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Emergency Water Treatment with Bleach in the United States: The Need to Revise EPA Recommendations

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Supporting Information

ABSTRACT: During emergencies in the United States, the Environmental Protection Agency (EPA) currently recommends using bottled water, or boiling or treating water by adding $^{1}/_{8}$ teaspoon (or 8 drops) of bleach to 1 gal of water. This bleach recommendation is internally inconsistent, a relatively high chlorine dose (5.55−8.67 mg/L), and unsupported by evidence. In this study, bleach was added in three different dosages to six waters available to emergency-affected populations in each of six states; free chlorine residual (FCR) and *Escherichia coli*/total coliforms were measured 1−24 h after treatment. Data were analyzed using four efficacy criteria. Results indicated the dosages in the current EPA recommendation are unnecessarily high to ensure (1) maintenance of FCR for 24 h after treatment, (2) absence of *E. coli*/total coliforms, and (3) establishment of a CT-factor sufficient to inactivate *Giardia lamblia* and enteric viruses 1 h after treatment. Additionally, emergency-prone populations did not have the materials to complete treatment with bleach in their household. Therefore, we recommend EPA review and revise the current recommendation to establish an internally consistent, criteria-based recommendation that is usable by emergency-affected populations. We also recommend investigating the use of new or commercially available water treatment products for emergency response in the United States.

INTRODUCTION

In the event of a natural disaster or infrastructure failure, normal water supply systems can be disrupted. When water supply to households is potentially unsafe, the United States (U.S.) Environmental Protection Agency (EPA) recommends to first drink bottled water. If bottled water is not available, it is recommended to then treat water from other available water supplies to render it safe to drink by boiling, or, last, to treat water by adding household bleach.[1]

It is commonly believed that water quality is poor after all emergencies.[2] However, research has dispelled this myth, showing instead that populations have increased waterborne illness risk only in those emergencies that cause flooding or displacement,[3,4] or when infrastructure systems are damaged and do not provide safe, chlorinated water. For instance, after Hurricane Katrina in the U.S. in 2005, which caused both flooding and displacement, there was an outbreak of norovirus in a Houston "mega-shelter",[5] and concentrations of *Vibrio* organisms in Lake Pontchartrain increased by orders of magnitude.[6] The EPA currently recommends "bottled, boil, bleach" for water treatment in all U.S. emergencies, regardless of emergency type and duration, water sources available, water quality, or affected population characteristics.

The EPA bleach recommendation reads: "If you can't boil water, you can disinfect it using household bleach. Bleach will kill some, but not all, types of disease-causing organisms that may be in the water. If the water is cloudy, filter it through clean cloths or allow it to settle, and draw off the clear water for disinfection. Add $^{1}/_{8}$ teaspoon (or 8 drops) of regular, unscented, liquid household bleach for each gallon of water, stir it well and let it stand for 30 min before you use it. Store disinfected water in clean containers with covers... double the amount of chlorine for cloudy, murky or colored water or water that is extremely cold...[find sources of water by] draining your hot water tank or melting ice cubes. In most cases, well water is the preferred source of drinking water. If it is not available and river or lake water must be used, avoid sources containing floating material and water with a dark color or an odor."[1]

There are three technical concerns with this current bleach treatment recommendation, including (1) an inconsistent dosage regime, (2) a dosage of chlorine by either measurement

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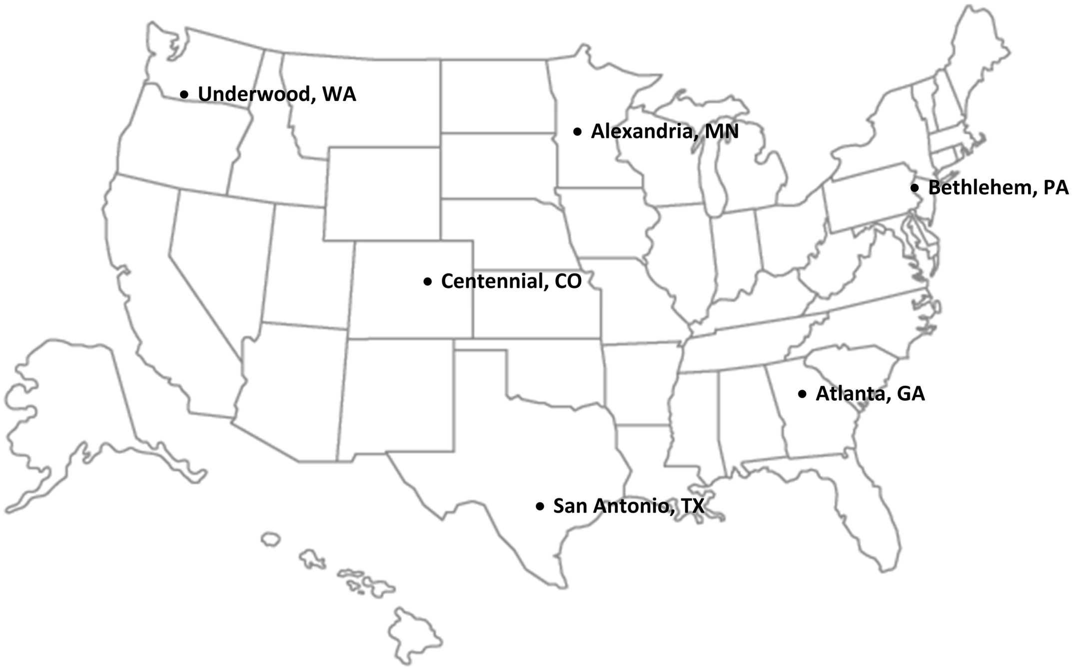

Figure 1. Sampling locations.

that is higher than recommended and used in emergencies worldwide, and (3) a lack of evidence supporting the development of the recommendation and how the dosages meet specific water quality criteria.

First, the recommended dosages are internally inconsistent: $^1/_8$ teaspoon is not equivalent to 8 drops. One U.S. teaspoon is defined as 5 mL, and thus $^1/_8$ teaspoon is 0.625 mL. The standard conversion factor between drops and mL is 20 drops per 1 mL, although there is variation in drop size, and thus a range of 15–25 drops/mL is commonly used.[7] At 20 drops/mL, 8 drops is equivalent to 0.40 mL. At 15 and 25 drops/mL, 8 drops is equivalent to 0.53 and 0.32 mL, respectively. Thus, depending on the size of the dropper used, the dosage dispensed from a dropper can be 51–83% of a $^1/_8$ teaspoon dosage.

Second, chlorine dosage by either measurement is higher than recommended and used in emergencies worldwide. The Centers for Disease Control and Prevention (CDC) and World Health Organization (WHO) recommendations for water treatment in the development and emergency contexts[8−14] specify to add sufficient chlorine to have a residual of 0.5 mg/L 30 min after addition, or to maintain a safe free chlorine residual (FCR) concentration of ≥0.2 mg/L for 24 h after treatment in household stored water containers by adding a dosage of 2 mg/L to waters of turbidity 0–10 NTU or a dosage of 4 mg/L to water of turbidity >10–100 NTU. Chlorination is not recommended at >100 NTU turbidity, or pH >8.0. The doses added per EPA recommendations (assuming 5.25% bleach and 3.875 L/US gal, using the equation below) are 8.67 mg/L for $^1/_8$ teaspoon per gallon, and 7.35, 5.55, and 4.44 mg/L for 8 drops/gal at 15, 20, and 25 drops/mL conversion factors, respectively. In normal contexts, the EPA Maximum Contaminant Level (MCL) for FCR is 4.0 mg/L and the maximum turbidity is 1.0 NTU.[15]

$$\begin{aligned}\text{Dose } (\text{mg}_{\text{Cl}}/\text{L}_{\text{water}}) &= \left(\text{bleach concentration } (\%) \times \frac{10\,000 \text{ mg}_{\text{Cl}}/\text{L}_{\text{Cl}}}{1\%}\right. \\ &\quad \left. \times \text{ bleach added } (\text{mL}_{\text{Cl}}) \times \frac{1 \text{ L}_{\text{Cl}}}{1000\text{mL}_{\text{Cl}}}\right) \\ &\quad /(\text{volume of water } (\text{L}_{\text{water}}))\end{aligned}$$

Third, evidence supporting the development of the recommendations, and demonstrating how the dosages meet current water quality criteria, is lacking. Due to a lack of citations, the authors have been unable to determine how EPA's recommendations were developed, nor how the method is expected to meet various specific water quality criteria.

To address these technical concerns, the goals of the study were to (1) conduct testing to determine the dosage of sodium hypochlorite necessary to adequately treat—as measured by multiple contemporary criteria—waters that EPA recommends emergency-affected populations in the United States use, and (2) to determine whether to recommend to a working group on this issue that EPA conduct a review process to determine whether, and how, to update the current recommendation for treating water with bleach in U.S. emergencies.

■ MATERIALS AND METHODS

Study Design. The study protocol was completed by the study team in private homes in six states (Figure 1) on the following dates: May 27–29, 2009 in Bethlehem, PA; August 3–5, 2009 in Centennial, CO; August 8–10, 2009 in Alexandria, MN; August 13–15, 2009 in Underwood, WA; January 10–12, 2010 in San Antonio, TX; and January 14–16, 2010 in Atlanta, GA. These sites represented a geographic distribution across the United States, varying water quality characteristics (including temperature), and susceptibility to different emergency situations—such as earthquakes in

Washington, hurricanes in Texas and Georgia, water supply breakages in any location, and storms, such as Superstorm Sandy, in Pennsylvania.

At each of the six project sites, 18 1-gal plastic bottles containing nonchlorinated distilled water were purchased, emptied of water, rinsed with distilled water, and air-dried. Using these containers, three gals of water were collected from each of six sources representative of water available to private homes in an emergency situation and recommended for use under existing EPA recommendations.[1] Targeted representative sources included (1) a bucket of tap water stored in the household for 3 or more days, (2) a deep well water source, (3) a shallow well water source, (4) water obtained from emptying the water heater in the home, (5) raw surface water from a nearby source, and (6) raw surface water filtered through a linen napkin. After collection, containers were labeled as source A−F and dose 1−3.

Water Quality Testing. Before chlorine addition, each of the 18 containers filled with the six sources of raw water were tested for turbidity, pH, temperature, and FCR. Turbidity was tested using a Lamotte 2020 turbidimeter (Chestertown, MD, USA) calibrated using standard solutions. pH was tested with a Hanna pH meter (Smithfield, RI, USA) calibrated at 4, 7, and 10 using standard solutions. Chlorine residual was tested using a LaMotte 1200 Colorimeter calibrated using Lamotte 0.0, 0.1, 1.0, and 2.65 mg/L standards and DPD-1 and DPD-3 tablets for free and total chlorine residual, respectively.

Escherichia coli (*E. coli*) and total coliforms analysis were completed on one sample from each of the six sources. For this analysis, water samples were collected aseptically in sterile WhirlPak bags with sodium thiosulfate to inactivate any chlorine residual, and stored in a refrigerator until analysis within 6 h of collection. Samples were diluted appropriately with sterile buffered water transported from Lehigh University laboratories, filtered aseptically through a 45-μm filter on a Millipore (Billerica, MA, USA) portable filtration stand, placed in a plastic Petri-dish with a mColiBlue24 media soaked pad, and incubated in a portable electric incubator at 35 °C for 24 h. Negative controls were included between each water source, and >10% of samples were duplicated. All procedures followed recommendations in Standard Methods[16]and this method is EPA approved.

Before each trip, 1.25% sodium hypochlorite solution was manufactured at Lehigh University by diluting laboratory-grade calcium hypochlorite in Millipore water, and adding laboratory-grade sodium hydroxide to adjust the pH to 11.9 to prevent degradation. The concentration of this stock solution was confirmed on site using the Hach 8209 portable iodimetric titration method. The 3 samples from each source were then dosed (time 0) with the 1.25% hypochlorite using a micropipet at three dosages: (1) 2 mg/L (0.60 mL of the 1.25% hypochlorite, the CDC/WHO dose for waters <10 NTU), (2) 4 mg/L (1.21 mL of the 1.25% hypochlorite, the CDC/WHO dose for water 10−100 NTU), and (3) 7 mg/L (2.12 mL of the 1.25% hypochlorite, within range of current EPA recommendations). After chlorine addition, each sample was gently mixed by shaking the container.

To document the chlorine demand of the raw water and measure chlorination efficacy, each of the 18 containers of water was tested, using the procedures described above, for free and total chlorine residual at 1, 2, 4, 8, and 24 h after hypochlorite addition and *E. coli* and total coliforms at 1 and 24 h after hypochlorite addition. Please note the authors completed all testing.

Data Analysis. Data were entered into Microsoft Excel (Redmond, WA, USA). Results were analyzed based on four criteria developed by the authors based on U.S. and international recommendations and with the intention of reducing exposure to disease-causing organisms (excluding cryptosporidium, which is resistant to chlorination): (1) maintaining a FCR concentration from 1 to 24 h after treatment that does not exceed the EPA MCL of 4.0 mg/L and does not drop below 0.2 mg/L (a level at which the water is safe from recontamination); (2) meeting EPA *E. coli*/total coliforms standards of 0 CFU/100 mL; (3) meeting the 3-log *Giardia* reduction as required by the Surface Water Treatment Rule;[17], and (4) meeting the 4-log enteric virus reduction as required by the Surface Water Treatment Rule.[17] To calculate these last two criteria, EPA tables were used to locate the CT-factor necessary for 3-log reduction of *Giardia* and 4-low reduction of enteric viruses using the initial temperature and pH, and 1-h after chlorine addition FCR of the treated waters.[18] This value was compared to the calculated CT-factor of 60 min multiplied by the FCR of each sample at 60 min after chlorine addition. Please note these calculated CT-factors are conservative, as the initial temperature was the lowest temperature during the study and the minimum FCR between 0 and 60 min was at 60 min; this value was used because the nonlinearity of the initial chlorine demand makes extrapolation inaccurate.

Statistical analysis was performed in Stata 10.0 (College Station, TX, USA) using nonparametric tests and logistic regression, using a p-value of <0.05 to indicate significance.

RESULTS

Water Sources and Initial Water Quality. A total of 36 water sources were sampled, six in each study location (Table 1), including six tap water sources, six water heater sources, six surface water sources (including both stagnant and flowing sources) tested both raw and after filtration through a linen napkin, and 11 wells of various depths. In Georgia, a rain barrel was tested in place of one well sample. All water sources were selected for testing because they are mentioned in the current EPA recommendation. The average pH of all samples was 7.85 (range 6.5−9.4; SD 0.6). Seven samples (19%) exceeded the WHO recommended maximum of pH 8.0 for chlorination.[12] The average turbidity of all samples was 3.89 NTU (range 0−23.2; SD: 6.8). Eighteen samples (50%) exceeded the normal EPA recommended 1.0 NTU maximum for chlorination.[19] Four samples (11%) fell into the CDC range of 10−100 NTU for a double dose of chlorination, and none (0%) exceeded 100 NTU (the range where direct chlorination is no longer recommended by CDC). In surface water samples >2 NTU (n = 4), cloth filtration reduced turbidity by 18−52%. This was not statistically significant using Wilcoxon rank-sum testing for matched pairs.

Temperature varied geographically and seasonally. *E. coli* were isolated only from untreated and filtered surface water supplies (range <10−180 CFU/100 mL), but no tap water, shallow well, deep well, or water heater sources. Total coliforms were isolated from all untreated and filtered surface water supplies (geometric mean 927 CFU/100 mL, range 160−13 000), as well as at low contamination levels from the rain barrel sample in Georgia (24 CFU/100 mL), the shallow well in Pennsylvania (3 CFU/100 mL), and all tap, well, and water heater sources in Texas (20−40 CFU/100 mL).

Table 1. Sources Tested

	pH	turbidity (NTU)	temp (°C)	note
		Colorado		
tap water	8	0.06	25	private home
water heater	7.9	2.42	26	private home
well	6.8	0.00	25	400 ft deep, filtered
well	7.9	0.07	25	900 ft deep, filtered
raw surface	8.4	17.2	25	reservoir
filter surface	8.4	8.81	25	reservoir
		Georgia		
tap water	9.4	0.2	9.5	private home
water heater	9.4	1.4	9.0	private home
well	6.5	0.15	9.0	community well
rain barrel	9.1	1.3	9.0	community rain barrel
raw surface	7.7	4.1	9.0	river tributary
filtered surface	7.6	3.7	10.0	river tributary
		Minnesota		
tap water	7.7	0.43	7.7	private home
water heater	8	0.39	8.0	private home
well	7.6	23.2	7.6	101 feet deep
well	7.3	22.9	7.3	120 feet deep
raw surface	8.4	3.42	8.4	lake
filtered surface	8.4	2.17	8.4	lake
		Pennsylvania		
tap water	7.7	0.12	22.0	Lehigh University tap
water heater	7.7	1.13	21.5	private home
well	8.0	0.92	16.8	Lehigh Golf Course
well	7.5	0.35	17.6	Lehigh fields
raw surface	7.9	1.36	21.5	creek
filtered surface	7.9	1.54	21.5	creek
		Texas		
tap water	7.6	0.15	16	private home
water heater	7.3	2.5	16	private home
well	7.6	0.75	15	30 ft deep
well	7.5	23.0	14	195 ft deep
raw surface	8.0	9.2	13	lake
filtered surface	8.0	4.4	12	lake
		Washington		
tap water	7.9	0.03	22.0	private home
water heater	7.6	0.68	22.0	private home
well	7.1	0.48	21.5	160 ft deep
well	7.3	0.13	21.0	230 ft deep
raw surface	7.7	0.69	21.0	river
filtered surface	7.8	0.79	22.0	river

2 mg/L Dosage Results. At the 2 mg/L dose, 29/36 (81%) samples fell within the 0.2−4.0 mg/L criteria for FCR (Table 2, Supporting Information (SI) Figure S1). No sample exceeded 4.0 mg/L at any point in time. The seven samples that did not meet criteria were all low, falling below 0.2 mg/L by 24 h after treatment, including surface water samples in Colorado and Texas, wells in Pennsylvania, and untreated surface water in Minnesota. Four samples fell below 0.2 mg/L by 8 h after treatment, including surface waters in Pennsylvania and Texas. Only one (3%) sample fell below 0.1 mg/L at 24 h after treatment. Meeting the 0.2−4.0 mg/L criteria was not associated with initial turbidity, initial pH, or initial temperature in logistic regression using breakpoints of 1, 5, and 10 NTU for turbidity, 8.0 for pH, and 20 °C for temperature. The numerical FCR value at 24 h was associated with initial turbidity (p = 0.034) in linear regression (with higher turbidity samples leading to lower FCR values at 24 h).

No *E. coli* were detected in any sample 1 and 24 h after treatment at the 2 mg/L dose, except at 24 h in the Texas shallow well at 6 CFU/100 mL. Total coliforms were seen >0 CFU/100 mL in Colorado, Texas, or Pennsylvania surface water or shallow well water samples (0−7 CFU/100 mL at 1 h, 7−>100 CFU/100 mL at 24 h). Of the 10 total samples with *E. coli*/total coliforms >0 CFU/100 mL at 1 and 24 h after treatment, 7 (70%) had FCR <0.2 mg/L at 24 h after treatment.

The calculated CT-factor at 1 h after treatment ranged from 8.4 to 205.2, with an average of 92.4 and a SD of 51.2. Overall, 20/36 samples (56%) met the 3-log reduction criteria for *Giardia*, and 36/36 samples (100%) met the 4-log reduction criteria for enteric viruses.

4 mg/L Dosage Results. At the 4 mg/L dose, 25/36 (69%) samples fell within the 0.2−4.0 mg/L criteria for FCR (Table 2, SI Figure S2). Five samples (14%) exceeded 4.0 mg/L at 1 h after chlorine addition—including tap water or water heater samples in Georgia, Pennsylvania, and Texas—with a maximum of 4.56 mg/L, due to presence of FCR before treatment. Six samples (16.7%) fell below 0.2 mg/L by 24 h after treatment, including treated and untreated surface water samples in Colorado, Minnesota, and Texas. Meeting the ≥0.2 mg/L criterion at 24 h was associated with initial pH (p = 0.014; odds ratio (OR) <0.01−0.52), but not initial turbidity or initial temperature in logistic regression using breakpoints of 1, 5, and 10 NTU for turbidity, 8.0 for pH, and 20 °C for temperature. All samples that did not meet the ≥0.2 mg/L criteria had initial turbidity of >1 NTU. The numerical FCR value at 24 h was associated with turbidity (p = 0.007) in linear regression (with higher turbidity samples leading to lower FCR values at 24 h).

No *E. coli* were detected in any sample 1 and 24 h after treatment at the 4 mg/L dose, except in the untreated Colorado surface water (10 CFU/100 mL). Total coliforms were >0 CFU/100 mL in Colorado, Minnesota, and Texas filtered or nonfiltered surface water samples (4−67 CFU/100 mL at 1 h, 0−>100 CFU/100 mL at 24 h) and the Minnesota shallow well (22 CFU/100 mL). Of the 13 total samples with *E. coli*/total coliforms >0 CFU/100 mL 1 and 24 h after treatment, 12 (92%) had FCR <0.2 mg/L at 24 h after treatment.

The calculated CT-factor at 1 h after treatment at this dose ranged from 43.8 to 277.2, with an average of 182.5 and a SD of 62.4. Overall, 26/36 samples (72%) met the 3-log reduction criteria for *Giardia* and 36/36 samples (100%) met the 4-log reduction criteria for enteric viruses.

7 mg/L Dosage Results. At the 7 mg/L dose, 5/36 (14%) samples fell within the 0.2−4.0 mg/L criteria for FCR in drinking water (Table 2, SI Figure S3). A total of 30 samples (83%) exceeded 4.0 mg/L at 1 h after chlorine addition, with a maximum of 7.52 mg/L, and one sample (2.7%) fell below 0.2 mg/L at 24 h after chlorine addition. The five samples that did not exceed 4 mg/L at 1 h after treatment were surface water samples and one deep well, all with >1 NTU turbidity (range 2.17−17.2 NTU). Not exceeding the criteria of 4 mg/L at 1 h was associated with initial turbidity >10 (p = 0.042) and initial turbidity >5 (p = 0.020) but not initial temperature or pH in logistic regression using breakpoints of 1, 5, and 10 NTU for turbidity, 8.0 for pH, and 20 °C for temperature. The numerical FCR value at 24 h was associated with turbidity (p = 0.001) in linear regression.

No *E. coli* were detected in any sample 1 and 24 h after treatment at the 7 mg/L dose, except in the shallow well in

Table 2. Results Summary

	2 mg/L dosage	4 mg/L dosage	7 mg/L dosage
met FCR criteria (0.2–4.0 mg/L) at all times	29/36 (81%)	25/36 (69%)	5/36 (14%)
exceeded 4.0 mg/L at 1 h	0 (0%)	5/36 (14%)	30/36 (83%)
exceeded 4.0 mg/L at 8 h	0 (0%)	4/36 (11%)	21/36 (58%)
exceeded 4.0 mg/L at 24 h	0 (0%)	1/36 (3%)	23/36 (64%)
fell below 0.2 mg/L at 1 h	1/36 (3%)	0/36 (0%)	0/36 (0%)
fell below 0.2 mg/L at 8 h	4/36 (11%)	1/36 (3%)	0/36 (0%)
fell below 0.2 mg/L at 24 h	7/36 (19%)	5/36 (14%)	1/36 (3%)
fell below 0.1 mg/L at 24 h	1/36 (3%)	0/36 (0%)	0/36 (0%)
met *E. coli* criteria (<1 CFU/100 mL)			
at 1 h	36/36 (100%)	36/36 (100%)	36/36 (100%)
at 24 h	35/36 (97%)	35/36 (97%)	35/36 (97%)
met total coliforms criteria (<1 CFU/100 mL)			
at 1 h	32/36 (89%)	30/36 (83%)	32/36 (89%)
at 24 h	31/36 (86%)	30/36 (83%)	32/36 (89%)
calculated CT-factor (average (min–max))	92.4 (8.4–205.2)	182.5 (43.8–277.2)	330.2 (151.8–451.2)
$CT_{calc} > CT_{99.9}$ for *Giardia*	20/36 (56%)	26/36 (72%)	35/36 (97%)
$CT_{calc} > CT_{99.99}$ for enteric viruses	36/36 (100%)	36/36 (100%)	36/36 (100%)

Texas (4 CFU/100 mL). Total coliforms were >0 CFU/100 mL only in surface water samples in Colorado, Pennsylvania, Texas, or Washington or the shallow well in Texas (0–5 CFU/100 mL at 1 h, 0–>100 CFU/100 mL at 24 h). Of the 9 total samples with *E. coli* /total coliforms > 0 CFU/100 mL, 2 (22%) had FCR <0.2 mg/L at 24 h after treatment.

The calculated CT-factor at 1 h after treatment ranged from 151.8 to 451.2, with an average of 330.2 and a SD of 88.0. Overall, 35/36 samples (97%) met the 3-log reduction criteria for *Giardia* and 36/36 (100%) met the 4-log reduction criteria for enteric viruses.

Mixed Dosage Analysis. Lastly, the 36 samples were analyzed using a dosage of 4 mg/L for nonsurface waters (n = 24) and 7 mg/L for surface waters (n = 12). Results from this analysis showed that 23/36 samples (64%) met the 0.2–4.0 mg/L FCR criteria. Of the 13 that did not meet criteria, 5 were in nonsurface water samples treated with a dosage of 4 mg/L with initial FCR > 0.2 mg/L (from tap and water heater samples) that exceeded 4.0 mg/L at 1 h after treatment. The remaining 8 were in surface water samples treated with a dosage of 7.0 mg/L, with 7 exceeding 4.0 mg/L at 1 h and 1 falling below 0.2 mg/L at 24 h.

At this mixed dosage, 0/36 (0%) samples had any *E. coli* at 1 or 24 h after treatment. Overall, 4/36 (11%) samples had total coliforms at 1 h (all <10 CFU/100 mL) and 4/36 (11%) had total coliforms at 24 h (from 1–>100 CFU/100 mL). All total coliforms concentrations >0 CFU/100 mL occurred in surface water samples, except for one shallow well sample at 24 h in Minnesota.

Using this mixed dosage, 32/36 (89%) of samples met the CT-factor criteria for 3-log inactivation of *Giardia*. The four samples that did not meet criteria included the three nonsurface water samples in Georgia with the highest pH values in the study (9.1–9.4) and one surface water sample whose calculated CT-factor was within 10% of the necessary CT-factor for 3-log reduction of *Giardia*. Overall, 36/36 samples (100%) met the 4-log reduction criteria for enteric viruses.

DISCUSSION

A total of 36 water samples were tested across representative waters in six U.S. states that emergency-affected populations are recommended to use at three bleach dosage regimes (2, 4, 7 mg/L). Anecdotally, it is of note that during the study it was found to be difficult to access the recommended sources, as many householders did not know how to empty their water heater or where to find a well.

The FCR and *E. coli*/total coliforms data collected were analyzed using four different criteria: (1) maintaining a FCR concentration from 1 to 24 h after treatment that does not exceed the EPA MCL of 4.0 mg/L and does not drop below 0.2 mg/L (a level at which the water is safe from recontamination), (2) meeting *E. coli*/total coliforms standards of 0 CFU/100 mL, (3) meeting the 3-log *Giardia* reduction as required by the Surface Water Treatment Rule, and (4) meeting the 4-log enteric virus reduction as required by the Surface Water Treatment Rule. The most appropriate dosage varied based on the criteria selected (Table 2).

At the 2, 4, and 7 mg/L initial dosages, 81%, 69%, and 14% of samples met the FCR criteria, respectively. At the 2 mg/L dose noncompliant samples fell below 0.2 mg/L and at the 7 mg/L dose noncompliant samples were above 4 mg/L. Initial water turbidity was inversely correlated with FCR at 24 h after treatment ($p < 0.05$) at all three dosages. Combined chlorine was formed in these samples, although ammonia was not tested in raw water samples.

Across all three dosages, there was *E. coli* present in only three samples (all 24 h after treatment and all ≤10 CFU/100 mL). Total coliforms were found in some shallow well and surface water samples at 1 and 24 h after treatment (1–<100 CFU/100 mL), with the majority at initial dosages 2.0 and 4.0 mg/L (but not at 7.0 mg/L) having <0.2 mg/L FCR at 24 h after treatment. There was no difference in meeting the *E. coli*/total coliforms standards between the three initial dosages.

All samples were above a CT-factor of 8 mg-min/L, which is sufficient to inactivate the majority of bacteria and viruses responsible for diarrheal disease transmission,[20] and all samples in the study met the 4-log enteric virus reduction rule. However, there was an increasing percentage of samples that met the 3-log reduction for *Giardia* required by the Surface Water Treatment Rule, from 56% at 2 mg/L, to 72% at 4 mg/L, to 97% at 7 mg/L initial dosage.

Overall, these results indicate that the current EPA-recommended dosages of 5.56–8.68 mg/L for clear water and 11.12–17.36 mg/L for cloudy, murky, colored, or cold water are unnecessarily high, with 4−7 mg/L being sufficient for all U.S. waters tested.

In addition, these results indicate that it is impossible to meet all four evaluation criteria when treating water with a fixed bleach dosage at the household level in the United States. One potential solution is the use of a mixed dosage recommendation, one for nonsurface waters and one for surface water. As can be seen in SI Figures S2−S4, there were dramatic differences in chlorine demand between surface and nonsurface sources. Mixed dosage led to promising results across all four criteria. It should be noted that surface water supplies had by far the most total coliforms contamination, and thus surface water supplies (and in particular flood waters) should only be used if there are no other options for water supply by the emergency-affected population.

In addition to technical concerns with the current EPA recommendations, there are also three social considerations. One key social concern is whether the recommendations accurately propagate through other U.S. agencies. In Table 3, we document considerable variation in recommendations across federal and state agencies, emergency response organizations, and technical groups. Some dose recommendations are significantly higher than EPA's, and many are internally inconsistent. The fragmented and conflicting information currently available from various expert agencies hampers the public's ability to cope with comprised water quality during emergencies.

Table 3. Propagated Recommendations

agency	recommendation	dosage	reference
FEMA	16 drops (or $^1/_8$ tsp) per gal	11.10 mg/L (8.67 mg/L)	29
FDA	$^1/_8$ tsp (or 0.75 mL) per gal	8.67 mg/L (10.42 mg/L)	30
Homeland Security	5−7 drops (or $^1/_8$ tsp) per gal	3.87−4.86 mg/L (8.67 mg/L)	31
King Country Public Health	$^1/_8$ tsp (or 16 drops) per gal	8.67 mg/L (11.10 mg/L)	32
LA Fire Department	8 drops per gal	5.55 mg/L	33
Lifewater International	5−10 drops per quart	13.87−27.74 mg/L	34

Two more social concerns were investigated in a separate research project conducted by the authors,[21] designed to ascertain whether the items necessary to complete the recommended treatment method are currently available in homes in the United States, and whether people feel confident and comfortable in completing this water treatment method. A qualitative evaluation was conducted, consisting of meetings with 86 stakeholders and interviews with 9 individuals in their homes to determine their ability to correctly follow the EPA instructions, and their perception on the instructions and the taste of the treated water. Of households interviewed, only 6/9 had any bleach in the home, and none had bleach appropriate for water treatment (unscented, nonexpired, <1 year old, near 5.25% in concentration) at the time of the interview. Additionally, only 1/9 had a $^1/_8$ teaspoon measure, only 2/9 had a dropper, and only 4/9 had a gallon container.

The perception of the meeting participants and household interviewees was, overwhelmingly, that government should, and does, provide bottled water in an emergency.[21] A minority of respondents reported knowing about the use of bleach for water treatment in emergencies, but none knew the correct dose. All reported serious concerns about the safety of drinking water treated with bleach, which is typically considered a poison. The household interviewees preferred the dropper method for treating water with bleach, but made suggestions for improvement of the instructions, including using a typically available container (such as a 2-L soda bottle instead of a gallon container), and using pictorial, bullet-pointed instructions rather than text only. Lastly, stakeholders overwhelmingly stated it would be preferable to have a water treatment kit—including laminated instructions, an appropriate storage container, and a premeasured bleach dose.

These results echo previously published research. After a Massachusetts water line break in 2010, 97% of survey respondents were aware of the boil water order, yet 34% of respondents were still exposed to untreated water.[22] In Gideon, Missouri in 1993, 31% of respondents reporting drinking unboiled water after a boil water order, because of "not remembering" or "disbelieving" the order.[23] Lastly, after Hurricane Rita in Louisiana, only 1 of 196 (< 1%) respondents knew the bleach dosage recommended by the Louisiana Department of Public Health and Hospitals.[24]

Another important question is, given the technical and social concerns detailed herein, whether to continue recommending water treatment with bleach in U.S. emergencies. This question could be informed by experience worldwide. There are six household water treatment and safe storage (HWTS) options, used in contexts where infrastructure is not yet available or is unreliable, that have been shown in research studies to improve microbiological quality of water and reduce the burden of diarrheal disease: sodium hypochlorite (bleach), flocculant/disinfection sachets, solar disinfection (SODIS), ceramic filters, biosand filters, and membrane filters.[25−27] In real-world contexts, however, effective use results are mixed. For example, in emergency-affected populations, the effective use of chlorine tablets (as measured by the populations' ability to use tablets to treat contaminated water to meet international *E. coli* guidelines) ranged from <1−56%, depending on context.[28] Overall, it was found that more successful programs provided the following: (1) an effective HWTS method, (2) with the necessary supplies and training provided, (3) to households with contaminated water who were already familiar with the method before the emergency.

Point-of-use devices (faucet mounts, countertop filters, under-sink filters, pour-through pitchers, and built-in refrigerator dispensers) and point-of-entry devices (such as larger water softening systems and filtering systems built into pipes) are other options to treat water at the household level. There is current, and projected, growth in this market, driven by concerns over (1) municipal tap water quality, (2) cost and environmental impacts of bottled water, and (3) desirability of nonsugar drink options to combat childhood obesity. However, taste and health concerns overwhelming drive this market, with Brita and PUR being the largest players. These products are primarily for softening water and improving taste. Water treatment products—such as camping filters—are used by a niche and wealthier population; and are not appropriate to treat large volumes of water (a minimum of 20 L per family per day). Overall, it is unlikely that more than a minority of the populations affected by emergencies will have products that effectively treat water in the home, or have access to these products if they are displaced.

Recently, and after submission of this manuscript, some major bleach producers in the United States raised the concentration of their normal household bleach products to 8.25% (with a new "concentrated" marketing campaign). According to the EPA emergency water treatment recommendations main web page (accessed March 7, 2014), the dosage regime remains $^1/_8$ of a teaspoon or 8 drops per gal. With the new 8.25% bleach, the chlorine doses using these recommendations are now even higher: 13.64 and 8.73 mg/L, respectively. However, there is also a secondary tab "Choose a Disinfection Method" on the main EPA emergency water disinfection Web site which can be clicked, and this provides a dosage recommendation for higher concentration bleach (7–10%) of 1 drop per quart or liter. Using this 1 drop per liter recommendation and 8.25% bleach, the chlorine dosage is 4.125 mg/L, close to the dosage found to best balance the criteria in this manuscript. This industry change exacerbates and highlights the concerns in this manuscript about treating household water with bleach in emergencies in the United States, including the technical concern of recommending the correct (and not too high) chlorine dosages for this higher concentration bleach and the social concerns of propagation of correct water treatment messages and the actual concentration of bleach available in the household (which will vary now as the new bleach is phased in and various products are available).

Based on the data presented herein, we conclude that the current recommendation for emergency water treatment with household bleach should be reviewed by EPA and its partners in the working group to establish an internally consistent, scientifically verified dosage regime that balances existing regulatory criteria, recommended water sources, population exposure to pathogens of concern, and availability of items (bleach, droppers, measurers, containers) necessary to treat water in the home. This review should include additional research of water sources populations might use in emergencies (not only sources currently recommended for use by EPA), establishment of appropriate criteria for evaluating the recommendation, and potential development of a new recommendation and/or water treatment products. Lastly, recommendations should be broadly disseminated across all government agencies and emergency response organizations to ensure that all agencies are using a consistent public health message for treating water in emergencies in the United States.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Figures S-1–S-3 as mentioned in the text. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) USEPA. *Emergency Disinfection of Drinking Water*. http://water.epa.gov/drink/emerprep/emergencydisinfection.cfm (April 7, 2014).

(2) de Ville de Goyet, C. Stop propagating disaster myths. *Lancet* **2000**, *356* (9231), 762–4.

(3) Ahern, M.; Kovats, R. S.; Wilkinson, P.; Few, R.; Matthies, F. Global health impacts of floods: Epidemiologic evidence. *Epidemiol. Rev.* **2005**, *27*, 36–46.

(4) Watson, J.; Gayer, M.; M, C. Epidemics after natural disasters. *Emerging Infect. Dis.* **2007**, *13* (1), 1–5.

(5) CDC. Norovirus outbreak among evacuees from hurricane Katrina–Houston, Texas, September 2005. *MMWR Morb. Mortal. Wkly. Rep.* **2005**, *54* (40), 1016–8.

(6) Nigro, O. D.; Hou, A.; Vithanage, G.; Fujioka, R. S.; Steward, G. F. Temporal and spatial variability in culturable pathogenic Vibrio spp. in Lake Pontchartrain, Louisiana, following hurricanes Katrina and Rita. *Appl. Environ. Microbiol.* **2011**, *77* (15), 5384–93.

(7) Young, R.; Glover, T. *Measure for Measure*; Sequoia Publishing: Littleton, CO, 2002.

(8) Kotlarz, N.; Lantagne, D.; Preston, K.; Jellison, K. Turbidity and chlorine demand reduction using locally available physical water clarification mechanisms before household chlorination in developing countries. *J. Water Health* **2009**, *7* (3), 497–506.

(9) Preston, K.; Lantagne, D.; Kotlarz, N.; Jellison, K. Turbidity and chlorine demand reduction using alum and moringa flocculation before household chlorination in developing countries. *J. Water Health* **2010**, *8* (1), 60–70.

(10) Lantagne, D. Sodium hypochlorite dosage for household and emergency water treatment. *J. Am. Water Works Assoc.* **2008**, *100* (8), 106–119.

(11) CDC. *Chlorine Residual Testing Fact Sheet*. http://www.cdc.gov.

(12) WHO. *Guidelines for Drinking-Water Quality*, 4th ed.; Geneva, Switzerland, 2011.

(13) WHO. *Household Water Treatment and Safe Storage Following Emergencies and Disasters*. http://www.who.int/household_water/resources/emergencies.pdf.

(14) CDC. *Safe Water for the Community: A Guide for Establishing a Community-based Safe Water System Program*; Centers for Disease Control and Prevention: Atlanta, GA, 2008.

(15) USEPA. *List of Drinking Water Contaminants and their MCLs: National Primary Drinking Water Regulations*. http://water.epa.gov/drink/contaminants/index.cfm (June 4, 2012).

(16) APHA/AWWA/WEF. *Standard Methods for the Examination of Water and Wastewater*, 20th ed.; Washington, DC, 1998.

(17) EPA. *Surface Water Treatment Rule*. http://water.epa.gov/lawsregs/rulesregs/sdwa/swtr/ (November 30, 2012).

(18) USEPA. *LT1ESWTR Disinfection Profiling and Benchmarking Technical Guidance Manual*; Washington, DC, 2003.

(19) USEPA. *Long Term 1 Enhanced Surface Water Treatment Rule: A Quick Reference Guide*. http://www.epa.gov/ogwdw/mdbp/lt1eswtr-quick-ref.pdf (June 4, 2012).

(20) CDC. *Safe Water System (SWS) – Effect of Chlorination on Inactivating Selected Pathogens*; Centers for Disease Control and Prevention: Atlanta, GA, 2008.

(21) Blanton, E.; Person, B.; Lantagne, D. *Harmonizing Messages for Ensuring Water Quality in Emergencies in the United States: The use of chlorine bleach for water treatment*; Centers for Disease Control and Prevention: Atlanta, GA, to be published.

(22) Wang, C. J.; Little, A. A.; Holliman, J. B.; Ng, C. Y.; Barrero-Castillero, A.; Fu, C. M.; Zuckerman, B.; Bauchner, H. Communication of urgent public health messages to urban populations: Lessons from the Massachusetts water main break. *Disaster Med. Public Health Preparedness* **2011**, *5* (3), 235–41.

(23) Angulo, F. J.; Tippen, S.; Sharp, D. J.; Payne, B. J.; Collier, C.; Hill, J. E.; Barrett, T. J.; Clark, R. M.; Geldreich, E. E.; Donnell, H. D., Jr.; Swerdlow, D. L. A community waterborne outbreak of salmonellosis and the effectiveness of a boil water order. *Am. J. Public Health* **1997**, *87* (4), 580–4.

(24) Ram, P. K.; Blanton, E.; Klinghoffer, D.; Platek, M.; Piper, J.; Straif-Bourgeois, S.; Bonner, M. R.; Mintz, E. D. Household water disinfection in hurricane-affected communities of Louisiana: Implications for disaster preparedness for the general public. *Am. J. Public Health* **2007**, *97* (Suppl 1), S130−5.
(25) Lantagne, D.; Quick, R. E.; Mintz, E. *Household Water Treatment and Safe Storage Options in Developing Countries: A Review of Current Implementation Practices*; Woodrow Wilson International Center for Scholars, Environmental Change and Security Program: Washington, DC, 2006.
(26) Stauber, C. E.; Ortiz, G. M.; Loomis, D. P.; Sobsey, M. D. A randomized controlled trial of the concrete biosand filter and its impact on diarrheal disease in Bonao, Dominican Republic. *Am. J. Trop Med. Hyg.* **2009**, *80* (2), 286−93.
(27) Peletz, R.; Simunyama, M.; Sarenje, K.; Baisley, K.; Filteau, S.; Kelly, P.; Clasen, T. Assessing water filtration and safe storage in households with young children of HIV-positive mothers: A randomized, controlled trial in Zambia. *PLoS One* **2012**, *7* (10), e46548.
(28) Lantagne, D.; Clasen, T. Use of household water treatment and safe storage methods in acute emergency response: Case study results from Nepal, Indonesia, Kenya, and Haiti. *Environ. Sci. Technol.* **2012**, *46* (20), 11352−60.
(29) FEMA. *Guidelines for Managing Water Supplies*. http://www.fema.gov/plan/prepare/watermanage.shtm-chlorination (June 1, 2012).
(30) FDA. *FDA Offers Tips about Medical Devices and Hurricane Disasters*. http://www.fda.gov/MedicalDevices/ProductsandMedicalProcedures/HomeHealthandConsumer/ConsumerProducts/BreastPumps/ucm055987.htm (June 1, 2012).
(31) DHS. *Emergency Water Storage*. http://www.nationalterroralert.com/safewater/ (June 1, 2012).
(32) KCPH. *King County Public Health: How to prepare safe water after a disaster*. http://www.kingcounty.gov/healthservices/health/preparedness/disaster/safewater.aspx (June 1, 2012).
(33) LAFD. *Los Angeles Fire Department Emergency Preparedness*. http://lafd.org/eqbook.pdf (June 1, 2012).
(34) LI. *Lifewater International: Making Safe Drinking Water*. http://www.lifewater.ca/Appendix_T.htm (June 1, 2012).