is reflected in the change in FRC going from distribution to consumption, and the cumulative effect of all decay factors active at a site (including how often they occur and their effect strength) are therefore implicitly captured in the distribution-to-consumption FRC data we collected. Discrete contamination events in which new organic material, including, potentially, waterborne pathogens, are introduced to water are likely highly important for waterborne disease transmission in these settings. A discrete contamination event has the effect of pulling the FRC down from where it would otherwise be based on prevailing decay conditions. In a population where unhygienic water handling practices are more prevalent, discrete contamination events and associated FRC drops will happen more frequently and will result in a greater apparent chlorine decay (and vice versa). Overall empirical kinetic modelling using distribution-to-consumption FRC dataprovides a way to mathematically represent the apparent chlorine decay due to the aggregated effect of all decay-influencing factors(including discrete contamination events) as a function of time. Since decay-influencing factors are unique to each site, model representations of post-distribution chlorine decay are site-specific. This is consistent with chlorine decay modelling in distribution systems which similarly relies on site-specific model representations of chlorine decay (Biswas et al., 1993; Vasconcelos et al., 1997).

In order to maximize the utility and replicability of our analytical procedure in refugee/IDP camp water systems, we sought to model post-distribution chlorine decay using just the water quality data that is commonly available in these settings. Routine water quality monitoring in refugee/IDP camps focuses on monitoring FRC at water distribution points and, since the 2018 revision of the Sphere Handbook, at households as well. Turbidity and pH are also commonly measured at the point of treatment and/or distribution, but seldom thereafter. Humanitarian water quality guidelines (c.f., Médecins Sans Frontières, 2010; Sphere Association, 2018) specify that turbidity should be less than 5 NTU and pH less than 8 in order for chlorination to be most effective, and these conditions also apply to the present analysis. Other physical, chemical, biological, and/or radiological water quality parameters are generally only measured when a new source is commissioned or during seasonal spot-checks. We therefore modelled chlorine decay using commonly available FRC data from distribution points and households in the integrated rate law (El Seoud et al., 2017):

$$\frac{1}{C^{n-1}} = \frac{1}{C_0^{n-1}} + (n-1)kt \tag{1}$$

$$C = \left(C_0^{1-n} + (n-1)kt\right)^{\frac{1}{1-n}} \tag{2}$$

Where C is the FRC in mg/L at time t in hours, C_0 is the initial FRC at time zero (i.e., at the point of distribution), n is the dimensionless rate order, and k is the rate constant with units $mg^{1-n}\ L^{n-1}\ hr^{-1}$. The integrated rate law at $n = 1$ becomes Eq. 3:

$$C = C_0 e^{-kt} \tag{3}$$

With the FRC-time data collected at each site, we used the above relationships to estimate model parameters n and k in order to create an empirical kinetic representation of overall post-distribution chlorine decay that encompasses all reactions in the bulk fluid phase and with the container wall driven by the decay-influencing factors active at that site. As discussed above, rate order, n, in distribution system chlorine decay modelling is typically characterized as 0, 1, or 2. Non-integer rate orders are also physically possible where overall reactions are composed of multiple elementary steps. Given the complex array of reactions and factors that may influence post-distribution chlorine decay, we sought to avoid assumptions as to what the overall empirical rate order should be and left it unconstrained during modelling. Since Eq. 2 cannot converge to $n = 1$, Eq. 3 was evaluated separately, and the performance of the first-order model was compared to models in which n was unconstrained. Conversely, Eq. 2 can converge to $n = 0$ or 2, or any non-integer value in this range or above, should any of these be the best fit for the data. We stratified our analysis by site as we sought to generate site-specific chlorination targets. For the two Jordan datasets, we applied an additional level of stratification in order to account for the practice of storing water in direct sunlight, which was unique to this site (c.f., Appendix: Data Cleaning and Stratification). Only non-sun-exposed data are reported here as this is reflective of normative practice.

We used the numerical downhill simplex (Nelder-Mead) method, a widely used optimization technique, in GNU Octave 5.2.0 (Eaton, 2020), an open-source mathematical programming software, to estimate model parameters n and k using pooled vectors of the FRC-time data from each site. For model optimization, we minimized the sum of square errors (SSE):

$$SSE = \sum_{i=1}^{N} \left(C_{obs} - C_{pred}\right)^2 \tag{4}$$

Where N is the number of samples in the dataset. C_{pred} was calculated using Eq. 2 and initial assumptions for n and k, and SSE was calculated using Eq. 4. The Nelder-Mead algorithm is a gradient descent approach which improves on initial estimates of n and k by following downward trends in the error surface until the change with each iteration is below a specified tolerance. These tolerances were selected as: on error function value, SSE = 10^{-4}; on input values, k and $n = 10^{-4}$; and maximum number of iterations = 400. Additional error functions (e.g., relative error) were also evaluated for use but did not yield meaningful improvements in modelling performance and were thus dropped from further consideration. In order to evaluate modelling performance across sites, overall model goodness-of-fit, R^2 (Eq. 6), as well as sum of residuals ($S\sigma$) (Eq. 7), an indicator of model skewness, were also calculated. In addition to R^2 for the overall model, R^2 was also calculated for predictions at the point of consumption only (R^2_{poc}).

$$SST = \sum_{i=1}^{N} (C_{obs} - mean(C_{obs}))^2 \tag{5}$$

$$R^2 = 1 - \frac{SSE}{SST} \tag{6}$$

$$S\sigma = \sum_{i=1}^{N} \left(C_{obs} - C_{pred}\right) \tag{7}$$

In order to evaluate whether the numerical algorithm was converging to a local or global minimum, we implemented solution sets in which we randomized initial assumptions for n and k and evaluated whether the routine converged to the same or multiple solutions over five runs. We varied n between 0 and 2 (the range reported in the distribution systems chlorine decay literature) and k between 0 and 0.60 (0.11 was the highest value for k generated during exploratory modelling, so six-times this figure was used). Datasets for each site were split into 90% training and 10% testing subsets, and modelling performance metrics were compared between these subsets. This is good model calibration practice that prevents model over-fitting and maintains model generalizability. In situations where solution sets generated multiple solutions representing different local minima, we preferentially used the solution that appeared more often and had superior modelling performance with respect to goodness-of-fit (referred to in the following as the "dominant" solution).

In order to generate conservative estimates for decay model parameters n and k at each site, we implemented a confidence region estimation in which we generated contour plots of n and k against error by solving the integrated rate law (Eq. 2) over a range of n and k values to build a matrix of SSE. To cover the relevant solution space, n was varied between 0 and 3, and k was varied between zero and three times the optimized k obtained from the solution set for each site (i.e., that which minimized SSE). 300 steps were used for both parameters to build a 301×301 matrix of SSE values at each combination of n and k, with contour lines plotted every 5% above the minimum SSE. For each site, two combinations of n and k were selected to compute initial FRC required to achieve a desired downstream FRC: 1) the 'optimum solution' representing the n and k combination which minimized SSE (i.e., the best performing n and k combination from the solution set); and 2) the 'maximum decay prediction', the n and k combination that represented the most rapid decay that could be anticipated within a 5% error envelope. Prior to analysis, FRC-time data from each site were cleaned of erroneous entries following a uniform set of rules (c.f., Appendix: Data Cleaning and Stratification). All site datasets and analytical code are included in the supplementary material.

2.4.2. Site-specific distribution point FRC targets

Using the 'optimum solution' and 'maximum decay prediction' n and k parameter combinations developed for each site, with Eq. 2 we computed the distribution point FRC targets, C_0, that would result in an FRC concentration at the point of consumption, C, of 0.2 mg/L at variable lengths of time up to 24 hours post-distribution. We generated distribution point FRC target design graphs for each site wherein distribution point FRC to achieve a household FRC of 0.2 mg/L was plotted as a function of elapsed hours post-distribution. We also sought to account for chlorine taste and odour acceptability in the FRC target design graphs. While the WHO sets a maximum health-based guideline value for free chlorine of 5 mg/L (WHO, 2017), taste- and odour-driven rejection of chlorinated water can occur at much lower concentration levels. In a study on chlorine dosing for household water treatment in LMIC settings, Lantagne (2008) found 2.0 mg/L to be the upper limit above which user acceptability became a concern based on focus group testing in Ethiopia and Zambia. More recently, Crider et al. (2018) found a median acceptability threshold of 1.25 mg/L FRC among adults in urban Bangladesh. As we did not collect primary data on chlorine taste and odour acceptability as part of this study, we adopted the more conservative figure from the literature (i.e., 1.25 mg/L FRC) for our analysis. Chlorine taste and odour acceptability however is population specific and should ideally be evaluated at each site. Chlorine acceptability thresholds are also not fixed and can be modified through organoleptic habituation and/or health promotion messaging on the public health importance of water chlorination (Piriou et al., 2015; Sikder et al., 2020).

In order to evaluate the household water safety effectiveness of the site-specific FRC targets developed from this modelling approach compared to the status quo Sphere FRC target, we first selected a distribution point FRC target from the design graph for each site that would maximize the level of protection, up to 24 hours post-distribution where possible, without exceeding the chlorine taste/odour acceptability limit. We then assessed the proportion of sampled households at each site having safe water (i.e., $\geq$0.2 mg/L FRC) at follow-up when distribution point FRC was in line with the site-specific FRC target (using a bin with a range of the FRC target minus 0.2 mg/L). This was compared to the proportion of sampled households having safe water at follow-up at the same time post-distribution when distribution point FRC was in line with the Sphere FRC target (i.e., 0.2-0.5 mg/L).

3. Results

Overall water quality at the point of distribution at each site is summarized in Table 2. Site FRC data at the four measurement points (five in the case of Rwanda) are summarized in Fig. 2. An overview of key household water handling practices at each site is provided in Table 3.

From Table 2, we observe that distribution point water quality at all sites met the turbidity and pH requirements for effective chlorination stipulated in the humanitarian water quality guidelines (i.e., <5 NTU and pH <8). The downward trend in the FRC data presented in Fig. 2 going from tap to household follow-up reflects the rate of chlorine decay at each site, with more rapid decay evident in South Sudan 2013 and Jordan 2014, and less rapid decay evident in Jordan 2015 and Rwanda 2015. Moreover, the dispersion of the FRC data in Fig. 2 shows that the more acute emergencies in South Sudan 2013 and Jordan 2014 had poorer operational control of chlorination than the more stabilized situations in Jordan 2015 and Rwanda 2015. Temperature is also known to strongly influence chlorine decay rates (Powell et al., 2000). South Sudan 2013 and Jordan 2014 had higher air and water temperatures than Jordan 2015 and Rwanda 2015 (i.e., an approximate 10°C difference respectively can be seen in Table 1 and Table 2), which may have contributed to the more rapid chlorine decay evident at these sites. While temperatures decreased going from the Jordan 2014 study to the 2015 study, so did turbidity levels at water distribution points (mean turbidity 2.16 NTU and 0.77 NTU, respectively), which could have also played a role in reducing chlorine decay at this site.

Key differences in water handling practices among study sites can be seen in Table 3, which reflect the acuteness of the emergency situation at each site, and may also contribute to the variable chlorine decay observed across sites. Of all the sites, only South Sudan 2013 had a large number of respondents (20%) who drew water by dipping a cup into stored water, an unhygienic practice that can introduce contaminating material from hands, utensils, and vessels directly into stored drinking water. At all other sites, the majority of respondents ($\geq$90%) reported pouring water

Table 2
Descriptive statistics of water quality at the point of distribution at each site.

		FRC (mg/L)	TRC (mg/L)	Turbidity (NTU)	Water Temp. (°C)	Conductivity (μS/cm)	pH
South Sudan 2013	Mean	1.16	1.14	2.06	31.09	1110	7.11
	Standard Deviation	1.01	0.94	1.72	1.47	690	0.70
	Min.	0.01	0.02	0.01	27.30	140	5.64
	Max.	5.20	5.20	8.81	37.60	2990	8.86
Jordan 2014	Mean	0.98	1.00	2.16	27.06	992	7.60
	Standard Deviation	0.43	0.44	1.16	0.96	354	0.24
	Min.	0.38	0.35	0.02	24.80	355	6.24
	Max.	4.50	4.50	8.74	30.00	1896	8.22
Jordan 2015	Mean	0.73	0.74	0.77	19.84	1182	7.52
	Standard Deviation	0.10	0.10	0.52	2.11	296	0.25
	Min.	0.46	0.49	0.01	16.40	627	6.95
	Max.	1.04	1.03	2.87	26.10	1926	8.09
Rwanda 2015	Mean	0.65	0.70	0.31	19.69	95	6.74
	Standard Deviation	0.19	0.20	0.32	1.29	36	0.31
	Min.	0.23	0.34	0.01	16.20	23	6.00
	Max.	1.18	1.52	1.32	23.10	266	8.99

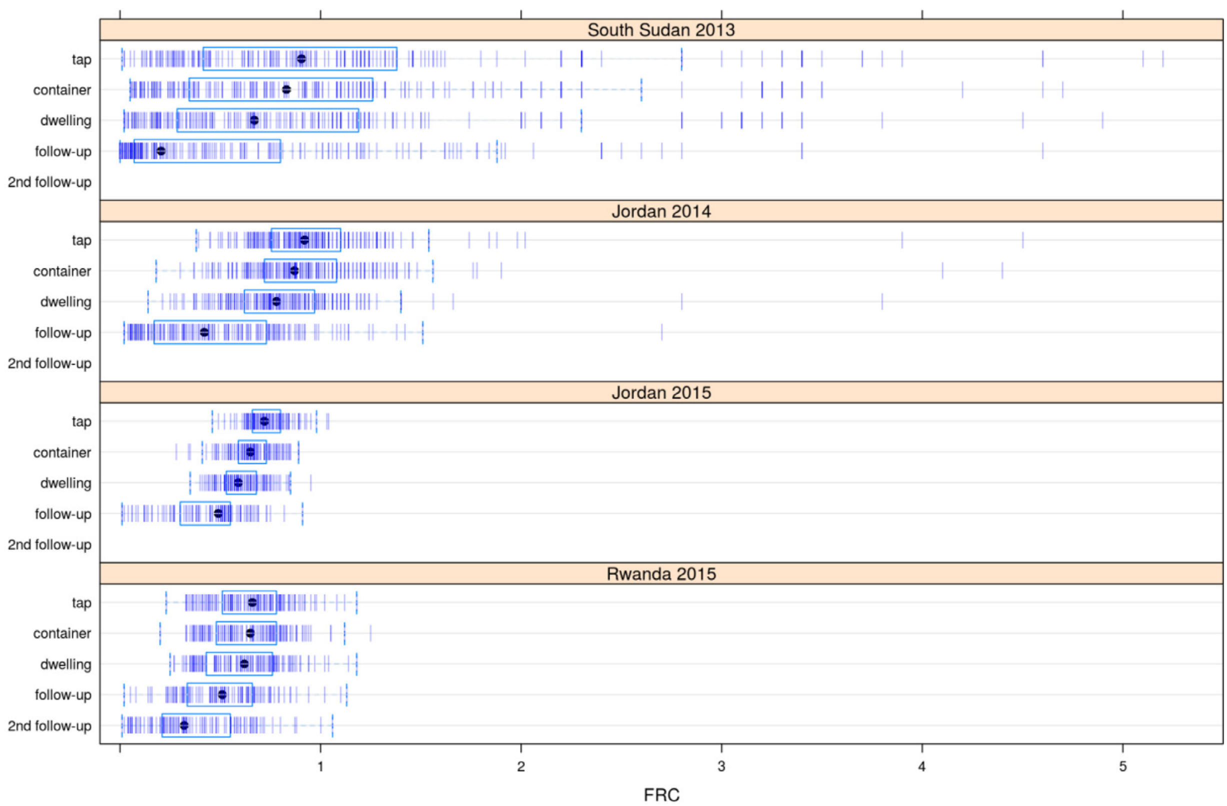

Fig. 2. All FRC measurements at each observation point at each site are plotted as vertical blue marks. Boxplots extend from the first to the third quartiles, thus containing the middle 50% of the values; black circles represent the position of the median. The decrease in FRC going from distribution points (tap) to households (follow-up) at all sites illustrates the importance of post-distribution chlorine decay and the need for FRC targets that can provide protection up to the point of consumption.

out of storage containers into drinking vessels which is more hygienic. Incidentally, South Sudan 2013 was the only site at which respondents reported using a tap to draw water (20%), reflecting the types of water storage containers available at that site—namely, the Oxfam container (29%), a specially designed bucket for transporting and storing water fitted with a tap for drawing water. In general, South Sudan 2013 had a greater diversity of water storage containers including both narrow-mouth options (~40%), such as rigid and collapsible jerrycans, and wide-mouth options (~50%) such as Oxfam containers, common plastic 20 litre buckets, and UNHCR buckets. Narrow-mouth containers are preferable to wide-mouth options as the smaller opening restricts the ease with which contaminating material can come into contact with stored water and effectively precludes dipping to draw water. All of the other sites had majority narrow-mouth storage containers (~70% in Rwanda 2015 and ≥90% in Jordan 2014 and 2015). Container covering is also important for limiting the opportunity for recontamination to occur. In South Sudan 2013, there was a nearly even split upon spot observation in households (42% uncovered vs. 54% covered), whereas Jordan 2014 and 2015 had very high levels of container covering (~80%). Rwanda 2015 had the lowest level of container covering (20%); however, the adverse impact could have possibly been mitigated by the narrow-mouth containers that were prevalent in Rwanda (compared to South Sudan where wide-mouth containers were more common). Container cleanliness was also an issue in South Sudan and Rwanda where only a small proportion of household storage containers were clean during spot observations (16% and 10%, respectively), compared to 59% and 72% in

Table 3
Overview of key water handling practices at each study site.

		South Sudan 2013	Jordan 2014	Jordan 2015	Rwanda 2015
Water drawing method	Pour out from container	54%	94%	92%	90%
	Dip cup into container	20%	-	-	-
	Use tap to draw from container	20%	-	-	1%
	Not recorded	6%	6%	8%	10%
Type of household water storage container	Rigid jerrycan	36%	51%	77%	62%
	Collapsible jerrycan	5%	40%	14%	8%
	Bucket	6%	1%	-	1%
	UNHCR bucket	15%	-	-	-
	Oxfam Container	29%	-	-	-
	Other types	5%	-	-	20%
	Not recorded	5%	9%	9%	9%
Container covering in household	Covered	54%	83%	80%	20%
	Uncovered	42%	11%	13%	71%
	Not recorded	5%	6%	7%	9%
Cleanliness of household water storage container	Clean	16%	59%	72%	10%
	Unclean	47%	34%	21%	71%
	Dirty	32%	2%	-	10%
	Not recorded	5%	6%	7%	9%
Water storage location exposed to direct sunlight	Stored in direct sunlight	No data	24%	13%	1%
	Stored in shaded area		36%	79%	90%
	Not recorded		40%	8%	9%

Jordan 2014 and 2015 respectively. Overall, South Sudan 2013 had the most unhygienic water handling practices, followed by Rwanda 2015, whereas water handling practices were generally good in Jordan 2014 and 2015. The cumulative effect of these water handling practices across the population at each site is captured in the FRC data we collected in the field and represented in the post-distribution decay modelling, as discussed in Section 2.4.1. During the Jordan 2014 field study, we also observed about a quarter of surveyed households storing water in direct sunlight in order to drive-off excess chlorine residual. This practice emerged during the initial phase of the emergency when FRC levels at water distribution points had been grossly excessive (i.e., $\geq$3 mg/L FRC as seen in Fig. 2). Unaccustomed to chlorinated water supplies back home, the rural Syrian refugee population adopted this practice in order to make the camp's chlorinated water more palatable during the initial settlement period, but the practice remained prevalent even as distribution point FRC levels stabilized to lower levels in 2015 (c.f., Fig. 2). This practice was not observed in South Sudan or Rwanda. As discussed in Section 2.4.1, we have reported only non-sun-exposed data from Jordan 2014 and 2015 as this is reflective of normative practice.

Chlorine decay modelling outputs are presented in Table 4. SSE contour plots from the confidence region estimation are presented in Fig. 3. Optimum and maximum decay prediction parameter combinations for each site are presented in Table 5. These modeling outputs are discussed at length in the next section in order to generate site-specific distribution point FRC target design graphs.

As discussed in Section 2.4, the first-order model (Eq. 3) was also evaluated. In all cases, models with $n = 1$ performed worse than models where n was unconstrained (results are not included here for brevity), indicating that better post-distribution decay modelling performance can be obtained by allowing n to remain unconstrained.

4. Discussion

The modeling outputs presented above are discussed in the following sub-sections in order to develop site-specific distribution point FRC target design graphs. In addition, household water safety evaluations of the design FRC targets versus the status quo Sphere FRC target are also presented.

4.1. South Sudan 2013

In the decay modeling outputs for South Sudan in Table 4, all five training runs converged to $n = 0.75$ and $k = 0.1098$ suggesting this is a global minimum in the error function (corroborated visually by the SSE contour plot in Fig. 3a). This solution had a high degree of goodness-of-fit ($R^2 = 0.8706$), as did the test runs ($R^2 = 0.9441$), suggesting good model generalizability for this site. The model was also moderately good at making predictions at later time points ($R^2_{poc} = 0.6402$), which was corroborated in the test runs ($R^2_{poc} = 0.8579$). The sum of residuals, $S\sigma$, signifies model skewness wherein negative values indicate that the model tends to over-predict downstream FRC compared to observed data and thus under-predicts decay rates. All site models were negatively skewed indicating that we should use the maximum decay prediction in order to be most conservative. Based on the confidence region estimation, the maximum decay prediction parameter combination for South Sudan 2013 was $n = 0.66$ and $k = 0.1463$ (Table 5). The distribution point FRC target design graph for South Sudan 2013, based on the optimum and maximum decay models for the site, is presented in Fig. 4.

From Fig. 4, we see that the distribution point FRC required to protect water up to 24 hours post-distribution at this site would be excessive (i.e., 5.38 mg/L based on the maximum decay prediction model). This suggests that ensuring 24 hours of protection may not be feasible at this site due to chlorine taste/odour rejection concerns; a shorter duration of protection may have to be accepted. If, for instance, distribution point FRC was set to the designated chlorine taste and odour acceptability limit of 1.25 mg/L, our maximum decay prediction model indicates that water would be protected up to 10 hours post-distribution. The household water safety evaluation for this distribution point FRC target for South Sudan 2013 compared to the current Sphere FRC target is presented in Fig. 5.

We observe from Fig. 5 that, in the South Sudan 2013 dataset, the current Sphere FRC target range resulted in sufficient FRC (i.e., $\geq$0.2 mg/L) at household follow-up 6 to 12 hours post-distribution in 14% (4 out of 28) of sampled households. In comparison, the site-specific FRC target resulted in 71% (15 out of 21) of sampled households having safe water during the same time period, representing a considerable improvement in the degree of household water safety achieved.

Table 4
Chlorine decay modelling solution sets for all sites. The number of samples used to develop each site model post-cleaning is included in the leftmost column. The training/testing split of data was 90/10.

Site Dataset (Number of samples)	Run	Initial Guesses		Model Estimates		Modelling Performance Metrics					
		k	n	k	n	SSE	SSE_{poc}	R^2	R^2_{poc}	$S\sigma$	$S\sigma_{poc}$
South Sudan 2013 (N = 196)	Train 1	0.2883	1.81	0.1098	0.75	85.4941	36.3489	0.8706	0.6420	-41.2002	-0.8748
	Train 2	0.4191	0.26	0.1098	0.75	85.4941	36.3489	0.8706	0.6420	-41.2013	-0.8758
	Train 3	0.3648	0.63	0.1098	0.75	85.4941	36.3493	0.8706	0.6420	-41.1962	-0.8717
	Train 4	0.1318	0.91	0.1098	0.75	85.4941	36.3490	0.8706	0.6420	-41.2003	-0.8751
	Train 5	0.3856	0.25	0.1098	0.75	85.4941	36.3491	0.8706	0.6420	-41.1959	-0.8712
	Test 1	-	-	0.1098	0.75	3.1754	1.5572	0.9441	0.8579	-3.8917	-0.4721
	Test 2	-	-	0.1098	0.75	3.1755	1.5573	0.9441	0.8579	-3.8918	-0.4722
	Test 3	-	-	0.1098	0.75	3.1755	1.5573	0.9441	0.8579	-3.8912	-0.4717
	Test 4	-	-	0.1098	0.75	3.1755	1.5573	0.9441	0.8579	-3.8917	-0.4721
	Test 5	-	-	0.1098	0.75	3.1754	1.5572	0.9441	0.8579	-3.8913	-0.4718
Jordan 2014 (N = 133)	Train 1	0.4115	1.51	0.0710	1.65	23.5574	10.3565	0.7925	0.2872	-25.4849	-2.4337
	Train 2	0.2163	0.01	0.0710	1.65	23.5574	10.3564	0.7925	0.2872	-25.4866	-2.4350
	Train 3	0.3605	1.27	0.0710	1.65	23.5574	10.3563	0.7925	0.2872	-25.4870	-2.4354
	Train 4	0.2127	1.74	0.0710	1.65	23.5574	10.3565	0.7925	0.2872	-25.4855	-2.4344
	Train 5	0.2175	0.93	0.0710	1.65	23.5574	10.3563	0.7925	0.2872	-25.4831	-2.4317
	Test 1	-	-	0.0710	1.65	2.7649	1.0942	0.5396	0.2901	-3.4843	0.0648
	Test 2	-	-	0.0710	1.65	2.7648	1.0942	0.5396	0.2901	-3.4845	0.0646
	Test 3	-	-	0.0710	1.65	2.7648	1.0942	0.5396	0.2902	-3.4846	0.0646
	Test 4	-	-	0.0710	1.65	2.7648	1.0942	0.5396	0.2901	-3.4844	0.0647
	Test 5	-	-	0.0710	1.65	2.7649	1.0943	0.5396	0.2901	-3.4840	0.0651
Jordan 2015 (N = 88)	Train 1	0.0312	0.72	36.5226	12.55	3.5481	2.0926	0.5415	-0.0822	-1.9727	0.0854
	Train 2	0.4824	0.20	36.5226	12.55	3.5481	2.0926	0.5415	-0.0822	-1.9727	0.0854
	Train 3	0.2426	0.82	0.0282	1.35	5.9357	2.7936	0.2330	-0.4448	-18.7910	-3.0399
	Train 4	0.5153	0.22	36.5227	12.55	3.5481	2.0926	0.5415	-0.0822	-1.9727	0.0854
	Train 5	0.0305	1.48	36.5226	12.55	3.5481	2.0926	0.5415	-0.0822	-1.9727	0.0854
	Test 1	-	-	36.5226	12.55	0.3790	0.1876	0.5172	-0.2027	0.3020	-0.2128
	Test 2	-	-	36.5226	12.55	0.3790	0.1876	0.5172	-0.2027	0.3020	-0.2128
	Test 3	-	-	0.0282	1.35	0.7359	0.4127	0.0625	-1.6455	-2.5608	-0.8077
	Test 4	-	-	36.5227	12.55	0.3790	0.1876	0.5172	-0.2027	0.3020	-0.2128
	Test 5	-	-	36.5226	12.55	0.3790	0.1876	0.5172	-0.2027	0.3020	-0.2128
Rwanda 2015 (N = 100)	Train 1	0.3500	0.20	0.0303	0.79	4.8425	3.2557	0.8054	0.5926	-5.6189	-1.9140
	Train 2	0.5402	0.68	0.0386	1.14	4.8805	3.3267	0.8038	0.5837	-5.1710	-1.8724
	Train 3	0.3188	1.29	0.0303	0.79	4.8425	3.2557	0.8054	0.5926	-5.6176	-1.9130
	Train 4	0.1971	1.76	0.0303	0.79	4.8425	3.2557	0.8054	0.5926	-5.6183	-1.9135
	Train 5	0.0549	0.90	0.0303	0.79	4.8425	3.2557	0.8054	0.5926	-5.6180	-1.9133
	Test 1	-	-	0.0303	0.79	0.3943	0.2189	0.8439	0.7090	-0.8782	-0.1918
	Test 2	-	-	0.0386	1.14	0.4001	0.2279	0.8416	0.6969	-0.7087	-0.0534
	Test 3	-	-	0.0303	0.79	0.3943	0.2189	0.8439	0.7090	-0.8780	-0.1916
	Test 4	-	-	0.0303	0.79	0.3943	0.2189	0.8439	0.7090	-0.8781	-0.1917
	Test 5	-	-	0.0303	0.79	0.3943	0.2189	0.8439	0.7090	-0.8781	-0.1917

Table 5
Optimum solution and maximum decay prediction model parameter combinations for each site.

Site Dataset	Decay Scenario	Model Estimates		
		k	n	R^2
South Sudan 2013	Optimum Solution	0.1098	0.75	0.8706
	Maximum Decay Prediction	0.1463	0.66	0.8896
Jordan 2014	Optimum Solution	0.0710	1.65	0.7925
	Maximum Decay Prediction	0.0889	1.25	0.7724
Jordan 2015	Dominant Optimum Solution	36.5226	12.55	0.5415
	Maximum Decay Prediction (linked to dominant)	2.8933	8.56	0.4677
	Non-Dominant Optimum Solution	0.0282	1.35	0.2330
	Maximum Decay Prediction (linked to non-dominant)	0.0183	0.44	0.0949
Rwanda 2015	Non-Dominant Optimum Solution	0.0386	1.14	0.8038
	Dominant Optimum Solution	0.0303	0.79	0.8054
	Maximum Decay Prediction (linked to dominant)	0.0282	0.46	0.7956

4.2. Jordan 2014

From the decay modeling outputs for Jordan 2014 in Table 4, we observe that the five training runs consistently converged to $n = 1.65$ and $k = 0.0710$, suggesting this is a global minimum in the error function (visually corroborated by the SSE contour plot in Fig. 3b). The model has good fit ($R^2 = 0.7925$), but the test runs performed slightly worse ($R^2 = 0.5396$), raising the possibility of model overfitting. The model performs poorly at later time points ($R^2_{poc} = 0.2872$) and is also negatively skewed, reinforcing the need to use the maximum decay prediction in order to be conservative. Based on the confidence region estimation, the maximum decay prediction parameter combination for Jordan 2014 was $n = 1.25$ and $k = 0.0889$ (Table 5). The distribution point FRC target design graph for Jordan 2014, based on the optimum and maximum decay models for that site, is presented in Fig. 6.

From Fig. 6, we observe that 24-hours protection of household stored water can be achieved at this site by setting distribution point FRC to 1.17 mg/L, based on the maximum decay model. This is within the designated chlorine acceptability limit. The household

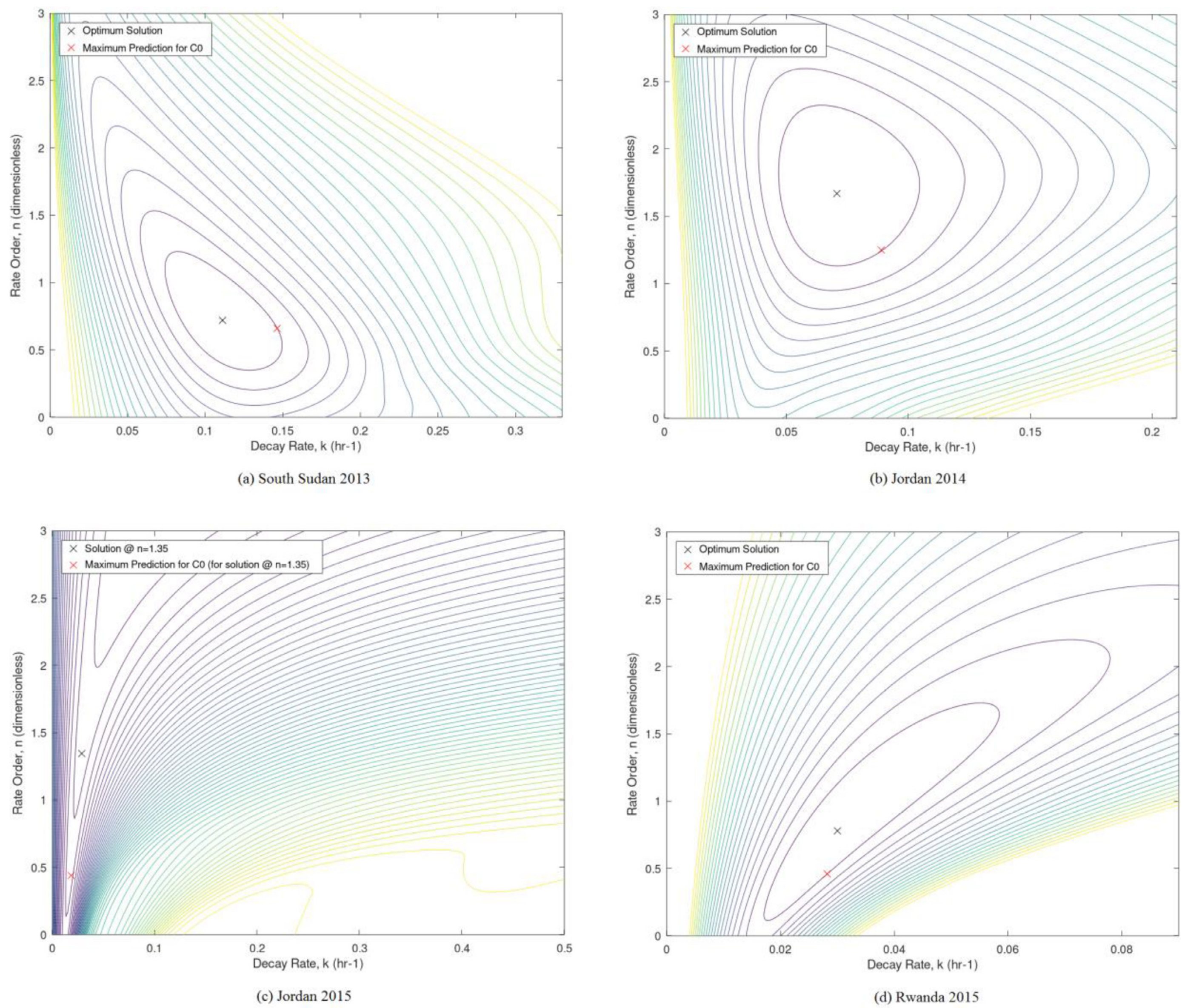

Fig. 3. Confidence region estimation for decay model parameters at all sites. Contour lines are drawn at every 5% increase in SSE. Decay parameter combinations representing the optimum solution (black 'x') and maximum decay prediction (red 'x') are indicated.

water safety evaluation of this site-specific distribution point FRC target for Jordan 2014 compared to the current Sphere FRC target is presented in Fig. 7.

We observe from Fig. 7 that, in the Jordan 2014 dataset, the site-specific FRC target generated from our modelling resulted in 82% of sampled households having safe water at follow-up at 16 to 28 hours post-distribution (average: 20.9 hours). There were no data representing the Sphere FRC target range at distribution points during this time period so no direct comparison can be made; however, we can infer the Sphere range would have a smaller proportion of households having safe water based on the downward trend apparent in the distribution of the plotted data as distribution point FRC decreases.

4.3. Jordan 2015

From the modelling outputs for Jordan 2015 in Table 4, we observe there was more modelling instability at this site compared to others. Across five training runs, four converged to a physically unrealistic solution where $n = 12.55$ and $k = 36.5226$ ($R^2 = 0.5415$), and once to a solution where $n = 1.35$ and $k = 0.0282$ ($R^2 = 0.2330$). The test runs similarly had poor R^2 values. While the dominant solution ($n = 12.55$, $k = 36.5226$) outperformed the non-dominant solution ($n = 1.35$, $k = 0.0282$) with respect to goodness-of-fit, the tendency as n and k increase is for chlorine decay to become flatter in absolute terms. We see that for the high n and k values of the dominant optimum solution and its associated maximum decay prediction ($n = 8.56$, $k = 2.8933$) (Table 5), there is flat chlorine decay in the distribution point FRC target design graph for Jordan 2015 (Fig. 8).

It appears that for the low levels of absolute chlorine decay observed (c.f., Fig. 2) in the relatively cool and clean conditions of the Jordan 2015 site, a wide range of very large n and k values could potentially fit the data and represent the slow decay observed. This mutability is reflected in the relatively poor R^2 and R^2_{poc} values for this site compared to others. It appears that in situations of small absolute chlorine decay, our modelling approach may fail to converge to a meaningful solution.

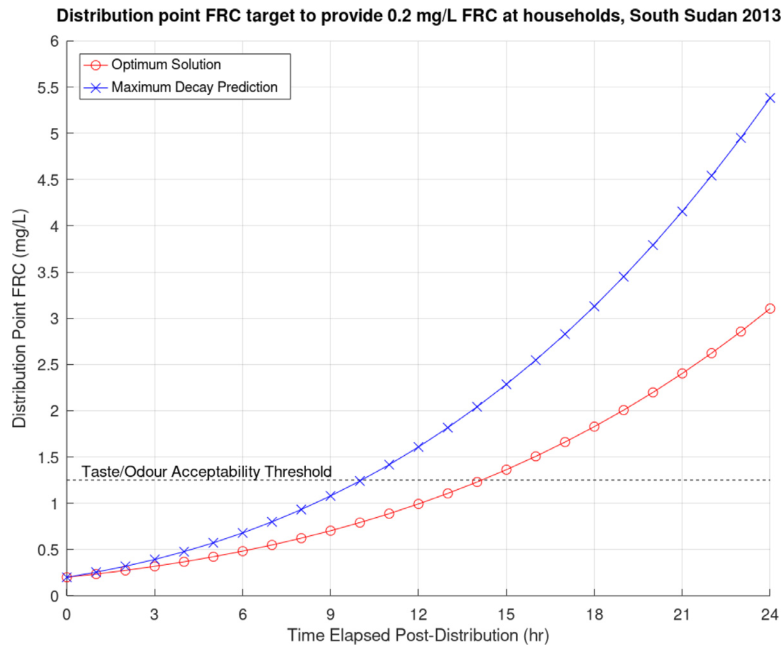

Fig. 4. Distribution point FRC target design graph for South Sudan 2013.

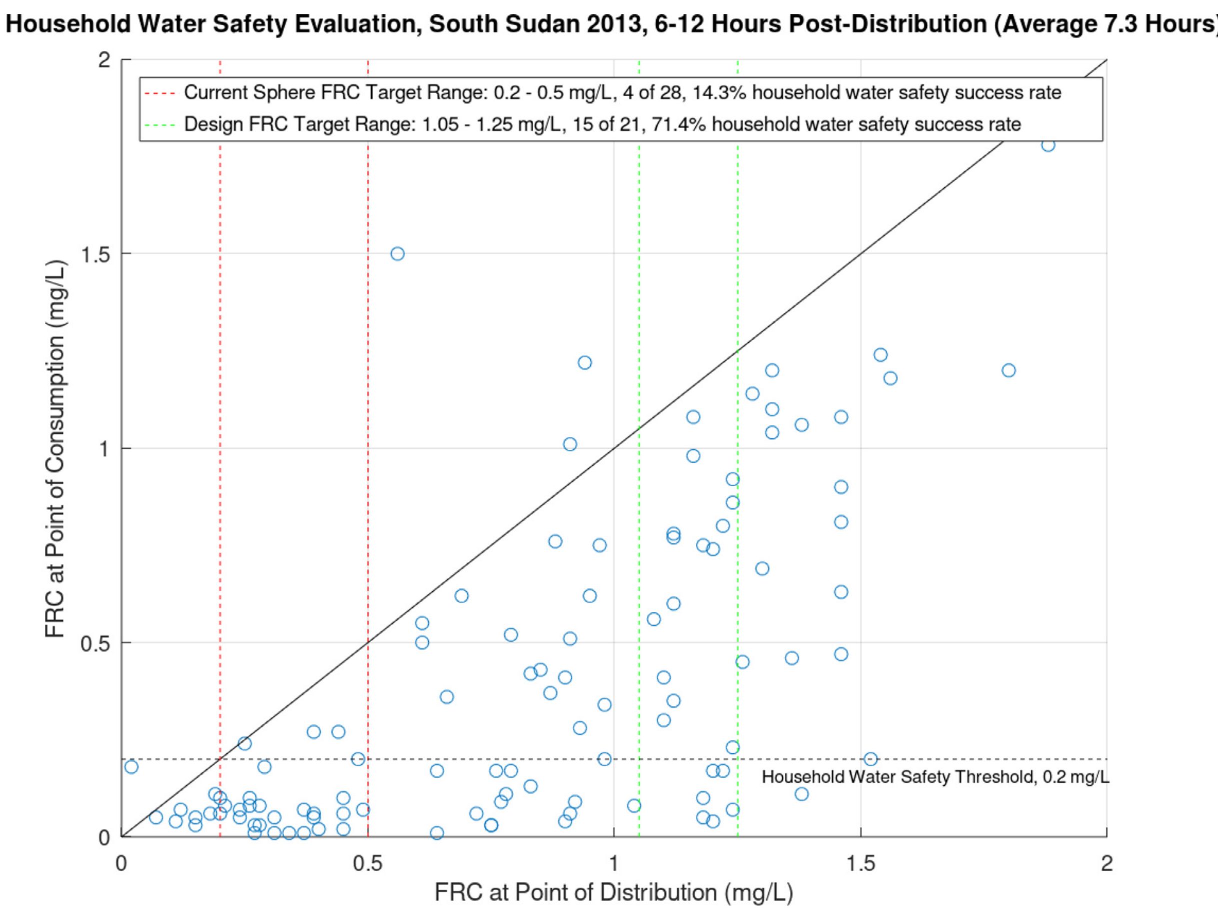

Fig. 5. Household water safety evaluation of site-specific FRC target compared to Sphere FRC target, South Sudan 2013; data included from samples with household follow-up at 6-12 hours post-distribution (average 7.3 hours).

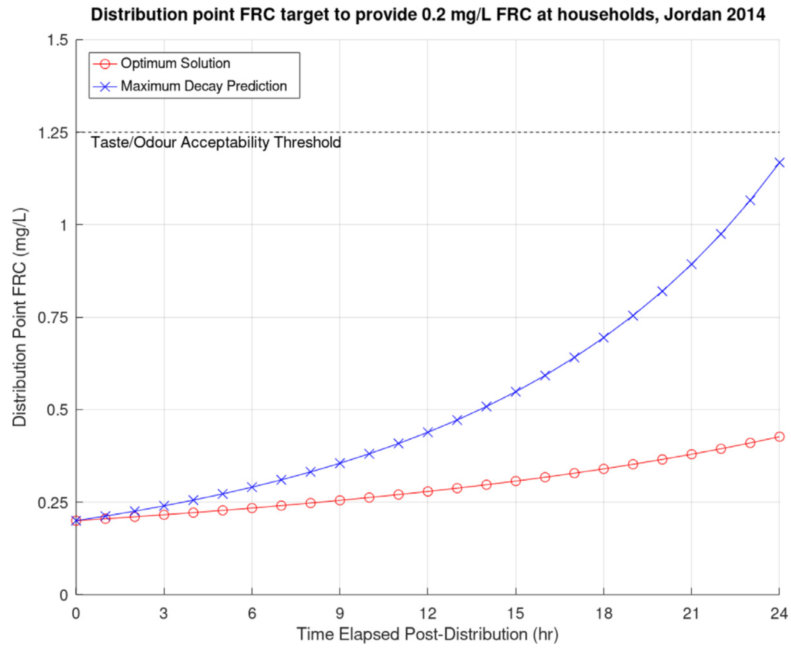

Fig. 6. Distribution point FRC target design graph for Jordan 2014.

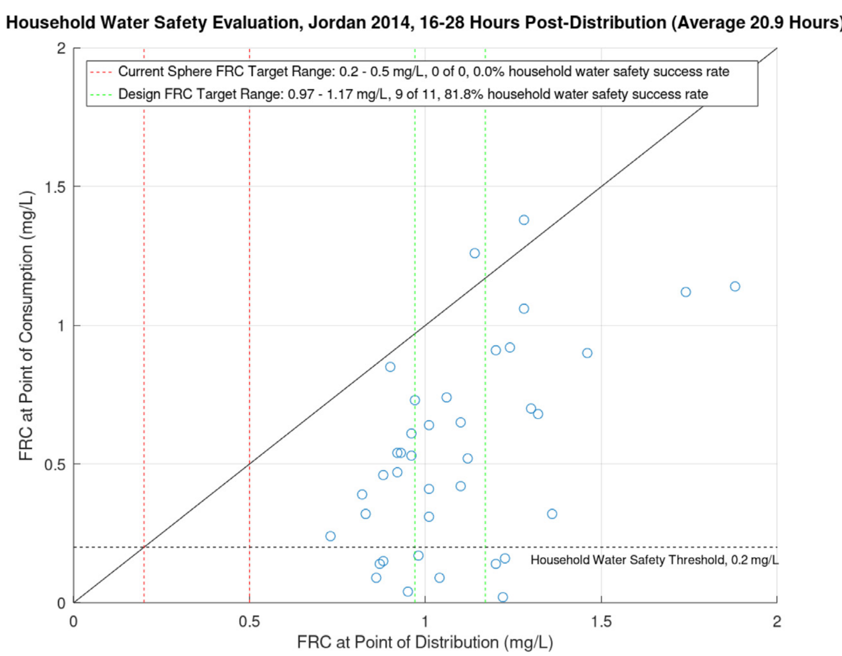

Fig. 7. Household water safety evaluation of site-specific FRC target compared to Sphere FRC targe, Jordan 2014; data included from samples with household follow-up at 16-28 hours post-distribution (average 20.9 hours).

Given the flat decay represented by the dominant solution, it may be interesting in this situation to look at the non-dominant solution ($n = 1.35$, $k = 0.0282$) and its associated maximum decay prediction ($n = 0.44$, $k = 0.0018$), which, despite their much poorer fit, may represent a 'worse case' scenario of faster chlorine decay, and would therefore yield a more conservative distribution point FRC target (the parameter estimates are also in a range similar to those found at other sites). The error space around the non-dominant optimum solution and its associated maximum decay prediction is shown in Fig. 3c, and the distribution point FRC targets based on these non-dominant models are also shown in Fig. 8. The non-dominant maximum decay model appears to indicate that the upper limit of the current Sphere FRC target range of 0.5 mg/L would provide sufficient FRC protection up to 24 hours post-distribution in this setting. It appears that in relatively cool and clean conditions where there is little observed FRC decay like Jordan 2015, there is no evidence suggesting that the upper range of the current Sphere FRC target would not provide adequate protection. This is also borne out in the household water safety evaluation for this site (Fig. 9).

The difference in the required distribution point FRC to protect water for up to 24-hours post-distribution in Jordan 2014 and Jor-

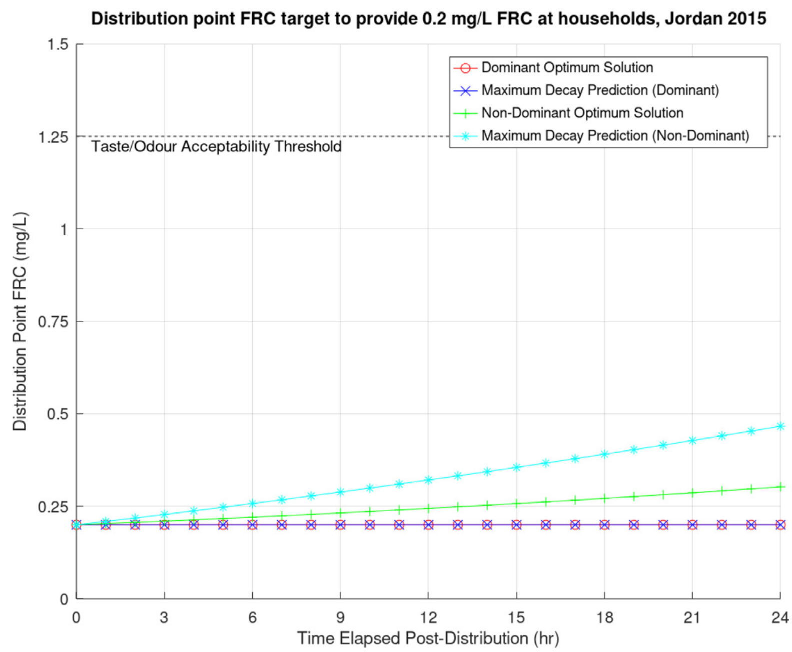

Fig. 8. Distribution point FRC target design graph for Jordan 2015. The red circles and blue 'x's mark the dominant optimum solution and its associated maximum decay prediction. These both indicate complete flat decay (a horizontal line).

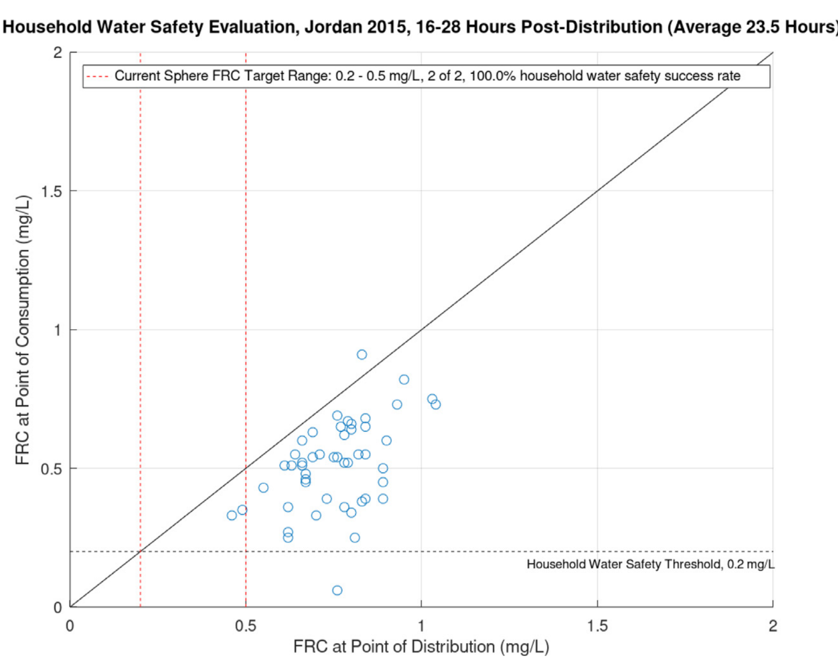

Fig. 9. Household water safety evaluation of Sphere FRC target, Jordan 2015; data included from samples with household follow-up at 16-28 hours post-distribution (average 23.5 hours).

dan 2015 suggests that seasonal temperature changes may affect post-distribution chlorine decay, although other explanations are also be possible, such as changes in turbidity at water distribution, as discussed at the outset of this section. Further research is required to better resolve the effect of temperature on post-distribution chlorine decay as site-specific FRC targets may need to be adjusted on a periodic or seasonal basis in order to account for temperature effects. Overall, the vast difference in post-distribution chlorine decay evident between the Jordan 2014 and 2015 studies demonstrates that decay-influencing factors will change over time even at the same site. Post-distribution chlorine decay models and the FRC targets that are generated from them must be specific to time and place.

4.4. Rwanda 2015

In the decay modeling outputs for Rwanda in Table 4, four out of five training runs converged to a minimum at $n = 0.79$ and $k = 0.0303$, and a single run converged to a local minimum at $n = 1.14$ and $k = 0.0386$. While only the dominant solution ($n = 0.79$, $k = 0.0303$) is plotted in Fig. 3d, the position of the non-dominant solution ($n = 1.14$, $k = 0.0386$) lays within the trough of

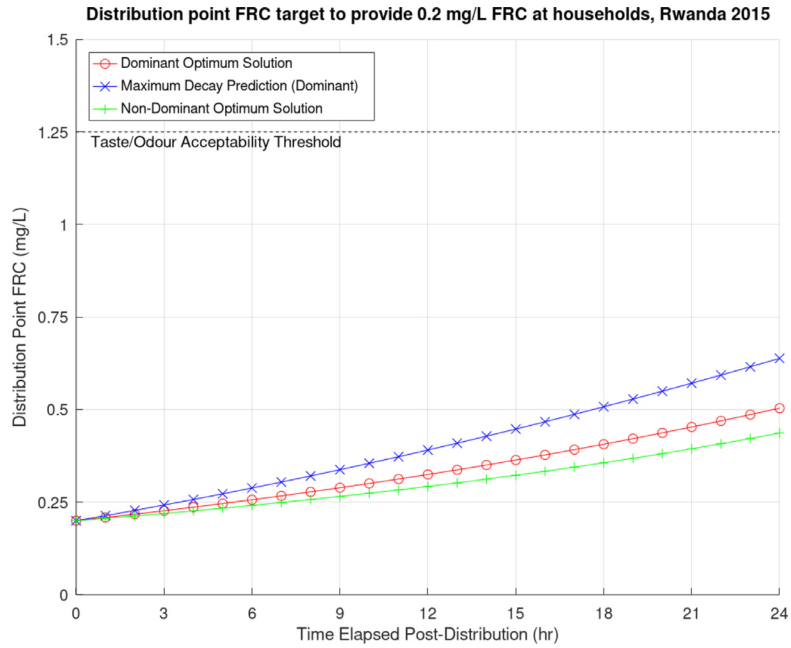

Fig. 10. Distribution point FRC target design graph for Rwanda 2015.

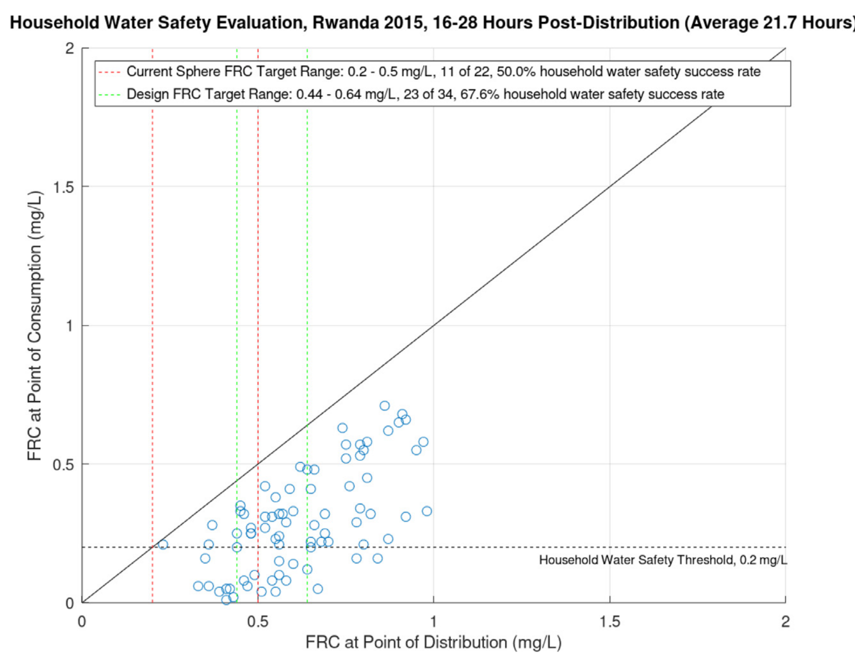

Fig. 11. Household water safety evaluation of site-specific FRC target compared to Sphere FRC, Rwanda 2015; data included from samples with household follow-up at 16-28 hours post-distribution (average 21.7 hours).

minimum error depicted in the middle of the contour plot. The goodness-of-fit of both solutions are good (R^2 ~ 0.80) and are corroborated by the test runs, which resulted in similar R^2 values. The dominant and non-dominant models are also moderately effective at later time points (R^2_{poc} ~ 0.59) but remain negatively skewed (albeit to a lesser degree than for South Sudan or Jordan 2014). The distribution point FRC target design graph for Rwanda 2015, based on the dominant and non-dominant solutions, and the maximum decay predication from the former, is presented in Fig. 10.

From Fig. 10, we observe that 24-hours protection can be achieved at this site by setting the distribution point FRC target to 0.64 mg/L, based on the maximum decay prediction associated with the dominant optimum model. This is well within the designated chlorine acceptability threshold. The household water safety evaluation of this site-specific distribution point FRC target for Rwanda 2015 compared to the current Sphere FRC target is presented in Fig. 11.

From Fig. 11, we observe that the site-specific FRC target resulted in sufficient FRC at household follow-up in 68% (23 out of 34) of sampled households in Rwanda, compared to 50% (11 out of 22) for the current Sphere FRC target range, representing a moderate improvement in household water safety.

4.5. Operational Recommendations

The post-distribution chlorine decay modelling approach we have demonstrated above can be used to generate site-specific and evidence-based water chlorination targets that protect household water safety for variable durations of household storage and use in refugee/IDP camp settings. The site-specific FRC targets were better able to achieve the desired public health objective of having sufficiently chlorinated water at the point of consumption than the Sphere FRC target in three out of the four refugee camps in which we carried out studies. The one notable exception to this was Jordan 2015, a site which had relatively cool temperatures and high levels of WASH service provision. At this site, it appeared that the upper limit of the current Sphere FRC target range (i.e., 0.5 mg/L FRC) was able to provide adequate protection up to 24 hours post-distribution. At all other refugee/IDP camp sites—particularly those in hot climates or where WASH conditions are poor—we recommend implementing post-distribution chlorine decay modelling in order to generate a site-specific chlorination target that suits local conditions . To facilitate this for refugee/IDP camp water system operators, we have made the post-distribution chlorine decay analytics demonstrated above available online as a web-based platform called the Safe Water Optimization Tool (2020). Refugee/IDP camp water system operators can use water quality data from their sites to generate a site-specific and evidence-based FRC target that protects water for a designated length of time they select, based on local water usage patterns, and then evaluate the proportion of households having safe water at this follow-up time for the site-specific FRC target versus the Sphere FRC target, before deciding whether to implement the site-specific FRC target in their water system.

The site-specific FRC targets produced through this modelling approach represent the minimum FRC required to achieve the public health goal of keeping water safe to drink for the entire duration of household storage and use. Proper chlorination is not, however, on its own sufficient for ensuring water safety; promoting and enabling safe and hygienic water storage and handling practices is also necessary. Increasing chlorination levels also presents some concerns of its own. For one, excessive chlorination can lead to taste and odour-driven rejection of treated water. Water system operators should endeavour to deliver the minimum FRC required for protecting public health, while not exceeding the population-specific chlorine acceptability threshold. If, at a particular site, the acceptability threshold is found to be lower than the site-specific FRC target, water system operators should not exceed the former, in order to minimize the risk that water-users turn to other untreated water sources. In these situations, better protecting the safe water chain via safe water storage practices (i.e., covered, narrow-mouth, and regularly cleaned and replaced storage containers with taps) are an important alternative to increasing chlorination levels. Further research is needed to develop and validate rapid methods for evaluating chlorine taste and odour acceptability thresholds in humanitarian response settings. Secondly, while the risk posed by waterborne diseases is the primary concern in humanitarian crises, disinfection by-products (DBPs) may also be a concern for vulnerable sub-groups such as pregnant women, especially when raw unclarified surface waters are rapidly chlorinated during acute emergencies (Ali et al., 2019). Field appropriate methods to characterize and manage DBPs in humanitarian water systems also warrant further development.

Limitations of our study included:

1. Given the complexity and range of potential factors influencing post-distribution chlorine decay in real-world settings, we did not attempt to define an analytical-mechanistic model that can explicitly characterize the specific effects of decay-influencing factors such as temperature or source water quality, or which models discrete contamination events linked to unhygienic water handling practices.
2. From the distribution systems modelling literature, it is known that source water quality influences chlorine decay (Powell et al., 2000; Vasconcelos et al., 1996). Our analysis assumes that initial chlorine dosing during water treatment adequately satisfies the inherent chlorine demand of the water and that breakpoint chlorination is fully achieved, resulting in a stable residual at water distribution points. This then becomes the 'lever' water system operators can act upon to optimize household water safety. However, breakpoint chlorination may not be reliably achieved in refugee/IDP camp water systems for several reasons including improper dosing, inadequate retention time, and slow decay reactions (e.g., with manganese). This means that the influence of source water quality could persist into the post-distribution period. This however would still be captured in the FRC data going from distribution to consumption and would thereby be accounted for in post-distribution chlorine decay modelling.
3. The household water safety evaluations of the site-specific FRC targets versus the Sphere FRC target we conducted were indicative of improved performance but were not sufficiently powered to confirm this effect. Future evaluations should be sufficiently powered to properly assess household water safety effectiveness in comparison to the Sphere FRC target.

5. Conclusions

- The current Sphere guideline for water chlorination in humanitarian emergencies is not designed to ensure water safety at the point of consumption in refugee/IDP camps. Multiple evaluations show that the Sphere FRC target range does not reliably ensure household water safety in camp settings, especially where temperatures are hot (>30°C) and/or WASH conditions are poor.
- Chlorination levels at water distribution points in refugee/IDP camps need to be increased (within taste/odour acceptability limits) by varying degrees in order to account for local post-distribution chlorine decay and ensure water remains safe to drink for the entire duration of household storage and use.
- The nonlinear optimization approach presented here can be used to generate site-specific and evidence-based distribution point FRC targets that provide sufficient residual to protect water for up to 24 hours post-distribution. Based on data from refugee camps in South Sudan, Jordan, and Rwanda, this modelling approach performed well at sites where there was appreciable chlorine decay between distribution and consumption, but not as well where chlorine decay was small in absolute terms. In these settings, which tend to be cooler (20-30°C) and have better WASH conditions, the upper limit of the current Sphere FRC target range (~0.5 mg/L) appears to be sufficient for protecting household water safety, and site-specific FRC targets may not be required.
- To maximize the utility and replicability of our methodology in refugee/IDP camps, we used only widely available FRC data. However, other water quality parameters, water handling practices, and contextual factors also likely influence post-distribution chlorine decay. Further research is required to investigate which factors matter most for post-distribution chlorine decay in order to rationalize monitoring programs and better support water safety optimization efforts in refugee/IDP camps.
- Chlorine decay in distribution systems is known to be a highly site-specific phenomenon, and this also appears to be the case for post-distribution chlorine decay. This means that a unique,

site-specific representation of post-distribution chlorine decay and, with it, a site-specific distribution point FRC target is ideal. To facilitate this, we have made the post-distribution chlorine decay modelling analytics demonstrated in this paper available online as an operational support tool for refugee/IDP camp water system operators. The *Safe Water Optimization Tool* (https://safeh2o.app/) can assist water system operators in analyzing distribution point and household FRC monitoring data in order generate a site-specific and evidence-based FRC target that provides residual chlorine protection for the entire duration of household storage and use.

- Current water quality monitoring practices in the humanitarian sector are focused primarily on water quality at the point of distribution. However, what really matters for public health is water quality where people actually consume it. Therefore, a greater emphasis should be placed on water quality monitoring at the household point of consumption in humanitarian operations.
- Enhancing residual chlorine protection of household stored water is an essential component of an overall WASH strategy for disrupting the transmission of waterborne pathogens and preventing water-related diseases amongst displaced populations in refugee/IDP camp settings, along with safe water storage, access to sufficient quantities of water, access to dignified sanitation, and the means to maintain good personal, domestic, and environmental hygiene. Taken together, these WASH measures can help reduce disease burden and prevent unnecessary deaths associated with water-related illnesses among displaced populations living through humanitarian crises.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Supplementary materials

Supplementary data associated with this article can be found, in the online version, at 10.1016/j.watres.2020.116642.

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