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Improving state-level emergency well disinfection strategies in the United States

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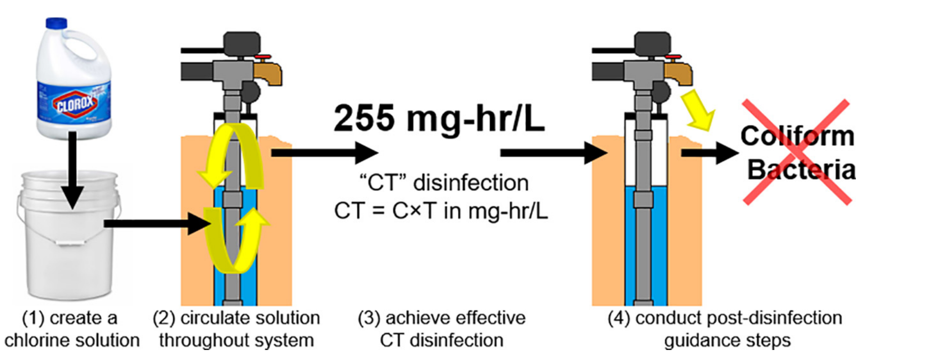
HIGHLIGHTS

- Evidence-based emergency well disinfection protocols are critically needed.
- Of the 8 identified disinfection steps, most protocols (64.5%) included 4–5 steps.
- It is unknown how differences in well water chemistry impact chlorine residuals.
- Research on a chlorine dose for inactivating well water pathogens is needed.

GRAPHICAL ABSTRACT



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ABSTRACT

After flooding events, well users are encouraged to disinfect their private wells. However, well disinfection strategies are not consistently applied or proven effective. This study examines the science-based evidence that disinfection procedures reduce microbial loading in well water; reviews inclusion of disinfection principles in state-level emergency protocols; and explores research gaps potentially hindering disinfection efficacy. Emergency well disinfection protocols from 34 states were reviewed based on instructions for creating chlorine solutions; circulating chlorine solutions throughout the distribution system; achieving effective CT disinfection (chlorine dose*contact time); and post-disinfection guidance. Many protocols were missing key information about fundamentals of disinfection. Only two protocols instructed well users to verify chlorine residuals and three protocols instructed users to measure water pH. Most protocols recommended that high chlorine doses be introduced into the well, circulated throughout the system, and stagnated for several hours. A CT value estimated to inactivate at least 99.9% (3-log removal) of *Cryptosporidium* (255 mg-hr/L) was predicted to be achieved by 72.7% of protocols, and estimated CT values ranged from 35 to 16,327 mg-hr/L. Two research gaps identified were determining whether chlorine doses should differ based on well water chemistries and evaluating the appropriate chlorine dose that should be recommended for inactivating pathogens. This effort underscores a need for consistent, evidence-based messaging in emergency well disinfection protocols.

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1. Introduction

An estimated 1.4 million private wells were impacted by floodwaters during the 2017 and 2018 hurricane seasons (Beitsch, 2018; Price, 2017). Flood-impacted private wells have an increased rate of microbial contamination, underscoring the on-going need for recovery guidance and increased monitoring (Dai et al., 2019; Eccles et al., 2017; Murawski, 2018; Smith, 2002; Van Biersel et al., 2007). However, drinking water supplied by private wells is not regulated at the state or federal level, leaving private well users solely responsible for their water quality (USEPA, 2016). Barriers such as lack of knowledge, risk misperceptions, and costs hinder well stewardship behaviors (Morris et al., 2016), so it is imperative that government agencies and organizations provide residents with effective well water outreach and recovery assistance. This is often challenging due to the limited information and data about these systems (Johnson and Belitz, 2017). Not surprisingly, despite the likely contamination, post-flood water testing rates among well users are low (Beitsch, 2018; Gilliland et al., 2019; Job, 2017).

There are multiple pathways that well water can become contamination by surface sources (Supplemental material; Fig. S1). Improper installation (e.g., lacking sanitary well cap and/or grouting) or deterioration of well components (e.g., cracks in well casing) provide direct pathways and such deficiencies increase the likelihood of microbial contamination (Bickford et al., 1996; Exner and Spalding, 1985). However, construction practices cannot eliminate contamination associated with groundwater, especially in aquifers that are under influence of surface water (e.g., bedrock aquifers) or other contamination sources such as septic systems (Gonzales, 2008; Hynds et al., 2014; Oliphant et al., 2002; Pieper et al., 2016; Swistock and Sharpe, 2005). To reduce microbial contamination, well disinfection (i.e., shock chlorination) is a commonly recommended remediation strategy. During well disinfection, free chlorine is introduced into water, which can be present in the form of hypochlorous acid (HOCl) or hypochlorite ion (OCl^-) depending on water pH (Branz et al., 2017). HOCl dominates below pH 7.5 and is a much stronger disinfectant. Reductions in microbial concentrations are achieved by maintaining a concentration of chlorine-based disinfectants (C) for a specified contact time (T), which is commonly referred to as "CT" disinfection. CT values ($CT = C \times T$ in mg-hr/L) are specified to demonstrate adequate disinfection for organisms of concern (U.S. CDC, 2012).

Although there is widespread use and data on the efficacy of chlorine-based disinfectants, little research has been done to evaluate the efficacy of well disinfection strategies. However, several studies have highlighted that emergency and routine chlorination methods do not always reduce total coliform and *E. coli* bacteria in well systems (Branz et al., 2017; Cavallaro et al., 2011; Garandeau et al., 2006; Luby et al., 2006; Rowe et al., 1998; Swistock and Sharpe, 2005). Since the concentration of chlorine (i.e., the "C" in CT) is assumed to be that of the added disinfection solution, any disappearance of chlorine from the water via chemical reactions would cause disinfection efficacy to be overestimated. For example, reactions with high levels of organic matter, ferrous iron, and manganese in water can cause chlorine to disappear quickly (Cavallaro et al., 2011; Garandeau et al., 2006; Luby et al., 2006; Oliphant et al., 2002). Moreover, there are concerns about well users performing disinfection steps correctly (Eykelbosh, 2013). Lastly, researchers have highlighted the high variability and uncertainty associated with drinking water grab samples. For instance, microbial detection rates are higher when wells are sampled more frequently (Atherholt et al., 2015). Despite these challenges, officials continue to promote well disinfection protocols during both routine and emergency conditions because there are no other practical alternatives.

Building on prior literature and research that has identified procedural gaps in routine chlorination protocols (Eykelbosh, 2013; Smith, 2002) and emergency potable water disinfection protocols (Lantagne et al., 2014), we herein review available state-level emergency well water disinfection protocols in the United States. The objectives of this paper are to: (1) examine the science-based evidence, or the lack thereof, that emergency disinfection procedures reduce waterborne pathogens in well water; (2) review the inclusion of important disinfection steps in state-level emergency disinfection procedures; and (3) explore research gaps potentially hindering the efficacy of these protocols.

2. Methods

2.1. Method for selecting protocols

State-level emergency well disinfection protocols were identified and retrieved using the Google search engine in January 2019. Due to non-standard language related to private wells, the following search terms were used: [state] and ("well water" or "private wells") and ("flooding" or "emergency" or "disinfection" or "chlorination" or "shock chlorination"). If the searches did not produce any disinfection protocols ($n = 2$), the state agencies websites were searched for terms ("well water" or "private wells") and ("flooding" or "emergency" or "disinfection" or "chlorination" or "shock chlorination"). Protocols were deemed emergency disinfection protocols if the title contained terms related to emergencies ($n = 22$), if flooding was listed as a source of contamination in the protocol ($n = 9$), or the protocol was posted on an emergency website ($n = 3$). Seven states only had well disinfection protocols intended for routine use (i.e., not specific to emergency response), of which, 2 states only had their protocols published in the state well regulations. Nine states had protocols that referred to or posted a disinfection protocol written by another state or organization. In total, 34 states (68%) published state-developed emergency protocols were considered in this analysis (Fig. S2).

2.2. Assessment of state protocols

As private wells are not regulated by a federal agency, there is no standard disinfection protocol, resulting in different protocols being recommended by various agencies (e.g., US Environmental Protection Agency [USEPA], U.S. Centers for Disease Control and Prevention [CDC], American Water Works Association [AWWA], National Ground Water Association). We determined that the AWWA Disinfection of Wells protocol (ANSI/AWWA C654-03) was the most comprehensive and science-based well disinfection protocol, as it was developed by drinking water professionals with expertise in water disinfection (American Water Works Association, 2003). However, this protocol focuses on the disinfection of well plumbing (i.e., does not include home plumbing) after constructing, servicing, or performing maintenance (i.e., not emergencies), and was not developed for the general public (i.e., protocol must be purchased from AWWA and includes technical terminology not easily understood by the general public).

Including steps outlined in the AWWA Disinfection of Wells protocol and important disinfection fundamentals, our review focused on four themes of water disinfection (Table 1): (1) *creating a chlorine solution*; (2) *circulating the chlorine solution throughout the distribution system* (i.e., from the well to taps); (3) *achieving effective CT disinfection* (chlorine dose*contact time); and (4) *post-disinfection guidance*. To assess the overall quality of each protocol, we looked for eight steps that are important to the efficacy of disinfection protocols, which are denoted as [theme]-[step]. When creating a chlorine solution, residents should (1-1) target a chlorine volume based on the well characteristics and (1-2) measure the water pH. When introducing the chlorine solution into the well system, residents should first (2-1) pump contaminated water out of the system, and then (2-2) circulate the chlorine solution through both the well and home plumbing systems and (2-3) measure the chlorine residual. This steps should achieve (3-1) a CT value that inactivates *Cryptosporidium* (255 mg-hr/L), which is very resistant to chlorine compared to other pathogens (Shields et al., 2008). After disinfection, (4-1) the chlorine solution should be removed from the well

Table 1
State well disinfection protocol analysis.

Protocol review categories	Protocol measures and classifications	Rationale for consideration in protocol review
Theme 1. Creating a chlorine solution		
Step 1-1.Target a chlorine volume based on well characteristics to add to the well		
Type of chlorine products recommended	Sodium hypochlorite, calcium hypochlorite, or chlorinated lime; Referred to sodium hypochlorite as household or laundry bleach; Described available chlorine concentration; Instructed residents to select unscented and/or no additives disinfectant; Instructed residents to check expiration date	To document the types of chlorine recommended and if protocols instruct residents to select appropriate chlorine products
Calculating the recommended chlorine concentration	Instructed residents to use a fixed-volume of chlorine regardless of volume of water to be treated or instructed residents to target a volume of chlorine based on well characteristics (e.g., depth, diameter); Used a one- or two-step method to determine volume of chlorine when considering well characteristics; Provided tables and/or equations to calculate the volume of chlorine	To determine chlorine dose introduced into the well and evaluate how doses are calculated
Step 1-2. Measuring water pH		
Measuring water pH	Instructed residents to test water pH	[a]To determine if HOCl or OCl^- will be dominate species, which affects CT efficacy
Theme 2. Circulating the chlorine solution throughout the distribution system		
Step 2-1. Pump contaminated water out of the system		
Inspecting well system for damage and purging	Instructed residents to check various parts of the well infrastructure for damage; Instructed residents to run water until it is clear (e.g., free of sediment or debris) before pouring in chlorine solution.	To determine if protocols ensure that the system is working and contaminated floodwater and debris with a chlorine demand are removed
Step 2-2. Circulate the chlorine solution through both the well and home plumbing systems and Step 2-3. Measure the chlorine residual		
Circulating chlorine solution through the plumbing system	Instructed residents to mix chlorine in water before pouring into well; Instructed residents to recirculate chlorine solution in well column before introducing it to the plumbing network (e.g., time length, detectable chlorine smell); Instructed residents to run cold water faucets in the home and for how long; Mentioned bypassing water treatment during circulation; Instructed residents to measure chlorine with at-home test kits	To evaluate if a consistent dose is achieved throughout the well column; to evaluate if chlorinated water is distributed throughout the system; and to determine if protocols confirm target doses were achieved
Theme 3. Achieving effective CT disinfection		
Step 3-1. Achieve a CT value that inactivates *Cryptosporidium*		
Stagnant times recommended	Disinfection time recommended	To document the stagnation times recommended
CT values achieved	CT value calculated based on chlorine concentrations and stagnant times stated in protocols	To determine if protocols achieve adequate CT values for appropriate log-removals of target pathogens
Theme 4. Post-disinfection guidance		
Step 4-1. Chlorine solution should be removed from the well and home plumbing		
Removing chlorine solution from the plumbing system	Instructed residents to flush to remove the chlorine solution; Instructed residents to flush indoor and outdoor taps, starting with outdoor taps; Instructed residents to run water until no longer smelled like chlorine or to use a chlorine test kit	To determine if protocols remove chlorine solution from the system
Step 4-2. Water should be tested for confirmation of microbial reduction		
Validating if disinfection was successful	Stated timeframe for retesting water for microbial contamination; Instructed residents to test for chlorine levels before collecting sample; Suggested re-chlorinating the system	To determine if protocols confirm that disinfection was effective for indicator organisms

[a] HOCl is a stronger oxidant and therefore the preferred disinfectant to maintain during disinfection. HOCl dominates at pH below 7.5.

and home plumbing and (4-2) the water should be tested for confirmation of microbial reduction.

2.3. Deriving a protocol's CT value

For protocols that considered the volume of water within the well column to be disinfected ($n = 22$), CT values were calculated. When multiple chlorine types were listed, sodium hypochlorite was used. If a protocol listed the amount of available chlorine within the product, the percentage was converted to ppm. When available chlorine was not listed or multiple concentrations were listed, 5.25% available chlorine was used. Some protocols ($n = 10$) recommended diluting the chlorine in water before introducing it into the well. When recommended, the volume of water used for dilution was added to the volume of water within the well column, to determine total water volume to be disinfected. When a range of dilution volumes were listed ($n = 5$), the smallest volume was used. When given well casing diameter options, chlorine volumes were calculated for 6 in. well casing, except in one state where the largest drilled well listed was 4 in. Using the dilution equation (concentration*volume), the resulting chlorine concentration was determined for each protocol. CT values were then calculated using the reported time(s) in the protocols.

3. Results

3.1. Overview of state-level disinfection protocols

Emergency well disinfection protocols were found for 43 of the 50 states (86.0%; Fig. S2). For the seven states without an emergency protocol, five of the states had routine disinfection protocols and two states had disinfection protocols in their well construction regulations (Table 2). Nine of the 43 states (20.9%) with emergency protocols directed users to information supplied by other organizations, such as Cooperative Extension and the USEPA. Thus, 34 emergency protocols developed by state agencies were identified. Half of the identified protocols were published from health departments, 15 from environmental departments (44.1%), and the remaining two protocols were by departments who had joint health and environmental responsibilities or as a collaborative effort (5.9%). Protocols were typically available as

Table 2
Summary statistics of state-developed emergency disinfection protocols.

Protocols selected		
Identification of well disinfection protocols (n = 50)		
Emergency protocols	43	86.0%
Protocol developed by state agency	34	79.1%
Protocols developed by other organizations	9	20.9%
Routine protocols	7	14.0%
Standalone routine disinfection protocol	5	71.4%
Published in construction regulations	2	28.6%
Publication characteristics		
Protocol format (n = 34)		
Published as a PDF	30	88.0%
Number of pages (range, median)		1-22; 3
Published on a webpage	4	11.8%
Stated year published	20	58.8%
Range; median		1999-2018; 2016
Referenced resources used for development	3	8.8%
Department that published protocol (n = 34)		
Health department	17	50.0%
Environmental department	15	44.1%
Joint health/environmental departments	2	5.9%
Theme 1. Creating a chlorine solution		
Step 1-1. Target a chlorine volume based on well characteristics to add to the well		
Type of disinfectant (n = 32)		
Listed multiple types of chlorine products to use	12	37.5%
Sodium Hypochlorite	31	96.9%
Described as household or laundry bleach	28	90.3%
Reported available chlorine concentration	17	54.8%
5-6%	12	70.6%
8.25 or 12%	2	11.8%
Multiple concentrations	3	17.6%
Advised to avoid products with additives or scents	18	58.1%
Recommended using a fresh bottle	5	16.1%
Calcium hypochlorite	13	40.6%
Advised to avoid products with additives	5	38.5%
Chlorinated Lime	1	3.1%
Calculating the appropriate chlorine solution (n = 32)		
Recommended a fixed-volume chlorine dose	10	31.3%
Range		0.125-1 gal.; 1 gal.
Recommended a volume-specific chlorine dose	22	68.8%
One-step approach	15	68.2%
Provided a table with chlorine dose based on well depth and diameter	12	80.0%
Provided an equation to calculate the chlorine dose	3	20.0%
Two-step approach	7	31.8%
Provided table(s)	6	85.7%
Provided examples of volume-specific chlorine dose calculations	6	85.7%
Considered static water level	6	27.3%
Step 1-2. Measuring water pH		
Measuring pH of water (n = 33)		
Instructed to test water pH	3	9.4%
Theme 2. Circulating the chlorine solution throughout the distribution system		
Step 2-1. Pump contaminated water out of the system		
Inspect well system for damage (n = 34)		
Instructed to assess the well system	14	41.2%
Instructed to run water until it is clear	18	52.9%
Step 2-2. Circulate the chlorine solution through both the well and home plumbing systems and		
Step 2-3. Measure the chlorine residual		
Circulating throughout the plumbing network (n = 33)		
Instructed to mix chlorine in water before pouring into well	21	63.6%
Instructed to recirculate chlorine solution in well column	27	81.8%
Stated a time for circulation (e.g., duration, detection of odor)	10	37.0%
Recommended circulating based on the smell of chlorine	12	44.4%
Did not specify how long to circulate	3	11.1%
Recommend circulating during the process	1	3.7%
Instructed to run the inside faucets to distribute the chlorine solution	31	93.9%
Instructed to replace and/or bypass water treatment devices	11	33.3%
Mentioned draining and/or chlorinating the water heater	6	18.2%
Testing chlorine residual (n = 32)		
Instructed residents to measure chlorine with at-home test kits	2	6.1%
Theme 3. Achieving effective CT disinfection		
Step 3-1. Achieve a CT value that inactivates *Cryptosporidium*		
Stagnant times recommended (n = 33)		
Provide time recommended	33	100.0%
Recommended a specific time	11	33.3%
Recommended a range of times	22	66.7%
CT values achieved		
CT values calculated (n=22 protocols with 34 CT values)		
Range		35-16,327 mg-hr/L
Median	1,127 mg-hr/L	
% above 255 mg-hr/L using minimum stagnant time	16	72.7%
% above 255 mg-hr/L using maximum stagnant time	19	86.4%
Theme 4. Post-disinfection guidance		
Step 4-1. Chlorine solution should be removed from the well and home plumbing		
Removing chlorine solution from the plumbing system (n = 33)		
Instructed to flush to remove the chlorine solution	31	93.9%
Based on absence of chlorine odor	30	96.8%
Based on using chlorine test kit	1	3.2%
Instructed to flush outdoor taps	18	54.5%
Instructed to flush indoor taps	21	63.6%
Provided time or volume estimate for flushing	10	30.3%
Step 4-2. Water should be tested for confirmation of microbial reduction		
Validating if disinfection was successful (n = 34)		
Recommended follow-up testing after well disinfection	31	91.2%
Following the completion of the chlorination	15	48.4%
Within a few days	7	22.6%
After a week or more	7	22.6%
No timeframe given	2	6.5%
Reconfirm test results	8	25.8%
Used a chlorine test before collecting sample	4	12.9%
Suggested re-chlorination	8	24.2%

standalone documents, with 30 protocols (88.2%) as PDFs, booklets, or brochures. The length of these documents varied from 1 to 22 pages, with a median of 3 pages. Twenty protocols (58.8%) were written between 1999 and 2018 and 14 (41.2%) did not report a publication date.

3.2. Science-based evidence among emergency well disinfection protocols

Of the 8 steps identified, the reviewed protocols contained between 2 and 7 steps (median of 4), and no protocol included all 8 steps (Figs. 1A and S3). Most protocols (64.7%, n = 26) had 4 to 5 disinfection steps. There was no uniformity for which steps were missing, except most protocols recommended removing the chlorine solution from the plumbing network (93.9%; Step 4-1; Fig. 1B) and testing the water to confirm the absence of fecal indicator bacteria (91.2%; Step 4-2). The majority of protocols (52.9%–75.8%) instructed residents to use a volume of chlorine that was based on well characteristics (Step 1-1), perform pre-chlorination flushing (Step 2-1), and circulate chlorinated water through the entire plumbing network (Step 2-2), and would achieve a CT value that would inactivate *Cryptosporidium* (255 mg-hr/L) when considering the volume of water to be disinfected (Step 3-1). Only three protocols mentioned measuring water pH to ensure formation of HOCl (Step 1-2) and two protocols instructed residents to measure chlorine residuals (Step 2-3). Overall, protocols were missing important elements of disinfection fundamentals and methodologies among protocols were inconsistent.

It has been speculated that most well water disinfection protocols were derived from a 1955 Minnesota Department of Health method or the AWWA Standard C654-03 (Smith, 2002). Both are non-emergency well disinfection protocols that address contamination associated with well construction and/or repair. The 1955 protocol recommends using a fixed volume of chlorine (e.g., one quart of chlorine in small diameter wells) (Minnesota Department of Health, 1955), and only includes 1 of 7 steps (Step 2-1, removing contaminated water, was not applicable). Specifically, the protocol recommends circulating the chlorine solution through the well and home plumbing (Step 2-2). Although the protocol also instructs residents to remove the chlorine

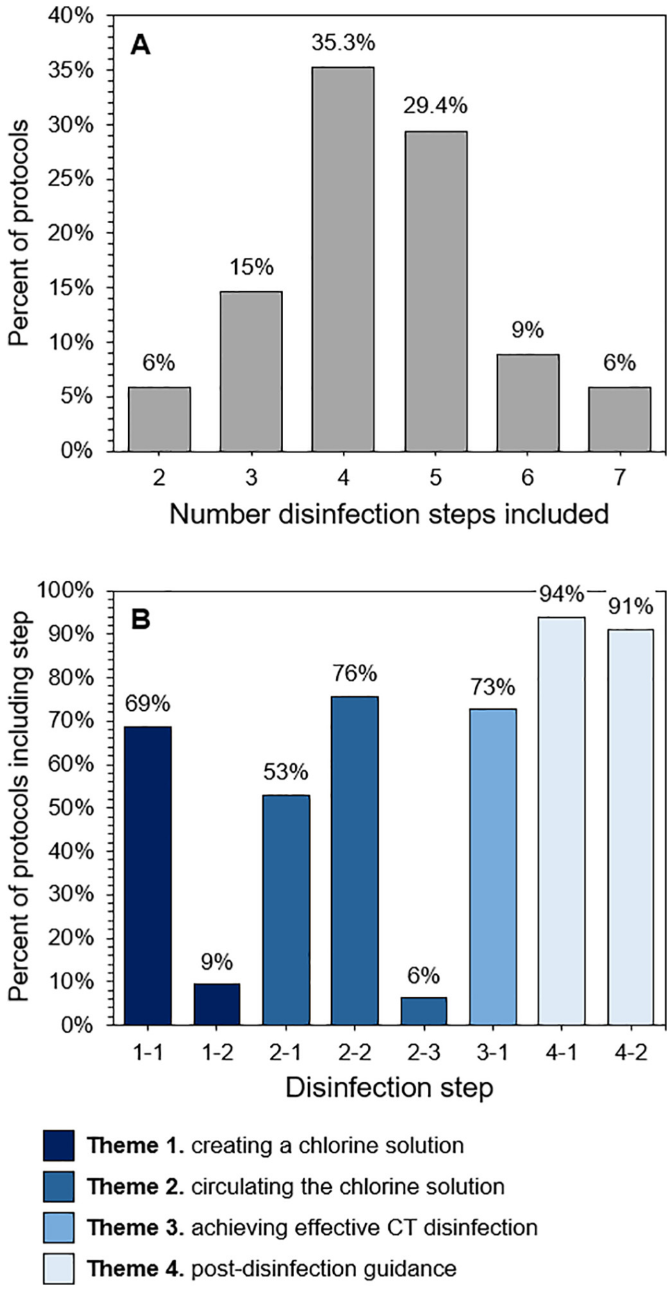

Fig. 1. (A) Percent of the 8 key disinfection steps included in protocols and (B) percent of each disinfection step included in protocols (n = 32). Themes: (1) creating a chlorine solution; (2) circulating the chlorine solution throughout the distribution system (i.e., from the well to taps); (3) achieving effective CT disinfection (chlorine dose*contact time); and (4) post-disinfection guidance. Disinfection steps: (1-1) target a chlorine volume based on well characteristics to add to the well; (1-2) measure the water pH; (2-1) pump contaminated water out of the system; (2-2) circulate the chlorine solution through both the well and home plumbing systems; (2-3) measure the chlorine residual; (3-1) achieve a CT value that inactivates Cryptosporidium (255 mg-hr/L); (4-1) remove the chlorine solution from the well and home plumbing; and (4-2) test water for confirmation of microbial reduction.

solution from the plumbing, it only states "[the chlorinated water] can be discharged to waste" (Step 4-1). The 2005 U.S. EPA protocol "What to Do After the Flood" (U.S. Environmental Protection Agency, 2005) was similar to the 1955 protocol, as it was a fixed volume chlorine approach but included 3 steps (2-1: purging contaminated water, 2-2: circulating chlorine throughout the entire system, and 4-2: post-disinfection testing). In addition, residents are instructed to remove the chlorine solution from the well, but not the home plumbing (Step 4-1). The AWWA protocol was more comprehensive and highlighted potential challenges during the disinfection process (American Water Works Association, 2003). Six of 7 steps were included (Step 2-1 was not applicable); only measuring water pH was missing. Only 3 protocols (8.8%) referenced the scientific source(s) behind the protocols, of which 2 cited AWWA and 1 cited the USEPA. In addition, it appeared that 4 other protocols using a fixed volume chlorine approach were modified versions of USEPA protocol and 3 additional states that were not included in this study directed residents to the USEPA protocol.

3.3. Creating a chlorine solution (theme 1)

3.3.1. Type of chlorine products recommended

Two protocols did not recommend types of chlorine products – one instructed residents to create a chlorine solution but did not provide information on how and the other instructed residents to hire a well contractor to perform the disinfection. Of the other 32 protocols, all but one recommended sodium hypochlorite ($NaOCl$), which 90.3% (n = 28 of 31) described as either "household" or "laundry" bleach. Roughly half (54.8%, n = 17 of 31) reported the amount of available chlorine concentration to purchase, with the majority (70.6%; n = 12 of 17) stating a concentration between 5 and 6%. The other 5 protocols suggested higher concentrations (8.25%, 12%, or 14%) and/or recommended multiple concentrations. There were no instructions on when or why to use household- vs. commercial-strength chlorine or where to purchase commercial-strength products. More than half of the protocols (58.1%; n = 18) advised residents to avoid products with additives or scents and 16.1% (n = 5) recommended using a fresh bottle of chlorine as chlorine decays over time.

Calcium hypochlorite ($Ca(OCl)_2$) was listed as type of chlorine to use in 40.6% (n = 13) protocols. Calcium hypochlorite is commonly used for the disinfection of swimming pools and is available as pellets and granules with 65–70% available chlorine. Only a third of protocols recommending calcium hypochlorite (38.5%; n = 5 of 13) advised residents to avoid products with additives or scents. Chlorinated lime (also known as bleaching powder; $CaOCl_2$) was noted as chlorine type in one protocol. Chlorinated lime is available as a powder or tablets and contains 30% available chlorine. Only one of the 12 protocols recommending 2+ chlorine products described when the different types of chlorine should be used, which was based on the well depth, with a belief that liquid and powdered chlorine would not sink to the bottom of the water column.

3.3.2. Calculating the recommended chlorine concentration

Of the 32 protocols that provided guidance on creating a chlorine solution, 10 protocols (31.3%) recommended using a fixed volume of chlorine regardless of well depth or type. The most commonly recommended volume was 1 gal (6 of 10 protocols) but ranged from 0.125–1 gal. Because the volume of water within wells varies substantially based on system construction, adding a fixed volume of chlorine will result in varying chlorine concentrations. To illustrate, a 30 ft. well water column will contain 166.8 L (44.1 gal) in a 6 in. diameter drilled well and 2669 l (705 gal) in a 2 ft. diameter bored well. Adding 1 gal of 5.25% sodium hypochlorite to the 30 ft. well water column would result in a chlorine concentration of 1135 mg/L in the 6 in. diameter well compared to 70.9 mg/L in a 2 ft. diameter well.

The other 22 protocols (68.8%) considered the volume of water within the well column to be disinfected before determining how much chlorine to add. There were two general approaches to determine the volume of chlorine needed for disinfection (Section S1): (1) determine the volume of chlorine based on the well diameter and well depth (one-step approach), and (2) calculate the volume of water in the well based on diameter and well depth and then calculate the volume of chlorine needed for that estimated water volume (two-step approach). Most protocols (68.2%, n = 15) used a one-step calculation approach. Of which, 12 protocols (80.0%) provided a table with chlorine volumes based on well depth and diameter, and 3 protocols (20%)

provided an equation to calculate the chlorine volume. Seven protocols (31.8%) used the two-step calculation approach. Most of these protocols (6 of 7) provided residents with tables – 1 provided a table to calculate the volume in the well and the other 5 provided tables for both volumes to be calculated. In addition, 6 of the 7 protocols provided examples of the calculations. Interestingly, different equations were used among the protocols (Section S2).

Only 6 protocols of the 22 (27.3%) considered the static water level when determining the chlorine dose (i.e., water level within the well under non-pumping conditions). Not considering static water level will results in an overestimate of the volume of water to be disinfected. For example, a 6 in. diameter well that is 100 ft. deep can contain up to 147 gal of well water. If this well had a 30 ft. static water level (i.e., only 70 ft. of the well column contains water), this well only contains 103 gal of well water (30% overestimation).

3.3.3. Measuring water pH

A target pH of 6.5–7.0 is recommended for disinfecting drinking water, to ensure the formation of HOCl, which is dominant below pH 7.5 and is about 100 times more effective than OCl^{-} (Branz et al., 2017). Only 3 of the 32 protocols (9.4%) mentioned measuring water pH and/or adjusting pH. Two protocols suggested that residents confirm that the pH is not above 7.5 or is between 6 and 7 but did not describe how to measure or lower water pH. The other protocol recommended addition of 3 parts white distilled vinegar to 1 part chlorine. Prior work has shown that vinegar (5% acetic acid) is capable of lowering water pH under laboratory settings (Schnieders, 2001). However, when total coliform bacteria were present after disinfection (i.e., the procedure was not effective), 8 of the 34 protocols (24.2%) stated that the residents re-shock chlorinate the system. Depending on the pH, this would not be as effective as optimizing the pH. Thus, protocols should incorporate at-home solutions that optimize pH, but such solutions must be tested and verified before being communicated to the public.

3.4. Circulating chlorine solution throughout the distribution system (theme 2)

3.4.1. Inspecting well system for damage

Before starting the chlorination process, 41.2% of protocols (n = 14 of 34) instructed residents to check the well for damage. During flooding events, well users have reported damage to their well pump and submersion of their wellhead under floodwaters (Gilliland et al., 2019). If systems are working, residents are recommended to run the water to remove sediment and other debris from the well water column, which was noted in 52.9% (n = 18) protocols. When floodwaters containing organic matter are introduced into the well, the chlorine solution will interact with the organic loading, resulting in a reduction of chlorine residual (Branz et al., 2017). Five protocols stated that flushing the water until clear (i.e., organic loading removed) could take 15 min, several hours, or even a day. However, this will be highly dependent on the volume of water within the well column, which will be based on characteristics such as well diameter, static water level, and well depth.

3.4.2. Circulating chlorine solution through the plumbing system

Almost two thirds of the protocols (63.6%; n = 21 of 33) recommended diluting the chlorine product(s) in a bucket of clean water, to prevent damage to the system when introducing the solution into the well casing (Eykelbosh, 2013). The most common volumes to dilute the chlorine products with were 3–5 gal (n = 10; 47.6%). However, one protocol recommended creating a chlorine solution of at least one well volume to displace all the water within the well column. The majority (81.8%; n = 27 of 33) of protocols recommended in-well circulation (i.e., continuously recirculating the chlorine solution in the well column), but methods were not consistent. Ten protocols stated a time for circulation, 12 recommended circulating based on the smell of chlorine, 3 did not specify how long to circulate, and 1 recommended circulating throughout the chlorination process. As before, the time required will be highly dependent on well characteristics. There was consistent agreement (93.9%, n = 31) that the chlorinated water should be circulated throughout the entire plumbing network (well and house plumbing). All but two protocols instructed residents to run the inside faucets to circulate the chlorine solution in the home plumbing system, but only 11 protocols (33.3%) mentioned replacing and/or bypassing water treatment devices and only 6 protocols mentioned draining and/or chlorinating the water heater, which could pose as a mechanism for recontamination. Protocols relied on the detection of chlorine smell to indicate that there was a sufficient residual at the indoor taps. However, residents have different odor thresholds, rendering detection of a sufficient chlorine residual via sensory assessment problematic (Dietrich, 2006). Only 2 protocols (6.1%) advised residents to use an at-home chlorine kit to measure the chlorine residual in the water.

3.5. Achieving effective CT disinfection (theme 3)

3.5.1. Stagnation times recommended

To derive each protocol's CT value, the chlorine concentration and contact time were identified and/or calculated. As with chlorine concentrations, there was a high degree of variability in contact time. All protocols providing instructions (n = 33) recommended a length of time the chlorinated water should be left in the well, but 11 protocols recommended a specific time (33.3%) while 22 recommended a time range (66.7%). In addition, 8 protocols (24.2%) recommended an “overnight” stagnation period, which was assumed to be 12 h for this analysis but could range from 6 to 18 h depending on when the disinfection is performed. One protocol recommended “several hours”, which was assumed to be 3 h. The contact time reported among protocols varied from 2 to 24 h (median of 12 h). For the 22 protocols with a time range, the minimum and maximum time differed by 4–22 h (median difference of 12 h). Two protocols had multi-step stagnation periods, which outlined a 30-min well water stagnation period followed by an 8-h household plumbing stagnation period.

3.5.2. CT values achieved

Due to discrepancies in chlorine concentrations and contact times, the resulting CT values varied substantially (Fig. 2). The 10 protocols with fixed-volume chlorine volume recommendations were removed from this analysis, as they did not have target chlorine concentrations. In general, a high CT value is recommended for the disinfection of private wells, as it aims to inactivate the most chlorine resistant pathogens (e.g., *Cryptosporidium*). For a 99.9% reduction in *Cryptosporidium*, a CT value of 255 mg-hr/L (i.e., 15,300 mg-min/L) at pH 7.5 at 25 °C is required (Shields et al., 2008). Of the 22 protocols, there were 34 CT values (12 protocols gave a contact time range). CT values ranged from 35 to 16,327 mg-hr/L, with a median of 1127 mg-hr/L. Sixteen protocols (72.7%) outlined methods that would achieve that CT threshold using the minimum contact time to achieve a 3-log reduction of *Cryptosporidium*. Three of the 6 protocols not achieving a calculated CT of 255 mg-hr/L would when using the maximum contact time. More attention to appropriate CT values is needed. While protocols need to achieve disinfection, substantially overshooting target CT values can have unintended consequences such as increased corrosion of plumbing materials and formation of disinfection byproducts (Seiler, 2006; Walker and Newman, 2011).

3.6. Follow-up testing guidance (theme 4)

3.6.1. Removing chlorine solution from the plumbing system

After the recommended stagnation period, most protocols instructed to flush the chlorine solution from the system (n = 31 of 33). Roughly half of the protocols (54.5%, n = 18) recommended flushing outside faucets first, and 36.4% (n = 12) did not recommend flushing the building plumbing networks. Again, 96.8% of protocols (n = 30) recommended flushing until there was no longer a chlorine smell, and only one protocol recommended using a chlorine test kit after flushing. Flushing times will be heavily dependent on system characteristics, and 9 protocols commented on the length of time potentially required and 1 noted a volume to be flushed. However, recommendations were sometimes vague (e.g., "a while", "a long time", "considerable period") or 15 min to several hours.

3.6.2. Validating if disinfection was successful

Most protocols (91.2%, n = 31 of 34) recommended follow-up microbial testing after well disinfection. Roughly half of these protocols (48.4%; n = 15) suggested testing should be done following the completion of the chlorination, while others directed well users to test their well water within a few days (22.6%; n = 7) or after a week or more (22.6%; n = 7). Two protocols did not provide a timeframe. Of the protocols that recommended testing (n = 31), 8 protocols also (25.8%) suggested that users should re-test to confirm bacteria test results. Unlike during the disinfection process, 4 protocols recommended (12.9%) using a chlorine test before sampling to ensure that the chlorine had been removed from the system.

3.7. Gaps in scientific knowledge potentially hindering protocol efficacy

3.7.1. Impact of well water chemistry

Disinfection protocols need to recommend a target chlorine residual, because chlorine levels can be reduced by reactions during the contact time. The instantaneous chlorine demand of the well water includes oxidation of inorganics (e.g., iron and manganese), chemical species (e.g., ammonia), organic carbon, and corrosion of iron pipe. However, we expect the instantaneous chlorine demand of the well water to have a relatively small impact on chlorine reduction. To illustrate, the 90th percentile iron concentration observed in a survey of private wells in Virginia was 0.23 mg/L (Pieper et al., 2015). During a national water quality assessment, ammonia was detected in 5% of groundwater samples with a median of 0.02–0.03 mg/L (Nolan and Stoner, 2000). Overall, these constituents would exert a chlorine demand of <1 mg/L, which is trivial compared to the >50 mg/L doses used. Natural organic matter and debris, which can be introduced to private wells during flooding events, could exert a much larger instantaneous chlorine demand (Branz et al., 2017), and highlights the importance of pre-chlorination flushing to remove such constituents. However, the instantaneous chlorine demand of the plumbing materials (e.g., iron well casing) in private wells remains relatively unexplored and could potentially remove all the chlorine, as has been observed in distribution systems (Haas et al., 2002; Rhoads et al., 2017).

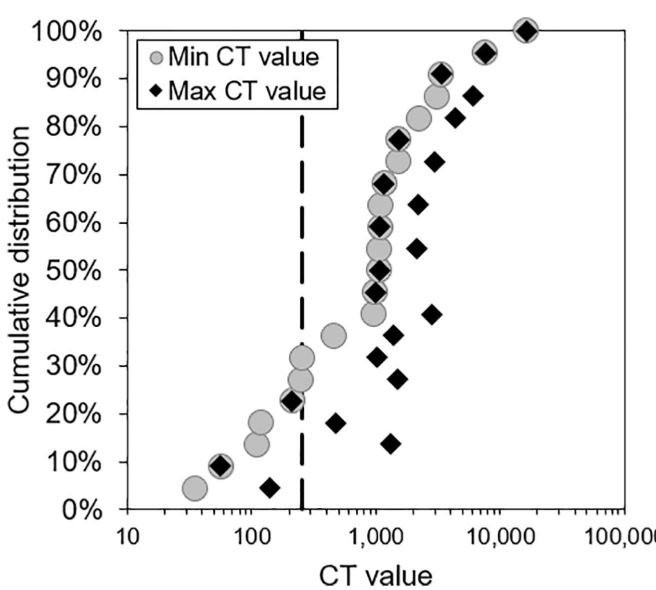

Fig. 2. Estimated CT values for 22 protocols with volume-specific chlorine dose recommendations. Gray circles represent the minimum CT values and black diamonds represent the maximum CT values (based on range of holding times recommended). Only one contact time was recommended (n = 11) when diamonds overlay circles. Black dashed line represents threshold when *Cryptosporidium* would be inactivated (255 mg-hr/L at pH 7.5 at 25 °C).

3.7.2. Evaluating the chlorine dose efficacy for deactivating water pathogens in practice

The CDC has identified 10 microbiological agents that are most commonly associated with disease outbreaks in private wells (U.S. CDC, 2015) that have documented susceptibility to chlorine disinfection (Table S1) (U.S. CDC, 2012). These pathogens can be introduced into private wells through surface water contamination or may be naturally present in groundwater (Brooks et al., 2004; Hynds et al., 2014; Korte et al., 2010; Riffard et al., 2001). Each fecal-based pathogen has a specified target CT for a given target log-removal rate, minimum water temperature, and maximum water pH. For example, 3-log removal of fecal-based bacteria such as *Escherichia coli* (*E. coli*), *Vibrio cholera*, and *Salmonella* all require a CT value <3 mg-hr/L at pH 7.5 and 25 °C while *Cryptosporidium* (fecal-based parasite) requires nearly 100 times here CT of 255 mg-hr/L under the same conditions. However, disinfection of emerging opportunistic pathogens (e.g., *Legionella* spp.) has yet to be adequately studied in detail in homes served by private wells, despite studies documenting their occurrence (Brooks et al., 2004; Dai et al., 2019; Korte et al., 2010; Riffard et al., 2001). These pathogens are different than traditional fecal-derived pathogens because they can be naturally present in environmental aquatic systems, grow in the well and home plumbing systems, and may be more persistent after disinfection because they are shielded from the chlorine by host organisms (e.g., amoebae or biofilm) (Dai et al., 2019; Kilvington and Price, 1990; Kuchta et al., 1993). In addition, shock chlorination may not act as a long-term solution for opportunistic pathogens, as studies have shown they can persist and/or recolonize within weeks after the shock event (Biurrun et al., 1999; García et al., 2008).

4. Discussion

While the best approach to disinfect a private well is often considered to be hiring a well water professional, waiting for such assistance may not be possible in the chaotic aftermath of a disaster and might cause unnecessary human health risks. To illustrate, Hurricane Florence impacted 34 counties in North Carolina (NC) and potentially flooded 351,936 NC private wells (FEMA, 2017; Price, 2017). With 1047 licensed well water professionals in the state (N.C. Department of Natural Resources, 2018), if every professional participated in well water recovery efforts, each professional would be responsible for remediation of an average 336 wells. Assuming 5 wells could be disinfected per day that would take 67 days to disinfect all 351,936 private wells. Moreover, this estimate does not consider the time required to repair damaged private wells and municipal water wells or barriers preventing travel (e.g., block roads) and communication (e.g., power outages). Thus, recommending that residents hire a well water professional for disinfection can be good advice under non-emergency situations and for residents with flood-related damage, but may not be a practical recovery strategy when numerous communities are impacted.

Although there is an appropriate emphasis on brief publications, protocols should be long enough to communicate the science and methodology of the procedures, as it would be helpful if well users had a basic understanding of the underlying disinfection concepts. Organizations should consider using and/or developing disinfection tools, such as online calculators and videos. For example, two organizations have eliminated the need for well users to determine the chlorine volume for dosing and pH optimization calculations by providing online calculators (Ohio Department of Health, 2012; Public Health Ontario, 2019). In addition, information should be provided on measuring water quality parameters throughout the process to ensure appropriate water pH, sufficient chlorine residuals, and absence of contamination after completion. At-home test kits options are available and should be incorporated into disinfection protocols. Although chlorine odor can be used as an indicator in protocols, the detection of chlorine odor will not confirm that a sufficient chlorine residual is present, and the absence of odor is not proof that potentially harmful levels of chlorine have been sufficiently removed – chlorine odor detection thresholds vary based on the water type and the individual (Dietrich, 2006).

To help residents disinfect their own systems, it would be useful to improve educational materials at the state-level. Disinfection protocols should be updated to incorporate the most current disinfection knowledge and science available. The AWWA Standard C654-03 was the most comprehensive protocol well disinfection protocol reviewed, but it only focuses on disinfecting the well plumbing and the target audience was water professionals. Considering its structure along with the key disinfection steps outline in this manuscript, we developed a well disinfection protocol framework for submersible pump systems (Section S3). However, as there have not been improvements in microbial contamination rates in the past decades (Francis et al., 1982), research to better understand the efficacy along with adoption of remediation strategies is imperative.

5. Conclusion

Private well users may not have access to clean, safe drinking water after flooding events, and emergency disinfection protocols are needed to assist in well water recovery. The evaluation of state-level disinfection protocols highlighted similarities and differences in available recommendations and suggests a need for more consistent and vetted messaging. Moreover, research is needed to ensure protocols are resulting in chlorine residuals that appropriate to inactivate water pathogens. Given that well water professionals may not be available immediately after an emergency in sufficient numbers to deal with contamination problems directly, it is important to provide the well community with more evidence-based, research-verified disinfection recovery protocols.

CRediT authorship contribution statement

Kelsey J. Pieper: Conceptualization, Methodology, Data curation, Formal analysis, Writing - original draft, Project administration, Funding acquisition.**William J. Rhoads:**Methodology, Data curation, Formal analysis, Writing - original draft, Funding acquisition.**Leslie Saucier:** Data curation, Formal analysis, Writing - original draft.**Adrienne Katner:**Methodology, Writing - review & editing, Funding acquisition. **Jason R. Barrett:**Conceptualization, Writing - review & editing.**Marc Edwards:**Writing - review & editing, Funding acquisition.

Declaration of competing interest

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

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Appendix A. Supplementary data

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