Chlorination of drinking water in emergencies: a review of knowledge to develop recommendations for implementation and research needed

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Clean water provision is a critical component of emergency response, and chlorination is widely used in emergencies to treat water. To provide responders with practical, evidence-based recommendations for implementing chlorination programmes and recommend areas for future research, we conducted a literature review of chlorination in emergencies, supplemented with a literature review on chlorination in general. We identified 106 total documents, including 7 with information on technical efficacy, 26 on chlorine dosage, 22 on technical challenges, 21 on product options, 8 on user acceptability, 33 on programmes for emergencies, and 8 on monitoring. We found that: 1) international chlorine dosage recommendations in emergencies are highly inconsistent; 2) high-quality information from the general chlorination literature on challenges of chlorination can be adapted for emergencies; 3) many chlorine products are available for use in point-of-delivery, point-of-source, and point-of-use emergency-response programmes; 4) information on the effectiveness of different

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chlorination programmes in emergencies varies, ranging from little data available to high-quality data that can inform programming; 5) information on user acceptability of chlorination in emergencies is lacking; and 6) monitoring data on chlorine programme effectiveness in emergencies are lacking. In this manuscript, we provide a summary of knowledge on chlorination in emergencies, recommendations for programme implementation, and recommendations for future research needed to assist communities and agencies responding to the increasing number of natural disasters and outbreaks worldwide.

Keywords: chlorine, disinfection, emergency, natural disaster, outbreaks, water treatment

SAFE WATER SUPPLY, SANITATION, and hygiene are immediate priorities for human survival and dignity in emergencies (SPHERE, 2011) such as in natural disasters (i.e. earthquakes, volcanic eruptions, landslides, tsunamis, floods, and drought), disease outbreaks, and complex emergencies. Complex emergencies are defined as 'situations of disrupted livelihoods and threats to life produced by warfare, civil disturbance and large-scale movements of people, in which any emergency response has to be conducted in a difficult political and security environment' (WHO, 2002).

Four common water, sanitation, and hygiene (WASH) interventions in emergencies are: 1) provision or repair of water supplies; 2) treatment of water centrally or at the household level; 3) provision of sanitation options such as latrines or latrine alternatives; and 4) promotion of hand washing and environmental hygiene. These WASH interventions are particularly important in response to emergencies that lead to an increased risk of infectious disease, including flooding events, natural disasters that may lead to displacement, outbreaks caused by untreated drinking water, and some complex emergency settings (Ahern et al., 2005, Shultz et al., 2005; Watson et al., 2007).

Chlorine is widely used in emergency response because of its availability, ease of use, cost-effectiveness, ease of verification, efficacy in inactivating bacterial and viral pathogens, and maintenance of a chlorine residual in treated waters that protects against recontamination during storage of water (Lantagne and Clasen, 2012b). However, despite this widespread use, effectively implementing chlorination programmes in emergencies remains challenging because: 1) recommendations for dosing and residual chlorine levels in emergencies vary among and within guidance documents such as those of the World Health Organization (WHO) and the United States Environmental Protection Agency (EPA) (Lantagne, 2008; Lantagne et al., 2014); 2) programmatic elements cannot necessarily be generalized among different types of emergencies or geographic and cultural settings; and 3) research on chlorination programmes in emergencies is limited. In fact, two recent systematic reviews of the evidence base on WASH interventions for cholera response (Taylor et al., 2015) and the health impact of WASH interventions in emergencies (Ramesh et al., 2015) concluded there is a lack of evidence to support implementing WASH interventions in outbreaks and emergencies. The reviews found that the overall quality of evidence is low, and high-quality results were primarily on household water-treatment interventions. However, both reviews had strict inclusion criteria that led to only 18 and 6 studies being included in the reviews, respectively. These strict inclusion criteria limit the applicability of the reviews.

Our objective in completing this article was to summarize the full scope of available evidence on the specific intervention of chlorination of drinking water in emergencies in order to: 1) provide practical, evidence-based recommendations and guidance for emergency responders; and 2) outline areas needed for future research.

Methods

To meet our objective, we completed three activities: 1) a literature review on chlorination in emergencies; 2) a review of supplemental technical information on chlorination in general that is relevant to emergencies; and 3) analysis and summary of the available data, particularly in extracting data to develop evidence-based recommendations for emergency responders and to outline areas for future research.

We first conducted a literature review to identify peer-reviewed articles and grey literature on chlorination in emergencies. Using the keywords included in Table 1,

Table 1 Review search terms

Water treatment	*Chlorine*	*Emergencies*
Water	Chlorin*	Emergenc*
'Water treat*'	Hypochlorite	'Natural disaster'
Household	'Calcium hypochlorite'	Disaster
HWTS	'Sodium hypochlorite'	'Complex emergenc*'
'Household water treatment'	'Sodium dichloroisocyanurate'	Outbreak
SWS	NaDCC	Epidemic
'Safe water system'	Disinfect*	Flood
POUWT	Aquatab	Earthquake
POU	PuR	Drought
'Point of use'	Waterguard	Tsunami
'Point-of-use'	Certeza	Cyclone
	Sur'Eau	Landslide
	'Gadyen Dlo'	Refugee
	Claro	'Humanitarian crisis'
	Bleach	Cholera
		Ebola

Notes: Please note that a * indicates any suffix of the word is allowed.
HWTS, household water treatment and safe storage; SWS, safe water system; POUWT, point-of-use water treatment; POU, point-of-use; and PuR, Purifier of Water
Please note we attempted to include as many searchable names of household water treatment products as possible (i.e. Certeza, Waterguard, Sur'Eau) to expand the search. However, we may have missed some specific product names, and we expect those products would be captured in the general category of 'point of use' or 'water treat*'.

we searched Medline, PubMed, and Engineering Village. Additionally, we searched the authors' individual reference databases, reviewed technical recommendations for chlorinating water in emergencies, and conducted reference chaining. We reviewed manuscripts for inclusion by first reading titles, then relevant abstracts, and then selecting full texts. Manuscripts were included in the review if studies: 1) were conducted in an emergency context, such as a natural disaster, outbreak, or complex emergency; 2) collected data and included information on how data was collected that was assessed by reviewers as scientifically accurate; and 3) were relevant to one or more of the seven selected topics (see below).

We supplemented the review with relevant technical information from non-emergency circumstances identified using targeted review methodology. This technical information was identified and obtained from the initial emergency-specific review, as well as targeted searches of international manuals and guidance documents, manuscripts on chlorination in development contexts, reference chaining, and personal reference databases and information from the nine authors, representing practitioners, researchers, and academics. Please note that we did not conduct a review or complete literature review for the term 'chlorination' due to the overwhelmingly high volume of non-relevant information doing so would return. As an example of this overwhelmingly high volume, only using one search term ('chlorin*') led to a return of 40,839 documents on only one database (PubMed) alone, most of them not relevant to water treatment.

We then categorized information from the included documents into seven key topics. The seven key topics were selected based on the authors' experience in conducting and evaluating chlorination programmes in emergencies, and included three 'technical' topics and four 'programmatic' topics. The three technical topics – which are not necessarily specific to emergencies – are technical efficacy, chlorine dosage, and technical challenges. The four programmatic topics – which are specific to emergencies – are product options, user acceptability, programmes for emergencies, and programme monitoring. After reading each included document identified in the reviews, we categorized each document into the appropriate topic(s). The results section is presented by topic, as for each topic we summarized (in text format) the results (if any) from the included documents, and extracted recommendations for implementation and research needed.

Overall, the manuscript is intended to summarize the available evidence on chlorination of drinking water in emergencies to provide practical, evidence-based recommendations for emergency responders and outline areas needed for future research. The manuscript is written with sufficient background information (in the first three technical topics) that a reader unfamiliar with chlorination in general can obtain the background information necessary for the four emergency-specific programmatic topics.

Results

The review returned 2,371 documents, of which 59 met all three inclusion criteria. Five pertained to technical efficacy, 21 to dosage, 3 to technical challenges, 10 to product options, 3 to user acceptability, 32 to programmes for emergencies, and 0 to programme monitoring (Table 2). Additionally, we included information from 47 documents from non-emergency contexts, including 2 pertaining to technical efficacy, 5 to dosage, 19 to technical challenges, 11 to products, 5 to user acceptability, 1 to programmes for emergencies, and 8 to monitoring (Table 3).

We summarize the results from the identified documents by topic in the following sections. An overall summary of information and recommendations for chlorination in emergencies, by topic, is presented in Table 4.

Technical efficacy

Technical efficacy is the first technical topic in this article, and herein we include information on the efficacy of chlorine at removing organisms that cause diarrheal disease, including factors that impact that efficacy. We identified five documents in the chlorination in emergency review, and two additional documents in the general literature, pertaining to technical efficacy. We summarize those documents below, providing a primer on chlorination.

Chlorine's efficacy is a function of pH, concentration and contact time, temperature, and chlorine demand of the water (Black & Veatch Corporation, 2010). When added to water, chlorine forms hypochlorous acid (HOCl), which dissociates into hypochlorite (OCl–) and hydrogen (H+) ions at pH levels >8, as the pKa = 7.53. HOCl is a strong disinfectant, as it has a neutral charge that allows it to cross the cell wall, alter the shape of cellular components, and disrupt pathogen functionality. OCl– is a weaker disinfectant, by a factor of about 100. Thus, chlorination is most effective at pH < 8.0, when HOCl is present (WHO, 2011).

The 'CT-factor' is a measure of chlorine's efficacy in inactivating a pathogen, and is experimentally established for each pathogen (CDC, 2008b). Multiplying the chlorine concentration (in mg/L) by the contact time (in minutes) necessary to inactivate a particular pathogen yields the CT-factor. Under laboratory conditions, chlorine can reduce disease-causing bacteria by 82–99.999999 per cent, viruses by 99–99.99 per cent, and protozoa by 99–99.9 per cent, although it is ineffective against the protozoa *Cryptosporidium parvum* and helminth eggs such as *Ascaris lumbricoides* ova. At ≥25°C, the standard contact time is 30 minutes; with each 10°C temperature drop, contact time should be doubled (WHO, 2011). This recommendation is particularly important for emergencies in cold climates. These effects of temperature and pH have been demonstrated under emergency conditions and in laboratory conditions (Marois-Fiset et al., 2013; Elmaksoud et al., 2014; Ali et al., 2015).

When chlorine is added to water, it reacts with inorganic and organic materials (such as metals and humic and fulvic acids) and becomes unavailable for disinfection (CDC, 2008a; Black & Veatch Corporation, 2010). The amount of chlorine used up in these reactions is termed the 'chlorine demand' of the water, and is determined empirically. After the chlorine demand is met, the remaining chlorine is termed total chlorine residual (TCR). A portion of the TCR reacts with nitrogen-containing molecules to form combined chlorine, which acts as a weak disinfectant. The concentration of remaining free chlorine (in the form of OCl– and HOCl,

Table 2 Documents included in the seven key topics in emergencies from review in emergencies

Paper	*Technical efficacy*	*Chlorine dosage*	*Technical challenges*	*Product options*	*User acceptability*	*Programmes for emergencies*	*Monitoring*
ACF, 2005		√					
Adams, 1999		√					
Ali et al., 2015	√	√				√	
Aquaya, 2005				√			
CARE, undated						√	
Cavallaro et al., 2011						√	
CDC, 2014		√					
Chalinder, 1994		√					
Clasen and Smith, 2005				√	√	√	
Colindres et al., 2007						√	
Connolly, 2005		√					
Deb et al., 1986						√	
Doocy and Burnham, 2006						√	
Dunston et al., 2001						√	
Elmaksoud et al., 2014	√						
EPA, 2016a		√	√				
Garandeau et al., 2006						√	
Godfrey, 2005						√	
Godfrey et al., 2003						√	
Guevart et al., 2008						√	
Gupta and Quick, 2006						√	
Gupta et al., 2007						√	

Paper	*Technical efficacy*	*Chlorine dosage*	*Technical challenges*	*Product options*	*User acceptability*	*Programmes for emergencies*	*Monitoring*
Hoque and Khanam, undated						√	
Hoque et al., 1995					√	√	
House and Reed, 1997		√					
Imanishi et al., 2014						√	
IMC, 2008						√	
Islam et al., 2007				√			
JHU and IFRC, 2008		√					
Lambert and Davis, 2002		√					
Lamond and Kinyanjui, 2012		√					
Lantagne, 2008	√	√	√	√			
Lantagne and Clasen, 2012b				√		√	
Lantagne and Clasen, 2012a						√	
Lantagne and Clasen, 2013				√		√	
Loo et al., 2012				√			
Luby et al., 2006						√	
Marois-Fiset and Dorea, 2013				√			
Marois-Fiset et al., 2013	√						
McLennan et al., 2009				√			
Mong et al., 2001						√	
MSF, 2010		√					
Murphy et al., undated						√	
Oxfam, 2001		√					
Oxfam, 2006		√					

(continued)

Table 2 Documents included in the seven key topics in emergencies from review in emergencies *(continued)*

Paper	*Technical efficacy*	*Chlorine dosage*	*Technical challenges*	*Product options*	*User acceptability*	*Programmes for emergencies*	*Monitoring*
Oxfam, 2015*						√	
Patrick et al., 2013				√		√	
Reller et al., 2001						√	
Roberts et al., 2001						√	
Rowe and Angulo, 1998						√	
SPHERE, 2011		√	√				
UNHCR, 2007		√					
UNICEF, 2007						√	
UNICEF, 2013		√					
WHO, 2002		√					
WHO, 2005		√√					
WHO, 2011	√				√		
Wildman, 2013						√	
Yates et al., 2015						√	

Note: * Oxfam internal memo: Sierra Leone, available from Andy Bastable, abastable@oxfam.org.uk

Table 3 Additional documents on seven key topics from non-emergency contexts

Paper	*Technical efficacy*	*Chlorine dosage*	*Technical challenges*	*Product options*	*User acceptability*	*Programmes for emergencies*	*Monitoring*
CDC, 2008a							√
CDC, 2008b	√		√				
CDC, 2008c				√			
CDC, 2010							√
Clasen and Bastable, 2003		√					
Clasen and Edmondson, 2006				√			
Black & Veatch Corporation, 2010	√						
Crump et al., 2004		√	√				
DINEPA, 2016							√
Drikas et al., 2003			√				
EPA, 2016b		√					
Gouveia et al., 2007					√		
HACH, 2016							√
Hunter and Nichols, 2002			√				
IARC, 1991			√				
IARC, 1999			√				
Iqbal et al., 2016				√			
Klorfasil, undated				√			
Korich et al., 1990			√				
Kotlarz et al., 2009			√				
Lantagne, 2009				√			
Lantagne, unpublished*					√		
Lantagne et al., 2008			√				

Note: * unpublished focus group results from chlorine taste testing, Tufts University, Medford, MA; available from daniele.lantagne@tufts.edu

(continued)

Table 3 Additional documents on seven key topics from non-emergency contexts *(continued)*

Paper	*Technical efficacy*	*Chlorine dosage*	*Technical challenges*	*Product options*	*User acceptability*	*Programmes for emergencies*	*Monitoring*
Lantagne et al., 2010			√				
Lantagne et al., 2014		√					
Lantagne et al., 2011				√			√
Mackey et al., 2004					√		
Medentech, 2015		√		√			
Mérat, 2015			√				
Mintz et al., 1995				√			
Mohamed et al., 2015			√				
Murray and Lantagne, 2015							√
Muyibi and Okuofu, 1995			√				
Null and Lantagne, 2012				√			
Ogutu et al., 2001				√			
Peletz et al., 2013			√				
Piriou et al., 2004					√		
POUZN, 2007					√		
Preston et al., 2010			√				
Pickering et al., 2015 Rook, 1974						√	
Sallon et al., 1988			√				
Sengupta et al., 2012			√				
Souter et al., 2003			√	√			
UNDP, 2009							√
WHO/UNICEF, 2012							√
WHO, 2004			√				

Table 4 Summary of knowledge on chlorination in emergencies from the seven key topics

Topic	*Summary and Recommendations*
Technical efficacy	• Chlorination is most effective when pH < 8.0. • Contact time at room temperature (25°C) should be 30 minutes. - For every 10°C below 25°C, double contact time. • Chlorine is not effective against cryptosporidium or ascaris.

Dosage	• Dose should meet chlorine demand and combined chlorine demand, maintain FCR during transport and storage, and not exceed international guideline values and user taste/odour thresholds.
	  - Balancing criteria may be impossible and recommendations must be adjusted.
	  - Goal is to have minimum of 0.2 mg/L at point of consumption.
	• Calculate dosage empirically or use a fixed dosage of:
	  - 2.0 mg/L in less turbid waters (<10 NTU), and
	  - 4.0–5.0 mg/L in more turbid waters (10–100 NTU).
	• Chlorination alone is not recommended at turbidity >100 NTU.

Technical challenges	• DBPs are a perception, rather than a real risk in emergencies.
	• Where risk of cryptosporidium or ascaris is high, use filtration/flocculation before chlorination.
	• When water is highly turbid, and an alternative source or treatment cannot be used, the following can be used:
	  - Cloth filtration, settling/decanting, sand and ceramic filtration, and alum and moringa seeds all reduce turbidity.
	  - Settling/decanting, sand and ceramic filtration, and alum reduce chlorine demand and as such a single dose of chlorine can be used after these treatment.
	  - Alum flocculation can reduce trihalomethane formation potential.
	  - A double dose of chlorine can be directly added if turbidity is 10–100 NTU.

Products	• Select products (powders, liquids, and tablets) by local availability, transportation, cost, familiarity, and other contextual factors. • Ensure concentration of products is within 10 per cent of advertised concentration. • Use high-quality raw materials for locally manufactured products. • Test concentration of liquid sodium hypochlorite solutions and stabilize to pH > 11.9 with sodium hydroxide if used >48 hours after production. • Store liquid solutions in sealed bottles, out of sunlight, and below 35°C.
User acceptability	• Taste and odour thresholds vary; most users object to concentrations above 1–2 mg/L, but some object at concentrations as low as 0.2 mg/L. • Users may reject microbiologically safe water with unaesthetic appearance in favour of contaminated water that appears to be clean. • Taste and odour tolerance can be determined through taste-testing in a focus group.

(continued)

Table 4 Summary of knowledge on chlorination in emergencies from the seven key topics *(continued)*

Topic	*Summary and Recommendations*
Programmes for emergencies	• Point-of-use water treatment and dispensers can be effective programmes. • Well chlorination and pot chlorination are only effective for a few days after treatment. • Data on water trucking, bucket chlorination, and in-line chlorination are insufficient to make a recommendation. • Point-of-use chlorination should have effective products, placement, and support: - Use high-quality products with instructions. - Select products familiar to users and implementer. - Conduct training and use community-based mobilization, education, and marketing techniques.
Monitoring	• FCR and raw chlorine product quality are important monitoring parameters.

Note: * unpublished focus group results from chlorine taste testing, Tufts University, Medford, MA; available from daniele.lantagne@tufts.edu and at pH < 2 chlorine gas) is termed the free chlorine residual (FCR). Breakpoint chlorination, the time it takes to complete these reactions, generally occurs within 30 minutes of chlorine addition.

FCR presence in treated water is a measure of potability, and indicates that sufficient chlorine was added to inactivate most pathogens and that water is protected from recontamination during transport, storage, and use for a certain time period (CDC, 2008a). During distribution, transport, and storage of chlorinated water before drinking, the FCR concentration decays due to exposure to heat, ultraviolet (UV) light, and introduced contaminants (Lantagne, 2008).

Chlorine dosage

The *chlorine dosage* topic, the second technical topic covered here, includes information on the amount of chlorine added to water to both treat the water and maintain an appropriate FCR concentration. We identified 21 documents in the chlorination in emergency review, and five additional documents in the general literature, pertaining to chlorine dosage. We summarize those documents below, providing information on the current recommendations for how much chlorine to add to effectively treat water in emergencies.

Three chlorine concentrations are relevant to chlorination in emergencies: 1) raw product concentration ('product concentration'); 2) the amount of chlorine added to a certain volume of water to be treated ('dosage'); and 3) the FCR available for disinfection in the treated water ('FCR'). Product concentration is usually expressed as a percentage of chlorine for liquid, powdered, and gas forms, and in milligrams for tablet forms. Dosage and FCR are expressed in milligrams of chlorine per litre of water (mg/L) or parts per million (ppm), which are (roughly) equivalent measures for chlorine solutions.

A significant challenge to implementing chlorination programmes in emergencies is that international guidance documents: 1) vary in recommendations for chlorine dosage and FCR; 2) contain internally inconsistent recommendations (Lantagne et al., 2014); 3) are inconsistent on when to measure FCR after chlorine addition; 4) are inconsistent across various chlorinated water delivery mechanisms (centralized treatment, point-of-source, point-of-use); 5) are inconsistent in defining emergencies and recommending different dosages for high/low risk of disease outbreak or development/emergency; and 6) are inconsistent in the recommended duration to maintain FCR at the household level. Additionally, while guidelines consistently recommend a double chlorine dose when turbidity is high, the value of turbidity at which to double the dose is not consistent. To document this variability, we have collated the various recommendations in Table 5.

Despite the variability among and within these guidelines, recommendations can be summarized as follows: 1) in emergencies with normal or low risk of disease outbreaks, FCR should be 0.2–0.5 mg/L; 2) in emergencies with a high risk of disease outbreaks, FCR should be 0.5–1 mg/L (Ali et al., 2015); and 3) FCR in drinking water should not exceed internationally recommended maximums (such as the EPA maximum contaminant levels of 4.0 mg/L or the WHO guideline value of 5.0 mg/L (WHO, 2011; EPA, 2016b). However, the recommendations are also unclear

Table 5 Recommendations for FCR from various international guidance agencies

	Emergency with low risk of outbreak	*Emergency with high risk of outbreak*	*Emergency with unspecified risk of outbreak*
Dosage (mg/L) at low turbidity (<10 NTU)			1.875[8] 6.547[9] 5.55–10.42[10] 1.0–5.0[11] 2.5[12] (bucket chlorination)
Dosage (mg/L) at high turbidity (10–100 NTU)			3.75[8] 13.09[9] 11.1–20.8[10] 6–8[21] (surface water)
FCR (mg/L) after 30 minutes		0.3–0.5[7] 0.5[18] (piped system) 1.0[18] (standpipe) 2.0[18] (tanker trucks at filling)	0.4–0.5[1] 0.4–0.5[2] ≥0.5[3] ≥0.2[6] 0.2–0.5[11] 1.0[12] (bucket chlorination) 0.2–0.5[13] 0.5–0.7[14] 0.2–0.5[15] 1.0[17] (refugee camps)
FCR (mg/L) after 1 hour			≤2[8]
FCR (mg/L) after 24 hours			≥0.2[8]
FCR (mg/L) at point of delivery	≥0.2[2] ≥0.5[4] (pipe)	≥0.5[2] ≥0.5[4] ≥1[4] (pipe) 0.5[12] 0.5–1[19] (well) 1.0[20]	0.5[3] (tanker trucks) 0.2–0.5[2] 0.2–0.5[12] (pipe) 0.5–1[12] (pipe with breakage) 0.2–0.5[14]
FCR (mg/L) at point of use	0.3–0.5[20]	≥ 0.5[3] ≥ 0.5[7] 0.8–1[20]	0.5–1[20]
FCR (mg/L) at unspecified point in time		1[2] (pipes in urban area after flood) 0.4–0.5[2] 0.8–1[7] (tanker truck) 0.2–0.5[16]	0.2–0.5[5] 0.3–0.5[18] 0.5–2[21]

Notes: [1] WHO, 2005; [2] WHO, 2002; [3] WHO, 2011; [4] SPHERE, 2011; [5] Oxfam, 2001; [6] Oxfam, 2006; [7] Lamond and Kinyanjui, 2012; [8] Lantagne, 2008; [9] EPA, 2016a; [10] CDC, 2014; [11] Lambert and Davis, 2002; [12] JHU and IFRC, 2008; [13] MSF, 2010; [14] UNHCR, 2007; [15] Adams, 1999; [16] Connolly, 2005; [17] Ali et al., 2015; [18] Chalinder, 1994; [19] UNICEF, 2013; [20] ACF, 2005; [21] House and Reed, 1997 because they do not indicate where and when testing should occur in an emergency. For example, if a response programme trucks water to a bladder and then recipients collect water from distribution points supplied by the bladder, the recommendations do not consistently specify where to sample FCR (in the tanker, the bladder, at the distribution point, or in a household container or cup). Ideally, the water would be protected during distribution, transport, and storage until consumption through to the 'distal end' of the system (Clasen and Bastable, 2003), and recent research has suggested increasing recommended dosages to ensure recipients' drinking water remains protected (Ali et al., 2015).

Thus, to comply with these FCR recommendations, the initial chlorine dosage must be calibrated to: 1) meet the chlorine demand of the water; 2) maintain FCR sufficient for disinfection during water distribution, transport, and household storage (potentially lasting from 8 to 24 hours or more); and 3) avoid exceeding international maximum guideline values and user taste and odour objections. Please note that in some contexts balancing these three criteria may not be possible.

The chlorine dosage can be calculated empirically or by using fixed dosages. Empirical calculations are completed by conducting jar testing, which consists of adding multiple chlorine dosages to source water and selecting the dose with the desired FCR at a specified time (often 0.2 or 0.5 mg/L at 30 minutes) (WHO, 2005). The benefit of empirical dosing is that a calibrated dose for each individual source water is calculated daily. The drawbacks are that testing is time-consuming and technically challenging, daily fluctuations in dosage recommendations can confuse staff and users, and testing does not account for FCR decay during distribution, transport, and storage of water.

Alternatively, commercial point-of-use water treatment products use a fixed chlorine dosage of 2.0 mg/L in less turbid waters (<10 nephelometric turbidity units (NTU)) and a dosage of 4.0–5.0 mg/L in more turbid waters (10–100 NTU) (Crump et al., 2004; Lantagne, 2008; Medentech, 2015). Fixed dosages, unlike their empirically derived counterparts, have been verified by empirical testing to ensure ≥0.2 mg/L FCR 24 hours after chlorine addition in households (Lantagne, 2008). The drawbacks of fixed dosages are that they may provide higher FCR concentrations than necessary in cleaner water or lower FCR concentrations than necessary in more contaminated water and they may exceed user taste and odour levels (discussed further in the 'User acceptability' section below).

Technical challenges

The *technical challenges* topic is the third and last technical topic and includes the known limitations of chlorine, including disinfection by-products (DBP) formation, chlorine-resistant pathogens, and chlorination of turbid waters. We identified three documents in the chlorination in emergency review, and 19 additional documents in the general literature, pertaining to technical challenges. We summarize those documents below, providing information on technical challenges, applicability to emergencies, and recommendations for addressing these technical challenges in emergencies, based primarily on extensive non-emergency documents.

Disinfection by-product formation. Chlorine reacts with organic material and bromine naturally present in source waters to form DBPs, including the commonly regulated trihalomethanes (THMs) (Rook, 1974). Two of the four THMs (chloroform and bromodichloromethane) are classified as possible human carcinogens, and the WHO has established guideline values for all four THMs (IARC, 1991, 1999; WHO, 2004, 2011). Please note that the WHO guideline values are based on an acceptable risk of one extra cancer in 100,000 people who drink 2 L of chlorinated water per day for 70 years. Despite this extremely low actual risk, the perception of THM risk can be quite high, as evidenced by an editorial in a Haitian newspaper during the cholera epidemic claiming chlorination recommendations to prevent cholera would lead to 500,000 cases of cancer in the next 25 years (Mérat, 2015). This editorial undermined public confidence in chlorination during the cholera outbreak.

Turbidity is often used as an easily testable proxy indicator for organic material contamination when considering how to minimize DPB formation. In research studies investigating THM formation in turbid source waters (4–889 NTU) treated with sodium hypochlorite solution and sodium dichloroisocyanurate tablets, THM levels 24 hours after treatment were all *below* the WHO guideline values (Lantagne et al., 2008; Lantagne et al., 2010).

In actuality in emergency settings, the high short-term risk of ingesting contaminated water far outweighs the low risk of long-term negative health consequences from THM exposure. The WHO *Guidelines for Drinking-Water Quality* states, ‘It is emphasized that adequate disinfection should never be compromised in attempting to meet guidelines for THMs’ (WHO, 2011).

Chlorine-resistant pathogens. The *Cryptosporidium parvum* oocyst has a CT-factor of 7,200 mg·min/L, which far exceeds the maximum CT-factor of 60 mg·min/L achieved by standard fixed chlorine dosages of 2 mg/L for 30 minutes (Korich et al., 1990; CDC, 2008a, 2008b). If cryptosporidium is a risk (mostly from surface sources), then chlorination alone is inadequate and a filtration or coagulation/flocculation step is also recommended (Souter et al., 2003; WHO, 2011; Peletz et al., 2013), as human infection with cryptosporidium is associated with malnutrition in children (Sallon et al., 1988) and chronic disease in immune-compromised individuals (Hunter and Nichols, 2002). Another chlorine-resistant pathogen with severe health impacts, ascaris, can be removed from water with sedimentation, filtration, or coagulation/flocculation.

Chlorination of turbid water. Turbid water is challenging to treat, both because treatment options are complex and because users may object to the finished water’s appearance, taste, and real or perceived risk of THMs. The following five mechanisms are options for when the water source is turbid: 1) locate an alternative non-turbid source; 2) use an alternative treatment (such as filtration/flocculation); 3) pre-treat before chlorination with a physical clarification mechanism, such as cloth filtration, settling/decanting, or sand or ceramic filtration (Kotlarz et al., 2009); 4) pre-treat before chlorination with a chemical coagulation/flocculation step, such as alum or moringa (Preston et al., 2010); or 5) as commonly recommended, double the chlorine dose (SPHERE, 2011; EPA, 2016a).

If an alternative source or treatment cannot be used, pre-treatment using cloth filtration, settling/decanting, sand and ceramic filtration, alum addition, and moringa addition significantly reduce turbidity (Muyibi and Okuofu, 1995; Kotlarz et al., 2009; Preston et al., 2010; Sengupta et al., 2012). Additionally, sand and ceramic filtration, settling/decanting, and alum addition significantly lower chlorine demand (Kotlarz et al., 2009; Preston et al., 2010). Cloth filtration does not affect chlorine demand (Kotlarz et al., 2009), and moringa addition increases it due to the addition of organic material (Preston et al., 2010). None of the physical clarification pre-treatment mechanisms decreases THM formation potential, likely because THM precursor compounds are too small for gross filtration mechanisms to remove (Kotlarz et al., 2009; Lantagne et al., 2010). However, chemical coagulation/flocculation with alum can slightly reduce THM formation potential (Drikas et al., 2003), while chemical coagulation/flocculation with moringa increases THM formation potential due to the concurrent addition of organic material (Lantagne et al., 2008).

To summarize, alum is the only pre-treatment option that reduces turbidity, chlorine demand, and THM formation potential. Unrefined alum is sold in markets as a naturally occurring mineral stone block, and is used for bulk and household coagulation/flocculation in emergencies. Using alum for bulk water treatment in emergencies is a straightforward and widely used turbidity reduction option. However, the promotion of alum for household coagulation/flocculation is limited because: 1) the quality of alum varies unpredictably; 2) no established recommended dosage or simple mechanism exists for users to add alum; and 3) overdosage causes a salty, unpalatable taste (Preston et al., 2010). Sand and ceramic filtration and settling/decanting reduce turbidity and chlorine demand in turbid waters. Thus, a single dose of chlorine can be thus be used after alum treatment, sand and ceramic filtration, or settling/decanting. Given that moringa increases both chlorine demand and THM formation, it is not recommended in conjunction with water chlorination programmes.

Another widely promoted option for treatment of turbid water is simply to double the dose of chlorine. While this is not recommended as adequate water treatment over the long term, studies show that a double dose can maintain adequate FCR and effectively reduce microbiological contamination at turbidities up to 100 NTU, but more refined evidence is needed (Crump et al., 2004; Lantagne, 2008, Mohamed et al., 2015). Chlorinating water with turbidity >100 NTU is not recommended, and chlorination of very turbid water rarely occurs in emergency contexts because of concerns about user rejection due to the strong taste of chlorine.

Product options

The *product options* topic is the first of four programmatic topics, and is specific to the emergency context, detailing chlorine products that are available for use in emergency response. We identified 10 documents in the chlorination in emergency review, and 11 additional documents in the general literature, pertaining to product options. We summarize those documents below, providing information on the benefits and drawbacks of powder, liquid, and tablet forms of chlorine used in emergency response, followed by a discussion on safe storage containers.

Powder. Sodium dichloroisocyanurate (NaDCC) and calcium hypochlorite (bleaching powder, HTH, chlorinated lime) powders are widely used in emergency response because of their high concentration and ease of transport. They are mixed with water to make liquid chlorine solutions. Both powders contain approximately 60–70 per cent chlorine and are stable for 3–5 years if not exposed to UV light or high temperatures. The efficacy of bleaching powder in removing fecal indicator bacteria has been demonstrated in emergency floodwaters (Islam et al., 2007). A drawback of NaDCC is that it is not stable in solution, and thus NaDCC solutions should be used within one day of preparation (Iqbal et al., 2016). A drawback of calcium hypochlorite is that it forms a precipitate that needs to settle out before decanting, or the solution can clog pipes. Care should be taken to use clean water for dilution and to avoid mixing HTH and NaDCC powders together, as doing so can cause explosions (Oxfam internal memo, Sierra Leone, available from Andy Bastable, abastable@oxfam.org.uk). The amount of powder to add to attain a specific concentration of liquid solution is calculated as shown in Equation (1) (equation by authors):

$$\begin{aligned} &\mathit{Powder\ to\ add}\,(mg) \\ &= \frac{\mathit{Solution\ concentration\ desired}\left(\dfrac{mg_{Chlorine}}{L_{Water}}\right)\times L_{Dilution\ water}}{\dfrac{\mathit{Powder\ concentration}\ (\%)}{100}} \end{aligned} \tag{1}$$

Please note for calculations that 10,000 mg/L (ppm) = 1% = 3.16 degrees chlorometrique; degrees chlorometrique is a unit often used by former French colony countries.

Two point-of-use products use chlorine powder: 1) Klorfasil uses specialized dosing caps to dispense 2 mg/L or 4 mg/L dosages of NaDCC granules for 20 L containers (Klorfasil, undated); and 2) products such as PuR Purifier of Water™ or WaterMaker are flocculant/disinfectant powders that contain powdered flocculant (such as aluminium or ferric sulfate) and calcium hypochlorite. Only PuR's efficacy has been demonstrated in laboratory waters representative of emergency water (McLennan et al., 2009; Marois-Fiset and Dorea, 2013). To treat water with PuR, users open the sachet, add the contents to an open bucket containing 10 L of water, stir for 5 minutes, let the solids settle to the bottom of the bucket, strain the water through a cotton cloth into a second container, and wait 20 minutes for the hypochlorite to inactivate the microorganisms (Souter et al., 2003; Aquaya, 2005).

Liquid. The benefits of sodium hypochlorite (NaOCl, bleach) are that it is locally available, familiar, and inexpensive. The drawbacks are that it is difficult to transport, often does not advertise concentration or fall within 10 per cent of advertised concentration, requires pH stabilization (pH > 11) for storage for more than 48 hours, and degrades with increasing concentration and when exposed to heat and UV light (Lantagne, 2009; Lantagne et al., 2011). A well-manufactured, pH-stabilized 1 per cent solution kept sealed, out of sunlight, and stored below 35°C has a shelf-life of approximately 18 months (Lantagne et al., 2011). The efficacy of liquid sodium hypochlorite in reducing fecal indicator bacteria has been demonstrated in both waters representative of emergency waters (Crump et al., 2004; Lantagne, 2008) and actual emergency waters (Islam et al., 2007).

The volume of sodium hypochlorite to add for a given dosage is calculated as shown in Equation (2) (equation by authors):

$$Sodium\ hypochlorite\ to\ add\,(mL) = \frac{Dosage\left(\frac{mg_{Chlorine}}{L_{Water}}\right) \times L_{Water\ to\ be\ treated}}{Sodium\ hypochlorite\ concentration\left(\frac{mg}{L}\right) \times \frac{1\,L}{1000\,mL}} \tag{2}$$

Please note that 1 per cent = 10,000 mg/L; 20 drops = 1 mL; and this equation is only valid for chlorine dosages of ≤5 mg/L).

Liquid sodium hypochlorite may be obtained in an emergency by: 1) producing it on-site using a high-quality hypochlorite generator and raw materials (clean salt, clean water, and electricity); 2) procuring it from a quality-controlled local manufacturer; or 3) procuring prepackaged solutions available locally for household water treatment (such as WaterGuard/SûrEau from Population Services International) (CDC, 2008c).

Tablets. Sodium dichloroisocyanurate (NaDCC) tablets, such as Aquatabs™, have been distributed extensively in emergency situations (Clasen and Smith, 2005; Lantagne and Clasen, 2012b; Patrick et al., 2013). Aquatabs use a dosage of 2 mg/L for 'non-emergency' water and 5 mg/L for 'emergency' water (Medentech, 2015). Their efficacy has been demonstrated in laboratory waters representative of emergencies (McLennan et al., 2009) and emergency waters (Lantagne and Clasen, 2012b; Patrick et al., 2013). They have a shelf-life of 3–5 years and are sold in various sizes, labelled with the mg of NaDCC, emergency or normal tablet type, and the volume of water to be treated. The calculation shown in Equation (3) can be used to determine the dosage for a chlorine tablet (equation by authors):

$$Dosage\left(\frac{mg}{L}\right) = \frac{Aquatab\,(mg) \times 0.60}{Liters_{Water}} \tag{3}$$

The benefits of NaDCC tablets compared with liquid NaOCl include lower cost of transport, longer shelf-life, and ease-of-use (Clasen and Edmondson, 2006). The drawbacks of tablets are a higher relative cost per volume of water treated, the need to import, and confusion for end users when multiple size tablets are distributed in the same emergency (Clasen and Edmondson, 2006; Loo et al., 2012; Lantagne and Clasen, 2013; Patrick et al., 2013).

Safe storage containers. Safe storage containers protect treated water by creating a physical barrier to recontamination (Mintz et al., 1995). Containers should: 1) have a small opening or lid to discourage users from placing potentially contaminated items such as hands, cups, or ladles into the stored water; 2) have a spigot or small opening to facilitate easy and safe access to the water without inserting hands or objects into the container; and 3) be appropriately sized, with permanently attached instructions and public health promotion activities for use and cleaning. The container's shape, age, and composition can affect FCR concentration. Of the potential container materials (plastic, metal, or clay) only clay pots (which are preferred in many communities because they are perceived to keep water cool) have been shown to exert more chlorine demand, depending on the firing quality during the manufacturing process (Ogutu et al., 2001; Lantagne, 2008; Null and Lantagne, 2012).

User acceptability

The *user acceptability* topic is the second of four programmatic topics covered in this article. Successful chlorination programmes depend not only on the technical and product aspects described in the first four topics, but also on user acceptability. Ease-of-use, taste, smell, and appearance are important in determining if users will accept chlorinated water. We identified three documents in the chlorination in emergency review, and five additional documents in the general literature, pertaining to user acceptability. We summarize this scant evidence below, providing some information on user acceptability of chlorination programmes in emergencies.

Ease-of-use, taste, smell, and appearance are important in determining if users will accept chlorinated water. The chlorine taste comes from both the FCR, as well as from compounds formed when the chlorine reacts with other compounds in the water. Users may avoid treated water that is unaesthetic but safe in favour of untreated water that is aesthetic but harmful (POUZN, 2007).

Many individuals taste or smell chlorine in drinking water at concentrations well below 5 mg/L, and some individuals can detect levels as low as 0.3 mg/L (WHO, 2011). While the research on the acceptability and variation of chlorine taste in infrastructure systems is well-established (Mackey et al., 2004; Piriou et al., 2004; Gouveia et al., 2007), little evidence exists for emergencies. Some initial evidence, and an oft-repeated belief, exists that people are more willing to accept the taste of chlorine in emergencies due to heightened sense of risk (Hoque et al., 1995; Clasen and Smith, 2005).

To assess taste and odour thresholds, focus groups can be conducted where participants drink water solutions with 0.0, 0.2, 0.5, 1.0, 2.0, 3.0, 4.0, and 5.0 mg/L FCR and state their reactions and perceptions. Regional, age-based, and cultural variability have been noted: for example, in various focus groups, Zambian participants reported acceptability at FCR 1.0 mg/L but not at 2.0 mg/L; Liberian participants reported acceptability at 4.0 mg/L; Ethiopian participants reported not tasting chlorine at 1.0 mg/L, noticing the taste at 2 mg/L, and objecting to the taste at 3 mg/L; and Burmese participants tasted and objected to FCR at 0.2 mg/L (unpublished focus group results from chlorine taste testing, Tufts University, Medford, MA; available from daniele.lantagne@tufts.edu). As stated previously, depending on the local context, balancing the competing criteria of meeting the chlorine demand of water, maintaining FCR sufficient for disinfection throughout the water collection and storage chain, and not exceeding international standards and user taste and odour objections may not be possible.

Chlorination programmes for emergencies

The *chlorination programmes for emergencies* topic is the third of four programmatic topics covered in this article. We identified 32 documents in the chlorination in emergency review, and one additional document in the general literature, pertaining to programmes in emergencies. We summarize the lessons learned from this plethora of evidence below, by programme type of point-of-delivery, point-of-source, and point-of-use chlorination programmes; noting that some programme types are well-researched and other commonly implemented programme types are severely under-researched.

Chlorination programmes in emergencies occur at the: 1) point-of-delivery (i.e. at the tap stand from water trucking or in-line chlorination); 2) point-of-source (i.e. well chlorination, pot chlorination, bucket chlorination, and dispensers); and 3) point-of-use (i.e. household distribution). These chlorination programmes use various chlorine products, as described in a previous section. A summary of recommendations for implementing various programmes in emergencies is found in Table 6.

Point-of-delivery. Water trucking is a short-term, acute emergency response that addresses water shortages or interruptions in access when people are travelling further than normal to access water, non-functional water points cannot be rapidly repaired, and no commercial water trucking market is present (Wildman, 2013). Chlorine is often added directly to tanker trucks during water collection, although tanker owners sometimes reject this due to concerns about chlorine compounds corroding their tanks. After the 2010 earthquake in Haiti, water from households that was reported to be collected from tanker truck sources and not further treated had 0 mg/L FCR 77 per cent of the time and *Escherichia coli* was found in 56 per cent of samples (Lantagne and Clasen, 2013). After the 2004 tsunami in Indonesia, only 56 per cent of the tanker trucks surveyed had FCR ≥0.1 mg/L in the truck, 18 per cent were contaminated with *E. coli,* and 32.5 per cent of the trucks reported filling from locations other than the designated one, likely because the line was too long (Gupta and Quick, 2006). Gupta and Quick recommended improvements including maintaining 0.2–0.5 mg/L FCR at the filling station during times of no cholera risk and 2 mg/L when cholera risk is present, and avoiding sediment accumulation in the trucks (which increases chlorine demand) (Gupta and Quick, 2006).

Centralized chlorination is often used in refugee camp settings, where water is pumped and treated centrally before distribution via a piped network and tapstands where users access water. Centralized chlorination includes in-line chlorination, in which automatic chlorinators continuousy add chlorine to water as it is distributed. In refugee camps in South Sudan served by in-line chlorination (with an aim of 0.8–1.0 mg/L FCR at the tapstand), the actual tapstand FCR was found to vary from <0.01–5.2 mg/L (Ali et al., 2015). Chlorine decay models developed from post-distribution FCR time series data found that maintaining adequate FCR at the

Table 6 Implementation recommendations for chlorination programmes in emergencies

Programme	*Implementation recommendations for emergencies*	*Studies in emergency context*
Water trucking	• Insufficient evidence at this time • Ensure adequate capacity of filling locations • Avoid accumulation of sediment in truck	Gupta and Quick, 2006 Lantagne and Clasen, 2013 Wildman, 2013
Centralized/ in-line chlorination	• Insufficient evidence at this time	Ali et al., 2015
Dispensers	• Install dispensers at point sources • Maintain high-quality chlorine solution • Ensure manufacturing and distribution chain • Maintain dispenser hardware • Integrate dispenser projects within other programmes • Remunerate promoters and utilize experienced project staff • Work with local partners to implement project • Conduct ongoing monitoring and have a project sustainability plan	Yates et al., 2015
Well/pot chlorination	• Well/pot chlorination is only effective for a few days after treatment, recommend reapplication every few days if completed	Garandeau et al., 2006 Luby et al., 2006 Rowe and Angulo, 1998 Cavallaro et al., 2011 Godfrey et al., 2003 Guevart et al., 2008
Bucket chlorination	• Insufficient evidence at this time	Murphy et al., undated Roberts et al., 2001
Household distribution	• Provide products with standardized dosage and instructions and accurate concentrations • Deliver products with a safe storage container • Direct programmes at households previously familiar with the household water treatment method • Select implementing organizations with prior experience with the product and programme • Aim for high access to, demand for, and compliance with products • Provide the necessary supplies and training • Utilize community-based mobilization, education, and marketing techniques • Consider prioritizing distribution in households that cannot be reached by centralized treatment	CARE, undated Clasen and Smith, 2005 Colindres et al., 2007 Deb et al., 1986 Doocy and Burnham, 2006 Dunston et al., 2001 Gupta et al., 2007 Hoque and Khanam, undated Hoque et al., 1995 Imanishi et al., 2014 IMC, 2008 Lantagne and Clasen, 2012b Lantagne and Clasen, 2013 Mong et al., 2001 Patrick et al., 2013 Reller et al., 2001 UNICEF, 2007

household level was only possible for up to 10 hours because of rapid chlorine decay. Currently researchers, manufacturers, and implementers express considerable interest in developing new products for treating water in line with chlorine in pipes and wellheads (Pickering et al., 2015).

Point-of-source – well chlorination. Well chlorination (also termed shock or spot chlorination) refers to the process of adding a calculated amount of liquid or powdered chlorine directly into a well to sanitize the water within it (Godfrey, 2005). Although implementers and recipients commonly perceive long-lasting protection, research in Guinea-Bissau, Liberia, and Bangladesh found that well chlorination provided only short-lived (<48 hours) maintenance of FCR and little to no improvement in water quality, and led to a false sense of security (Rowe and Angulo, 1998; Garandeau et al., 2006; Luby et al., 2006).

Point-of-source – pot chlorination. Pot chlorination is a variation on well chlorination in which a container (clay pot, plastic bottle, or jerrican) with layers of HTH, sand, and gravel is suspended in a well, ideally slowly diffusing chlorine. However, pot chlorinators: 1) frequently release chlorine too fast, resulting in very high FCR concentrations (up to 10 mg/L) (Garandeau et al., 2006); 2) do not maintain an FCR of 0.2–5.0 mg/L for long (62 per cent at 24 hours, 15 per cent at 48 hours, and 4 per cent at 72 hours) (Cavallaro et al., 2011); and 3) lead to a false sense of security that can result in discontinuation of more effective chlorination programmes (Cavallaro et al., 2011). However, when pot chlorination was completed weekly and fortnightly, thermotolerant coliform levels in an internally displaced persons (IDP) camp in Angola were consistently reduced to <10 colony-forming unit (CFU)/100 mL (Godfrey et al., 2003). Further, when pot chlorinators were regularly refilled, residual chlorine level was maintained for up to three days during a cholera outbreak in Cameroon (Guevart et al., 2008).

Point-of-source – bucket chlorination. In bucket chlorination, trained individuals (chlorinators) stationed at water sources add sodium hypochlorite solution to recipients' water-collection containers. Generally, the appropriate dosage for bucket chlorination is determined empirically on a daily basis. Data on the effectiveness of this method in emergencies is scarce, and we identified no published documents, but recent research during a cholera outbreak in Cameroon documented that 83 per cent of households had FCR <0.2 mg/L 24 hours after bucket chlorination (Murphy et al., undated). When researchers added a dose of 2.5 mg/L chlorine to buckets of water in a refugee camp in Malawi, *E. coli* was reduced by 99 per cent for four hours; however, by six hours, *E. coli* increased to >250 CFU/100 mL (Roberts et al., 2001).

Point-of-source – dispensers. Dispensers are a variation on bucket chlorination. Innovations for Poverty Action (IPA) developed the Chlorine Dispenser System in 2007. It includes three central elements: 1) hardware installed next to a water source that dispenses an appropriate dose of sodium hypochlorite solution for a collection vessel; 2) a local promoter who refills the dispenser and conducts community education; and 3) a supply chain of bulk chlorine refills. A study investigating the effectiveness of dispensers in emergency contexts in Haiti, Sierra Leone, Democratic

Republic of Congo, and Senegal found that results varied greatly across programmes (Yates et al., 2015). The percentages of households self-reporting treatment of stored household drinking water with a dispenser ranged from 9 to 97 per cent, the percentage of households with FCR ≥0.2 mg/L in dispenser-treated water ranged from 5 to 87 per cent, and the percentage of households that used the dispenser to improve the microbiological quality of their stored household water from contaminated to uncontaminated ('effective use') ranged from 0 to 81 per cent. Along with overall strong programme management elements, the more effective dispenser interventions maintained both dispenser hardware and a high-quality chlorine solution manufacturing and distribution chain.

Point-of-use. Distribution of chlorine-based point-of-use products, i.e. products that require households to treat their water (with sodium hypochlorite, NaDCC tablets, or flocculant/disinfectant sachets), have been evaluated in response to earthquakes, tsunamis, floods, cyclones, typhoid outbreaks, cholera outbreaks, and complex emergencies (Table 6). Benefits of point-of-use chlorination include global product availability, ease of distribution, and the potential for continued access to products as the response transitions from relief to development (if products are locally available). Drawbacks include user acceptability, need for appropriate training, and the difficulty of conducting promotion when different tablets with varying chlorine concentrations for varying volumes are distributed within the same emergency context (Lantagne and Clasen, 2012a).

While it is commonly believed that adherence to chlorination is relatively higher in emergency programmes because of the population's perception of risk in an emergency, there is actually good evidence on the programmatic factors that lead to successful chlorination in emergency programmes. Overall, the most successful chlorine-based distribution programmes in emergencies (across all programme types) are effective in three areas: products, placement, and support. Effective products have standardized dosage and instructions and accurately advertised chlorine concentrations, and are delivered with a safe storage container. Effective placement occurs where programmes are directed at households familiar with the chlorination method before the emergency; implementing organizations have prior experience with the product and programme; and there is high access to, demand for, and compliance with products. Effective support exists where implementing organizations provide the necessary supplies and training; coordinate with partner agencies; and utilize community-based mobilization, education, and marketing techniques such as health motivators or community health workers (Deb et al., 1986; Hoque et al., 1995; Dunston et al., 2001; Mong et al., 2001; Reller et al., 2001; Clasen and Smith, 2005; Doocy and Burnham, 2006; Colindres et al., 2007; Gupta et al., 2007; UNICEF, 2007; IMC, 2008; Lantagne and Clasen, 2012b, 2013; Patrick et al., 2013; Imanishi et al., 2014; CARE, undated; Hoque and Khanam, undated).

Programme monitoring

The *programme monitoring* topic is the last of four programmatic topics covered here. Programme monitoring is necessary to ensure the chlorination programme is operating as intended, and to identify and rectify any problems. We identified zero documents in the chlorination in emergency review, and eight documents in the general literature, pertaining to programme monitoring. Thus, we summarize recommendations for programme monitoring in emergencies based on the general literature below.

Programme monitoring is an ongoing process to continually provide information on a programme's progress (UNDP, 2009). Monitoring two parameters in chlorination programmes in emergencies is recommended: 1) FCR at appropriate locations including the household level; and 2) raw chlorine product quality (WHO/UNICEF, 2012). Formal evaluations can assess microbiological quality of treated water and health impact.

Regularly testing FCR at the household level is the most critical indicator in monitoring, as it indicates correct use, consistent use, and water safety. Many commercially available FCR test methods exist, with varying accuracy, precision, usability, and costs, including pool test kits, test strips, test tube kits, colour-wheel comparator test kits, and digital colorimeters (Murray and Lantagne, 2015). All these methods depend on a colour change to identify FCR presence and concentration. Murray and Lantagne found DPD-1-based test tube kits and colorimeters to be well suited for measuring FCR concentrations in drinking water in low-resource settings. Test-strip methods are the easiest to use, but are the least accurate. An example of a monitoring programme in emergencies is the SIS-KLOR programme in Haiti, which consisted of regularly measuring FCR in spontaneous settlements in Haiti, and reporting these results through the WASH Cluster to encourage a minimum FCR in all tapstands (DINEPA, 2016).

To assess raw chlorine product quality, responders can add a known amount of the product to chlorine-demand-free, unchlorinated water; calculate the expected FCR; measure the actual FCR with a test kit as described previously; and assess the difference. Generally, a 10 per cent error is considered acceptable (Lantagne et al., 2011). The quality of liquid sodium hypochlorite solutions can also be assessed using a portable iodimetric titration method (such as Hach Method 8209) (HACH, 2016) or working with a laboratory that can complete iodimetric titration. Additionally, testing the pH of liquid hypochlorite solutions to ensure stability with simple pH strips capable of testing in the pH 7–14 range is recommended to ensure stability.

Lastly, microbiological quality of treated water and/or health impact can be assessed, although these parameters are more complicated to measure and more suitable for external evaluation programmes than routine monitoring programmes (CDC, 2010; WHO/UNICEF, 2012).

Discussion

We conducted a review of chlorination in emergencies, supplemented with relevant technical information from the general chlorination literature, and identified 106 documents that provided insight into seven key topics relevant to chlorination of water in emergencies: technical efficacy, chlorine dosage, technical challenges, product options, user acceptability, programmes for emergencies, and programme monitoring. Our results document that: 1) there is inconsistency in international chlorine dosage recommendations in emergencies; 2) high-quality information is available from the general chlorination literature on the challenges of chlorination that can be adapted for emergencies; 3) numerous chlorine products are available that are used in point-of-delivery, point-of-source, and point-of-use programmes in emergencies; 4) there is a varying amount of information on the effectiveness of chlorination programmes in emergencies, ranging from none identified to high-quality data that can inform programming; 5) there is a lack of information on user acceptability of chlorination in emergencies; and 6) there is a lack of ongoing regular monitoring data collection on chlorine programme effectiveness in emergencies.

As presented herein, considerable variation exists in the FCR recommendations for chlorine in emergencies, and the dosage and FCR that should apply to each water source in each emergency context are quite unclear. As the ultimate goal of chlorination programmes is to ensure the presence of a minimum FCR level at the distal point of the system – which in emergencies is often after storage in a household container – international guidelines and standards should align to ensure a minimum FCR amount (0.2 mg/L) in the recipient's cup at the moment of consumption. To achieve this goal, additional research is needed: 1) to determine methods to accurately assess chlorine demand throughout the distribution, transport, and storage chain (including more than simply jar testing at the source, but understanding FCR degradation throughout the water chain); 2) to identify the acceptable turbidity range for double dosing of chlorine and determine the effectiveness of locally available pre-treatment strategies (such as cloth filtration, ceramic/sand filtration, settling/decanting, and alum addition) for turbid water in the field; and 3) to determine how to balance these criteria with taste and odour thresholds, as described later in this section.

Challenges of chlorination – THMs, resistant pathogens, and turbid water – are very well addressed in the non-emergency literature, and these lessons can be widely adapted to the emergency context. Additionally, several well-known products are available for chlorination of water in emergencies, and many of these are well researched and validated. However, additional research is needed on less well-known or locally manufactured chlorine solutions.

The irony of emergency response chlorination programmes is that many of those that are widely implemented – in-line chlorination, well chlorination, bucket chlorination, water trucking – lack sufficient evidence to support their effectiveness. Conversely, significant evidence supports the use of less implemented programmes such as dispensers, and there is a plethora of evidence on the commonly implemented point-of-use chlorination. Based on the available evidence, recommendations for implementing point-of-use chlorination and dispensers have been presented, and well/pot chlorination is only recommended if it is completed regularly. More information is needed on in-line chlorination, well chlorination, bucket chlorination, and water trucking to develop recommendations (Table 6). In particular, product development and evaluation are necessary in the realm of in-line chlorinators, both for systems and for wellheads. Lastly, research comparing multiple chlorination programmes in the same emergency is needed to devise better guidance for practitioners determining the most efficient method to utilize.

There are many assumptions made by emergency responders about user acceptability of chlorine in emergency response, ranging from the perspective that chlorine taste and odour are completely unacceptable to the belief that individuals will change their behaviour because of perceived increased risk in the emergency. No manuscript in our review primarily addresses the topic of user acceptability of chlorine in emergencies; it was only touched upon as a side topic. Research from the development context highlights cultural and contextual factors playing a large role in the acceptability of chlorination. Dedicated research is still necessary on the acceptability of chlorine taste in emergencies, in varying contexts, and on varying perceptions of increased risk by the population. Additionally, more information is needed on how to address the perceived risk of THMs during emergency chlorination programmes.

Monitoring of FCR and chlorine product concentrations is recommended in all chlorination programmes in emergencies. To ensure chlorine protection through to the distal end of the system, monitoring FCR from the point of distribution to the user's cup is further recommended by asking the question, 'Can you provide me a cup of water as you would provide your child?' to householders and testing the water provided. Improving monitoring ensures that water consumed by households has been effectively treated with chlorine and facilitates comparison and exchange among programmes. Chlorine decay data that trace the path of water from point of distribution to point of consumption allow us to develop a better understanding of post-distribution chlorine decay. Moreover, monitoring associated water quality parameters, water-handling practices, and other contextual factors alongside FCR decay may help to identify factors that preserve or compromise the safe water chain.

One of the greatest challenges in chlorination in emergencies is balancing the competing criteria of: 1) meeting the chlorine demand of the water; 2) maintaining FCR sufficient for disinfection during water distribution, transport, and household storage through to the distal end of the system; and 3) not exceeding international maximum guideline values of 4–5.0 mg/L of chlorine in drinking water and user taste and odour objections. The current recommendations for FCR and dosage in emergencies do not address in what contexts balancing these competing criteria is possible, and in what contexts it is not possible. Specifically, for contexts where balancing these criteria is not possible, additional research is needed to understand and develop alternatives, such as which criteria to prioritize, or alternate treatments/sources. Beneficiary input must be included when working to balance these criteria. The hope is that the succinct and complete summary of information presented herein will assist responders in determining how to balance these criteria within the contexts they face. The principal values of this paper are that it summarizes existing literature to provide evidence-based recommendations to responders, identifies areas in need of clarification and consensus by international agencies; and recommends research needed. However, a limitation (and strength) of this paper is that some topic areas relevant to chlorination in emergencies (particularly technical challenges and monitoring) have such minimal evidence from emergency contexts that we included review information from non-emergency contexts to provide a complete picture.

A more thorough understanding of the technical, programmatic, and social aspects of chlorination programmes in emergencies would help communities, responders, and governments to respond to emergencies better. While the data on the efficacy of chlorination are very good, the actual practice of using chlorine is often heterogeneous and context dependent. Further research into effectiveness of interventions and operational decision-making is necessary to ensure the efficacy and effectiveness of chlorination programmes. A better understanding of chlorination in emergencies is timely and necessary as natural disasters and their impacts have been increasing in recent decades, due to increases in populations living in hazard-prone locations; unplanned settlements and environmental degradation; and climate change causing more intense hurricanes, higher rainfall intensities, drought, and heatwaves (UNISDR, 2006). Additionally, outbreaks where chlorine is a key infection control and disease management component are currently increasing or emerging, such as cholera (Gaffga et al., 2007) and Ebola.

Conclusion

In this article we conducted a thorough review of the literature pertaining to chlorination of water in emergencies. We found that: 1) international chlorine dosage recommendations in emergencies are highly inconsistent; 2) high-quality information from the general chlorination literature on challenges of chlorination can be adapted for emergencies; 3) many chlorine products are available for use in point-of-delivery, point-of-source, and point-of-use emergency-response programmes; 4) information on the effectiveness of different chlorination programmes in emergencies varies, ranging from little data available to high-quality data that can inform programming, 5) information on user acceptability of chlorination in emergencies is lacking; and 6) monitoring data on chlorine programme effectiveness in emergencies are lacking. We developed recommendations for implementing programmes and recommendations for future research. We hope this summary is helpful for governments, responders, researchers, and communities.

References

ACF (2005) *Water, Sanitation and Hygiene for Populations at Risk* [pdf], Paris, France: Action Contre la Faim <www.actionagainsthunger.org/sites/default/files/publications/Water_sanitation_and_hygiene_for_populations_at_risk_12.2005.pdf> [accessed 21 November 2016].

Adams, J. (ed.) (1999) *Managing Water Supply and Sanitation in Emergencies*, Oxford, UK: Oxfam Publishing.

Ahern, M., R.S. Kovats, P. Wilkinson, R. Few and F. Matthies (2005) 'Global health impacts of floods: epidemiologic evidence', *Epidemiology Reviews* 27: 36–46 <http://dx.doi.org/10.1093/epirev/mxi004>.

Ali, S.I., S.S. Ali and J-F. Fesselet (2015) 'Effectiveness of emergency water treatment practices in refugee camps in South Sudan', *Bulletin of the World Health Organization* 93(8): 550–8 <http://dx.doi.org/10.2471/BLT.14.147645>.

Aquaya (2005) *Standard Operating Procedure for the Deployment of Procter & Gamble's PUR Purifier of Water in Emergency Response Settings* [pdf], San Francisco, CA <http://water.care2share.wikispaces.net/file/view/PUR%20Information.pdf/423780098/PUR%20Information.pdf> [accessed 25 November 2016].

Black & Veatch Corporation (2010) *White's Handbook of Chlorination and Alternative Disinfectants: 5th Edition*, New York: John Wiley & Sons.

CARE (undated). *Global Development Alliance, Safe Drinking Water Alliance, Report of Findings: Draft Outline*, Atlanta, GA: CARE (available from authors).

Cavallaro, E.C., J.R. Harris, M.S. Da Goia, J.C.dos Santos Barrado, A.A. Da Nobrega, I.C.de Alvarenga de Junior, A. P. Silva, J. Sobel and E. Mintz (2011) 'Evaluation of pot-chlorination of wells during a cholera outbreak, Bissau, Guinea-Bissau, 2008', *Journal of Water and Health* 9(2): 394–402 <http://dx.doi.org/10.2166/wh.2011.122>.

CDC (2008a) *Chlorine Residual Testing Fact Sheet* [pdf], Atlanta, GA: Centers for Disease Control and Prevention <www.cdc.gov/safewater/publications_pages/chlorineresidual.pdf> [accessed 21 November 2016].

CDC (2008b) *Effect of Chlorination on Inactivating Selected Pathogen* [online], Atlanta, GA: Centers for Disease Control and Prevention <www.cdc.gov/safewater/effectiveness-on-pathogens.html> [accessed 21 November 2016].

CDC (2008c) *Safe Water for the Community: A Guide for Establishing a Community-based Safe Water System Program* [pdf], Atlanta, GA: Centers for Disease Control and Prevention <www.ehproject.org/PDF/ehkm/cdc-safewater_community.pdf> [accessed 21 November 2016].

CDC (2010) *Microbiological Indicator Testing in Developing Countries: A Fact Sheet for the Field Practitioner* [pdf], Atlanta, GA: Centers for Disease Control and Prevention <www.hip.fhi360.org/file/28138/FactSheet on Microbiological Indicator Testing.pdf> [accessed 21 November 2016].

CDC (2014) *Water-Related Emergencies and Outbreaks: Personal Preparation and Storage of Safe Water* [online], Atlanta, GA: Centers for Disease Control and Prevention <www.cdc.gov/healthywater/emergency/drinking/emergency-water-supply-preparation.html> [accessed 25 November 2016].

Chalinder, A. (1994) *Water and Sanitation in Emergencies* [online], London: Overseas Development Institute <www.odihpn.org/hpn-resources/good-practice-reviews/water-and-sanitation-in-emergencies> [accessed 21 November 2016].

Clasen, T. and A. Bastable (2003) 'Faecal contamination of drinking water during collection and household storage: the need to extend protection to the point of use', *Journal of Water and Health* 1(3): 109–15 <http://jwh.iwaponline.com/content/1/3/109>.

Clasen, T. and P. Edmondson (2006) 'Sodium dichloroisocyanurate (NaDCC) tablets as an alternative to sodium hypochlorite for the routine treatment of drinking water at the household level', *International Journal of Hygiene and Environmental Health* 209(2): 173–81 <http://dx.doi.org/10.1016/j.ijheh.2005.11.004>.

Clasen, T. and L. Smith (2005) *The Drinking Water Response to the Indian Ocean Tsunami, Including the Role of Household Water Treatment* [online], Geneva: World Health Organization <www.who.int/household_water/research/tsunami/en/index.html> [accessed 21 November 2016].

Colindres, R.E., S. Jain, A. Bowen, P. Domond and E. Mintz (2007) 'After the flood: an evaluation of in-home drinking water treatment with combined flocculent-disinfectant following Tropical Storm Jeanne – Gonaives, Haiti, 2004', *Journal of Water and Health* 5(3): 367–74 <http://dx.doi.org/10.2166/wh.2007.032>.

Connolly, M.A. (2005) *Communicable Disease Control in Emergencies: A Field Manual* [pdf], Geneva: World Health Organization <http://apps.who.int/iris/bitstream/10665/96340/1/9241546166_eng.pdf> [accessed 21 November 2016].

Crump, J.A., G.O. Okoth, L. Slutsker, D.O. Ogaja, B.H. Keswick and S.P. Luby (2004) 'Effect of point-of-use disinfection, flocculation and combined flocculation-disinfection on drinking water quality in western Kenya', *Journal of Applied Microbiology* 97(1): 225–31 <http://dx.doi.org/10.1111/j.1365-2672.2004.02309.x>.

Deb, B.C., B.K. Sircar, P.G. Sengupta, S.P. De, S.K. Mondal, D.N. Gupta, N.C. Saha, S. Ghosh, U. Mitra and S.C. Pal (1986) 'Studies on interventions to prevent el tor cholera transmission in urban slums', *Bulletin of the World Health Organisation* 64(1): 127–31.

DINEPA (2016) 'Bulletins SisKlor' [online] <www.dinepa.gouv.ht/category/bulletin-sisklor/> [accessed 21 November 2016].

Doocy, S. and G. Burnham (2006) 'Point-of-use water treatment and diarrhoea reduction in the emergency context: an effectiveness trial in Liberia', *Tropical Medicine & International Health* 11(10): 1542–52 <http://dx.doi.org/10.1111/j.1365-3156.2006.01704.x>.

Drikas, M., C.W.K. Chow and D. Cook (2003) 'The impact of recalcitrant organic character on disinfection stability, trihalomethane formation and bacterial regrowth: an evaluation of magnetic ion exchange resin (MIEX®) and alum coagulation', *Journal of Water Supply: Research & Technology-AQUA* 52(7): 475–87.

Dunston, C., D. McAfee, R. Kaiser, D. Rakotoarison, L. Rambeloson, A.T. Hoang and R.E. Quick (2001) 'Collaboration, cholera, and cyclones: a project to improve point-of-use water quality in Madagascar', *American Journal of Public Health* 91(10): 1574–6.

Elmaksoud, SA., N. Patel, S.L. Maxwell, L.Y. Sifuentes and C.P. Gerba (2014) 'Use of household bleach for emergency disinfection of drinking water', *Journal of Environmental Health* 76(9): 22–5.

EPA (2016a) *Emergency Disinfection of Drinking Water* [pdf], Washington, DC: United States Environmental Protection Agency <http://water.epa.gov/drink/emerprep/upload/epa816f15003.pdf> [accessed 21 November 2016].

EPA (2016b) 'List of drinking water contaminants and their MCLs: national primary drinking water regulations' [online] <http://water.epa.gov/drink/contaminants/index.cfm> [accessed 20 April 2016].

Gaffga, N.H., R.V. Tauxe and E.D. Mintz (2007) 'Cholera: a new homeland in Africa?' *American Journal of Tropical Medicine and Hygiene* 77(4): 705–13.

Garandeau, R., A. Trevett and A. Bastable (2006) 'Chlorination of hand-dug wells in Monrovia', *Waterlines* 24(3): 19–21.

Godfrey, S. (2005) *Cleaning and Disinfecting Wells in Emergencies* [pdf], Geneva: World Health Organization <www.who.int/water_sanitation_health/hygiene/envsan/cleaningwells.pdf> [accessed 21 November 2016].

Godfrey, S., L. McCaffery, A. Obika and M. Becks (2003) 'The effectiveness of point-source chlorination in improving water quality in internally displaced communities in Angola', *Water and Environment Journal* 17(3): 149–51.

Gouveia, C., R. Nicolau, F. Ferreira and A. Camara (2007) 'Collaborative monitoring of chlorine flavours in drinking water', *Water Science and Technology* 55(5): 77–84.

Guevart, E., C. Van Hecke, J. Noeske, J. Solle, A. Bita Fouda and B. Manga (2008) 'Handmade devices for continuous delivery of hypochlorite for well disinfection during the cholera outbreak in Douala, Cameroon (2004)', *Med Trop (Mars)* 68(5): 507–13.

Gupta, S.K. and R.E. Quick (2006) 'Inadequate drinking water quality from tanker trucks following a tsunami disaster, Aceh, Indonesia, June 2005', *Disaster Prevention and Management* 15(1): 213–5.

Gupta, S.K., A. Suantio, A. Gray, E. Widyastuti, N. Jain, R. Rolos, R.M. Hoekstra and R. Quick (2007) 'Factors associated with *E. coli* contamination of household drinking water among tsunami and earthquake survivors, Indonesia', *American Journal of Tropical Medicine and Hygiene* 76(6): 1158–62.

HACH (2016) 'Digital Titrator' [online] <www.hach.com/digital-titrator/product?id=7640447369> [accessed 21 November 2016].

Hoque, B.A. and S. Khanam (undated) *Efficiency and Effectiveness of Point-of-Use Technologies in Emergency Drinking Water: An Evaluation of PUR and Aquatab in Rural Bangladesh*, Dhaka, Bangladesh: Environment & Population Research Centre (available from authors).

Hoque, B.A., M.J. Alam and R.B. Sack (1995) 'Household disinfection of drinking water', *Proceedings of the International Symposium on Assessing and Managing Health Risks from Drinking Water Contamination: Approaches and Applications, September 13, 1994 – September 17, 1994*, Rome, Italy: International Association of Hydrological Sciences.

House, S. and R. Reed (1997) *Emergency Water Sources: Guidelines for Selection and Treatment* [pdf], Loughborough, UK: Water Engineering and Development Centre <http://wedc.lboro.ac.uk/resources/books/Emergency_Water_Sources_-_Complete.pdf> [accessed 21 November 2016].

Hunter, P.R. and G. Nichols (2002) 'Epidemiology and clinical features of cryptosporidium infection in immunocompromised patients', *Clinical Microbiology Reviews* 15(1): 145–54.

IARC (1991) *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Volume 52: Chlorinated Drinking-Water; Chlorination By-Products; Some Other Halogenated Compounds; Cobalt and Cobalt Compounds*, Lyon, France: International Agency for Research on Cancer, World Health Organization.

IARC (1999) *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Volume 73: Some Chemicals that Cause Tumours of the Kidney or Urinary Bladder in Rodents and Some Other Substances*, Lyon, France: International Agency for Research on Cancer, World Health Organization.

Imanishi, M., P.F. Kweza, R.B. Slayton, T. Urayai, O. Ziro, W. Mushayi, M. Francis-Chizororo, L.R. Kuonza, T. Ayers, M.M. Freeman, E. Govore, C. Duri, P. Chonzi, S. Mtapuri-Zinyowera, P. Manangazira, P.H. Kilmarx, E. Mintz and D. Lantagne (2014) 'Household water treatment uptake during a public health response to a large typhoid fever outbreak in Harare, Zimbabwe', *American Journal of Tropical Medicine and Hygiene* 90(5): 945–54 <http://dx.doi.org/10.4269/ajtmh.13-0497>.

IMC (2008) *The Gateway Initiative: Sensitizing Children to Promote Healthy Behaviors and Families*, Santa Monica, CA: International Medical Corps (available from authors).

Iqbal, Q., M. Lubeck-Schricker, E. Wells, M. Wolfe and D. Lantagne (2016) 'Shelf-life of chlorine solutions recommended in Ebola virus disease response', PLoS ONE 11(5): e0156136 <http://dx.doi.org/10.1371/journal.pone.0156136>.

Islam, S., A. Brooks, M.S. Kabir, I.K. Jahid, M. Shafiqul Islam, D. Goswami, G.B. Nair, C. Larson, W. Yukiko and S. Luby (2007) 'Faecal contamination of drinking water sources of Dhaka city during the 2004 flood in Bangladesh and use of disinfectants for water treatment', *Journal of Applied Microbiology* 103(1): 80–7 <http://dx.doi.org/10.1111/j.1365-2672.2006.03234.x>.

JHU and IFRC (2008) *Public Health Guide in Emergencies* [pdf], Baltimore, MD: Johns Hopkins University <www.jhsph.edu/research/centers-and-institutes/center-for-refugee-and-disaster-response/publications_tools/publications/_CRDR_ICRC_Public_Health_Guide_Book/Forward.pdf> [accessed 21 November 2016].

Klorfasil (undated) 'Klorfasil Safe Water Program' [online] <www.klorfasil.org/> [accessed 21 November 2016].

Korich, D.G., J.R. Mead, M.S. Madore, N.A. Sinclair and C.R. Sterling (1990) 'Effects of ozone, chlorine dioxide, chlorine, and monochloramine on *Cryptosporidium parvum* oocyst viability', *Applied and Environmental Microbiology* 56(5): 1423–8.

Kotlarz, N., D. Lantagne, K. Preston and K. Jellison (2009) 'Turbidity and chlorine demand reduction using locally available physical water clarification mechanisms before household chlorination in developing countries', *Journal of Water and Health* 7(3): 497–506 <http://dx.doi.org/10.2166/wh.2009.071>.

Lambert, R. and J. Davis (2002) *Engineering in Emergencies: A Practical Guide for Relief Workers*, 2nd edition, London: ITDG Publishing.

Lamond, E. and J. Kinyanjui (2012) *Cholera Outbreak Guidelines: Preparedness, Prevention and Control* [pdf], Oxfam Great Britain <www.unicef.org/cholera/Annexes/Supporting_Resources/Annex_6B/OXFAM_Cholera_guidelines.pdf> [accessed 21 November 2016].

Lantagne, D. (2008) 'Sodium hypochlorite dosage for household and emergency water treatment', *Journal of the American Water Works Association* 100(8): 106–19.

Lantagne, D. (2009) 'Viability of commercially available bleach for water treatment in developing countries', *American Journal of Public Health* 99(11): 1975–8 <http://dx.doi.org/10.2105/AJPH.2009.160077>.

Lantagne, D. and T. Clasen (2012a) 'Point-of-use water treatment in emergencies', *Waterlines* 31(1-2): 30–52 <http://dx.doi.org/10.3362/1756-3488.2012.005>.

Lantagne, D. and T. Clasen (2012b) 'Use of household water treatment and safe storage methods in acute emergency response: case study results from Nepal, Indonesia, Kenya, and Haiti', *Environmental Science and Technology* 46(20): 11352–60 <http://dx.doi.org/10.1021/es301842u>.

Lantagne, D. and T. Clasen (2013) 'Effective use of household water treatment and safe storage in response to the 2010 Haiti earthquake', *American Journal of Tropical Medicine and Hygiene* 89(3): 426–33 <http://dx.doi.org/10.4269/ajtmh.13-0179>.

Lantagne, D., B.C. Blount, F. Cardinali and R.E. Quick (2008) 'Disinfection by-product formation and mitigation strategies in point-of-use chlorination of turbid and non-turbid waters in western Kenya', *Journal of Water and Health* 6(1): 67–82 <http://dx.doi.org/10.2166/wh.2007.013>.

Lantagne, D., F. Cardinali and B.C. Blount (2010) 'Disinfection by-product formation and mitigation strategies in point-of-use chlorination with sodium dichloroisocyanurate in Tanzania', *American Journal of Tropical Medicine and Hygiene* 83(1): 135–43 <http://dx.doi.org/10.4269/ajtmh.2010.09-0431>.

Lantagne, D., K. Preston, E. Blanton, N. Kotlarz, H. Gezagehn, E. van Dusen, J. Berens and K. Jellison (2011) 'Hypochlorite solution expiry and stability in household water treatment in developing countries', *Journal of Environmental Engineering* 137((2): 131–6 <http://dx.doi.org/10.1061/(ASCE)EE.1943-7870.0000299>.

Lantagne, D., B. Person, N. Smith, A. Mayer, K. Preston, E. Blanton and K. Jellison (2014) 'Emergency water treatment with bleach in the United States: the need to revise EPA recommendations', *Environmental Science and Technology* 48(9): 5093–100 <http://dx.doi.org/10.1021/es405357y>.

Loo, S-L., A.G. Fane, W.B. Krantz and T-T. Lim (2012) 'Emergency water supply: a review of potential technologies and selection criteria', *Water Research* 46(10): 3125–51 <http://dx.doi.org/10.1016/j.watres.2012.03.030>.

Luby, S., M.S. Islam and R. Johnston (2006) 'Chlorine spot treatment of flooded tube wells, an efficacy trial', *Journal of Applied Microbiology* 100(5): 1154–8 <http://dx.doi.org/10.1111/j.1365-2672.2006.02940.x>.

Mackey, E.D., H. Baribeau, G.F. Crozes, I.H. Suffet and P. Piriou (2004) 'Public thresholds for chlorinous flavors in U.S. tap water', *Water Science and Technology* 49(9): 335–40.

McLennan, S., L.A. Peterson and J.B. Rose (2009) 'Comparison of point-of-use technologies for emergency disinfection of sewage-contaminated drinking water', *Antimicrobial Agents & Chemotherapy* 75(22): 7283–6 <http://dx.doi.org/10.1128/AEM.00968-09>.

Marois-Fiset, J-T. and C.C. Dorea (2013) 'Sachet-type point-of-use (POU) water treatment product comparison for emergencies', *2013 36th WEDC International Conference: Delivering Water, Sanitation and Hygiene Services in an Uncertain Environment, July 1, 2013 – July 5, 2013, Nakuru, Kenya*, WEDC.

Marois-Fiset, J-T., A. Carabin, A. Lavoie and C.C. Dorea (2013) 'Effects of temperature and pH on reduction of bacteria in a point-of-use drinking water treatment product for emergency relief', *Applied and Environmental Microbiology* 79(6): 2107–9 <http://dx.doi.org/10.1128/AEM.03696-12>.

Medentech (2015) 'Aquatabs water purification tablets' [online] <http://www.medentech.com/home/industries/water-purification/> [accessed 21 November 2016].

Mérat, P. J. (2015) 'Le chlore en Haïti, la catastrophe annoncée' [online], Port-au-Prince, Haiti: Le Nouvelliste <http://lenouvelliste.com/lenouvelliste/article/140032/Le-chlore-en-Haiti-la-catastrophe-annoncee> [accessed 21 November 2016].

Mintz, E.D., F.M. Reiff and R.V. Tauxe (1995) 'Safe water treatment and storage in the home. A practical new strategy to prevent waterborne disease', *Journal of the American Medical Association* 273(12): 948–53.

Mohamed, H., J. Brown, R.M. Njee, T. Clasen, H.M. Malebo and S. Mbuligwe (2015) 'Point-of-use chlorination of turbid water: results from a field study in Tanzania', *Journal of Water and Health* 13(2): 544 <http://dx.doi.org/10.2166/wh.2014.001>.

Mong, Y., R. Kaiser, D. Ibrahim, Rasoatiana, L. Razafimbololona and R.E. Quick (2001) 'Impact of the safe water system on water quality in cyclone-affected communities in Madagascar', *American Journal of Public Health* 91(10): 1577–9.

MSF (2010) *Public Health Engineering in Precarious Situations* [pdf], Paris, France: Médecins Sans Frontières <http://refbooks.msf.org/msf_docs/en/public_health/public_health_en.pdf> [accessed 21 November 2016].

Murphy, J., E. Cartwright, B. Haenke, T. Ayers, W. Worthington, E. Mintz and D. Lantagne (undated) *Need for Revision of International Guidelines for Bucket Chlorination in Emergencies,* unpublished.

Murray, A. and D. Lantagne (2015) 'Accuracy, precision, usability, and cost of free chlorine residual testing methods', *Journal of Water and Health* 13(1): 79–90 <http://dx.doi.org/10.2166/wh.2014.195>.

Muyibi, S.A. and C.A. Okuofu (1995) 'Coagulation of low turbidity surface waters with *Moringa oleifera* seeds', *International Journal of Environmental Studies* 48(3-4): 263–73 <http://dx.doi.org/10.1080/00207239508710996>.

Null, C. and D. Lantagne (2012) 'Microbiological quality of chlorinated water after storage in ceramic pots', *Journal of Water, Sanitation, and Hygiene for Development* 2(4): 250–3 <http://dx.doi.org/10.2166/washdev.2012.028>.

Ogutu, P., V. Garrett, P. Barasa, S. Ombeki, A. Mwaki and R.E. Quick (2001) 'Seeking safe storage: a comparison of drinking water quality in clay and plastic vessels', *American Journal of Public Health* 91(10): 1610–1.

Oxfam (2001) *Oxfam Guidelines for Water Treatment in Emergencies* [pdf] <http://ec.europa.eu/echo/files/evaluation/watsan2005/annex_files/OXFAM/OXF5-Oxfam guidelines for water treatment in emergencies.PDF> [accessed 21 November 2016].

Oxfam (2006) *Water Quality Analysis in Emergency Situations* [online] <http://policy-practice.oxfam.org.uk/publications/water-quality-analysis-in-emergency-situations-126714> [accessed 21 November 2016].

Patrick, M., D. Berendes, J. Murphy, F. Bertrand, F. Husain and T. Handzel (2013) 'Access to safe water in rural Artibonite, Haiti 16 months after the onset of the cholera epidemic', *American Journal of Tropical Medicine and Hygiene* 89(4): 647–53 <http://dx.doi.org/10.4269/ajtmh.13-0308>.

Peletz, R., T. Mahin, M. Elliott, M. Montgomery and T. Clasen (2013) 'Preventing cryptosporidiosis: the need for safe drinking water', *Bulletin of the World Health Organization* 91(4): 238–8a <http://dx.doi.org/10.2471/BLT.13.119990>.

Pickering, A.J., Y. Crider, N. Amin, V. Bauza, L. Unicomb, J. Davis and S.P. Luby (2015) 'Differences in field effectiveness and adoption between a novel automated chlorination system and household manual chlorination of drinking water in Dhaka, Bangladesh: a randomized controlled trial', *PLoS ONE* 10(3): e0118397 <http://dx.doi.org/10.1371/journal.pone.0118397>.

Piriou, P., E.D. Mackey, I.H. Suffet and A. Bruchet (2004) 'Chlorinous flavor perception in drinking water', *Water Science and Technology* 49(9): 321–8 <http://wst.iwaponline.com/content/49/9/321>.

POUZN (2007) *Best Practices in Social Marketing Safe Water Solution for Household Water Treatment: Lessons Learned from Population Services International Field Programs* [pdf], Bethesda, MD: The Social Marketing Plus for Diarrheal Disease Control: Point-of-Use Water Disinfection and Zinc Treatment (POUZN) Project <http://pdf.usaid.gov/pdf_docs/Pnadi479.pdf> [accessed 25 November 2016].

Preston, K., D. Lantagne, N. Kotlarz and K. Jellison (2010) 'Turbidity and chlorine demand reduction using alum and moringa flocculation before household chlorination in developing countries', *Journal of Water and Health* 8(1): 60–70 <http://dx.doi.org/10.2166/wh.2009.210>.

Ramesh, A., K. Blanchet, J.H.J. Ensink, and B. Roberts (2015) 'Evidence on the effectiveness of water, sanitation, and hygiene (WASH) interventions on health outcomes in humanitarian crises: a systematic review', *PLoS ONE* 10(9): 1–20 <http://dx.doi.org/10.1371/journal.pone.0124688>.

Reller, M.E., Y.J. Mong, R.M. Hoekstra and R.E. Quick (2001) 'Cholera prevention with traditional and novel water treatment methods: an outbreak investigation in Fort-Dauphin, Madagascar', *American Journal of Public Health* 91(10): 1608–10.

Roberts, L., Y. Chartier, O. Chartier, G. Malenga, M. Toole and H. Rodka (2001) 'Keeping clean water clean in a Malawi refugee camp: a randomized intervention trial', *Bulletin of the World Health Organisation* 79(4): 280–7.

Rook, J.J. (1974) 'Formation of haloforms during chlorination of natural waters', *Water Treatment Examination* 23(2): 234–43.

Rowe, A.K. and F.J. Angulo (1998) 'Chlorinating well water with liquid bleach was not an effective water disinfection strategy in Guinea-Bissau', *International Journal of Environmental Health Research* 8(4): 339–40.

Sallon, S., R.J. Deckelbaum, I.I. Schmid, S. Harlap, M. Baras and D.T. Spira (1988) 'Cryptosporidium, malnutrition, and chronic diarrhea in children', *American Journal of Diseases of Children* 142(3): 312–5.

Sengupta, M.E., B. Keraita, A. Olsen, O.K. Boateng, S.M. Thamsborg, G.R. Pálsdóttir and A. Dalsgaard (2012) 'Use of *Moringa oleifera* seed extracts to reduce helminth egg numbers and turbidity in irrigation water', *Water Research* 46(11): 3646–56 <http://dx.doi.org/10.1016/j.watres.2012.04.011>.

Shultz, J., J. Russell and Z. Espinel (2005) 'Epidemiology of tropical cyclones: the dynamics of disaster, disease, and development', *Epidemiologic Reviews* 27(1): 21–35 <http://dx.doi.org/10.1093/epirev/mxi011>.

Souter, P.F., G.D. Cruickshank, M.Z. Tankerville, B.H. Keswick, B.D. Ellis, D.E. Langworthy, K.A. Metz, M.R. Appleby, N. Hamilton, A.L. Jones and J.D. Perry (2003) 'Evaluation of a new water treatment for point-of-use household applications to remove microorganisms and arsenic from drinking water', *Journal of Water and Health* 1(2): 73–84 <http://jwh.iwaponline.com/content/1/2/73>.

SPHERE (2011) *Humanitarian Charter and Minimum Standards in Humanitarian Response* [online], 2nd edition, Geneva: The Sphere Project <www.sphereproject.org> [accessed 21 November 2016].

Taylor, D.L., T.M Kahawita, S. Cairncross, and J.H.J. Ensink (2015) 'The impact of water, sanitation and hygiene interventions to control cholera: a systematic review', *PLoS ONE* 10(8): 1–19 <http://dx.doi.org/10.1371/journal.pone.0135676>.

UNDP (2009) *Handbook on Monitoring and Evaluation For Results* [pdf], New York: United Nations Development Programme <http://web.undp.org/evaluation/handbook/documents/english/pme-handbook.pdf> [accessed 21 November 2016].

UNHCR (2007) *Handbook for Emergencies* [pdf], 3rd edition, Geneva: United Nations High Commissioner for Refugees <http://www.ifrc.org/PageFiles/95884/D.01.03.%20Handbook%20for%20Emergencies_UNHCR.pdf> [accessed 21 November 2016].

UNICEF (2007) *Demonstration Project: Investing in Safe Water for Children - PuR Pilot Application in Vietnam. Final Report to the United States Fund for UNICEF/Procter and Gamble,* Vietnam: UNICEF Viet Nam Water, Environment & Sanitation (WES) Programme (available from authors).

UNICEF (2013) *Cholera Toolkit* [pdf], New York: United Nations Children's Fund <www.unicef.org/cholera/Cholera-Toolkit-2013.pdf> [accessed 21 November 2016].

UNISDR (2006) *2005: Disasters in Numbers* [pdf], Geneva: United Nations International Strategy for Disaster Reduction <www.unisdr.org/files/5401_2005disasterinnumbers.pdf> [accessed 21 November 2016].

Watson, J., M. Gayer and M. Connelly (2007) ‘Epidemics after natural disasters’, *Emerging Infectious Diseases* 13(1): 1–5 <http://dx.doi.org/10.3201/eid1301.060779>.

WHO (2002) *Environmental Health in Emergencies and Disasters: A Practical Guide*, Geneva: World Health Organization <www.who.int/water_sanitation_health/hygiene/emergencies/em2002intro.pdf> [accessed 25 November 2016].

WHO (2004) *Trihalomethanes in Drinking-water* [pdf], Geneva: World Health Organization <www.who.int/water_sanitation_health/dwq/chemicals/THM200605.pdf> [accessed 25 November 2016].

WHO (2005) *Household Water Treatment and Safe Storage Following Emergencies and Disasters* [pdf], Geneva: World Health Organization <www.who.int/household_water/resources/emergencies.pdf> [accessed 21 November 2016].

WHO (2011) *Guidelines for Drinking-water Quality* [pdf], 4th edition, Geneva: World Health Organization <http://apps.who.int/iris/bitstream/10665/44584/1/9789241548151_eng.pdf> [accessed 21 November 2016].

WHO/UNICEF (2012) *A Toolkit for Monitoring and Evaluating Household Water Treatment and Safe Storage Programmes* [pdf], Geneva: World Health Organization, UNICEF <www.who.int/household_water/WHO_UNICEF_HWTS_MonitoringToolkit_2012.pdf> [accessed 21 November 2016].

Wildman, T. (2013) *Technical Guidelines on Water Trucking in Drought Emergencies* [online], Oxfam Technical Briefing Notes, Oxford, UK: Oxfam <http://policy-practice.oxfam.org.uk/publications/technical-guidelines-on-water-trucking-in-drought-emergencies-301794> [accessed 21 November 2016].

Yates, T.M., E. Armitage, L.V. Lehmann, A.J. Branz and D.S. Lantagne (2015) ‘Effectiveness of chlorine dispensers in emergencies: case study results from Haiti, Sierra Leone, Democratic Republic of Congo, and Senegal’, *Environmental Science and Technology* 49(8): 5115–22 <http://dx.doi.org/10.1021/acs.est.5b00309>.