

# Sodium hypochlorite dosage for household and emergency water treatment: updated recommendations

Natalie Wilhelm, Anya Kaufmann, Elizabeth Blanton and Daniele Lantagne

## ABSTRACT

Household water treatment with chlorine can improve the microbiological quality of household water and reduce diarrheal disease. We conducted laboratory and field studies to inform chlorine dosage recommendations. In the laboratory, reactors of varying turbidity (10–300 NTU) and total organic carbon (0–25 mg/L addition) were created, spiked with *Escherichia coli*, and dosed with 3.75 mg/L sodium hypochlorite. All reactors had >4 log reduction of *E. coli* 24 hours after chlorine addition. In the field, we tested 158 sources in 22 countries for chlorine demand. A 1.88 mg/L dosage for water from improved sources of <5 or <10 NTU turbidity met free chlorine residual criteria ( $\leq 2.0$  mg/L at 1 hour,  $\geq 0.2$  mg/L at 24 hours) 91–94% and 82–87% of the time at 8 and 24 hours, respectively. In unimproved water source samples, a 3.75 mg/L dosage met relaxed criteria ( $\leq 4.0$  mg/L at 1 hour,  $\geq 0.2$  mg/L after 24 hours) 83% and 65% of the time after 8 and 24 hours, respectively. We recommend water from improved/low turbidity sources be dosed at 1.88 mg/L and used within 24 hours, and from unimproved/higher turbidity sources be dosed at 3.75 mg/L and consumed within 8 hours. Further research on field effectiveness of chlorination is recommended.

**Key words** | chlorination, chlorine dose, emergency, household water treatment, turbidity, water treatment

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## INTRODUCTION

Worldwide, approximately 663 million people lack access to an improved water source and an estimated 1.2 billion more rely on contaminated water sources (Onda *et al.* 2012; WHO/UNICEF 2015). Household water treatment (HWT) can be a cost-effective means of improving drinking water quality (Clasen *et al.* 2007a) and reducing diarrheal disease in households where access to microbiologically safe water is limited (Clasen *et al.* 2007b; Clasen 2015). HWT is therefore recommended as part of a comprehensive strategy to prevent diarrheal disease in low-income settings without access to safe drinking water (WHO/UNICEF 2011).

Household chlorination is a common HWT method, and chlorination programs generally include three elements: water treatment with sodium hypochlorite or sodium

dichloroisocyanurate at the household level; storage of chlorinated water in a safe container; and behavior change communication to improve hygiene and water and food handling practices (Lantagne *et al.* 2006). Generally, the sodium hypochlorite solutions are packaged in bottles with instructions to add one full bottle cap of the solution to clear water (or two caps to turbid water) in a standard sized storage container, agitate, and wait 30 minutes before drinking. The sodium dichloroisocyanurate tablets are packaged ten tablets to a strip, and (similarly to above) users are instructed to add one tablet to clear water (or two to turbid water) agitate, and wait 30 minutes before drinking. A meta-analysis of 21 health impact studies of household chlorination with sodium hypochlorite found

an average 29% reduction in diarrheal disease in users and a 41% reduction in confirmed users (Arnold & Colford 2007).

This documented impact has encouraged broad dissemination of household chlorination in over 40 countries, and in emergency response (POUZN 2007; Medentech 2015). As access has expanded in areas where many water sources contain suspended organic material, questions have been raised about the efficacy of chlorinating turbid waters. Current guidelines recommend that infrastructure waters directly treated with chlorination have turbidity values of <1 (USEPA 2006) or <5 (WHO 2011) nephelometric turbidity units (NTU). For HWT, the Centers for Disease Control and Prevention (CDC) and World Health Organization (WHO) both recommend a chlorine dosage of ~2 mg/L for waters with <10 NTU turbidity, and ~4 mg/L for water with >10 NTU (CDC 2008; WHO 2011). These dosages were selected because they: (1) do not exceed WHO and United States Environmental Protection Agency (USEPA) maximum guidelines for free chlorine residual (FCR) in drinking water of 5 mg/L and 4 mg/L, respectively (USEPA 2006; WHO 2011); (2) generally do not exceed consumer taste and odor concerns (Lantagne 2008); and, most importantly, (3) maintain a minimum of 0.2 mg/L FCR throughout transport and storage of water for 24 hours in the home to protect water from recontamination. WHO also recommends a maximum pH of 8.0 for chlorinating waters (WHO 2011).

These CDC and WHO dosage guidelines were developed after testing chlorine demand of 106 drinking water sources from 13 countries (Lantagne 2008). Among non-chlorinated source waters of turbidity <10 NTU or from a protected source, results were consistent, with 71 (87%) of 82 samples treated with a 1.875 (1.88) mg/L sodium hypochlorite dose maintaining FCR  $\geq 0.2$  mg/L for 24 hours after dosing. The results from the 14 non-chlorinated water samples from unimproved sources with turbidity between 10 and 100 NTU were not as consistent: only five (42%) of the 12 samples analyzed at the 3.75 mg/L dosage had FCR  $\geq 0.2$  mg/L for 24 hours after dosing. Direct chlorination was not recommended for waters >100 NTU. These results were expanded upon in a more recent study in Tanzania, where the chlorine demand of 43 hand dug wells was tested (Mohamed *et al.* 2015). The results were roughly similar, finding that single doses of sodium hypochlorite and

sodium dichloroisocyanurate were effective to 20 NTU, double doses to 50 NTU, that sodium dichloroisocyanurate could be effective at a double dose to 100 NTU, and that neither was effective at >100 NTU. However, the results were limited by small sample size (between two and 14 samples in each of the seven turbidity categories), and because the percent of samples meeting a criterion of FCR  $\geq 0.2$  mg/L at 24 hours was not presented. Additionally, both studies were limited because turbidity was used as a surrogate for chlorine demand, instead of harder-to-test more accurate indicators of chlorine demand, such as total organic carbon (TOC).

Another limitation of the above studies is that neither included measurements of microbial reduction after chlorination of turbid waters, which is a concern as pathogenic organisms can be shielded within organic material and thus be more resistant to chlorination (LeChevallier *et al.* 1981). We identified two studies where microbiological efficacy of chlorination of turbid water was investigated. In the first, water samples from six watersheds in the United States subjected to chlorination-only treatment of surface water were tested, and an inverse relationship between chlorine disinfection efficacy and turbidity was documented (LeChevallier *et al.* 1981). At doses from 0 to 2.5 mg/L of calcium hypochlorite with 1 hour of contact time, coliform reduction varied from >3 log (>99.9%) in water with 1.5 NTU turbidity to ~1 log (90%) in water with 8–13 NTU turbidity. In the second study, in Western Kenya, a 5 mg/L dose of sodium hypochlorite was added to 30 water samples, ten of which were <10 NTU, ten with 10–100 NTU, and ten with >100 NTU (Crump *et al.* 2004). The mean *Escherichia coli* level in untreated water was 3,938 CFU/100 mL (1–43,900). After treatment, the mean *E. coli* level was 0.5 (<1–10.9), with 90% of samples in the <10 NTU category, 100% of samples 10–100 NTU, and 60% of samples >100 NTU meeting the WHO drinking water guideline value for *E. coli* of <1 CFU/100 mL (WHO 2011). These results highlight that – at high enough dosages – chlorination can effectively inactivate bacteria in turbid waters.

Our goal was to address the limitations of the above studies – including small sample sizes (particularly in the  $\geq 10$  NTU turbidity range), the lack of controlled microbiological efficacy data at high turbidities, and use of turbidity as a surrogate for chlorine demand, and as such, we

conducted: (1) laboratory research to assess the efficacy of sodium hypochlorite to reduce *E. coli* and maintain FCR in waters with 10–300 NTU turbidity and 0–25 mg/L TOC; and (2) additional chlorine demand testing in water sources in developing countries, specifically expanding the range of samples in the 10–100 NTU turbidity range.

## METHODS

### Laboratory study

Using deionized water, white kaolin clay (Lion China Clay USP, Charles B. Chrystal Co., Larchmont, NY), and TOC stock solution (Hach, Loveland, CO), we manufactured 12 different representative 10-liter plastic containers of water ('reactors'), with turbidity levels from 10 to 300 NTU and TOC concentrations from 0 to 25 mg/L (Figure 1). The full protocol, described below, was replicated 3–5 times per reactor.

Each reactor was spiked with an overnight culture of  $10^9$  CFU/100 mL *E. coli*, grown in LB broth using a frozen stock of ATCC 25922 (Manassas, VA), to achieve a target concentration  $10^8$  CFU as determined by spectrometer reading at 600 nm wavelength, and confirmed by most probable

number testing using IDEXX Quanti-Trays, Colilert<sup>®</sup> media, and sealer (Westbrook, ME). Five to ten minutes after spiking, reactors were dosed with 3.75 mg/L sodium hypochlorite using Clorox<sup>®</sup> bleach, the concentration of which was confirmed daily using Hach digital iodimetric titration Method 8209 (Loveland, CO). The reactors were mixed twice: initially to allow the *E. coli* to react with the particulate matter, as it might in natural water and once more when the chlorine was added. The reactors were then left to settle for the remainder of the experiment (24 hours) to replicate a user adding chlorine to their water and then letting it sit. A control reactor (with no sodium hypochlorite added) was included during each sampling round to account for growth or die-off of *E. coli*; the NTU and TOC levels and concentrations in the control were varied each sample day such that by the end of testing there was one control reactor for each NTU/TOC combination tested.

Temperature, pH, turbidity, TOC, FCR, and total chlorine residual (TCR) were measured in each reactor before chlorine addition, with methods described as follows. In each reactor, after chlorine addition: (1) temperature and pH were measured at 1 and 24 hours after addition using a thermometer and Hanna multimeter (Bedfordshire, UK); (2) turbidity and TOC were measured at 1, 2, and 24 hours

	10 NTU	100 NTU	300 NTU	<b>Control</b>	x NTU x mg/L TOC
2 mg/L TOC	1	2	3	No Chlorine Addition	13
10 mg/L TOC	4	5	6		
25 mg/L TOC	7	8	9		
TOC Controls (0 mg/L)	10	11	12		

Figure 1 | Laboratory trials.

after addition using a Hach 2100 Portable Turbidimeter (Loveland, CO) and a Shimadzu TOC analyzer (Kyoto, Japan), respectively; (3) FCR and TCR were measured at 1, 2, 4, 10, and 24 hours after addition using a LaMotte 1200 chlorine colorimeter and DPD-1 and DPD-3 (N,N-diethyl-paraphenylene diamine) tablets (Chestertown, MD); and (4) *E. coli* concentrations were measured at 1, 10, and 24 hours after addition using the IDEXX MPN method as described above. Meters were calibrated daily using non-expired calibration solutions, and duplicate samples for turbidity and FCR were completed every ten tests for quality control purposes.

All data were entered, cleaned, and analyzed in Microsoft Excel (Redmond, WA), and statistical analysis was completed in Analyst Soft StatPlus (Walnut, CA). Analysis of variance (ANOVA) and Bonferroni tests were performed to compare turbidity and TOC with FCR results, with the added TOC or turbidity dosages of the independent groups and the FCR results as the continuous variable. The ANOVA tests determined whether the mean FCR at a given time point was significantly different between the independent TOC/turbidity groups; specifically, the ANOVA tested the null hypothesis that the mean FCR of each TOC or turbidity group was the same. If the ANOVA returned a significant result, a post-hoc Bonferroni test was performed to determine which group was significantly different. The FCR data were normally distributed and therefore the ANOVA test was appropriate. When evaluating which variables met FCR criteria, chi-square tests were performed; the independent variable was the TOC level, and the dependent, dichotomous variable was whether the FCR was  $\geq 0.2$  at 24 hours. The chi-square test evaluated the null hypothesis that the TOC groups and the FCR  $\geq 0.2$  at 24 hours outcomes were independent of each other.

*E. coli* data from each reactor were analyzed by calculating the geometric means for each reactor (with samples  $< 1$  CFU/100 mL adjusted to 1 CFU/100 mL) and by calculating log reductions from initial *E. coli* concentrations to results at 1, 10, and 24 hours. A  $\geq 4$  log reduction of *E. coli* was considered the highest tier reduction (three stars) as per the WHO HWT Evaluation Scheme criteria (WHO 2015). The WHO HWT Evaluation Scheme provides performance-based criteria for independently evaluating the efficacy of HWT in removing bacterial, protozoal, and viral

organisms. Kruskal–Wallis ANOVA tests were performed to compare turbidity and TOC groups as the independent groups with median *E. coli* concentrations as the continuous variable. The Kruskal–Wallis ANOVA was chosen, as it is a non-parametric method that does not assume normal distribution. The relative percent difference (RPD) of duplicate samples was calculated to determine precision of results for each water quality parameter.

### Field chlorine demand testing

From 2003 to 2011, the authors completed or assisted with the water quality testing, product development, government approval processes, and training necessary to begin large-scale chlorination programs in 22 countries, including chlorine demand testing. Countries were selected based on partner non-governmental organization strategic plans for starting new projects and the availability of funding for technical assistance and project initiation. In each country, drinking water sources were identified by consulting local staff, water experts, and/or national statistics. After representative sources were selected for sampling, the authors confirmed the source was used for drinking by the local population. Source water was collected in multiple clean, locally purchased containers, called 'jerrycans', which are 10- to 20-liter plastic recycled vegetable oil containers commonly used to transport and store water. Water quality analysis occurred within 24 hours of sample collection. This dataset from 22 countries fully includes the 13 countries of data analyzed in Lantagne (2008).

To characterize source water, each sample was analyzed for turbidity, pH, conductivity, and FCR and TCR before sodium hypochlorite addition. Turbidity was measured after agitation with a Lamotte turbidimeter calibrated weekly with non-expired stock calibration solutions (Chestertown, MD). Conductivity and pH were measured with a Hanna multimeter calibrated weekly with non-expired stock calibration solutions (Bedfordshire, UK). FCR and TCR were measured using a Lamotte chlorine colorimeter and DPD-1 and DPD-3 tablets calibrated daily using non-expired stock calibration solutions at 0, 0.1, 1.0, and 2.65 mg/L (Chestertown, MD). For all water quality parameters, a minimum of 7% of samples were duplicated for quality control.

Sodium hypochlorite solutions were purchased locally in each country, and their concentrations were measured using Hach digital iodometric titration Method 8209 (Loveland, CO). After source water characterization, varying sodium hypochlorite doses were added to each of the containers for each of the source waters, with most doses in the 1.88 mg/L and 3.75 mg/L category. FCR and TCR were measured at 1, 2, 4, 8, and 24 hours after chlorine addition, as described above. Please note constraints (such as access to the jerrycans at night) did not allow for FCR data to be collected at exactly the precise time points in all contexts, and time periods within 30% (at 8 hours) and 20% (at 24 hours) of intended time were included.

All data were entered into, cleaned, and analyzed in Microsoft Excel (Redmond, WA); statistical analysis was completed in Analyst Soft StatPlus. Samples were categorized according to the following characteristics. (1) *Source type*. Improved sources include public standpipes, protected dug wells, protected springs, and rainwater collection (WHO/UNICEF 2015). Unimproved sources include unprotected wells, unprotected springs, vendors, and rivers. Please note in this study a collapsed category termed 'open water' (including lakes, rivers, created ponds used as reservoirs, unprotected springs, rainwater stored in created ponds, and tanked river water) was created and was considered unimproved. (2) *Turbidity breakpoint*. Samples were stratified at two different turbidity breakpoints, at <5 and  $\geq 5$  NTU and at <10 and  $\geq 10$  NTU, based on the discrepancy between recommendations of 5 or 10 NTU in WHO guidelines (WHO 2011). Further stratification of turbidity by decile (10–20, 21–30, 31–40, and so on) was also performed for sources in the 10–100 NTU turbidity range. (3) *Chlorine dose*. Samples were stratified by whether a dosage of 1.88 or 3.75 mg/L was applied.

The outcomes analyzed were: (1) if FCR was  $\leq 2.0$  mg/L 1 hour and  $\geq 0.2$  mg/L 24 hours after chlorine addition; and (2) if FCR was  $\leq 4.0$  mg/L at 1 hour and  $\geq 0.2$  mg/L 24 hours after chlorine addition. These two different outcomes were evaluated at both 8 and 24 hours after addition, and stratified by the above presented categories of source type, turbidity breakpoint and decile, and chlorine dosage. For consistency, any sample not collected in a jerrycan, that had FCR before chlorine addition or that did not have FCR data collected at 24 hours, was excluded from analysis.

In evaluating the source turbidity, pH, and conductivity, median values are reported and Kruskal–Wallis ANOVA tests were performed to compare median water quality parameters of improved versus unimproved water sources. Each water quality parameter was the continuous, non-parametric variable with the source improvement category as the independent group variable. To compare <5 and <10 NTU cutoffs and the percentage meeting FCR criteria, the 95% confidence intervals were calculated and compared. As the two cutoffs are not independent groups, a chi-square test could not be performed comparing the cutoffs with the criteria outcomes.

Logistic regressions were performed to analyze factors contributing to water samples meeting criteria at 8 and 24 hours, with the output variable of meeting FCR criteria and input variables of source type, turbidity, and chlorine dose.

## RESULTS

### Laboratory study

Temperature and pH were constant for all reactors during all time points, with a mean and standard deviation temperature of 19.4°C (0.5) and a mean and standard deviation pH of 7.54 (0.1) (Table 1). Turbidity decreased over time as the clay settled: the mean turbidity in the 10 NTU reactors declined from 10.0–11.1 NTU at 1 hour to 2.7–3.5 NTU at 24 hours; the mean turbidity in the 100 NTU reactors declined from 80.2–91.9 NTU at 1 hour to 12.3–15.0 NTU at 24 hours; and, the mean turbidity in the 300 NTU reactors declined from 101.2–170.3 NTU at 1 hour to 23.4–33.0 NTU at 24 hours. Variability between time points in TOC was minimal, and therefore the mean across time points was calculated: 31.6–33.4 mg/L across all the time points in the 2 mg/L addition reactors, 39.5–43.1 in the 10 mg/L addition reactors, and 52.9–58.5 in the 25 mg/L addition reactors; as well as 31.9–38.7 mg/L in the 0 mg/L addition reactors. Please note additional TOC (from the broth in the *E. coli* spiking) was present in all reactors.

FCR and TCR decreased over the 24 hours of testing (Table 1). All 12 reactors had FCR <2 mg/L at 1 hour,

**Table 1** | Mean FCR, TCR, turbidity, and TOC over time in 12 reactors

Reactor	N	FCR (mg/L) mean (stdev)				TCR mg/L mean (stdev)				Turbidity (NTU) mean (stdev)				TOC (mg/L) mean (stdev)	
		1 hour		24 hour		1 hour		24 hour		1 hour		24 hour		All time points	
1	4	1.26	(0.3)	0.15	(0.1)	1.55	(0.2)	0.47	(0.1)	10.7	(1.1)	2.7	(0.4)	33.4	(1.4)
2	4	0.99	(0.6)	0.17	(0.1)	1.36	(0.6)	0.53	(0.1)	82.9	(19.9)	14.5	(5.4)	33.0	(2.0)
3	3	1.00	(0.8)	0.17	(0.1)	1.31	(1.0)	0.51	(0.1)	132.8	(51.0)	30.6	(4.4)	31.6	(1.2)
4	3	0.71	(0.3)	0.28	(0.2)	0.94	(0.3)	0.60	(0.1)	11.1	(0.7)	2.9	(0.5)	43.1	(1.6)
5	4	0.94	(0.4)	0.11	(0.1)	1.28	(0.2)	0.35	(0.2)	91.9	(20.6)	15.0	(3.6)	40.0	(1.7)
6	3	0.87	(0.5)	0.29	(0.1)	1.21	(0.7)	0.47	(0.0)	170.3	(15.1)	29.2	(8.8)	39.5	(1.1)
7	3	0.45	(0.1)	0.12	(0.1)	0.92	(0.4)	0.53	(0.2)	10.5	(0.9)	3.0	(0.1)	58.5	(1.3)
8	3	0.46	(0.2)	0.18	(0.2)	0.77	(0.2)	0.47	(0.2)	80.2	(2.5)	12.6	(5.1)	52.9	(9.8)
9	3	0.62	(0.4)	0.14	(0.0)	0.99	(0.3)	0.40	(0.1)	101.2	(4.5)	23.4	(6.7)	55.2	(1.7)
10	4	0.38	(0.2)	0.02	(0.0)	0.65	(0.3)	0.52	(0.0)	10.0	(2.0)	3.5	(0.2)	38.7	(1.5)
11	3	0.35	(0.5)	0.30	(0.1)	1.88	(0.8)	0.53	(0.0)	86.7	(7.3)	12.3	(1.8)	31.9	(1.9)
12	5	0.74	(0.5)	0.04	(0.1)	1.05	(0.7)	0.55	(0.1)	146.8	(17.9)	33.0	(4.1)	36.0	(3.7)

and three reactors had average FCR  $\geq 0.2$  mg/L at 24 hours. By reactor test, 38% (16) of 42 total reactor tests had FCR  $\geq 0.2$  mg/L at 24 hours. When stratified by initial turbidity, the average FCR was 0.13 mg/L for 10 NTU turbidities and 0.14 mg/L for 300 NTU turbidities; this difference was not statistically significant ( $p = 0.56$ ). In each of these turbidity strata, 36% (5) of the samples had a FCR  $\geq 0.2$  mg/L at 24 hours. When stratified by TOC, the average FCR was 0.19 mg/L in reactors with 2 or 10 mg/L TOC added, and 52% (11) of the samples had FCR  $\geq 0.2$  mg/L at 24 hours. In reactors with 25 mg/L TOC added, the mean FCR was 0.14 mg/L at 24 hours and 22% (2) of the samples met criteria. The difference between the TOC strata was not statistically significant ( $p = 0.27$ ).

The average RPD in the temperature, pH, turbidity, TOC, and *E. coli* results were all  $< 1\%$ . The average RPD in FCR and TCR data were 14.1% and 3.2%, respectively.

The initial geometric mean *E. coli* concentrations ranged from  $4.24 \times 10^7$  to  $2.27 \times 10^8$  CFU/100 mL (Table 2). At 1 hour, geometric *E. coli* concentrations were 6.7–2,031.9 CFU/100 mL, with log reduction values (LRVs) ranging from 5.0 to 7.3 for all reactors. At 10 hours, geometric *E. coli* concentrations were 1.0–7.0 CFU/100 mL, with LRVs ranging from 6.8 to 8.4 for all reactors. At 24 hours, geometric *E. coli* concentrations were 1.0–87.6 CFU/100 mL, with LRVs ranging from 6.4 to 8.4 for

all reactors. All reactors met WHO's three-star criteria for microbiological performance at all time points. There was no significant difference between reactors with varying turbidities at all time points; 1, 10, and 24 hours ( $p = 0.057$ , 0.175, and 0.396). *E. coli* did vary between TOC at hours 10 and 24 ( $p = 0.043$  and  $p = 0.034$ ), but not at 1 hour ( $p = 0.0558$ ). After 1 hour, 10% of samples had *E. coli* with  $< 1$  CFU/100 mL ( $n = 4$ ); after 10 hours, 67% of

**Table 2** | Geometric mean *E. coli* (CFU/100 mL) over time in 12 reactors (with log reduction)

Reactor	0 hr	1 hr	10 hr	24 hr
1	$1.89 \times 10^8$	47.4 (6.6)	1.8 (8.0)	$< 1$ (8.3)
2	$7.04 \times 10^7$	59.6 (6.1)	$< 1$ (7.8)	$< 1$ (7.8)
3	$4.24 \times 10^7$	13.9 (6.5)	$< 1$ (7.6)	$< 1$ (7.6)
4	$2.27 \times 10^7$	12.6 (7.3)	$< 1$ (8.4)	$< 1$ (8.4)
5	$7.65 \times 10^7$	6.7 (7.1)	$< 1$ (7.9)	2.5 (7.5)
6	$5.21 \times 10^7$	8.4 (6.8)	$< 1$ (7.7)	$< 1$ (7.7)
7	$1.79 \times 10^8$	21.8 (6.9)	$< 1$ (8.3)	$< 1$ (8.3)
8	$4.88 \times 10^7$	91.5 (5.7)	4.7 (7.0)	$< 1$ (7.7)
9	$4.66 \times 10^7$	11.9 (6.6)	7.0 (6.8)	13.4 (6.5)
10	$2.12 \times 10^8$	2,031.9 (5.0)	ND	87.6 (6.4)
11	$4.50 \times 10^7$	10.7 (6.6)	3.3 (7.1)	$< 1$ (7.7)
12	$6.65 \times 10^7$	198.0 (5.5)	$< 1$ (7.8)	14.5 (6.7)

samples had <1 CFU/100 mL ( $n = 34$ ); and after 24 hours, 74% of samples had <1 CFU/100 mL ( $n = 31$ ).

The control reactors that were used for each trial reactor accounted for any natural growth or die-off of *E. coli*. The temperature and pH were similar for the control reactors compared to the trial reactors. There were some differences between control and trial reactors for the turbidities, with an RPD ranging from 6 to 20% at 1 hour and from 14 to 49% at 24 hours. The TOC had lower RPD, with 0 to 11% RPD for the varying TOC groups. There was no chlorine residual in the control reactors. There was no *E. coli* reduction in the control reactors and the *E. coli* counts remained greater than  $2.4 \times 10^8$  CFU/100 mL for all reactors except for one, which was too numerous to count for all four time points. Thus, *E. coli* results are not adjusted for die-off in the results presented herein.

The RPD for the duplicate samples taken every ten samples was, on average, between 0.0 and 0.85% for temperature, pH, turbidity, and TOC. The average RPD for FCR and TCR data were 14.1% and 3.2%, respectively.

### Field chlorine demand testing

A total of 195 drinking water sources were sampled from 22 countries at various chlorine dosages, for a total of 495 samples analyzed. After applying exclusion criteria, 158 sources remained with 394 samples analyzed. Sources excluded were 11 sources in Tajikistan, Uzbekistan, and Madagascar that were collected in only open buckets and 28 samples from 16 other sources because they were not in jerrycans. Ten sources were excluded because they had FCR present in initial source water testing, and an additional 33 samples because of missing FCR data as only time periods within 30% (at 8 hours) and 20% (at 24 hours) of intended time were included (Table 3).

Overall, 54% (86/158) of the sources were categorized as improved, the majority of which were protected wells and urban standpipes (Table 3). Of the 46% (72/158) of sources categorized as unimproved, most (45, 58%), were 'open water' sources. Wells, both protected and unprotected, were tested in 18 of the 22 countries, and represented 35% of the sources tested.

The median turbidity of the 158 included sources was 3.37 NTU (range 0–551), with 113 (72%) of turbidity

0–<10 NTU, 42 (27%) of turbidity 10–100, and three (2%) of turbidity >100 (Table 4). Within the 10–100 NTU range, turbidity was not normally distributed, with 43% (25) <30 NTU. At the five and ten NTU breakpoints, 90 sources were <5 and 68 sources were  $\geq 5$  and 113 sources <10 and 45 sources were  $\geq 10$ . The median pH was 7.0 (range 4.1–9.4); 24 (15%) sources had pH >8.0. The median conductivity was 160  $\mu\text{mhos/cm}$  (range 0–2,000).

Improved sources had significantly lower median turbidity (1.23 NTU) than unimproved sources (11.1 NTU) ( $p < 0.001$ ). The pH and conductivity did not significantly differ in unimproved sources as compared to improved sources.

Overall, 160 samples were tested at the 1.88 mg/L dose from the 149 sources and 141 samples were tested at the 3.75 mg/L dose from 136 sources. Please note 16 sources were tested for both sodium hypochlorite and sodium dichloroisocyanurate, 11 at 1.88 mg/L dose and five at 3.75 mg/L dose. All samples not tested at the higher 3.75 mg/L were from improved sources. Duplicate samples were conducted on turbidity and FCR samples, with 9% and 8% of samples duplicated, respectively. The RPD of duplicate samples was 6.5% for FCR and 3.5% for turbidity.

### Stratification by source type

At 24 hours, 84% of improved sources and 45% of unimproved sources tested with the 1.88 mg/L dose met the 0.2–2.0 mg/L FCR criteria (Table 5). These percentages increase slightly (to 85% and 46% in improved and unimproved sources, respectively) with the 0.2–4.0 mg/L FCR guideline. At the 3.75 mg/L dose, 12% of improved sources and 26% of unimproved sources met the 0.2–2.0 mg/L FCR criteria, which increased to 96% and 64% of improved and unimproved sources at the 0.2–4.0 mg/L FCR criteria.

At 8 hours, 92% of improved sources and 57% of unimproved sources tested with the 1.88 mg/L dose met the 0.2–2.0 mg/L FCR criteria (Table 5). These percentages increase slightly (to 93% and 95% in improved and unimproved sources, respectively) with the 0.2–4.0 mg/L FCR guideline. At the 3.75 mg/L dose, 11% of improved sources and 38% of unimproved sources met the 0.2–2.0 mg/L FCR criteria, which increased to 98% and 83% of improved and unimproved sources at the 0.2–4.0 mg/L FCR criteria.

**Table 3** | Sources analyzed, by country

	N	Improved sources					Unimproved sources		
		Urban tap	Rural tap	Protected well	Protected spring	Rainwater	Open water	Open well	Vendor
Angola	11	4		2	1		3	1	
Benin	6	1		1			1	3	
Burundi	12		6		3		3		
Cameroon	12		2	3	3		2	2	
DRC	5	1		1			3		
Ethiopia	4		1				2	1	
Guinea	10	2		3	1		1	3	
Guyana	4	3				1			
Haiti	12			2	2		8		
Kenya	10				1		9		
Liberia	6	1		1	1		1	1	1
Malawi	4		1	1			1	1	
Mali	5			2			2	1	
Mozambique	7	2		1			1	3	
Nepal	12	2	1	4	2			3	
Niger	6	2		2			1	1	
Nigeria	5	1		2				1	1
Rwanda	4	2		1	1				
Swaziland	8			2			4	2	
Tanzania	5	2		1			1	1	
Yemen	5	1			3		1		
Zambia	5	2		1			1	1	
Total: n (%)	158	26 (16)	11 (7)	30 (19)	18 (11)	1 (1)	45 (28)	25 (15)	2 (2)

**Table 4** | Source water physical and chemical characteristics, by source type

Source type	Number of sources	Turbidity (NTU)		pH		Conductivity ( $\mu$ mhos/cm)	
		Median	Range	Median	Range	Median	Range
Urban tap	26	1.70	(0.1–10.3)	7.4	(6.2–9.4)	135	(10–780)
Rural tap	11	1.54	(0.0–4.62)	6.5	(4.8–9.0)	100	(50–610)
Protected well	30	1.33	(0.0–87.1)	6.8	(5.0–8.7)	175	(10–1,130)
Protected spring	18	0.31	(0.0–10.5)	6.2	(4.3–8.5)	180	(0–2,000)
Rainwater	1	1.78	(–)	6.6	(–)	20	(–)
Open water	45	11.5	(0.0–551)	7.1	(5.1–9.0)	130	(0–1,200)
Open well	25	8.21	(0.69–136)	7.3	(4.1–8.9)	355	(0–1,110)
Vendor	3	0.85	(0.0–1.7)	6.7	(6.1–7.3)	280	(120–440)
Total	159	3.37	(0.0–551)	7.0	(4.1–9.4)	160	(0–2,000)



**Table 5** | Sources meeting FCR criteria at two different doses and time points, stratified by source type and turbidity breakpoints

	Number of sources tested	1.875 mg/L dose						3.75 mg/L dose					
		8 hours			24 hours			8 hours			24 hours		
		Number of samples	FCR 0.2–2.0 mg/L	FCR 0.2–4.0 mg/L	Number of samples	FCR 0.2–2.0 mg/L	FCR 0.2–4.0 mg/L	Number of samples	FCR 0.2–2.0 mg/L	FCR 0.2–4.0 mg/L	Number of samples	FCR 0.2–2.0 mg/L	FCR 0.2–4.0 mg/L
Urban/Rural tap	37	39	90%	92%	41	83%	85%	27	7%	100%	29	3%	97%
Protected well	30	29	93%	93%	33	88%	88%	20	15%	95%	24	21%	96%
Protected spring	18	15	100%	100%	16	81%	81%	14	14%	100%	15	13%	93%
Rainwater	1	1	0%	0%	1	0%	0%	0	0%	0%	0	0%	0%
Open water	45	36	50%	53%	42	38%	40%	42	43%	86%	48	23%	58%
Open well	25	22	73%	73%	24	58%	58%	21	33%	81%	23	35%	78%
Vendor	2	3	33%	33%	3	33%	33%	2	0%	50%	2	0%	50%
<i>Improved</i>	86	84	92%	93%	91	84%	85%	61	11%	98%	68	12%	96%
<i>Unimproved</i>	72	61	57%	59%	69	45%	46%	65	38%	83%	73	26%	64%
<i>Turbidity &lt;5</i>	90	88	86%	88%	95	81%	82%	69	13%	93%	77	16%	92%
<i>Turbidity ≥5</i>	68	57	63%	65%	65	46%	48%	57	40%	88%	64	23%	64%
<i>Turbidity &lt;10</i>	113	110	85%	87%	120	75%	77%	88	15%	92%	99	16%	89%
<i>Turbidity ≥10</i>	45	35	51%	51%	40	43%	43%	38	50%	87%	42	26%	57%
<i>T &lt; 5, Improved</i>	67	65	94%	94%	69	87%	87%	49	12%	100%	54	11%	98%
<i>T &lt; 5, Unimproved</i>	23	23	65%	70%	26	65%	69%	20	15%	75%	23	26%	78%
<i>T ≥ 5, Improved</i>	19	19	84%	89%	22	73%	77%	12	8%	92%	14	14%	86%
<i>T ≥ 5, Unimproved</i>	49	38	53%	53%	43	33%	33%	45	49%	87%	50	26%	58%
<i>T &lt; 10, Improved</i>	79	78	91%	92%	84	82%	83%	57	12%	98%	63	11%	95%
<i>T &lt; 10, Unimproved</i>	34	32	72%	75%	36	58%	61%	31	19%	81%	36	25%	78%
<i>T ≥ 10, Improved</i>	7	6	100%	100%	7	100%	100%	4	0%	100%	5	20%	100%
<i>T ≥ 10, Unimproved</i>	38	29	41%	41%	33	30%	30%	34	56%	85%	37	27%	51%
<i>Total</i>	158	145	77%	79%	160	67%	68%	126	25%	90%	141	19%	79%

At both doses and both time points, unimproved water sources had lower median FCR concentrations than improved sources ( $p < 0.001$  for all four tests at two doses and time points).

### Stratification by turbidity breakpoints

In water sources with  $<5$  NTU, the 1.88 mg/L dose met the 0.2–2.0 mg/L and 0.2–4.0 mg/L FCR criteria at 8 and 24 hours in 81–88% of samples. In water sources with  $\geq 5$  NTU, the 3.75 mg/L dose met the 0.2–4.0 FCR criteria in 88% and 64% of samples at 8 and 24 hours, respectively (Table 5). In water sources with  $<10$  NTU, the 1.88 mg/L dose met the 0.2–2.0 mg/L and 0.2–4.0 mg/L FCR criteria at 8 and 24 hours in 75–87% of samples. In water sources with  $\geq 10$  NTU, the 3.75 mg/L dose met the 0.2–4.0 FCR criteria in 87% and 57% of samples at 8 and 24 hours, respectively.

Sources with higher turbidity ( $\geq 10$ ) had lower FCR at both 8 and 24 hours at both doses ( $p < 0.001$ , for all four tests). At the 1.88 mg/L and 3.75 mg/L doses, there was no significant difference between the  $<5$  and  $<10$  NTU breakpoints for meeting FCR criteria at 8 hours and 24 hours (95% confidence intervals for proportions encompassed all percentages).

### Stratification by source type and turbidity breakpoints

Using a dose of 1.88 mg/L in improved water sources with turbidities of  $<5$  or  $<10$ , the 0.2–2.0 FCR criteria were met 91–94% of the time at 8 hours and 82–87% at 24 hours (Table 5). In unimproved water sources across all turbidities ( $<5$ ,  $\geq 5$ ,  $<10$ ,  $\geq 10$ ), a 1.88 mg/L dose led to meeting the 0.2–2.0 FCR criteria 41–72% of the time at 8 hours and to meeting the 0.2–4.0 FCR criteria 41–75% of the time at 8 hours; the 24 hour results ranged from 30 to 69% for the two criteria. In unimproved water sources across all turbidities ( $<5$ ,  $\geq 5$ ,  $<10$ ,  $\geq 10$ ), a 3.75 mg/L dose led to meeting the 0.2–2.0 FCR criteria 15–56% of the time at 8 hours and to meeting the 0.2–4.0 FCR criteria 75–87% of the time at 8 hours; the 24 hour results ranged from 25 to 27% for the 0.2–2.0 FCR criteria and from 51 to 78% for the 0.2–4.0 criteria.

### Stratification by turbidity deciles

Using a dose of 1.88 mg/L in water sources with turbidities  $<10$  and 10–20, the 0.2–2.0 and 0.2–4.0 FCR criteria were met 78–87% of the time at 8 hours and 62–77% of the time at 24 hours (Table 6). While using the 3.75 mg/L dose in water sources with turbidities  $<10$  and 10–20, the 0.2–2.0 FCR criteria were met only 15–38% of the time at

**Table 6** | Sources meeting FCR criteria at two different doses and two time points, grouped by turbidity deciles

Turbidity	1.875 mg/L dose						3.75 mg/L dose					
	8 hours			24 hours			8 hours			24 hours		
	N	0.2–2.0 mg/L	0.2–4.0 mg/L	N	0.2–2.0 mg/L	0.2–4.0 mg/L	N	0.2–2.0 mg/L	0.2–4.0 mg/L	N	0.2–2.0 mg/L	0.2–4.0 mg/L
<10	110	85%	87%	120	75%	77%	88	15%	92%	99	16%	89%
10–20	18	78%	78%	21	62%	62%	16	38%	94%	18	22%	72%
20–30	2	0%	0%	3	0%	0%	3	67%	100%	4	25%	50%
30–40	6	17%	17%	7	29%	29%	8	63%	88%	9	22%	33%
40–50	3	100%	100%	3	67%	67%	3	67%	100%	3	33%	67%
50–60	2	0%	0%	2	0%	0%	2	100%	100%	2	50%	50%
60–70							1	0%	100%	1	0%	100%
80–90	1	0%	0%	1	0%	0%	1	100%	100%	1	100%	100%
90–100	1	0%	0%	1	0%	0%	1	0%	0%	1	0%	0%
>100	2	0%	0%	2	0%	0%	3	33%	33%	3	33%	33%

8 and 24 hours, while the 0.2–4.0 FCR criteria were met 72–94% of the time at 24 hours. At higher turbidity deciles, there are fewer samples in certain strata, with wider ranges of results. In 30–50 NTU water sources with a 1.88 mg/L dose, 0.2–2.0 and 0.2–4.0 FCR criteria were met 17–100% at 8 and 24 hours. Using a 3.75 mg/L dose, 0.2–2.0 FCR criteria were met 63–67% of the time at 8 hours, dropping to 22–25% at 24 hours. The 0.2–4.0 FCR criteria were met 88–100% of the time at 8 hours, and dropped to 33–67% at 24 hours. Higher turbidity deciles (50 NTU and higher) were mostly tested at the 3.75 mg/L dose and five of the eight samples in these strata met either criteria.

### Regression results

A binary stepwise logistic regression was performed to understand which factors were most significant in predicting whether or not a water sample would have a FCR  $\geq 0.2$  mg/L at 8 hours and at 24 hours. The input variables were: source improvement (binary), turbidity (continuous), and two dose categories: 1.88, 3.75 (binary). The outcome variable (dependent) was whether that water sample had  $\geq 0.2$  FCR at 8 hours and at 24 hours (binary).

At 8 hours, the strongest predictive factor was a 3.75 mg/L dosage (odds ratio 11.0, 95% confidence interval 4.5–27.3), followed by improved source (OR: 3.7, 95% CI: 1.9–7.0), 1.88 mg/L dosage (OR: 2.6, 95% CI: 1.3–5.1), and turbidity (OR: 0.975, 95% CI: 0.962–0.989). At 24 hours, the strongest predictive factor was a 3.75 mg/L dosage (OR: 6.8, 95% CI: 3.4–13.6), followed by improved source (OR: 4.3, 95% CI: 2.5–7.3), 1.88 mg/L dosage (OR: 2.4, 95% CI: 1.4–4.6), and turbidity (OR: 0.972, 95% CI: 0.957–0.988).

## DISCUSSION

We conducted laboratory and field studies to further investigate the relationship between turbidity and chlorination efficacy to inform HWT with chlorination recommendations. In the laboratory work, we created reactors of varying turbidity (10–300 NTU) and TOC (0–25 mg/L addition), spiked the reactors with *E. coli*, dosed the reactors with 3.75 mg/L of sodium hypochlorite, and documented

that (although the majority of samples fell below 0.2 mg/L FCR within 24 hours) all samples at all time points had  $>4$  LRV of *E. coli*, meeting the most stringent ‘three star’ WHO Evaluation Scheme criteria for HWT products. In the field chlorine demand testing, we tested 158 sources across 22 countries, and found that a 1.88 mg/L dosage for improved waters of  $<5$  or  $<10$  NTU met FCR criteria of  $\leq 2.0$  mg/L after 1 hour and  $\geq 0.2$  mg/L after 24 hours 91–94% of the time after 8 hours, and 82–87% of the time after 24 hours. Using breakpoints of improved water, water with  $<5$  NTU turbidity, and water with  $<10$  NTU turbidity all led to a similar percent of samples that met criteria. For unimproved sources, we found a 1.88 mg/L dosage met FCR criteria of  $\leq 2.0$  mg/L after 1 hour and  $\geq 0.2$  mg/L at 24 hours 57% of the time after 8 hours, and 44% of the time after 24 hours. A 3.75 mg/L met relaxed criteria of  $\leq 4.0$  mg/L after 1 hour and  $\geq 0.2$  mg/L 83% of the time after 8 hours, and 65% of the time after 24 hours. Using breakpoints of unimproved water, water with  $\geq 5$  NTU turbidity, and unimproved water with  $\geq 10$  NTU turbidity all led to a similar percent of samples that met criteria. Overall, our combined laboratory and field results highlight that: (1) chlorine can be efficacious at treating contaminated water; (2) a 1.88 mg/L dosage is sufficient to maintain adequate FCR in 82–94% of water samples that are either improved sources or low turbidity worldwide, for up to 24 hours; and (3) a 3.75 mg/L dosage is sufficient to maintain adequate FCR in 83% of unimproved or higher turbidity samples for 8 hours and 65% of samples for 24 hours. We thus recommend that improved/low turbidity sources be dosed at 1.88 mg/L and used within 24 hours, while unimproved/higher turbidity sources be dosed at 3.75 mg/L and, if possible, consumed within 8 hours.

Our laboratory results are generally consistent with previous literature, as large *E. coli* reductions have been previously documented in field waters treated with higher doses of chlorine (Crump *et al.* 2004). Of note, studies using lower doses of chlorine have not documented these same reductions (LeChevallier *et al.* 1981). While it is commonly perceived that chlorine is not efficacious in turbid water, our and previous studies do show that chlorination of turbid water with a higher dose (4–5 mg/L) does meet the WHO three-star criteria for laboratory-based performance.

Additionally, our field results are consistent with previous literature, as previously 87% of improved and/or <10 NTU samples treated with a 1.88 mg/L sodium hypochlorite dose maintained FCR  $\geq 0.2$  mg/L for 24 hours after dosing (our results were 85–92%). The primary value of this study was in the additional samples in the 10–100 NTU range, as previous work examining chlorine performance in these ranges of turbidity was very limited.

In order to contextualize our results, however, there are three important factors to consider: (1) disadvantages to chlorinating turbid water; (2) the difference between efficacy in the laboratory, field testing, and effectiveness in actual use circumstances; and (3) user acceptance.

In addition to dosage difficulties, there are additional disadvantages to chlorinating turbid water, including trihalomethane (THM) formation potential and taste and odor objections. THMs are disinfection by-products (DBP) formed when chlorine reacts with organic material, and they have been shown to have a slight long-term risk of cancer (Rook 1974). While the addition of sodium hypochlorite to six source waters of turbidity 4.23–305 NTU near Kisumu, Kenya and the addition of sodium dichloroisocyanurate (NaDCC) tablets to six sources of water of 0.6–888.5 NTU near Arusha, Tanzania did not lead to formation of THM concentrations that exceeded WHO guideline values for any of the four individual THMs or the additive total THM (TTHM) ratio guideline value (Lantagne *et al.* 2008, 2010), there is still significant concern regarding the potential risk from THMs and other DBPs in chlorinating turbid water. The precautionary principle would advise against chlorinating turbid waters, if possible. Additionally, chlorine taste and odor are key concerns for user acceptability in HWT chlorination programs. Focus groups on taste testing have found that the majority of SWS users are comfortable drinking water with a FCR of up to 2.0 mg/L; however, there is significant regional variation in the acceptable maximum residual (Lantagne 2008). The higher sodium hypochlorite dosages necessary to ensure maintenance of chlorine residual in turbid waters exacerbate the taste and odor concerns.

While the WHO Evaluation Scheme for HWT products currently only considers laboratory efficacy, HWT products are used in real-world circumstances, and effectiveness in

actual use in households is likely to be lower than laboratory efficacy. The FCR maintenance percentages documented herein are ideal circumstances, in cleaned, sealed jerrycans, without introduction of foreign objects or material into the water to increase the chlorine demand over time. It is likely that FCR would not be maintained as well in actual household use. In a study conducted in non-turbid waters in Western Kenya with households using ceramic storage containers, it was found that 82% of households self-reported using HWT chlorination, but only 60% of households had TCR in their drinking water (Null & Lantagne 2012). Of the 60% with TCR, 69% reported treating in the last 24 hours, and 87% of those households had water with <1 MPN/100 mL *E. coli*. Of households without TCR in their drinking water, 49% reported treating in the last 24 hours, and only 32% had <1 *E. coli* in their drinking water. This work highlights the importance of maintaining FCR in stored household water to prevent recontamination. As such, it is recommended that HWT chlorination programs also promote safe storage and safe handling of water to ensure field effectiveness can match laboratory efficacy.

Lastly, users will only consume water products they find acceptable, and the taste and odor implications of chlorinating turbid waters, along with a lack of visual improvement in water during chlorination treatment may be impediments to use, although the relationship between treatment and use is complex. A study in Western Kenya found that having turbid water was significantly associated with initially using a flocculant/disinfectant sachet (which also clarifies the water) instead of sodium hypochlorite solution, but consistent long-term use of the flocculant/disinfectant sachet was low, as users switched to sodium hypochlorite alone for turbid water due to the high cost and multi-step process necessary to use the sachet (Dubois *et al.* 2010). Additionally, users may or may not be able to use their treated water within the recommended 8–24 hours (Null & Lantagne 2012). One solution is to target chlorine dosing to the exact water source by completing jar testing of water sources to determine the exact chlorine demand on a regular basis, and adjusting the dose regularly, as is commonly completed in emergency response programs (WHO 2005). This requires significant resources and local testing, however, which

are not often available in larger regional or national-scale HWT chlorination programs.

The limitations of this work include the limited number of samples in high turbidity ranges, which can be attributed to the fact that 'real-world' water sources were used, and only a small percentage of the global population uses very high turbidity waters for drinking. Additionally, time constraints in field data did not allow for FCR data to be collected at exactly the precise time points in all contexts. In the laboratory experiments, the kaolin clay and the plastic material used for the reactors in the laboratory experiments may have leached organic carbon into the buckets, but we believe that any leaching was insignificant compared to the organic carbon from the *E. coli* broth. TOC was present in the 0 mg/L reactors, and higher than the TOC addition in the other reactors, due to the carbon content of the broth used to grow the *E. coli* stocks. The *E. coli* growth patterns were not characterized, but there was no significant die-off of *E. coli* overnight and in the next day. An additional limitation is that the chlorine demand created in the laboratory testing, which was a mix of clay, TOC standard, and TOC from the *E. coli* broth that led to high TOC levels, may or may not be representative of real-world chlorine demand. In addition, the *E. coli* may not have had sufficient mixing/contact time to associate with particles (one reason why chlorination in high turbidity is so difficult). However, we feel that the results, showing *E. coli* reduction and (for the most part) maintenance of this reduction in the absence of detectable FCR, are valid. Due to these limitations, we feel our results present a very conservative estimate of chlorination efficacy in turbid waters. Further laboratory and field research on chlorine demand in real-world high-turbidity waters (>50 NTU) would be of utility, and further work comparing FCR maintenance in sodium hypochlorite solution and sodium dichloroisocyanurate tablets is also needed.

One of the greatest challenges in chlorination is balancing the following competing criteria: (1) meeting the chlorine demand of the water; (2) maintaining FCR sufficient for disinfection during water transport and household storage; (3) not exceeding international maximum guideline values of 4–5.0 mg/L of chlorine in drinking water; and (4) meeting user taste and odor requirements. The current recommendations for chlorine dosage

and FCR in turbid waters do not adequately address the contexts in which balancing these competing criteria is possible. Additional research is needed to understand the context in which balancing these criteria is, and is not, possible, and to develop alternatives which include selection criteria to prioritize alternate treatments or water sources. Lastly, it is important to note the doses proposed are appropriate for approximately 90% of waters. While this is the vast majority, it is not 100%. Further research is needed to understand: (1) what the raw water quality characteristics are that lead to FCR not being maintained (by testing water quality parameters of real-world waters that do not meet criteria); and (2) how to address these with pre-treatment (filtering, pH adjustment, etc.). Although most HWT products are sensitive to source water variation, it is important to bring the percentage of waters appropriate to be treated as high as possible.

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## CONCLUSIONS

Based on our results, we recommend that improved/low turbidity sources be dosed at 1.88 mg/L and used within 24 hours, while unimproved/higher turbidity sources be dosed at 3.75 mg/L and, if possible, consumed within 8 hours. We further recommend that HWT chlorination programs promote safe storage and handling of water, and that additional laboratory and field research be conducted on chlorination of water in the 50–100 NTU range.

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