Field Evaluation of Emergency Well Disinfection for Contamination Events

Final Project Report

National Ground Water Association
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Table of Contents

List of Tables

List of Figures

Acknowledgments

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Stuart Smith is the author of this report and he and Michael Vaught conducted the field work and refined methodologies used and recommended.

Field Evaluation of Emergency Well Disinfection for Contamination Events

Executive Summary

Hurricane Floyd (September 1999) caused extensive flooding in North Carolina and adjacent Atlantic coastal areas. In the flooding, thousands of homes were made uninhabitable and 48 people died. Potential fecal and pathogenic bacterial contamination of wells due to their immersion by floodwaters was identified by state authorities as a significant health risk, consistent with other flooding events. To restore many of the 12,000 affected wells, over 2000 of which showed total coliform positive (potentially unsafe) results, wells were disinfected in the affected areas. However, a significant fraction of wells were still not providing coliform-free water after multiple treatments. Disinfection methods developed for preventive use, or to inactivate bacteria introduced during service or other small-scale contamination may be inadequate in response to flood water inundation. Floodwaters contain very high loads of sediment, debris, and chemical and biological contaminants. Significant depth of immersion can force contaminants into the aquifer formation.

To improve response to such large-scale flooding events in the future, the U.S. Federal Emergency Management Agency (FEMA) identified the need to develop procedures and protocols for emergency well disinfection that it can recommend to state and local emergency management agencies. To develop these plans and recommendations:

1. A literature review of disinfection methods and information relevant to the NC well flooding, and a survey of disinfection providers nationally and local health departments in North Carolina were conducted.
2. A field evaluation of well disinfection methods, involving identification of potential candidate wells in North Carolina affected by Hurricane Floyd in 1999, sampling candidate wells, and testing treatment methods on selected candidate wells was undertaken in spring and summer 2002 in Edgecombe and Pender counties, NC. A sampling of wells representative of those impacted by the flooding (mostly shallow bored wells and shallow-to-deep 2-inch drilled wells) was conducted to obtain area information and to identify candidates for disinfection testing. From this group, a subset of wells representing the population was selected for disinfection testing. These were bored and 2-in. wells in a cluster in Edgecombe County and a cluster of 2-in. wells in Pender County.

Background (Literature Review and Survey)

An extensive literature on well disinfection illustrates that there is abundant advice published on the practice of well disinfection. On the balance, published advice tends to be based on the incidental experience of case histories. No officially published well disinfection procedures discussed any research basis for efficacy. The procedures provided are presented as authoritative, but seem to be simply copied from source to source since the 1950s with little evaluation of efficacy. Recently, work in Illinois and Michigan has addressed this with the first published systematic studies of well disinfection.

The survey helped to narrow the search for wells to the counties that reported actual well effects. It was also informative (and confirming state impressions) that private wells were predominantly affected, and that all classes of wells were involved. Most NC counties reported that multiple treatments were needed to achieve coliform-negative results. However, respondents still expressed confidence in procedures normally used despite multiple failures. Among the regional contractor, national disinfection expert, and health personnel respondents, a wide range of method chemistry and application was reported. On the average, the group reported being experienced (time involved in disinfection weighted toward 10+ years), but apparent knowledge of methods did not necessarily match with our expectations for people with the experience reported.

Testing Phase

Wells in the study areas tested were analyzed for physical-chemical parameters in the field and sampled for analysis of total coliform bacteria and heterotrophic plate count. Wells were also sampled for indicators of microbial ecology that may affect chlorination (culturing by BART Method). Selected wells were tested for organic chemicals (negative results). Profiles of area water quality were established, which were also relevant to disinfection treatment chemistry.

Because of the potential for harm to functioning potable water wells, and the availability of abandoned but unplugged wells on "FEMA buy back" properties in the study areas (in close proximity to tested wells), the field team made the decision to seek to use "FEMA" wells for treatment experimentation. Wells available included shallow bored wells and a deep two-inch well in close proximity to one another in Edgecombe County and two-inch wells in Pender County, also in close proximity to tested wells both with and without reported disinfection problems post-flooding in 1999.

Disinfection methods were designed to 1) incorporate recent recommendations on solution chemistry (maximizing disinfecting hypochlorous acid (HOCl) in solution) but trying both solid and liquid hypochlorite products, 2) test the effects of improved application (brushing dug wells, development and mixing in others) and 3) be achieved with components available off-the-shelf from hardware or home-improvement stores.

Conclusions and Observations

Water quality

The well water quality of shallow sand aquifers could be readily distinguished from more anaerobic and higher-dissolved-solids aquifer water in deeper wells using the physical-chemical methods chosen. Shallow sand water had distinctively lower total dissolved solids and higher redox potential (ORP). Such profiles are useful in identifying the aquifers and hydrogeochemical zones tapped by wells and distinguishing sources tapped by wells in neighborhoods when little other information is available. For example, the information is useful in identifying wells finished in vulnerable aquifers, or wells that will have higher chlorine demand during treatment. Such information is a tool for targeting resources on the most vulnerable or most highly affected areas.

Well TC and other biological results were site-specific. TC results from the reconnaissance phase were generally negative, with positives common for shallow bored wells. The only *E. coli* results were from a bored well in Edgecombe County. After almost three years since the 1999 inundations, surface-derived coliforms may have declined below detection by conventional methods in other wells. However, BART results indicated the presence of bacteria known as "environmental" coliforms (known to be native to aquifers but part of the TC bacteria group) and other heterotrophic bacteria in high numbers in all the tested wells (those used for disinfection testing). The BART profiles suggest that a residual effect of inundation on microbial ecology still persists. Such ecological profiling by BART methods could potentially be an easy-to-use and cost-effective method that is applicable to widespread study of the long-term effects of events such as aquifer inundation, and in designating vulnerable areas. However, additional parallel studies comparing microbial ecology interpretations of BART results with those of other methods should be conducted to better define their benefit in public health monitoring.

Disinfection procedure test results

Disinfection methods selected and tested on both shallow bored wells and 2-inch wells in Edgecombe and Pender counties were generally successful in producing disinfecting conditions despite well faults:

1. It is possible to produce disinfecting conditions in the wells tested. Solutions made and applied achieved disinfecting ORP and chlorine residual levels. Maintaining target total chlorine values in the treated two-inch wells required repeated treatment.
2. Acidification aids in forming optimal disinfecting solutions (favoring HOCl) in ambient well water encountered. This was accomplished with small amounts of acid, and can be done safely by trained personnel. Of the readily available acid choices, dilute acetic acid (e.g., distilled white vinegar) is safer, yet effective.
3. Mixing was required to distribute disinfecting solutions through water columns, echoing recent studies in Illinois and Michigan and other literature, and was achieved in tests.
4. Disinfecting solutions and residual water quality effects can be persistent.
5. $Ca(OCl)_2$, which is more easily stored for long periods (if stored cool and dry), drops to well bottoms better, and is favored by some, but harder to regulate in solution. Mixing in even a little too much makes a solution very "hot." Sodium hypochlorite is easier to use in mixing solutions.
6. The treatment program was conducted successfully using off-the-shelf equipment and solutions, and mimicked the disaster-relief scenario, but expertise and time are required to assemble the proper equipment and solutions, and to apply them to make these procedures work. Disinfection can be temporary if impaired water can return to the well.
7. Well construction and structural faults and aquifer-scale contamination will defeat the effects of effective well disinfection by permitting impaired water to return.

Recommendations

1. Strategically, in the context of coastal NC and similar settings, it may be best to think of emergency well disinfection as first an emergency response task and second as a technical task. That is, specific methodology recommendations are secondary to developing and implementing a Private Water Supply Emergency Response Plan to respond rapidly with equipment and training, and having people available to respond effectively locally. However, technique and solution characteristics are important impacts on treatment effectiveness.
2. Emphasize restoring pump function and pumping wells clear for several bore volumes to several hours (or more if severely affected by dirty water) as a first step, then go to disinfection, as needed, for example if sampling for indicator bacteria indicates contamination is persisting.
3. The involvement of experienced, trained people is also crucial for success. Plan to mobilize professional well service providers to aid in future events, as their equipment and expertise appear to be crucial to success, and develop a mechanism to fund their costs through the recovery period.
4. In preparation for a future large-scale inundation event such as a large hurricane, emphasize prevention, such as through improved well code enforcement, starting now.
5. Baseline data collection prior to and in response to emergencies is recommended as part of the prevention and response process.
6. Specify a standard disinfection procedure that includes clearing the well, injecting a 100-200 mg/L NaOCl solution (acidified to < pH 6) to the bottom of the well, and mixing it throughout the water column. $Ca(OCl)_2$ can be used in initial emergency response.

As such disaster events and need for appropriate response are common events in the United States (and elsewhere in the world), this study's field testing program can be extrapolated to additional well types, and other hydrogeologic, social, and climate settings.

1. Conducting a larger-scale study could provide a statistical-analysis capacity superior to that which could be applied to these tests. The repeatability of experience with stratification and high chlorine demand in narrow (e.g., 2-in.) wells should be assessed.
2. Treatment method suitability for other difficult conditions (great depth, high and very low temperatures, remote locations) should also be assessed.
3. Extrapolation to Developing World situations should be assessed.
4. Training and better market penetration of effective publications (some multilingual) should be reviewed and improved as needed. If the first-response and "trained responder" program were successful in NC, it could be expanded nationally and adapted internationally.

While not specifically based on the findings of this project work, the following are recommended:

1. NC and similar affected states should develop a “trained responder” program that equips and trains people to properly assess and treat wells affected by flooding.
2. Local environmental health personnel would benefit from being trained and equipped to conduct the recommended well reconnaissance and training oversight.

3. Greater cooperation with and involvement of water well contractors (equipped to work on wells) is encouraged.

Preliminary Recommendation for Emergency Well Disinfection

In North Carolina and other states that may be affected by such large-scale events, FEMA should take steps to assure that the recommended well inundation emergency response plan (ERP), including the following provisions, is drafted and its provisions implemented. Begin with planning for a potential event. Include a specific response plan and follow up. The following is a preliminary step-by-step procedure recommendation.

Pre-disaster well restoration planning (involve all applicable departments and agencies):

1) In each county/district of local government environmental health, teams will be trained and equipped to evaluate, help and equip wells as needed to restore private water supply function and potability. The team should include government environmental health staff, private-sector personnel experienced in well and pump service, and other people with specific knowledge of local ground water quality and occurrence, such as hydrogeologists.
2) These teams in turn should train
   a) retail workers, such as those working in hardware stores and home-improvement superstores who work with pumps, plumbing, and chemical selection and
   b) "neighborhood helpers" - those people found in any neighborhood or community who are capable, helpful and competent in fixing things - to safely and effectively assist people with basic pump repair and well disinfection. All such responders must be insured or otherwise protected under state "good Samaritan" provisions to the extent appropriate.
3) Draft and supply simply worded and illustrated fact sheets with detailed recommendations for safe pump function restoration, well flushing, and well disinfection.
4) In support of activities triggered under the local well restoration ERP:
   a) Have wells spotted and located on county GIS plat maps, with a database of essential well characteristics (type, depth, diameter). Make hard-copy and electronic file backups regularly.
   b) Develop profiles of ambient hydrogeological, physical-chemical and microbial ecology baseline conditions for use in recognizing adverse impacts even when indicator parameters such as TC are negative. Include this hydrogeochemical data in the GIS database and as map layers for use by the well ERP team.
   c) The plan should include a well triage strategy for use in the event of an emergency, as follows:
      i) Survey, assess the situation and to formulate a response.
      ii) Accurately mark and bypass 2-in. deep wells with in-line jets, and 2-in. jetted or driven wells, and other wells requiring specific training and equipment to restore.
      iii) Instruct people on how to treat shallow bored wells.
5) Equip response teams with supplies, tools, equipment and information needed to install functional systems on typical installations. Have calcium hypochlorite in stock for initial emergency response, and stocks of other necessary chemicals needed for treatment, rotated

periodically, as well as measurement and dosing equipment with instructions. Maintain well water testing equipment similar to that used in this study as part of triage and follow up.

6) Local environmental health jurisdictions should aggressively work to reduce the number of substandard and unsafe private water supplies vulnerable to flooding inundation.
7) This inspection and response plan should have a regular review and revision cycle with measurable goals set.

During an inundation event:

1. Determine that an emergency exists, assess its magnitude and implement the well restoration ERP elements appropriate to the emergency.
2. Inform the public of appropriate and safe responses and activate the network of certified well responders and professional contractors. Make instructions for disinfection that can be attempted by well owners and contacts for assistance available to affected residents.
3. As soon as it is safe, begin the reconnaissance to determine necessary responses for specific wells and assign them to the appropriate responders. Use the predetermined well designations from disaster-preparedness inspections. Inform residents of the response plan and schedule. Assist them as needed in obtaining potable and wash water. Identify and record problems for follow up.
4. As soon as possible, restore well function and instruct residents to pump wells several hours to clear contamination. Sample for contamination indicators.
5. Implement disinfection as follows when needed.

While disinfection procedures are somewhat specific to the individual well's characteristics, the following are general requirements of emergency disinfection in response to inundation.

1. Restore pump function as needed and pump inundated wells clear for several hours to clear dirt and flood water contaminants. Do not pump flush water through treatment and distribution systems. The time should be determined for local conditions.
2. Treat with a premixed 100 mg/L (ppm) chlorine solution, maximized for hypochlorous acid. People involved must be trained in specific chemical safety and use per detailed instructions. Make sure that the entire well water column is treated. Allow to stand up to 24 hr.
3. Pump clear in an environmentally responsible manner, then treat the water system as recommended or required by the state or local environmental health rules.
4. Follow up with indicator testing, repeat treatment and repair/replacement as indicated.

In follow up to the response to an inundation event:

1. Take steps to replace vulnerable and substandard well water supplies, with specific plans, goals and schedules, developed through consultation with the public, regulatory officials, stakeholders, and funding sources.
2. Review the well restoration ERP and its implementation and make adjustments needed.

Final Project Report: Field Evaluation of Emergency Well Disinfection for Contamination Events

1 Introduction

Hurricane Floyd (September 1999) caused extensive flooding of the coastal areas of North Carolina, South Carolina and Virginia. In the flooding, thousands of homes were made uninhabitable and 48 people died. Wastewater treatment plants, septic tanks, landfills, hazardous waste sites, storage tanks, and animal waste lagoons were flooded, with the pollution amended by the contribution of animal deaths including about 28,000 hogs (Devine, Baran and Sewall, 2002) and an estimated 500,000 turkey and 2 million chicken deaths (U.S. Geological Survey and Wright, 1999). State and federal emergency management and state health agencies identified fecal and pathogenic bacterial contamination of wells due to their immersion by floodwaters as a significant health risk, consistent with other flooding events (e.g., Domyahn, 1994; CDC, 1998). Residents reported oily floodwater residues that, in some cases, repressed the regrowth of grass and other vegetation.

To restore many of the 12,000 affected wells, over 2000 of which showed total coliform positive (unsafe) results (Linda Sewall, NC Department of Public Health, pers. comm.), wells were disinfected in the affected areas. However, results of disinfection attempts were mixed, with a significant fraction of wells not providing coliform-free water after treatment (pers. comm. Mike Vaught, EGIS, P.A., Chapel Hill, NC, from review of county databases). Such results were similar in this regard to the 1993 Midwestern flooding and other large-scale flooding events (e.g., Job, 1994 and accounts provided in this project report's Section 2 literature review and Section 3 survey results). Disinfecting wells after flood inundation, such as experienced with Hurricane Floyd, is potentially a greater challenge than disinfection for preventing purposes or after milder contamination. Flood waters (as described above) contain large loads of sediment, debris, and chemical and biological contaminants, and deep inundation forces such contaminated water into aquifer formations.

The Hurricane Floyd experience is not uncommon in the United States. According to the Federal Emergency Management Agency (FEMA), as cited by Devine, Baran and Sewall (2002), North Carolina has experienced 25 hurricane landfalls in the 1900-1996 period, 11 of them Category 3 or above in intensity. This risk can be expected to continue in the future, with hurricane occurrences depending upon a complex interaction of global and regional climatic factors. Nationally, North Carolina's experience with hurricanes is multiplied by the experience of other hurricane-affected states, and added to by other small- and large-scale flooding occurrences associated with other weather phenomena.

To improve response to such large-scale events in the future, FEMA identified the need to develop procedures and protocols for emergency well disinfection that it can recommend to state and local emergency management agencies. FEMA contracted with the National Ground Water Association (NGWA) to identify and describe methods of disinfection that can be recommended for well disinfection in response to flooding and well inundation in future emergencies. NGWA contracted with Smith-Comeskey Ground Water Science LLC (Ground Water Science), Upper

Sandusky, OH (www.groundwaterscience.com), to manage the project and to develop a project team in North Carolina to conduct field testing (supplied by EGIS, P.A., Chapel Hill, NC), and an evaluation team for peer review. The scope of this specific investigation is drinking water wells in North Carolina and an evaluation of disinfection methods identified and suitable for emergency disinfection of such wells.

For the purpose of clarity, for this project:

1. "Wells" are drilled or bored cased shafts constructed for the purpose of accessing ground water (other dug wells and springs are excluded).
2. "Disinfection" is a procedure intended to reduce indicator (at present: total coliform (TC) bacteria) and pathogenic microorganisms below detectable levels in pumped well water. Holben (2002), as discussed in the Literature Review (Section 2), defines well disinfection as including preparation and physical cleaning as well as chlorination. "Disinfection" is also the objective of a disinfection treatment: Achieving water with indicator bacterial numbers (TC) below detection.

The project included the following steps:

1. Development of a work plan, conducting a literature review of disinfection methods, and conducting a survey of health department personnel in North Carolina, and well disinfection providers regionally and nationally.

2. Conducting a field evaluation of well disinfection methods, involving identification of potential candidate wells in North Carolina affected by Hurricane Floyd in 1999, sampling candidate wells, and testing treatment methods on selected candidate wells.

2 Well Disinfection in Response to Bacterial Contamination: Literature Review

2.1 Introduction

A literature review was conducted to identify and obtain critiques of well disinfection methods potentially available for use in emergency disinfection of wells affected by flooding events. This information was used to develop methods for testing in the field phase of this project, in which wells were treated and tested to determine the effectiveness of treatment methods (Section 5). A secondary but important purpose and result was to identify practical issues that affect how well disinfection is actually carried out in emergency situations, and the efficacy of these treatments.

2.2 Literature Review Method

Search parameters were defined by the Project Technical Lead (PTL) and provided to the NGWA's Ground Water Information Center. These were used to generate literature searches of print literature indexed in the Center's literature database. Records generated were reviewed by the PTL and relevant items selected. Copies of these documents were provided to the PTL, who along with other Ground Water Science personnel, reviewed and summarized them for this review. Where additional potentially useful references were identified by the PTL, copies were requested from the NGWA or from the source. Additionally, the PTL reviewed literature in the Ground Water Science library and other libraries, as identified by Ground Water Science's research librarian.

Additionally, the World Wide Web was searched for official and unofficial sources of information on well disinfection, wells (including standards), and hydrogeology. A standard text search, using the Google.com search engine, was conducted for "well disinfection" ("well" and "disinfection" occurring together). U.S. Geological Survey sources were consulted for information on North Carolina hydrogeology.

2.3 Literature Review Summary

2.3.1 Basic Treatment for Disinfection

"Disinfection" as used here is either the 1) water condition in which the removal or inactivation of bacteria (as tested by a valid total coliform bacteria analysis method) in water samples is below detection of the relevant method or set standard or 2) procedure used in the attempt to achieve the standard. Currently, the total coliform (TC) standard is "absence" in 100 mL using the presence/absence (P/A) enzyme substrate TC test (*Standard Methods* Section 9223, APHA-AWWA-WEF, 1998) or < 1 colony forming units per mL on the TC membrane filtration method (Section 9222). It should be noted that disinfection may not result in a "sterile" condition, in which all bacteria are killed or inactivated, and it may be temporary due to 1) sometimes episodic detachment of TC bacteria (some of which are native aquifer microflora) from biofilms attached in the well (Mansuy, 1999) or 2) reseeding from a source outside the well.

There are various products and procedures for use in disinfection of devices and systems. Among these are treatment with halogens known to disinfect (chlorine, iodine and bromine compounds, hydrogen peroxide, and ozone) and heating, all of which are used in industrial or water supply disinfection. In reviewing information on recommended well disinfection procedures (see the following), only treatment with chlorination is recommended in published procedures for well disinfection. For that reason, the scope of this literature review will be confined to the application of chlorine compounds for disinfection.

Chlorine product choices: There is no unanimity on the type of chlorine to use. Many literature contributors prefer liquid sodium hypochlorite (NaOCl) due to its solubility in water and lack of residual sludge (e.g., Mansuy, 1999; Hanson, 2001; Holben, 2002). However, NaOCl is volatile in solution, with chlorine more easily escaping to the gas phase (and thus not being available for disinfection) compared to solid forms. For this reason, plus portability, others prefer solid (calcium) hypochlorite ($Ca(OCl)_2$). Wise (2001), cites North Carolina State University research that shows that 1) $Ca(OCl)_2$ is more effective in the presence of organic matter for maintaining residual and preventing *E. coli* bacteria and 2) maintains a residual longer (a higher residual at 5 hr than for NaOCl at 15 min.). Wise also notes that some $Ca(OCl)_2$ products have NSF 60 certification. Certified NaOCl products exist for water treatment chlorination, most typically in 12-percent solution form. Disadvantages of $Ca(OCl)_2$ products include lack of solubility and calcium residues in alkaline water and instability (spontaneous combustion potential) if warm and moist (Hanson, 2001; Lifewater Canada, 2001). Gaseous chlorine (Cl_2), commonly used in water treatment, has not been described as being used in well disinfection, except in a well rehabilitation mode (e.g., Alford and Cullimore, 1999), probably due to practical issues of handling the material. The State of Alaska (2001) and Virginia Cooperative Extension (2001) provide (not all-inclusive) lists of disinfectants approved drinking water or well disinfection.

Treatment method components for shock chlorination: Shock chlorination is a short-duration disinfection using a relatively high chlorine concentration, in contrast to typical water treatment chlorination (continuous at low concentration). An early recommendation for shock disinfection chlorination was made by the Minnesota Department of Health (MDH) Division of Environmental Sanitation (e.g., MDH, 1955). It is unclear whether this was the original published disinfection procedure, but the recommendation indicates that the practice was already established by 1955. It includes:

3. Premixing a hypochlorite solution with water
4. Washing the chlorine-water solution into the well to treat the casing
5. Permitting a time for contact (4 hr)
6. Circulation through the attached water system
7. Discharging to waste.

Variations on this basic procedure represent the standard well disinfection method to the present day. While incorporating the basic five steps, various aspects (e.g., contact time, type and method of dose) are modified in other descriptions of the procedure. Among typical modifications are:

3. Circulation in the well prior to contact time
4. Contact time after circulation in the water system

5. Extension of contact time (typically to 12-24 hr)
6. Dosage and premixing.

Most methods for well disinfection are intended for general prophylactic treatment, e.g., chlorination following well service, or treatment when TC bacteria are detected. California Groundwater Association (1995) makes the distinctions among these uses based on practical and regulatory requirements. Pertinent to the scope of the present project are methods specifically for disinfection of wells that have been subject to immersion during flooding. These methods are not identified as being qualitatively different from other well chlorination procedures, except for checking and restoring pumping systems that may be inoperative and clearing debris (which is a major practical issue). California Groundwater Association (1995) recommends that higher chlorine concentrations may be needed and more stringent procedures followed for treating known or suspected contaminated wells.

Table 2.1 is a summary of methods from various literature sources for well disinfection.
Table 2.2 is a summary of methods from official sources in the United States.
Table 2.3 is a summary of methods recommended specifically for immersed wells.

Additional features of the summarized step-by-step procedures

In addition to the disinfection procedure, state and county documents on well disinfection provided advice on how disinfection should be conducted (e.g., by well contractor) and additional follow-up. Procedurally, the consensus was to perform bacteriological testing after a waiting period. Most also recommend repair or replacement of defective well components, and well repair or replacement if unsafe water conditions persist (advice echoed elsewhere in literature concerned with well water quality, e.g., Smith, 1997 and 1999).

Procedures for treatment after flooding events (e.g., MDH, 2001; USEPA, 2001) emphasize inspecting and restoring electrical power and mechanical operation, and cleaning debris from wells. Swanson (1994) is a case history of such an event.

USEPA (2001) cautions that water may not be safe for months after flooding due to malfunctioning septic tanks and chemicals leaching into the ground, emphasizing how regional impacts may play a role in the water quality of individual wells.

Table 2.1. Well disinfection methods summary

Chemicals	1) common household bleach or 2) $Ca(OCl)_2$	NaOCl or $Ca(OCl)_2$	unscented household bleach	NaOCl or $Ca(OCl)_2$	$Ca(OCl)_2$	liquid bleach (NaOCl)	1) NaOCl or 2) $Ca(OCl)_2$	1) NaOCl or 2) $Ca(OCl)_2$
Amounts	1) 8 cups/1000 gal	For $Ca(OCl)_2$, 2 oz. or 4 tsp. in 100 gal. well water	1 qt/100 gal, about 100 ppm	50 mg/L + calculate well volume	4 oz. per 100 ft in 6-in. well (1.5 gal/ft)	1 gal/100 gal water	from provided chart, no ppm stated	250 mg/L (new wells) or 50 for established wells
	2) 1 tsp/2 gal.							
Preparation of solution	mix $Ca(OCl)_2$ with water, sit 30 min.	premix and dissolve $Ca(OCl)_2$	mix in tank, volume = bore volume	increase for higher-pH water	do NOT premix	premix	1) mix in 5 gal. water	premix as needed
							2) mix in 10 gal water	Adjust dose for pH
Application of solution	1) clean the well, removing debris, then 2) flow into well with carrier water	wash solution into well. In artesian wells, lower perforated container to bottom.	pour in well and displace entire well water column.	pour down well	pour in dry, granules sink 100 ft on their own..	pour into well	wash "pump cylinder" with solution, pour into well	Pour NaOCl in well, mix $Ca(OCl)_2$ in 5-gal. bucket then pour in, or place in porous container to lower in.
Mixing in well	pump to recirculate, wash down well casing		displacement and pump to recirculate	surge with pump or recirculate	circulate for 1/2 hour, confirm with OTO(3) kit, flood well with ≥ 100 gal water.	run water back into well 15-20 min.	pump until a Cl odor is recognized	Agitate with pump until chlorine odor detected or agitate container until dissolved.
Contact time			24 hr	> 12 hr	24 hr.	12-24 hr	24 hr	12-24 hr
System dosing	bypass water treatment, drain appliances, refill with Cl water, circulate.		flush until Cl smell is noticed and shut down.	mix through system as needed.	avoid contact with RO and softeners.	run taps until Cl smell is noticed or use OTO kit.		Disinfect pumping system during discharge of chlorine water.
Discharge			Discharge to waste.	Discharge to waste	Discharge 2-3 days.		Discharge to waste	Discharge to waste
Warnings and comments	Cl is hard on rubber diaphragms in pressure tanks		Avoid shrubs and landscaping	Very detailed handling, discharge, ventilation	Avoid shrubs and landscaping			Skin, eye, inhalation hazards, reactivity, avoid plants, animals
Application	repair/preventive	completion, sanitation	unsafe well, contaminated	unsafe well, contaminated	unsafe well, contaminated	repair, preventive	preventive	preventive
Source	Midwest Plan Service, 1979	Campbell and Lehr, 1973	Herrick, 1994	California GW Assn., 1995	Gallup, 1999	AGWT, 1999	Wallace, 2000	Lifewater Canada, 2001

(1) R-OClx = hypochlorite compound; (2) For drilled wells. Dosage of 1 gal per 1000 gal in dug wells; (3) OTO = orthotolidine (Cl + is orange).

Table 2.1, continued

Chemicals	bleach	NaOCl or $Ca(OCl)_2$	NaOCl or $Ca(OCl)_2$	NaOCl or $Ca(OCl)_2$ without additives	$Ca(OCl)_2$ (pellet or granular)	NaOCl	NaOCl	bleaching powder, NaOCl or $Ca(OCl)_2$
Amounts	2 qt of bleach (no concentration stated	50 mg/L, use table to mix	chart of amount per well by size/depth, no concentration stated	50 mg/L (new), 200 mg/L reconstruction (Mn Rules Ch 4725)	1 oz. sanitizer per 100 gal = 50 mg/L, add more for Fe or S water	50-200 mg/L	50-200 mg/L	amounts from chart supplied
Preparation of solution	mix in 10 gal of water (repeat)	increase if high pH or turbid	dissolve $Ca(OCl)_2$ in water	mix chlorine and several gal of water	dissolve $Ca(OCl)_2$ in water	adjust Cl-water solution to pH 5-6	mix vol. 4 X standing, adjust pH to 4.5-5.0, add NaOCl	premix $Ca(OCl)_2$ in bucket of water
Application of solution	pour in well with pump running	repeat as needed	pour chlorine in well, flush with water		pour in well, using pipe		1. pump well 24-48 hr, then tremie in bottom to top	pour into well
Mixing in well	when Cl smell at taps, turn off, recirculate with hose in well 1 hr	circulate until odor of Cl	circulate using hose		circulate 15 min., repeat as needed	conduct well development	develop (surge or swab) 30-60 sec per ft of screen or hole	Agitate
Contact time	12-24 hr	12-24 hr +	12-24 hr	overnight to 24 hr	6 hr to overnight		overnight	12-24 hr
System dosing			flush through system	pump through plumbing system	bypass treatment, circulate			
Discharge	flush away from septic tank, shrubs, flowers until odor gone		flush		flush until clear of Cl odor		surge and evacuate > 20 well volumes	
Warnings and comments		keep out of septic tank	detailed on safety, handling of chemicals, use only plain NaOCl bleach	corrosion of pumps, avoid septic tanks and lawns, pH > 7.5 is adverse	prefers $Ca(OCl)_2$ for organic residue and turbidity, pellets good for well bottom, Cl solution is corrosive	mix NaOCl in acidified water in well ventilated location	mix NaOCl in acidified water in well ventilated location (water pH > 5.0, no Cl gas)	not suitable for humans or animals
Application	general prevention	preventive	unsafe well response	preventive, unsafe response	preventive	unsafe response	unsafe response	preventive
Source	Brady, 2001	Hillblufer, 2001	Ohio State Univ. Extension, 2001	Mn Rural Water Assn. and Mn. Rules 2001	Wise, 2001	Hanson, 2001	Schneiders, 2001	Centre for Ecological Studies, 2001

Table 2.2. Well disinfection procedures from North Carolina and selected other U.S. and Canadian official jurisdictions[1]

Chemicals	standard laundry bleach or other R-OClx[2]	NaOCl	household bleach, unscented	plain laundry bleach, unscented	$Ca(OCl)_2$ tablets or granules	$Ca(OCl)_2$ tablets or granules	Nonscented household bleach
Amounts	1 qt/3 gal of water)[3]	1/2 gal. bleach to 3 gal. water (4 in. 100-ft well), 50 mg/L per MN Rules Chap 4725.5550	amount based on provided chart	determine by well depth and size (table), increase if Fe bacteria present	sufficient to produce 100 mg/L chlorine	sufficient to produce 100 mg/L chlorine	
Preparation of solution	mix $Ca(OCl)_2$ in water in pail	mix in bucket	pump well 30 min. to waste	mix bleach in 5 gal. bucket with water	at least 2 Tsp. dropped in well or 10 gal. of mixed solution of at least 100 mg/L	at least 2 Tsp. dropped in well or 10 gal. of mixed solution of at least 100 mg/L	Pump clear cloudy water
Application of solution	wash solution into casing	pour mixture into well	pour bleach into well, rinsing casing and equipment	pour solution into well	drop in tabs or granules or	tremie solution to bottom or pour in top & wash casing	1) pour in 1 gal NaOCl, run water to wash down
Mixing in well		recirculate with hose about 2 hr	none mentioned	recirculate into casing with hose for at least 15 min, wash casing	Agitate thoroughly: cycle pump or develop with rig	displace entire well volume with 100 mg/L Cl solution	
Contact time	4 hr in well	overnight	24 hr	24 hr +	12 hr	12 hr	6-24 hr
System dosing	circulate for 2+ hours	Isolate critical areas, disinfect, run water to faucets until odor or OTO test +	run in home until Cl odor is noticeable	bypass carbon filters, treat system until odor appears at faucets	If connected, circulate through system	If connected, circulate through system	Circulate through system using cold faucets, bypass treatment
Discharge	Discharge to waste.	flush with garden hose, avoid plants and septic tank	flush outside until odor is gone.	after 24 hr, flush outside until odor is gone, then same inside	If 5 mg/L residual after 12 hr, pump to waste, if less, repeat	If 5 mg/L residual after 12 hr, pump to waste, if less, repeat	flush outside avoiding plants, surface water, septic tank until odor gone
Warnings and comments	Remove well seal or pour in through removable plug	Detailed warnings on electrical, chemical, respiratory safety, when to disinfect.	Avoid septic tank, house and foundation	Use personal protection, chemical safety, do not drink			Personal protection, do not drink Cl water
Application	preventive sanitation	preventive, unsafe response, flooding	unsafe response, flooding	unsafe response, contamination	preventive	unsafe response	preventive, unsafe response
Source	MDH, 1955	MDH, 1999	NC DHHS, 2001	Morgan, 1999	MD Code of Reg. 26.04.04 # 1	MD Code of Reg. 26.04.04 # 2	SC DHEC, 2000

Table 2.2, continued.

Chemicals	household bleach	household bleach, unscented	$Ca(OCl)_2$ or household bleach	$Ca(OCl)_2$ tablets or granules or bleach	$Ca(OCl)_2$ or NaOCl bleach, no additives	household NaOCl bleach without additives or $Ca(OCl)_2$
Amounts	chart: 1 qt per 100 ft, greater if cloudy	chart: 7 gal of solution (below) to 10 ft of well depth (4-in. well), 15 gal/10 ft in 6" well	200 mg/L amount based on provided chart by Cl type	determine by well depth and size (table)	50 mg/L or 200 mg/L shock chlorination, volume by chart provided.	100 mg/L when mixed in well, volume determined by chart provided.
Preparation of solution		mix in 25 gal. new garbage can: 1 pt bleach to 100 parts water (1 qt/25 gal)	mix solution in 5-gal. nonmetallic bucket	Pump clear cloudy water, make 50-ppm solution	mix according to chart provided (1 vol. NaOCl bleach to 10 vol. water)	Mix recommended chlorine compound in at least 45 L (10 Imp. gal) of water ($Ca(OCl)_2$ tablets may be dropped in directly
Application of solution	pour bleach into well	pour mixture into well, rinsing down casing	pour solution into well, rinsing casing and equipment	pour solution into well, allow to settle 30 min.	pour solution into well, avoid contact with pump wire connections	pour into well between drop pipes and casing
Mixing in well	recirculate with hose about 1 hr	recirculate with hose about 5-10 min	recirculate with hose about 1 hr	Surge well to agitate.	Agitate: recirculate with hose 15 min. and cycle pump, contact 2 hr	
Contact time	overnight - 24 hr	24 hr	24 hr	24 hr +	2 hr to overnight	12 hr but < 24 hr
System dosing	run faucets in home until Cl odor is noticeable at each	Open taps until Cl smell is noted at each	Open taps while circulating in well until Cl odor	Open taps at dead ends and far end, test for Cl with test kit	Bypass treatment and circulate through system, turn off, drain water heater	Open faucets and circulate through system until odor is noticed, repeat well treatment
Discharge	Discharge to waste until clear and odor free, repeat as needed.	flush with garden hose, avoid damage	flush outside until odor is gone.	flush outside until odor is gone	after contact, pump to waste, backwash softeners, flush WH and replace filters	flush outside avoiding plants, surface water, septic tank until odor gone, too long in well causes corrosion
Warnings and comments		Make sure hose is connected to system being treated, avoid plants and fish, septic tank or sewer.	Avoid septic tank, streams, lakes, plants; Fe bacteria are more resistant to procedure		Use personal protection, avoid septic tank, lawns, gardens with discharge	Used Cl in ventilated areas, avoiding plants and surface water, safety issues with $Ca(OCl)_2$ including burns, no stabilizer.
Application	unsafe response, contamination	preventive, unsafe response	prevention, unsafe response	prevention, unsafe response, flooding	preventive, flooding	preventive, unsafe response
Source	TX NRCC, 2001	WI DNR, 1996	NE HHS, 2001	Tooele Co. UT DEH, 2001	Dakota Co. MN, 2001	RMEP, Nova Scotia, 2000

(1) Additional ones repeating same procedures were omitted. (2) R-OClx = hypochlorite compound; (3) For drilled wells. Dosage of 1 gal per 1000 gal in dug wells.

Table 2.3. Emergency response procedures for flooded well events.

Prior to treatment(1):	Professionally check electrical system, pump operation, restore as needed, clean the well of debris and pump until clear.	Professionally check electrical system	Pump well to remove as much contaminated water as possible	Clean out well to remove foreign bodies or deposits.
Chemicals	NaOCl bleach or $Ca(OCl)_2$ as permitted	NaOCl bleach or $Ca(OCl)_2$ granules	Laundry bleach	Chlorine bleach (NaOCl)
Amounts	4 gallons (1 gal. bleach + 3 gal. water)	Use chart provided (no dosage provided)		4 L
Preparation of solution	Mix bleach in water.	Mix Cl compound in 10 gal. water, totally dissolve granules		
Application of solution	Pour into well	Pour into well	Apply disinfectant (no procedure supplied)	Pour into well
Mixing in well		Recirculate using hose, wash down casing, 15 min +		
Contact time	24 hr	several hr or overnight		24 hr
System dosing	Run water from all faucets until Cl odor, repeat as needed.	Open all faucets until Cl odor is detected, shut down, cap well	Flush well and water supply lines to remove Cl.	One after another, open all faucets until Cl odor is detected, shut down
Discharge	After 24 hr, turn on faucets until Cl odor is gone, best to bypass septic tank	turn on faucets until Cl odor is gone, best to bypass septic tank		turn on faucets until Cl odor is gone, run outside using a hose to avoid septic tank
Warnings and comments	Best disinfected by a well or pump contractor. Retest after 10 days.	Modified dosage for dug wells.		Do not use flooded well.
Source	USEPA 2001and OnTap, 2000	IL DPH, undated	ND DOH, 2001	DSP, 2000

(1) Procedures in Tables 2.1 and 2.2 assume an operational well or one being put into service.

2.3.2 North Carolina Criteria and Standards for Water Wells

The State of North Carolina has rules governing the siting, construction, repair and abandonment of wells, including water wells (North Carolina Administrative Code: 15A NCAC 02C). Section 15A NCAC 02C.0111 provides requirements for water supply well disinfection as follows:

(1) Chlorination

(a) Chlorine shall be placed in the well in sufficient quantities to produce a chlorine residual of at least 100 ppm in the well. A chlorine solution may be prepared by dissolving high test $Ca(OCl)_2$ (trade names include HTH, Chlor-Tabs, etc.) in water. Do not use stabilized chlorine tablets or hypochlorite products containing fungicides, algaecides, or other disinfectants. Follow manufacturer directions with storing, transporting and using $Ca(OCl)_2$ products. About three ounces of hypochlorite containing 65 percent to 75 percent available chlorine is needed per 100 gallons of water for at least a 100 ppm chlorine residual... [example calculation provided].

(b) The chlorine shall be placed in the well by one of the following or equivalent methods:

(i) Chlorine tablets may be dropped in the top of the well and allowed to settle to the bottom;

(ii) Chlorine solution shall be placed in the bottom of the well by using a bailer or by pouring the solution through the drill rod, hose, or pipe placed in the bottom of the well.

(c) Agitate the water in the well to ensure thorough dispersion of the chlorine.

(d) The well casing, pump column and any other equipment above the water level in the well shall be thoroughly rinsed with the chlorine solution as part of the disinfecting process.

(e) The chlorine solution shall stand in the well for a period of at least 24 hr.

(f) The well shall be pumped until the system is clear of the chlorine solution before the system is placed in use.

(2) Other materials and methods of disinfection, at least as effective as those in Item (1) of this Rule, may be used upon prior approval of the Director.

This procedure is typical of the more thorough of the procedures recommended by state and local authorities.

2.3.3 North Carolina Procedure Comparisons

The procedure in 15A NCAC 02C.0111, which is specified for use after well completion, maintenance, repair or testing, varies somewhat from the procedures recommended by North Carolina sources in response to contamination (NC DHHS, 2001; Morgan, 1999), neither of which references the codified procedure. The latter two procedures specify using NaOCl bleach rather than $Ca(OCl)_2$. The two uncodified procedures specify a 200 mg/L dosage (Morgan, 1999, directly and NC DHHS, 2001, by comparison) while the preventive dosage in the codified procedure is 100 mg/L. The codified procedure specifies 1) agitation and 2) rinsing down above-water components with chlorine, The two other procedures include a rinse-down step but not development (agitation), and both address the water system (including allowance for water treatment systems (Morgan, 1999)), while the codified procedure does not. All use a 24-hr standing period and all include discharging to waste until clear. Table 2.4 is a comparison of the three procedures.

Table 2.4. Comparison of three North Carolina well disinfection procedures

Procedure:	15 NCAC 02C.0111	NC DHHS, 2001	Morgan, 1999
Chemicals:	$Ca(OCl)_2$	unscented NaOCl bleach	plain NaOCl bleach
Dosage:	100 mg/L (ppm)	units per well dimension	200 mg/L (table provided)
Dosing method:	Drop in pellets or make solution and place in well bottom by a positive method	Pump well for 30 min. Pour in bleach, rinse down	
Well agitation:	Yes	No	No
Well rinsing:	Yes	Yes	Yes, including recirculation with hose
Contact time:	24 hr	24 hr	24 hr
Includes water system:	No (specifically a well procedure)	Yes	Yes, and addresses water treatment issues
Safety and environment addressed:	"Follow manufacturer directions," no personal protection (PP) instructions	No PP instructions, (drinking bottled or other disinfected water), avoid chlorinating septic tank	Yes (chemical safety and PP), do not drink chlorinated water.
Test water	Not mentioned	Yes (contact health dept., boil until "safe")	Yes (after a few weeks)

The uncodified procedures may be "at least as effective" as the codified procedure (15A NCAC 02C.0111(2)) but this is unknown at the present time. Among the below-mentioned improvements (see following), the codified procedure includes well agitation, but not pH adjustment. Like the Maryland procedure (MD Code of Reg. 26.04.04), and unlike neighboring South Carolina's (SC DHEC, 2001) and others, the codified procedure does not mention NaOCl products, although they may be approved in practice under 15A NCAC 02C.0111(2).

The existence of (at least) three varying procedures in North Carolina reflects the nonstandardized nature of well disinfection procedures used in the United States and internationally. How this variety impacts disinfection effectiveness in the state is not documented.

2.3.4 Post-Flood Well Disinfection Method Research in Illinois

Among the little systematic research identified concerning well disinfection was work by the Illinois Association of Groundwater Professionals (IAGP) after the 1993 Midwestern floods. This resulted in a series of recommendations in addition to disinfection procedures (IAGP, 1997), which were highlighted in Swanson (1997) and Ross (1998).

The introduction to IAGP (1997) states that preparation of the document was in response to flooding that occurred in the Midwest in 1993 and 1994. That statement suggests that these disinfection procedures are to be applied to a well after it has been inundated by surface floodwaters.

Disinfection of two types of wells was covered in the Illinois work: bored wells (common in Illinois in areas with low-conductivity aquifer materials) and drilled wells. Apparently Illinois has specific procedures for constructing bored wells, and these disinfection procedures are based on a relatively uniform construction. Within the category of bored wells, distinctions are made 1) between wells that have never been disinfected (new construction or simply untreated within memory) and wells on a regular disinfection schedule, and 2) between wells with or without a disinfection tube installed. All procedures emphasize the need to disinfect the entire interior surface area of the well and the gravel pack in the annulus around the concrete tile (casing). All procedures involve

1. pumping the water level down
2. introducing enough chlorine to bring the concentration to 100 ppm
3. allowing the well to recover
4. adding more chlorine to 100 ppm
5. circulating the solution with the pump through the home system (or disinfection tube)
6. adding chlorine solution brought from off site to fill the well nearly to land surface.

Contact time for a bored well being disinfected for the first time is overnight, otherwise contact time totals 3 hours. A note on the disinfection tube: It is a PVC tube from land surface to the buried cement top on the large diameter cement tile (casing). Chlorine solution is pumped down the tube so that it flows over the cement top and down the gravel pack surrounding the casing, thus cleaning the entire length.

Drilled wells are classified as “clean” and “not clean." "Clean" wells are those not having any biofouling (certainly a rare occurrence), while "not clean" wells are those in which biofouling occurs.

Persistence of biofouling can be a factor in repeated coliform-positive samples as discussed elsewhere in this report. The method for removing the biofouling, however, is simply to lift the pitless and pump to waste until clear, reconnect the pitless, and wash down the casing with a garden hose until clear. Based on modern experience with biofouling removal in wells (e.g., Smith, 1995; Mansuy, 1999; Alford and Cullimore, 1999; Ground Water Science, 2001), it is unlikely that the recommended biofouling removal procedure is effective.

Otherwise, drilled wells are treated in a similar manner as bored wells except that there is no expectation of filling the well casing to land surface and letting it stand. In this case, the chlorine solution is circulated with the pump through the home system and the interior of the casing is washed down with chlorine solution using a hose. Total contact time is 3 hours.

The authors of IAGP (1997) note that to successfully circulate chlorine solution throughout the entire well length, the pump must be within 20 ft. of the bottom. If the pump is set too high (>50 ft.), the procedure for circulating requires temporarily setting the pump lower. Presumably pumps set between 20 and 50 ft from the bottom effectively circulate water to a greater or lesser extent. The presence of pump centralizers and torque arrestors is cited as preventing the installation of a tube to the bottom of the well to circulate chlorine solution through.

The contact times recommended are notably shorter than other modern recommendations. Ross (1998) noted that in the IAGP study, the Illinois-recommended disinfection procedure was determined to be effective for restoring drilled wells when properly applied, but disinfection of bored wells was less effective, requiring access to the well's annulus. Statistical data on efficacy, if available, were not included in IAGP (1997).

Other conclusions from the IAGP study (Ross, 1998):

- The average homeowner lacks knowledge and competency to disinfect or maintain a water system.
- Regular maintenance and water sampling tends to prevent serious health risks and major repairs.
- Proper construction is the leading factor in continued water system reliability.
- Relatively extensive (and expensive) disinfection is required after catastrophic flooding events.

2.3.5 Chlorination Treatment Improvement

The procedures summarized in Tables 2.1 to 2.4, and in the highlighted North Carolina and Illinois procedures, vary considerably in how chlorine is applied in the well. The following are recommended improvements on the basic "simple chlorination" (Holben 2002) procedure of:

1. Add chlorine
2. Circulate
3. Contact time
4. Discharge procedure.

Some of these improvements are included in some of the summarized procedures as referenced.

Displacement of the well water column: One possible cause of repeat TC positives (where well faults are ruled out) is that chlorine solution does not reach all the water and surfaces harboring TC bacteria. Displacement is one method used to force chlorine solution through the water column. To achieve displacement of solution in the column:

1. Determine the well column's volume in gallons per foot.
2. Mix Na hypochlorite at 1 qt per 100 gal for 100-ppm solution in a stock solution at the surface.
3. Pour in, displacing water column.
4. Circulate to mix (through system as desired), allow to sit 24 hr.
5. Pump to (safe) waste. (Herrick, 1994).

This procedure is cited in MD Code of Reg. 26.04.04 (State of Maryland).

An alternative is to treat with dry Ca hypochlorite (4 oz. per 100 gal.). Flush with 100 gal. clean water (typical 6-in. well) (Gallup, 1999). Schnieders (2001), based on a recent State of Michigan study, recommends using two to four well volumes and Holben (2002) of the State of Michigan recommends five well casing and screen-gravel pack (combined) volumes and more for fractured limestone and other highly porous formations.

Development: Well development involves a number of methods that induce agitation of the well water column. Methods are described in NGWA (1998). Development removes debris that hide bacteria and is more effective in moving treatment solution into low flow areas, more effectively than displacement flushing, as flushed water goes to the path of least resistance (Hanson, 2001). Hanson also cites the role of thin casing films (in addition to more-obvious biofilms) in hiding coliform bacteria (see also Schnieders, 2001), with development removing these films. Development is included in MD Code of Reg. 26.04.04 (State of Maryland), Tooele Co. UT DEH (2001) and Holben (2002, see following). Methods are described in detail in industry literature on well construction and well rehabilitation (e.g., ADITC, 1997; NGWA, 1998).

Moderating chlorine ion solution: Several procedures mention increasing chlorine dose to compensate for higher pH, iron, or turbidity. Laboratory work cited by Schnieders (2001) indicates that, at least for model wells, doses higher than 500 mg/L chlorine are counterproductive. Hanson (2001) cites a 200 mg/L value as the recommended limit. An apparent mechanism reducing chlorine-contact effectiveness at high Cl dosages is oxidation of biofilm polysaccharides, sealing off coliform bacteria and protecting them against lethal contact with bacteria. Another is the high pH associated with chlorine solutions. Schneiders (2001) recommends 50 to 200 mg/L. This is within the range of reviewed procedures (Tables 2.1-2.4) and included as recommended policy in Holben (2002, see following).

Managing solution pH: Reflecting technical literature on chlorine solution behavior (e.g., Faust and Aly, 1998), Hanson (2001) and Schnieders (2001) describe the improvement in chlorine effectiveness realized by managing pH to maximize the concentration of hypochlorous acid (HOCl) and minimizing hypochlorite ion (OCl^-) solution, which is oxidizing and not effective as a bactericide. In a 50-mg/L solution in pH 7 water, which raises pH to 8, the chlorine present is 15 percent HOCl and 85 % OCl^-. Hanson (2001) recommends maintaining pH at 5 to 6 (100 to 95 % HOCl, according to Schnieders, 2001). Holben (2002) recommends 50 mg/L at pH 6.0-6.5.

2.3.6 An Example State Manual Incorporating Well Disinfection Theory and Practice with Recommendations

The State of Michigan Department of Environmental Quality (DEQ) has developed an On-site Water Supply Disinfection Manual. This manual (Holben, 2002) states: "Disinfection does not simply mean treatment of a water supply with chlorine. Disinfection involves a process of 1) proper water supply system preparation, 2) purging of the water supply 3) treatment with a chlorine solution."

This manual sets several standards for disinfection:

1. (In the case of the State of Michigan) disinfection should be performed by a Michigan registered water well contractor. Well owners may disinfect if they have a working

knowledge of water supply system operation and safety (e.g., avoiding chemical burns and electrocution).
2. Disinfection (in preventive mode) effectiveness is improved by the sanitation of original construction (recommendations are provided).
3. Wells should be developed (new wells) or cleaned (older wells) and flushed prior to disinfection (processes briefly described) to avoid defeat of the treatment by removing debris, mud, contaminants, and encrustations that use up chlorine. Flushing is a Michigan well code requirement (State Well Code Part 127, 1978 PA 368 R 325.1639 Rule 139).
4. Flushing prior to chlorination should remove 20 casing volumes. Sometimes flushing clears up contamination without disinfection.
5. Disinfection is conducted according to Michigan well code requirements (R 325.1661 Rule 161) setting forth concentrations and contact times.
6. Disinfectants to be used are defined with standards set (R 325.1640 Rule 140).
7. Well construction deficiencies (discussed and illustrated) must be corrected in conjunction with the disinfection process.

Such a manual appears to provide the benefit of providing a compact, illustrated, authoritative source for planning and implementing well and water system disinfection.

2.3.7 Scope of Well Contamination Impacts in North Carolina due to Floyd

Devine, Baran and Sewall (2002) supply a summary of the geospatial distribution of wells affected by Hurricane Floyd flooding. This project built a geospatial database of contaminated wells in affected eastern North Carolina counties. Their well population of interest included 2,490 private wells selected from a merged database created from the state Water Sample and Well Construction survey and water quality testing database of results obtained from the state Public Health Laboratory. These were subjected to proximity analysis to determine what relationships may exist (if any) between well contamination and distance from swine operations.

The conclusion of the Devine, Baran, and Sewell report was that immediate proximity to swine farms was not associated with total coliform, *E. coli*, or nitrate contamination. In fact, the positive indicator results frequencies were lower within 0.5 miles of swine operations. However, frequencies were higher at the 0.5 to 2-mile distance. No speculation was made as to what that pattern represents. However, it could reflect nonpoint pollution from manure spreading. The associated maps and data points are being used in the presentation of this current work.

2.3.8 Hydrogeology of the Affected Area in North Carolina

Hydrogeology in relation to well construction and vulnerability

Well construction methods are controlled by hydrogeology. Chlorination effectiveness in response to contamination can vary considerably by well construction type, controlled by hydrogeology, as documented in Illinois. Large diameter bored or dug wells used in low hydraulic-conductivity areas are cited as being very difficult to disinfect (IAGP, 1997; Swanson, 1997; Ross, 1998). Additionally, areas with poor surficial protection between sources of surface contamination and aquifers used may have higher incidents of disinfection failure due to widely contaminated ground water (e.g., Horrick, 1995), as do locations with nearby contamination sources (CDC, 1998).

Well construction deficiencies are statistically associated with both total and fecal coliform occurrence in water samples for both flooding conditions (CDC, 1998) and routine conditions over time (Illinois DPH, 1995). North Carolina has an established well construction code (15A NCAC 02C) that addresses well siting, casing features etc. typically associated with avoiding contamination of individual wells. This code takes into consideration variations in local hydrogeology that affect casing depth (paragraphs .0116 and .0117). Such variations, as well as the quality of installation and flaws in wells constructed prior to the current codes that are now substandard, affect disinfection efficacy. A thorough disinfection to the standards of Holben (2002) or others may be temporary in effect for these reasons.

Hydrogeologic summary

The U.S. Geological Survey's Ground Water Atlas of the United States segment on the Northern Atlantic Coastal Plain aquifer system, HA 730-L (USGS, 2001), including North Carolina, provides an overview of the region's hydrostratigraphic system and its features and influences.

Winner and Coble (1996) is a comprehensive synthesis of previous work conducted in the coastal plain of North Carolina and will provide most of the geologic and hydrogeologic reference for this study. They utilized extensive exploratory work conducted by the North Carolina Department of Natural Resources and Community Development, as well as U.S, Geological Survey investigations and commercial oil and gas exploration records. The acknowledgments and previous studies sections are a valuable resource alone and can fulfill the goals of the hydrogeologic literature review for this study. The result is an authoritative picture of the geology and hydrogeology of the coastal plain.

Winner and Coble (1996) related hydrogeologic units (hydrostratigraphic units) to formal time-stratigraphic units so that correlation outside North Carolina is possible. The text contains a description of each hydrogeologic unit, including estimated recharge rates. Those hydrogeologic units and associated confining units are (from oldest to youngest) the: unnamed lower Cretaceous (overlying preCambrian crystalline basement), Cape Fear Fm., Middendorf Fm., Black Creek Fm., Peedee FM., Beaufort Fm., Castle Hayne Limestone, River Bend Fm., Belgrade Fm., Pungo River Fm., Eastover Fm., Yorktown Fm., and Quaternary surficial aquifer. Of the upper Cretaceous units, the Black Creek and Peedee formations compose a large part of the southern half of the inner coastal plain and the Yorktown is a common Cenozoic aquifer in the northern inner coastal plain (Mike Vaught, personal communication).

Total thickness of the Coastal Plain aquifer ranges from 0 at the fall line to over 10,000 ft. eastward at Cape Hatteras. The sediments fill a depression in the basement that became active 150 million years ago with the opening of the Atlantic Ocean. Both fluvial deposition and marine transgressive-regressive cycles are represented by the sediments. Structure and tectonics in the basement are in part responsible for a complex vertical and lateral unit distribution.

Figure maps supplied in Winner and Coble (1996) illustrate the areal extent of each unit, and which units overlie and underlie each. Each unit is internally complex also. Most of the hydrogeologic units are composed of numerous individual lenticular deposits of limited areal extent that are grouped based on similar heads, chemistry, and response to stresses. In contrast, the Castle Hayne Limestone is the only hydrogeologic/lithologic unit of extensive areal continuity and may present a unique set of conditions relevant to this study in terms of lithology and hydraulic continuity, especially in contrast to the overlying Quaternary surficial aquifer system.

Winner and Coble (1996) plate maps illustrate structure contour, percentage of lithology, chloride concentration, and thickness of the overlying confining unit. The plates are most useful for quick reference to identify units in which wells are completed (based on elevation data), and which units serve as aquifers in an area (based on chloride concentration).

Hydrogeologic sections are presented as plates and contain head data that present a picture of the regional flow system. Head relationships relative to land surface may help identify areas where wells occur under flowing conditions, which may present unique conditions in terms of vulnerability or techniques for disinfection.

Sun (n.d.) also provides an overview of the hydrogeology of the coastal plain from North Carolina to New Jersey. It is a more simplified presentation, because the information was compiled to support a large-scale numerical model of the coastal plain. However, like USGS (2001), for quick reference of units and their relationships, especially relationships outside North Carolina, it is also a useful tool for this study. Lyke and Winner (1990), considering the hydrogeology in the vicinity of Onslow and southern Jones County, is representative of numerous smaller-scale studies that will prove useful as the study area is more closely defined.

2.3.9 Conclusions about the Available Literature

An extensive literature on well disinfection reviewed in this work illustrates that there is abundant advice published on the practice of well disinfection. The IAGP studies and work preceding the drafting of Holben (2002) represent some of the few attempts at systematic studies of well disinfection. Other published advice tends to be based on the incidental experience of case histories. No published (print or online) well disinfection procedures discussed any research basis for efficacy. The procedures provided are presented as authoritative, typically with a reference to contact appropriate authorities. It is presumably in this consultation step that difficulties or poor results are addressed. Otherwise, it appears that advice on well disinfection has simply been copied from source to source since the 1950s with little evaluation of efficacy.

Likewise, the literature on the hydrogeology of North Carolina is extensive. The literature reveals the complex, localized nature of shallow North Carolina hydrogeology.

There are presumably many possible risks associated with contaminated overland flow. Devine, Baran and Sewall (2002) assess one set of relationships between a potential risk (swine farm operations) and well water quality. As these authors point out, determining relationships among wells and between wells and potential problems will require application of more specific local knowledge.

3 Survey Results and Summaries

3.1 Introduction

A survey of well disinfection experience was conducted, using a series of written questionnaires provided to potential respondents as follows:

1. The National Ground Water Association's Master Ground Water Contractor list (about 100 individuals) representing a national list of very experienced well contractors. These were mailed to the list members with a cover letter asking response and a business reply envelope.

2. Environmental health supervisors or specialists in 55 North Carolina counties of interest to the project (designated as being affected). These were mailed to the list members with a cover letter asking response and a business reply envelope.

3. North Carolina ground water contractors: Project team member Mike Vaught asked attendees at the North Carolina Ground Water Association convention to fill out the questionnaire. These were collected and mailed as a group to NGWA. There were 14 respondents.

4. Virginia ground water contractors: Project team member Mike Vaught asked attendees at the Virginia Ground Water Association convention to fill out the questionnaire. These were collected and mailed as a group to NGWA. There were 21 respondents.

5. South Carolina ground water contractors: Project team member Mike Vaught asked attendees at the South Carolina Ground Water Association convention to fill out the questionnaire. These were collected and mailed as a group to NGWA. There were also 21 respondents.

6. Specially selected well contractor and public health list: A selection of 13 well contractors, ground water professionals associated with well service, and public health people who dealt with flooding around the U.S. and Canada known to Ground Water Science team members Stuart Smith (PTL) and Allen Comeskey (other team members were asked to supply names but did not) were sent the questionnaire and a cover letter and stamped addressed envelop for return.

All responses were sent to NGWA, which collected and sent them to the PTL for review. Public health people were also sent a second short questionnaire inquiring about experience with flooding and well disinfection in the Hurricane Floyd aftermath.

Table 3.1 Total responses summary.

MGWC list (100)	31	31 %
North Carolina EHS list (55)	19*	35 %
NC ground water contractors**	14	NA
Virginia ground water convention	21	NA
South Carolina ground water convention**	21	NA
Special list (13)	5	38 %
Total	111	

Table 3.1 Notes:

* *21 respondents sent the accompanying county experience questionnaire.*
** *These include in total 4 who marked "well owner" only and 3 other noncontractors.*

3.2 Results

3.2.1 County Experience Questionnaire

Items are listed by question numbers on the questionnaire. Not all respondents completed all items, so not all responses add up to the respondent total.

1. Respondents:

Environmental Health Supervisors or Coordinators:	11
Environmental Health Specialists:	10
Total:	21

2 through 4. Counties responding: Of the 21 counties responding, 10 reported some impact from Hurricane Floyd flooding, as follows (Table 3.2):

Table 3.2 Responding North Carolina counties

County	Wells affected
Hyde	10
Brunswick (estimated)	800
Duplin	130
Beaufort (estimated)	300
Wake (less than:)	10
Lenoir	89
Pamlico	66
Pitt	200
Nash	700
Craven	199
Total	2,504
Average per affected county	250
Median wells per affected county	165

All of the following were from the ten respondents reporting impacts:

5. Inundation resulted which of the following types of contamination?

Total coliform positives	10 Yes	0 No
Fecal coliform/*E. coli* positives	6 Yes	1 No
Non-coliform enteric (e.g., enterococci) positives	0 Yes	3 No

Most did not test for non-coliform enterics.
6. Identified cause(s) of well inundation was/were (some reporting more than one):

Storm surge: 3 Rising and overflowing stream waters: 9 Overland flooding: 6

7. What types of wells were affected (check as many as apply):

Wells affected were predominantly private water supply, with only 1 public water supply well reportedly affected. Of these, 7 respondents reported sandpoint wells being affected, 4 reported dug (including bored) wells and 9 reported drilled wells as being affected.

8. If you have this information, what aquifer(s) was/were affected?

There was little knowledge of the formation types affected. We automatically assigned those reporting sandpoint or bored wells to the Quaternary. Five respondents reported Castle Hayne (limestone) aquifer influence and one reported deeper aquifer influence (the Yorktown Fm.).

9. In assessing the numbers of treatments needed to achieve total-coliform negative samples, 4 respondents reported only one was needed, five reported an average of 2 to 3 treatments, and one reported requiring more than 3. The weighted average was 2 treatments were required for wells in the responding areas.

10. Two counties reported that water well contractors assisted with disinfection while 7 counties reported that they did not.

As this survey was sent out to counties reported to us as being in the area of interest (affected by the storm), it was useful to have information to narrow the search for wells to the smaller group of counties that reported actual well effects. It was also informative (and confirming state impressions) that private wells were predominantly affected, and that drilled wells were also involved.

The numbers of treatments needed was interesting, especially in light of the confidence that environmental health professionals had in the treatments they use (see following), as it probably reflects problems with the wells affected (see following). From the viewpoint of the National Ground Water Association (NGWA), the low level of reported participation by contractors in the emergency response effort is a result that should be examined further. Comments by well contractors on the methods survey (following) indicate that they view their skills and capabilities as essential to effective well disinfection. Were their skills not needed, not asked for, not volunteered, or refused in the affected areas of North Carolina? If so, in each case, why is that?

3.2.2 Well Disinfection in Response to Contamination Events

This survey was conducted among six distinct groups as described above. Results of the following questions are reported by group (lumping MGWC and "special" respondents) and in total

1. B. Please categorize your expertise in well disinfection:

Table 3.3 Self-description of experience

Category	0-1 years	2-5 years	6-10 years	10+ years
Total group	1	9	10	91
Special + MGWC		0	0	36
VA contractors		2	1	18
NC contractors		4	4	6
SC contractors	1	1	3	16
NC EH people		2	2	15

Average and median reported experience directly with well disinfection was > 10 years in all categories. The respondents who filled out surveys at the state conventions are by definition self-selected. The "special" group was preselected but the MGWC questionnaire was sent to all members of this list. In all, this is a group with significant experience in terms of time.

1. C. How would you describe your level of expertise?

Table 3.4 Self-described level of expertise

Category	Amateur	Good theoretical	Regular practical use	Supervisory	Research
Total group	2	25	75	28	2
Special + MGWC	0	6	29	14	0
VA contractors	1	4	15	2	0
NC contractors	0	4	10	1	0
SC contractors	0	5	13	6	2
NC EH people	1	6	8	5	0

Totals reflect multiple answers for some respondents. The groups' self-perception is that they each have practical experience and some theoretical understanding. The MGWC + Special group (reflecting their experience) reports a higher percentage of supervisory experience (39 % of respondents) than others.

2. Are you aware of specific procedures for use in emergency disinfection of wells (distinguished from preventive or maintenance treatments)?

Table 3.5 Awareness of emergency disinfection methods

Category	Yes	No	Av. Yes
Total group	74	30	68 %
Special + MGWC	24	8	67 %
VA contractors	14	7	67 %
NC contractors	10	4	71 %
SC contractors	14	6	67 %
NC EH people	14	5	74 %

The groups' self-perception is that they are familiar with specific methods for emergency disinfection. This appears to be highest in North Carolina, where there is recent experience with rehabilitating flooded wells.
3. Please identify what of the following are included in the emergency disinfection procedure with which you are familiar (distinguish from preventive well disinfection or water treatment).

A. Chemicals used:

Table 3.6 Chemicals used

Chemicals	Total group	MGWC + Special	VA contractors	NC contractors	SC contractors	EH professionals
Ca hypochlorite	81	31	17	11	13	10
Na hypochlorite	72	31	12	6	10	15
gas chlorine	7	5	1		1	
Peroxide	4	3			1	
Bromine	2	2				
Iodine	3	2				1
Ozone	9	7			1	1
Organic acids	8	6			2	
Mineral acids	17	11	1	2	3	
Surfactants	11	9			2	

The "expert" group appears to have experience with a broader range of chemicals in emergency use. The nonchlorine oxidant responses (bromine, iodine, ozone and peroxide) are somewhat surprising as these were not reported in literature identified in the Literature Review for this purpose, although peroxide is used in well cleaning and bromine and iodine used in emergency drinking water disinfection and ozone in ongoing disinfection. The expert group has the most experience with modifying pH and improving penetration with additives. This group also reflects the ecumenical view of the other groups on hypochlorite type, but also has experience with using gaseous chlorine, probably in municipal settings. The three more local contractor groups do not report a similar level of experimentation with chemicals, except for additives in South Carolina. A significant number of respondents from the more local groups skipped over the chlorine questions.
3.B. How are chemicals applied?

Table 3.7 Chemical application used

Application or modification	Total group	MGWC + Special	VA contractors	NC contractors	SC contractors	EH professionals
Premixed	57	26	7	5	10	9
Applied in well	36	20	3	2	8	3
pH is modified	34	19	1	3	9	2
Hose circulation	50	23	9	4	6	8
Spot applied	29	17	2	3	6	1
Mechanical development	43	24	7	5	6	1

Pump to clear debris	37	18	6	4	7	2
Contact < 6 hr	3	2	0	0	1	0
Contact 6-12 hr	11	9	1	0	1	0
Contact 12-24 hr	29	10	5	3	6	5
Contact 24+hr	32	9	7	3	8	5

Not all respondents completed all items (and some no items) in question 3. The differences among the groups probably illustrate differences in experience and training. Of the 36 "expert" respondents, 19 (53 %) reported experience with pH modification (although only a total of 17 noted use of acids in item 3.A). Among North Carolina contractors, 3 of 14 (21 %) reported experience with pH modification, however 42 % of South Carolina respondents so reported. The expert group reported more experience with more sophisticated preparation (premixing chemicals) and application (specific to screen or zone), development, and prepumping than other groups, including the other contractors. This group was also more likely to report short treatment times (11 or 31 % reporting 12 hr or less to achieve results).

A possible disconnect can be observed in the responses of North Carolina EH people between their self-perception of experience and expertise (experienced and having a good theoretical or supervisory level of experience) and what might be the expertise need. Experienced EH personnel provided minimal response to the questions on chemicals and their application.

3.C. Testing after treatment to determine effectiveness:

Table 3.8 Testing after treatment

Category	Total coliform	Additional bacterial	Additional analyses
Total group	72	27	20
Special + MGWC	34	15	9
VA contractors	8	4	3
NC contractors	6	2	3
SC contractors	13	4	2
NC EH people	13	3	4

Of interest here is that fewer than 100 % of the environmental health respondents (the group responsible for enforcing health regulations) reported total coliform testing after disinfection (some of this group skipped the middle of the questionnaire). The expert group appeared to be highly aware of the need for TC testing, with South Carolina respondents leading the rest.

4. Where chlorine is used, solution concentrations used for emergency disinfection are (mg/L) are:

Table 3.9 Reported solution concentrations

Category	50	100	200	200-500	500-1000	>1000
Total group	15	25	12	14	12	6
Special + MGWC	4	6	7	8	4	4
VA contractors	4	6	3	1	2	0
NC contractors	0	2	0	3	3	0

SC contractors	5	6	1	0	2	1
NC EH people	2	5	2	2	1	2

The expert group reported quite diverse numbers (reflecting their expressed opinion that methods must match the situation, see comments). Virginia and South Carolina contractors report using lighter dosages on average than North Carolina contractors. The amount of very high dosage used suggests that a "more is better" view prevails over published application charts for disinfection (as distinguished from well rehabilitation biofouling treatment). However, some contractors appear to be aware of the message to reduce chlorine amount and to use it better coming from authoritative sources of information (see Literature Review, Section 2).

5. What reference sources do you use or cite for disinfection:

Table 3.10 Disinfection reference sources cited

Sources or references used	Total group	MGWC + Special	VA contractors	NC contractors	SC contractors	EH professional s
Government regulation	71	26	9	7	15	14
Industry or consensus standards	17	12	2	0	3	0
Technical references	38	20	3	5	8	2
Government guidelines	20	5	3	2	3	7
Product literature	16	7	4	1	4	0
Consultant-supplied procedures	19	14	1	0	3	1
Company procedures	37	19	6	5	6	1

It is typical for different groups to have differing biases about sources of information. In this case, the citation of government regulation is naturally high, but not unanimous, even among environmental health professionals (although not all answered the question). The "expert" group appears more diverse in its choice of information sources. The low choice or awareness of technical references among the Virginia and North Carolina contractors should be of interest to the NGWA and purveyors of standards, such as the American Water Works Association. In total, product literature or consultant-supplied procedures (presumably informed by technical standards and experience) were consulted as frequently as standards.

6. In your opinion and experience, in general, are the procedures you know effective on essentially sound wells? The answer to this question was a definite "yes" across all groups (105 respondents choosing "yes" and 1 "no" responses).

Table 3.11 Opinions on disinfection effectiveness

Drilled wells	Yes	No	Av. Yes*	Total respondents
Total group	94	2	87%	106*

Special + MGWC	33	1	92 %	36
VA contractors	15	0	100 %	21
NC contractors	13	0	100 %	14
SC contractors	16	1	76 %	21
NC EH people	17	0	100 %	19

Driven point wells	Yes	No	Av. Yes
Total group	28	11	26 %
Special + MGWC	13	3	36 %
VA contractors	0	0	0
NC contractors	3	2	21 %
SC contractors	4	1	19 %
NC EH people	8	5	42 %
Dug wells	Yes	No	Av. Yes
Total group	25	29	23 %
Special + MGWC	8	13	22 %
VA contractors	8	2	36 %
NC contractors	4	2	28 %
SC contractors	4	2	19 %
NC EH people	3	12	16 %

* "Average yes" percentages are calculated from the total responding number by group (e.g., Special + MGWC = 36) with "total group" referenced to 106 responding to the first question of this group.

The total group was very positive about effectiveness in drilled wells, with a single negative each among the "expert" and South Carolina respondents. The confidence breaks down with driven point wells as fewer reported experience with them, and fewer had positive experiences. Dug wells were not viewed as being as likely to be successfully disinfected, however the Virginia contractors were rather less negative at 36 %, while the environmental health professionals from North Carolina were the most negative, followed by SC contractors and experts, some of the latter having extensive dug well experience (see comments supplied).

7. Under what circumstances do they fail to remove contamination to the relevant state standard?

Table 3.12 Well impediments to disinfection

Well problem	Total group	MGWC + Special	VA contractors	NC contractors	SC contractors	EH professionals
Mechanical fault	82	30	14	12	10	18
Large-scale contamination	46	19	4	9	8	7
Wastewater	26	7	5	3	5	6
Water inundation	17	3	5	4	2	3
Wells in vulnerable spots	43	16	9	5	6	8
Wells not cleared of debris	38	18	7	3	5	6
Other	6	2	2	0	2	0

Mechanical or other faults in wells were strongly chosen as causes by all groups, including the responding environmental health professionals. Vulnerable well location was selected by all the groups at nearly the same rate. The "expert" group also provided a strong response for not clearing wells of debris and large-scale contamination. Among "other" responses were rust or biofouling, fecal matter or flesh in wells, unused and other exposed wells.

8. In your experience or knowledge, what are the weaknesses in the procedures you know about?

Table 3.13 Reported procedure weaknesses

Procedure problems	Total group	MGWC + Special	VA contractors	NC contractors	SC contractor s	EH professionals
Disinfection choice	34	11	5	8	9	1
Inadequate solution mixing	41	14	7	7	7	5
Inadequate mixing in wells	58	19	10	6	11	12
Lack of contact time	60	21	9	5	12	13
Inadequate chlorine concentration	41	13	9	7	7	5
Poor chlorine chemistry	26	13	2	6	4	1
Inconvenience	64	22	11	9	9	13

Across the groups, solution application was judged more important than solution characteristics. The recently reemphasized importance of solution chemistry (specifically pH) was lightly acknowledged. The inconvenience factor (people unwilling to wait long enough or to permit adequate redevelopment) was strongly acknowledged. The Literature Review reveals that referenced procedures are more vague on application than on solution characteristics and chemical choices.

9. In your experience, what well features affect effectiveness of well disinfection?

Table 3.14 well effects on disinfection

Well characteristics	Total group	MGWC + Special	VA contractors	NC contractor s	SC contractors	EH professional s
Type of well (public or private)	36	11	8	3	7	7
Public is better	11	4	0	0	1	6
Private is better	23	8	6	3	6	0
Shallow is better	6	1	1	1	3	0
Deeper is better	37	9	7	5	6	10
Certain formations are better or worse	38	19	4	6	5	4
Construction features	37	13	5	5	5	9

The response to this item was weak. The reversed impressions about public wells vs. private wells between the environmental health professionals and well contractors may be due to biases in training or ideology, rather than actual experience, in some cases. Deeper wells were generally preferred, but shallow wells preferred by a few, notably one-half of the six positives were from South Carolina, probably relating to experience with lack of success in disinfecting deep wells. Formations were also widely acknowledged as an issue, more so by contractors, and construction feature interference also acknowledged by all groups, with strong response from environmental health respondents. Other responses added included "initial development" and "contractor knowledge" (both expert groups).

10. Do you know of procedures that work well for shallow 2-in. sand-point wells?

Table 3.15 Knowledge of procedures effective on 2-in. wells

	Yes	No	Av. Yes
Total group	26	73	25 %
Special + MGWC	14	15	48 %
VA contractors	4	14	22 %
NC contractors	2	12	14 %
SC contractors	6	13	32 %
NC EH people	0	19	0 %

The response in this case was less than positive, and in contrast to the positive response in item 6. People making a distinction may have made it based on the "shallow" distinction, or may reflect simply a contradiction in response. The "expert" group was most positive. North Carolina contractors (with recent experience with large numbers of inundated sand point wells) were more negative. Also interesting is the difference between the North Carolina environmental health response (entirely negative) and some comments (following), which indicate some positive experience.

Suggested actions checked (among 20 yes choices, all contractors) were 17 for circulation, 15 for development, and 10 for precleaning wells among the total. All such responses were from contractor and expert sources.

3.3 Survey Comments

1. Comments on specific survey items:

1. A. "Categorize your well expertise"

Written in: "None, hand out directions as provided by state of N.C." (Q.39 (PH official), 10 yr experience with well disinfection, described expertise as "amateur")

Written in: "I do not actively disinfect wells, I only advise on how to disinfect and sample water from these wells." (Q.19, PH official with 2-5 yr experience)

Other: "Do work on public, private, irrigation, and community wells." (Q.7. MGWC list)

1.B. Several respondents noted experience considerably beyond 10+ years (40+, 50+).

2. Are you aware of specific procedures for use in emergency disinfection of wells?

"I use my county health dept procedure" (Q.12-N, NC well contractor, 10+ years experience).

"The emergencies require much more chlorination, higher concentration and extended follow-up." (Q.6, contractor, disinfection chemical spec, and PH official).

3. Chemicals used:

"High dosages of hypochlorites are required for longer periods of time to effect complete disinfection. Recirculation of chlorinated product (the water) required." (Q.6) (Also noted discussion of additives at Pa. GWC Annual Conference 1/25/02 by John Schneiders.)

3. Chemical dosing and mixing:

"Specific situation dictates the procedures" (Q.21, MGWC list)

"Procedures change per situation." (Q.SC14, SC GWA)

Referring to items in turn: "some-times" and "It is impossible to prescribe a method of well treatment that is applicable to every well condition" and "The methods used should be altered with judgement and based on experience and success" (Q.49, MGWC list)

4. Solution concentrations:

"Variable by situation." (Q.21)

"We find no increase kill level over 1000 ppm." (Q.45, MGWC list)

"Must be determined by well log, well record, water analysis" (Q.49)

5. Sources you cite or use for disinfection

[Referring to state or other government regulations]: "Not always good, in general county health depts are staffed by people from the 16th Century." (Q.37, MGWC with NC experience).

"Need more info from NGWA - more literature." (Q.28, MGWC)

6. Effectiveness on wells by type

B. driven point wells:

"Not in my area." but noted: "I know that sand-point wells are placed in extensive aquifers that are essentially all surface water inundated." (Q.6)

"Most 2 in wells are impossible to disinfect w/o removing the drop pipe assy." (Q.23, MGWC).

C. dug wells:

"Problems reoccur in a short time" (Q.6).

"Nothing effective on dug wells over long term unless constructed to drilled well standards." (Q.14, MGWC)

"To [sic] low water volume (in gpm) to purge" (Q.37)

"Dug wells over 15 + ft tightly sealed on tiles can be good source of water if well is located away from contaminated sources & is sealed at the surface & run off sloped away from well. If specific capacity is great, well has a better chance to hold back contaminants from getting to supply." (Q.52 MGWC)

7. Failures occur when...

"Waste source has to be relocated and entire area cleaned up. (Q.21)

[Referring to "wells have mechanical faults"] "then fix leaks, generally local to well." (Q.43, special contractor list).

[Other:] "If we cannot, for whatever reason, mechanically develop until chlorine demand is met, outcome is not favorable." (Q.42, special contractor list)

[Other:] "If a large quantity of rust or bacteria biofilm is present, mechanical agitation is usually required." (Q.45, MGWC list)

[Other:] "Fecal or dead flesh in the well" (Q.11-V, Virginia well contractor)

[Other:] "Most wells can be cleaned. Contact time is needed more so on the plumbing in the home. Plumbing supplies need to be cleaned after installation." (Q.12-V, Virginia well contractor)

[Other:] "We have very few problems - when problems occur I believe they are related to minerals and Ph." (Q.SC21).

[Other:] "Wells that are unused for long periods of time, wells with no protection from sunlight." (Q.SC6, SC GWA).

See General Comments 5, 7, 8, 9.

8. Weaknesses in procedures:

See general comment 1.

"A chemist put us onto using an acetic acid solution first to break down the biologicals resistance before chlorination and this has proved very effective then a 'shock' of chlorine. Entire inside of casing should be washed down with solution, all pipe and pump equipment and solution worked out into gravel pack and formation." (Q.21).

"Adding too much chlorine. We have been adding too much chlorine for years. We will have better information in a few months." (Q.SC21)

[Referring to "people unwilling to cooperate with inconvenience"]: "!!! County Health Depts." (Q.37).

9. What features affect effectiveness?

"None of these - its the contractors knowledge and efforts i.e., 'elbow grease'." (Q.21).

Referring to the public well versus private well choice: "This does not apply to the question!" (Q.49) [ed note: The intent was to discover what the respondents' perceptions were.] and "A great % of all wells can and should be chemically treated successfully." (Q.49)

Referring to checking that shallow wells are better: "Only better when well is completed sealed (aka) unvented to atmosphere." (Q.SC12, SC GWA).

10. Procedures to help shallow 2-in sand-point wells:

"Backwashing large volumes of water with disinfectant." (Q.7)

[Use all procedures and] "pumping disinf-solution through screen into formation, i.e., injection" (Q.37)

See General Comment 4.

General Comments:

1. (Q.7, MGWC) "Well disinfection has a cost a lot of people are not willing to pay for. A lot of people want a quick, economical solution. That is not always the case. A lot of money is not always the answer, time is. Most people aren't that patient. Disinfection seems to work best if decontamination fluid can be backwashed into the formation and left undisturbed for 24 hours."

2. (Q.16, MGWC list, H. Floyd experience): "Wells that were submerged for 3-7 days during the aftermath of Hurricane Floyd 11/99 - took in large quantities of contaminated floodwater - in some cases wells were allowed to pump open discharge for 10-14 days before clearing and several chlorinations were necessary to produce satisfactory water samples. In 2 cases, we resorted to UV disinfection systems and found that 3-4 months later raw water samples showed that they were no longer needed. In one case we displaced total volume of well 4-5 times with premixed 200 ppm chlorine/water mix - results satisfactory water samples 3 days after procedure."

3. (Q.19, local PH official). "All wells in our county are in sandy soils, shallow, and usually only show contamination after a flooding event such as storm surge. We had little flooding due to Hurricane Floyd in areas where well point numbers are high. For our wells, 1 gallon of bleach (5.25 % sodium hypochlorite) poured into well point then distributed throughout the entire system and allowed to sit for at least 24 hrs almost always solves the problem!"

4. (Q.33, MGWC). "In some cases well will require casing scrubbing/swabbing - the removal of all foreign debris from well. Then pump well to waste for extended period. Then place disinfecting product into well with enough volume to get back into the affected formation in aquifier & contact entire well may require starting placement of disinfectant at bottom of well continuing placement while extracting tremie line entire length of well and adding more disinfectant at top of well." [ed. note: misspellings/sentence structure preserved - however this should not be considered a bad reflection on a sensible procedure.]

5. (Q.20, PH official, 10+ years experience). "Properly drilled & grouted wells seem to be better protected from contamination than 'washed down' wells. Wells 'cut off' underground seem better protected from contamination by flooding from tidal surge (average 6 hr inundation)." [ed note: "?" added before last statement, probably indicating "counterintuitive".]

6. (Q.37, MGWC from NC). "1. Some state regs preclude proper disinfecting - 2. Most county health dept. people are ignorant of state regs, proper chemistry, and methodology. North Carolina!!!"

7. (Q.10, PH official). "Our state needs mandatory well regulations."

8. (Q.17, PH official). "99 % of new wells installed are 2-in >60% have TC+ results after 1st chlorination."

9. (Q.22, MGWC). "Design well to prevent flooding. that is, water seals, flowing pitless spools - snorkles, code wells."

10. (Q.43, special list, Washington state). "too often we don't identify the problem before we go to work. There may have been prior unnoticed problems but after the flooding now compromise often used methods to reclaim a flooded well. technology, chemistry + products are improving. to bypass diagnostic procedures to say 'one size fits all' is the best way I know to get bit with failure." [ed note: "Diagnose and fix problems or failure likely."]

11. (Q.44, special list, Illinois). "In the summer of 95, our area was hit with a 17" rain in less than 24 hours. There were numerous wells that were immersed. There were almost as many methods for disinfecting these wells as there were wells immersed. The only fail-safe method was to thoroughly flush the well - pump open discharge for at least 24 hours. After the well was flushed, chlorine was added to the well as water was circulated in the well. The well was flushed again. The chlorine was added again to the well and pumped into the house. The house was flushed. The water system was disinfected.

"The above procedure worked every time. The only time the procedure has not worked is when the well is defective or the formation is contaminated.

"Without flushing the well, the water system was very seldom disinfected. Those water systems that were disinfected by other procedures usually were disinfected after several attempts. The several attempts were actually disinfecting the system. There was one well that was 120' deep that the people dumped in 15 gallons of 15% sodium hypochlorite. The system was not disinfected until the pump was lowered to the bottom of the well and the well flushed. All the chlorine was at the bottom."

12. (Q.46, PH person): Submitted copy of Alamance County, NC's well disinfection procedure.

13. (Q.50, PH person): "We have many wells that the locals call 'a point and a joint.' These are shallow wells that are either driven or washed into the sand. They are normally 1-1/4" pipe without a casing, grout and they may or may not have a well seal. These wells are easily compromised. Most have never been chlorinated. I'll include a copy of the paper that we provide the public to chlorinate a well [ed note: this was attached]. (see notes at top.) We also have handouts to inform the public what to do to the water if they think it has been contaminated and they must drink the water."

Enclosed with Q.50 (these are supplied with this report as attachments): 1) Private Water Supply Sampling and Information Protocol Following Disasters, 2) How to Chlorinate a Well (Craven County Health Department

14. (Q.1-V, Virginia well contractor): "Have 51 years in well drilling, own my own company for 41 years. Most of my work has been in the larger rotary gravel pack well for city-towns and industrial plant."

15. (Q.2-V): "Proper construction & proper amounts of clorene is adequet. To much of a good thing is not."

16. (Q.20-V): "When drilling, sand, tools, pit, everything is chlorinated, and after developing well, chlorine is injected into well casing and stand for min. of 24 hr."

17. (Q.SC14): "No one procedure is the right one. There are several good methods. Most effective for problematic wells is Ph control - <u>Shock</u> methods do not always work!!!"

18. (Q.48, special list, Richard Van Gilder): Mr. Van Gilder, who has considerable experience with emergency well disinfection, cleaning and repair after the 1993 Midwestern flooding (see Swanson, 1994 in the Literature Review) enclosed extensive and useful comments and procedure commentary. These are supplied in the attachments to this report. [Note: Available upon request]

4 Well Identification, Selection, and Testing Methodology

4.1 Well Selection for Testing

The project's selection criteria for wells to be included in the study were that 1) existing wells would be used in the project, and 2) as a population of wells, they would be representative of the following in the FEMA-designated inundation area in North Carolina:

- wells of types that supply the most people
- the most (numerically) affected wells
- the age range of wells within the population of wells that appear to be properly constructed
- more than one aquifer system and hydrologic conditions.

Within the counties responding to project inquiries and to the survey (Section 3), wells meeting these criteria were located in the known inundated areas as follows:

- Two-inch driven sand point and deeper drilled two-inch wells, typically equipped to be pumped by jet pumps (some shallow-well (suction lift) and some deep well (with in-well ejectors) depending on local water level), and shallow bored wells of 18-24 inch diameter, also equipped with shallow-well jet pumps, met the criteria of being the most typical types and serving the most people in inundated areas, as well as spanning the available age range. These are typically housed in small well houses near the structure supplied by the well.
- Wells tapping two aquifer settings were encountered: Shallow (Quaternary) sand supplying water under unconfined (water table) conditions and limestone (Castle-Hayne) wells tapping either confined (sometimes artesian or flowing) or unconfined conditions.

Based on responses by local health department personnel and the availability of wells meeting the criteria, clusters of wells in Edgecombe and Pender counties were selected for further evaluation (Figure 4.1).

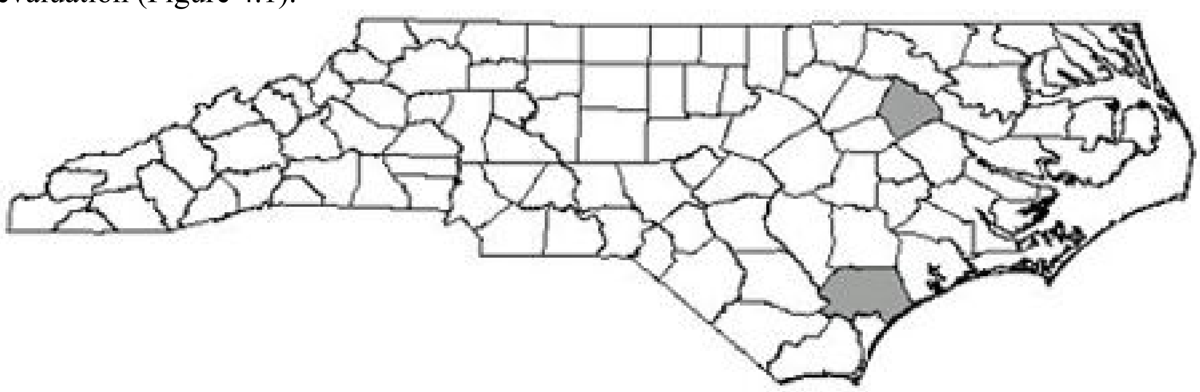


Figure 4.1 Location of Edgecombe and Pender Counties in North Carolina

Local health department people identified affected neighborhoods and FEMA "buy back" areas. The PTL and field service provider then physically visited neighborhoods, explained the project and requested permission to sample wells. People were consistently courteous and receptive.

These settings included affected neighborhoods that provided clusters of wells for testing and comparison, as follows:

4.1.1 Edgecombe County

Bogey Road neighborhood (southeast of Tarboro/Princeville near the intersection of Bogey and Dowens roads): Approximate locations of the wells in Edgecombe County are indicated in Figure 4.2. Included in one neighborhood were shallow bored wells tapping a water table sand and two-inch wells pumped with deep well jets, tapping Castle-Hayne water. This neighborhood is adjacent to and inundated by flooding of the Tar River. The neighborhood has a number of buy-back properties in the process of abandonment. All wells were affected, but some were recovered after cleaning. Others did not respond to treatment. Nitrates remain high locally.

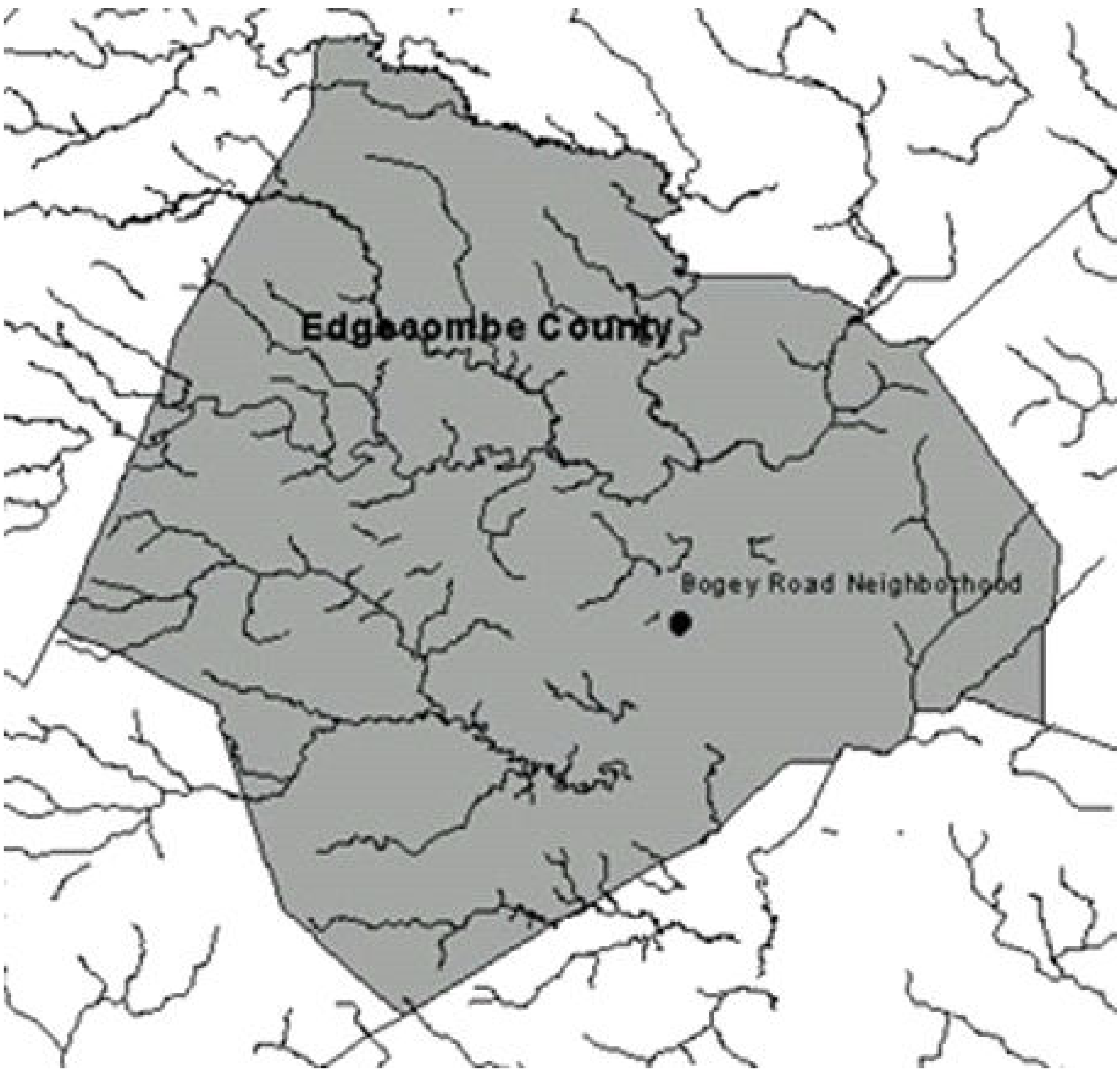


Figure 4.2. Bogey Road neighborhood well location, Tar River watershed, Edgecombe County

4.1.2 Pender County

Affected neighborhoods studied here were near Burgaw in northern Pender County (Figure 4.3), inundated by flooding associated with the Cape Fear River, often areally extensive.

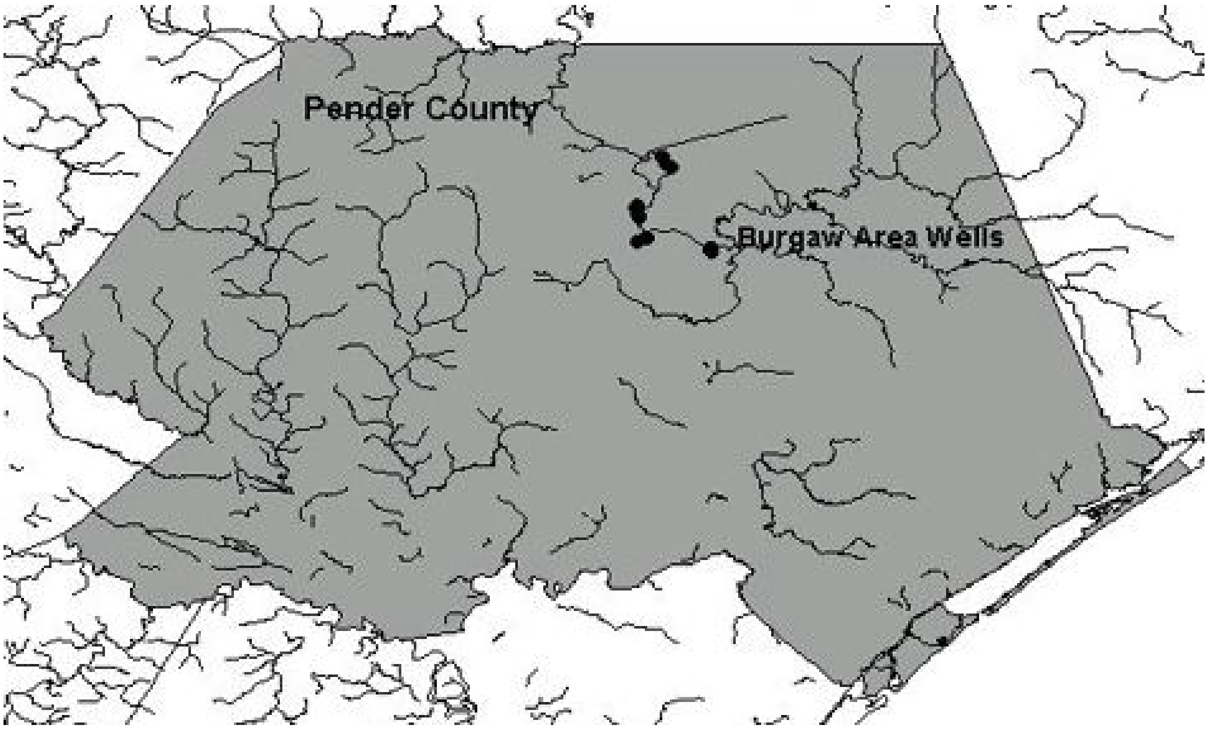


Figure 4.3. Burgaw area wells, Cape Fear River watershed, Pender County

1. Croomsbridge Road: There were homesteads with typically large acreage and occasionally secondary homes sharing wells. Wells were typically two-inch deep-well jet types, but included one four-inch well with a high-capacity submersible pump. Some wells were inundated while others were not, depending on land surface altitude. Wells inspected and tested were of relatively good design and well-maintained.

2. Whitestocking Road A (including well on State Route 53): These wells were all two-inch wells tapping a deeper aquifer, presumably the Castle-Hayne. Wells were flowing or pumped with shallow-well jets. Wells inspected and tested were mostly of relatively good design and well-maintained. The entire area was inundated with water rising into houses that was potentially contaminated based on descriptions of aftereffects. Flowing wells were unaffected by flooding, but nonflowing wells were more difficult to make potable.

3. Whitestocking Road B (near Sand Hill AME Church): This cluster is closer to the Cape Fear River in an area that was deeply inundated, with numerous wells and homes ruined. Wells are a mixture of deeper flowing wells and shallow driven points. Well condition ranged from very poor to good condition.

4. Riverbend Road Homeowners' Association: This neighborhood is adjacent to the river and wetlands (mangrove swamp), with many homes built above local flood stage. Homes mostly were not inundated above floor levels, but lower levels and wells were inundated by potentially contaminated water.

Wells were selected from these areas for treatment testing, based on testing results from this well population (33 wells), as described following. Figure 4.4 is a typical dug well in Edgecombe County (and the only one *E. coli* positive) and Figure 4.5 is a 2-in. well with in-line deep-well jet (Pender County). Characteristics of tested wells are described in Table A.1 found in the Appendix.

Figure 4.4. Bored well, Bogey Road, Edgecombe County

Figure 4.5. Two-inch well with in-line deep-well jet pump, Pender County

4.2 Sampling and Treatment Variability Issues to be Minimized

As this disinfection treatment study is field-oriented, employing wells, including existing water supply wells of various types and conditions, in evaluating disinfection methods, potential for introducing bias in water quality samples and treatment results exists. The unique nature of individual wells in terms of hydrology, geochemistry, construction, and hydraulics is well understood and extensively discussed in the literature. Sampling also can have many variables that may interfere with the comparability of results. In addition to the possible variables involved in manual sampling of water from an individual sampling point, the anticipated well sampling may be affected by changing hydrologic conditions over time and biofouling effects.

The effects of treatments likewise may be influenced by a multitude of variables among wells: age, use, degree of biofouling, maintenance history, formation and construction variables. The major construction/condition feature of interest is the occurrence of faults (of various kinds) in wells to be treated that permit coliform-containing water to reenter the treated well soon after treatment. Other features identified are the unique characteristics of individual types of wells (e.g., two-inch sandpoint and deeper limestone wells vs. larger-diameter drilled limestone wells), and size classes of wells. Small diameter wells with internal obstructions, such as two-inch diameter wells with in-line deep-well jets, are know to be difficult to treat thoroughly with disinfectant (e.g., Holben, 2002) and shallow dug wells are both more vulnerable to contamination from the surface and widely considered to be difficult to disinfect thoroughly.

4.3 Sampling Protocols

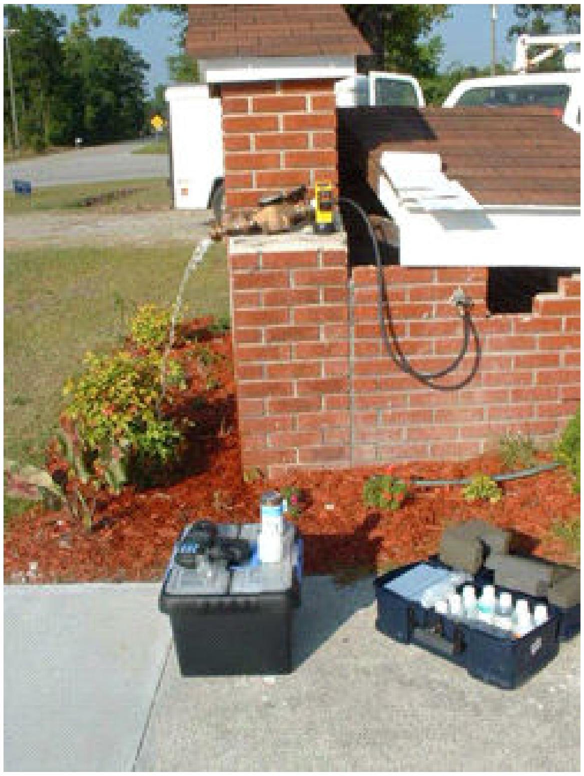
Well locations are described by property/owner name and address by county, and mapped using Global Positioning System (GPS) supplied latitude and longitude data (Table A.2). Locations were made on the base map supplied by Perver Baran (North Carolina State University) using ArcView. Sampling bias is addressed by the sampling protocol adopted for the well selection task.

1. Sampling was designed to include a purging step of a known volume, monitoring of water quality parameters to identify the end of needed purging by the arrival of presumed ground water, and appropriate sanitation in sample collection.
2. Wells are sampled in such a way to minimize sample-error bias. Samplers use aseptic technique, including gloves discarded after each sampling event or if soiled.
3. At the conclusion of each sampling event, any adjustments made in the well and water system for sampling were returned to the operational mode, as applicable.
4. Sampling point descriptions are recorded.

4.3.1 General Sampling and Analysis Event Procedure

This procedure was used for 1) testing wells in an area that are potential candidates and periodic sampling of "sentinel" wells, 2) "before" sampling of control wells, 3) sampling during well treatment events, and 4) follow-up (after 1 week) sampling of treated and parallel sampling of control wells:

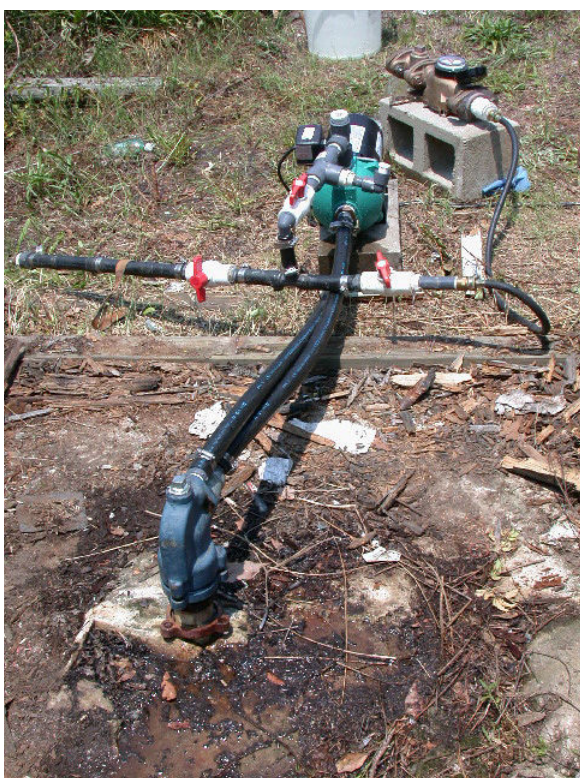
1. The well is started after a quiet period of at least 20 min., and using a project-supplied hose for diversion to waste, the sample tap and well is flushed at least one bore volume (typically 10 or more) or pump cycle, whichever is greater. Bore volume is calculated from a) tested output rate at the tap used and b) known well dimensions. Pumped water volume is metered using a totalizing meter suitable for the range of flow rates encountered and pumping rates calculated by flow volume in gallons over time in minutes (gallons per minute, gpm), and recorded. Standard bacteriological water sample collection protocol is followed.
2. During flushing, samples of "first flush" discolored water may be collected in aseptic sample containers for microscopic observation.
3. After flushing the first bore volume, samples are collected for well-site analysis of pH, temperature, conductivity (uS/cm), and oxidation-reduction potential (ORP) in millivolts (mV) using a Hanna model HI 98204 multi-parameter meter, and results recorded. This physical parameter suite was collected periodically during the flushing step to provide a profile of water quality during pumping. QA/QC as defined in the Work Plan was followed.
4. When it was determined that casing water was removed or replaced, a sample is collected for on-site analysis of total iron (Fe_{tot}), ferrous Fe (Fe^{2+}), Ca-Mg hardness, and alkalinity. Mn (total) was initially included but found to be largely below detection (<0.01 mg/L) and not considered to be a factor in disinfection planning. Fe_{tot}, Fe^{2+}, Mn, and (later during chlorination) total and free chlorine were analyzed using a Hach DR800 colorimeter and reagents appropriate to the specific analysis. Ca-Mg hardness, alkalinity, pH, and total and free chlorine were also measured using Hach Aquachek test strips. The flow is stopped, and the tap disinfected, then flushed five minutes at open flow, avoiding splash, then reduced to a pencil-sized stream.
5. A sample is collected for BART inoculation (HAB, DN, SRB, IRB), then another each for heterotrophic plate count (selected samples) and total coliform analysis (100-mL in sterile



QC-traceable 125-mL sample bottles). Samples are recorded, handled, transported and analyzed as described in the Work Plan.

6. Additional samples for nitrate-nitrite, and selected samples for synthetic organic chemicals (SOC) and volatile organic chemicals (VOC) were collected in the reconnaissance phase of testing. After approximately each bore volume, the flow is reduced to a pencil width stream, and a) a sample is collected for measurement of temperature, pH, conductivity, and millivolts, and b) a coliform sample collected.

Figure 4.6. Field sampling and analysis. This figure illustrates features of the field sampling procedure: Metered flow and instruments as described above.



As part of the sampling procedure for wells without pumps (e.g., FEMA buy-back properties) and for disinfection treatment and sampling, a combination jet pump with a sampling-purging valve and tap tree was employed. The pump was a WaterAce convertible (deep well - shallow well) with 1/2-horsepower (HP) motor equipped for 110-V power (supplied by generator or by available line power) and capable of yields up to about 10 gpm depending on pumping head. The discharge side was equipped with the valve-tap tree. Figure 4.7 illustrates this apparatus at well Bogey C (see following).

Figure 4.7. Apparatus for sampling wells without pumps

Notes about bacteriological testing

BART tube methods (Droycon Bioconcepts, Inc. (DBI), Regina, Saskatchewan) described in Cullimore (1993 and 2000) permit field collection and inoculation into dehydrated media to form a culture broth that can be observed for rate and type of reaction. These patterns can be linked to the occurrence of certain microbial consortia (Cullimore, 2000). BART types available include models for recovery of sulfate-reducing bacteria (SRB), general heterotrophic bacteria, slime-forming bacteria, denitrifying bacteria, iron-precipitating heterotrophic bacteria, acid-producing bacteria (implicated in corrosion) and selected others. The utility of BART methods was field-evaluated for AWWA Research Foundation by Smith (1992), who also has defined a standard protocol for their use in environmental investigations (Smith, 1996).

Four types (HAB-BART, IRB-BART, DN-BART and SRB-BART) were employed to provide 1) information on the range of electron acceptors used by microflora in each sample, and 2) presumptive identification of microbial types and bacterial genera present.

- HAB-BART: Substitute for HPC but more sensitive according to DBI.
- IRB-BART: Recovers a range of aerobic and facultatively anaerobic heterotrophs as well as iron-precipitating bacteria.
- DN-BART: Nitrate-reducing bacteria (using nitrate as an electron acceptor)
- SRB-BART: Recovers sulfate-reducing bacteria and some other anaerobes and sulfur oxidizers.

Once inoculated (at the well site) and transported to EGIS's facility the samples were maintained at room temperature (~75 F). BART information is internally sufficient for defining the microbial ecology, but microscopy and additional analyses are typically useful for additional information (Smith, 1992; 1996). Additionally, BART tubes are field portable and have a long shelf life, making them attractive in a program of field triage testing and treatment evaluation (see Recommendations, Section 6).

The heterotrophic plate count media used by the laboratory employed was *Standard Methods* plate count media. A factor in attempting to use HPC as a monitoring parameter is the limited laboratory schedule for HPC sample delivery (deliver Monday to Wednesday). HAB-BART were substituted.

4.3.2 Sampling Types

1. Long-term sentinel (control) wells: One well representing each cluster and hydrologic location was selected as a project-long sentinel well. The well was untreated during the period and sampled during area site visits.

2. Treated wells: Wells picked were those (a) representative of the target well types and (b) available for treatment without compromising ongoing potable water supply for properties. In Edgecombe County, these were wells on FEMA buy-back properties in the Bogey Rd. area (both bored and deep two-inch) and shallow and deep two-inch wells in Pender County (on St. Rt. 53 and in the Whitestocking B (AME church) cluster, both buy-back and otherwise abandoned wells. Wells are sampled as described above 1) prior to treatment, 2) during treatment, 3) after treatment (same day as discharging solution), and 4) one week after treatment.

4.4 Well Disinfection Testing

4.4.1 Edgecombe County Wells

Because of the potential for harm to functioning potable water wells, and the availability of abandoned but unplugged wells on "FEMA buy back" properties, the field team made the decision to seek to use "FEMA" wells for treatment experimentation. FEMA properties inspected in the Bogey Road neighborhood included shallow bored wells and a deep two-inch well with a still-installed ejector in close proximity to one another and to other wells tested in the area to offer the option of comparison. Permission was granted by the Edgecombe County Planning Department, which instructed demolition contractors to delay plugging of wells until treatment testing was completed. The department also supplied maps of the area of interest. The wells selected for treatment testing were designated as follows (with descriptions):

1. Bogey A (exact location available as needed): This was a 24-in-diameter 24.7-ft-deep bored well (Driller registration number 757, constructed 4/9/1987) situated in a brick aboveground well house. When inspected, the metal well lid was off, there was no well seal and the 6-in. opening in the concrete lid was open. At inspection, static water level (SWL) was 10.3 ft below top of casing (BTC). When pumped down to 12 ft, a stream of ground water was observed entering through a crack or seam.
2. Bogey C (exact location available as needed, 2-in. diameter casing with in-line ejector, reported to be 75 ft deep with screen from 50 to 75 ft. Jet pump adapter found to be attached at inspection, but not sealed. SWL could not be determined initially.
3. Bogey D (exact location available as needed): This was a bored well (Figure 4.8) starting at 24 in. diameter, reducing to 18 in. at 17.5 ft (Driller registration number 757, constructed 4/9/1987), situated in a low concrete block well house. The jet-pump casing seal was intact. When pumped during testing, the water was colored, iron biofouling evident, and the well emptied in about 25 minutes.

Figure 4.8. Well Bogey D, Edgecombe County.

Table 4.1 summarizes Edgecombe County well features.

Table 4.1 Summary of Edgecombe County treatment test well data at inspection

Well	Diameter (in)	Depth (ft)	SWL (ft BTC)	Yield (gpm)	Date
Bogey A	24	24.7	10.3	7.57	June 4, 2002
Bogey C*	2	75		2.86	June 4, 2002
Bogey D	24 - 18	28	7.7	6.96	June 4, 2002

*Bogey B was a well on the Riddle property that was found to be filled in to 1 ft below SWL.

4.4.2 Pender County Wells

1. Ballard 1 (exact location available as needed, Burgaw, Whitestocking B cluster) : This is a shallow (uncertain depth) 2-in. jet-pumped well, located in a low concrete-block well house serving a now abandoned (FEMA buy back) property.
2. Ballard 2 (exact location available as needed, Whitestocking B cluster): Shallow galvanized 2-in. well in a brick well house with 1-1/4 in. suction pipe with foot valve that failed. A 3-4-in. PVC pipe is inserted inside the 1-1/4-in. This well produced very little water.
3. Davis place (exact location available as needed, Whitestocking A cluster): A deeper 2-in. PVC well in a brick well house that had been neglected for some time.

Figure 4.9. Well Ballard 1, Pender County

The structure of the wells made it impossible to determine depths, there were not available records and depths were not known to those familiar with the properties. None of these wells were cleaned or pumped since the flood like the Bogey area (Edgecombe County) test wells.

4.4.3 Well Disinfection Treatment Methods Used

Method selection was conducted deliberately, factoring in the following parameters:

- The experiences and opinions of the surveyed groups (Section 3) who emphasized the primary importance of application in disinfection effectiveness, and the lessons of other national work (Literature Review, Section 2) along the same lines: more than one solution type is effective as long as solutions reach the bacteria to be deactivated.
- The descriptions of problems with disinfection and solutions related by well owners in the study area: Primarily the difficulty of getting chlorine to make contact throughout well bore volumes of two-inch jet-equipped wells.
- Expected "field conditions" during a large-scale flooding event involving thousands of wells: The decision was made to attempt disinfection with the equipment and solutions that could be obtained in eastern North Carolina (or other similar U.S. settings) on a retail basis.
- We anticipated that two-inch wells would probably require pressurization, backflushing and surging to mix solution through the water column, requiring trained treatment providers.
- Bored wells would require a means of physical development and thoroughly disinfecting concrete caisson surfaces.
- Most wells are in some state of deterioration: Based on the wells observed and tested, not all wells in eastern North Carolina are ideally constructed, sealed and maintained.
- It would be possible to have false-negative total coliform results: Chlorine solutions can (based on experience) persist in wells for long periods, and sampling near the chlorine "bubble" may yield false negatives. Chlorine solutions have to be entirely flushed out and ground water recharged into the well.

The Work Plan directive to test a range of solutions was also factored in to evaluate solution handling. The following general methods were devised for the specific wells (but subsequently field modified as described following):

Bogey A (apparatus illustrated in Figure 4.10):

1. In clean, new 32-gallon plastic trash cans, mix and settle $Ca(OCl)_2$ to make a well-bore volume of 100-mg/L solution.
2. Pump well down and clear.
3. Dose with chlorine solution and brush well walls
4. Recirculate with jet pump
5. Wait 24 hr
6. Pump clear (to < 0.2 mg/L by chlorine test kit)
7. Pump more than one well volume, then test for TC, ion parameters
8. In one week, pump again and test for BARTs and TC.

Figure 4.10. Bored well cleaning equipment at well Bogey A

Bogey D (other dug well that can be pumped dry):

1. Pump down
2. Brush walls down with chlorine solution (brush on PVC pipe with Pump Puller or manually)
3. Employ "Bogey A" surface-mixed $Ca(OCl)_2$ solution treatment (dose, recirculate, contact time) and repeat for chlorine demand.
4. Let refill (about one week). Note: This scenario would also model a procedure of treating wells at flooded, vacated homesteads.
5. Pump clear
6. Pump more than one well volume, then test for TC, ion parameters
7. In one week, pump again and test for BARTs and TC.

Bogey C (2-in in-line jet well)

1. Pump clear 3 well volumes or fresh ground water by parameters
2. Mix NaOCl to treat 2 well volumes, acidify to 5.5 for mixing in this pH 7.4 buffered water
3. Pull in-well pipe and jet (inspect and clean)
4. Displace in chlorine solution: Air used to displace solution downward (apparatus illustrated in Figure 4.11).
5. Wait 24 hr
6. Reinstall pump components and hook up jet pump
7. Pump off to clear
8. Pump one well volume + after Cl is < 0.2 and test for TC and ion parameters.
9. In one week, test BARTs and TC.

Figure 4.11. Air injection apparatus for solution displacement, well Bogey C

These methods incorporate method improvements described in IAGP (1997), and Hanson, Schnieders, and Holben (2002), as discussed in Section 2. In the Pender County testing, NaOCl was used in all circumstances.

5 Results of Testing

Methods of water quality testing are described in Section 4.3 and well treatments in Section 4.4.

5.1 Well Selection Testing Results

5.1.1 Physical-Chemical Data

Well water data (TC, HPC, N-series, Fe, pH, conductivity, temperature, ORP, alkalinity, hardness, and flows) collected are supplied in Table A.3 in the Appendix (locations are depicted in Figures 4.2 and 4.3). As described in the sampling and analysis procedure, temperature, pH, conductivity and ORP were tracked during purging to identify when fresh ground water was being pumped.

The four physical parameters (especially pH, conductivity and ORP), plus alkalinity and hardness, were useful in distinguishing shallow sand aquifer water and deeper (Castle-Hayne) water.

Table 5.1 Ranges of parameters and aquifer designation

Neighborhood	pH	conductivity (µS/cm)	ORP (mV)	alkalinity (mg/L)	total hardness (mg/L)	aquifer type
Edgecombe County						
Bogey	5.7-6.9	30-175	97-281	0-80	120	shallow sand
Bogey	7.5	309	-58	120	120	C-H
Pender County						
Croomsbridge	7.6-8.2	185-529	-35 to -145	180-240	100-120	C-H
Riverbend	7.2-9.0	241-800	156 to -118	120-240	50-420	C-H
Whitestocking A	7.4-8.7	280-601	-91 to -147	120-240	50-250	C-H
Whitestocking B	8.0-8.3	863-940	-104 to -143	180-240	120	C-H

Pender County wells tested were all 2-in. deep wells, many flowing or confined. Low (< 7.0) pH, conductivity below 200 µS/cm, ORP above negative values, and alkalinity below 120 mg/L were only encountered in bored wells in Edgecombe County, and prior to disinfection. Deeper 2-in. well water consistently exhibited negative mV ORP values (prior to disinfection) and more alkaline, higher dissolved solids characteristics. The above values are final, stable values during testing events.

In terms of health-related chemical and bacteriological results, positive nitrate and total coliform results occurred only for shallow bored wells in the sample set. Even "Bogey C", adjacent to bored Bogey Rd. neighborhood wells and the unused Pender County property wells (all abandoned and left open for three years) were negative for total coliform during initial testing.

5.1.2 BART results

BART results obtained are tabulated in Table A.4 and summarized and interpreted in Tables 5.2 and 5.3. The BART results, both for the Edgecombe County and Whitestocking B neighborhood wells showed evidence of inundation by contaminated water, based on interpretation of reaction patterns (Cullimore, 2000). This is presumptive information, but suggestive of the use of these tools in investigating the long-term impacts of such inundation events on ground water ecology, even when total coliform values are negative.

Table 5.2 BART results summaries

Well	Positive IRB	Positive SRB	Positive DN	Positive HAB
Bogey A	X	X	X	X
Bogey C	X	X	X	X
Bogey D	X	X	X	X
Ballard 1	X	X	X	X
Ballard 2	X	X	X	X

Table 5.3 Presumptive microbial types present (Cullimore, 2000)

Well	Approximate density (log CFU/mL)	Presumptive types*
Bogey A	2 - 3.6	*Enterobacter, Citrobacter* and other TC group members, *Pseudomonas*, aerobic heterotrophs undifferentiated, strict anaerobic heterotrophs, SRBs, nitrate-reducing bacteria.
Bogey C	2 - 3.6	Slime-forming and iron-precipitating bacteria, *Enterobacter, Serratia, Pseudomonas, Bacillus, Alcaligenes*, undifferentiated aerobic heterotrophs, nitrate-reducing bacteria, strict anaerobic bacteria with SRBs
Bogey D	3.6 - 6.0	*Enterobacter, Citrobacter* and other TC group members, *Pseudomonas*, strict anaerobic heterotrophs, very aggressive aerobes (*Pseudomonas* may do this) harboring SRBs, nitrate-reducing bacteria, *Gallionella* by microscopy. The rapid 'RC' reaction suggests abundant enterics.
Ballard 1	2.0 - 3.6	*Enterobacter, Citrobacter* and other TC group members, *Pseudomonas*, strict anaerobic heterotrophs, aerobic heterotrophs, SRBs, nitrate-reducing bacteria.
Ballard 2	2.0 - 5.0	*Enterobacter, Citrobacter* and other TC group members, *Pseudomonas*, strict anaerobic heterotrophs, very aggressive aerobes (*Pseudomonas* may do this) harboring SRBs, nitrate-reducing bacteria, The rapid 'RC' reaction suggests abundant enterics.

* Identifications from Cullimore (2000) interpretations of BART reaction patterns.

Of the Edgecombe County wells, Bogey D consistently exhibited the most rapid SRB responses. HAB BART results (analogous to heterotrophic plate count) were very rapid (< 3 days) even after disinfection.

5.2 Well Disinfection Testing Observations and Results

General methods of treatment are described in Section 4.4.3, but modified as follows. Table A.5 tabulates Edgecombe County results and Table A.6 tabulates Pender County results.

5.2.1 Edgecombe County

Bogey A (24-ft bored well)

During the June 23-26, 2002, disinfection test, treatment began with filling two 32-gallon plastic trash cans with clean well water (from a nearby coliform-negative well). In one 32-gal. container, 1 (volume) ounce (oz.) of 20 % muriatic acid was added to the water, lowering pH to 3.4 (from pH 6.5), followed by 1 oz. of 47 % $Ca(OCl)_2$ in the 32-gal. container. Ten more oz. each of $Ca(OCl)_2$ powder and muriatic acid were added to the container. Circulation in the well (about 348 gal. volume) was started, and the chlorine solution siphoned into the well while circulation was maintained continuously. Chlorinated water was jetted around the casing inside and immediate area of the casing top to prevent recontamination and circulation maintained for one-half hour, then permitted to sit for contact time. Chlorine content in the well bore was 150 mg/L. ORP was raised from ambient to the disinfection range of +814 mV and pH at 6.8-6.9 at shutdown (indicating that preferred HOCl was the predominant Cl ion in solution). Conductivity and temperature rose.

Upon resumption of pumping on June 24 after recover of SWL to 10 ft., total chlorine was 200 mg/L, pH was 6.7, ORP +861 mV, rising to +923 mV, while total chlorine dropped to 100 mg/L and pH dropping to 6.5 as PWL dropped, prior to pumping off (22.1 ft) in 44 min. The total chlorine rise from 150 to 200 mg/L probably reflected greater concentration in the lower part of the well water column. The pumping was resumed a little under two hours later at SWL = 11 ft, pH 6.5 and ORP +884 mV. ORP again rose as PWL dropped, and ORP was +908 mV when pumped to the foot valve again in 42 min. Total chlorine was being depleted, starting at 30 mg/L and dropping to 2.0 (total and free) mg/L.

Pumping was resumed after 1 hr (pH = 6.2, ORP = +857 mV, total Cl = 2.2 mg/L) and again pumped off after 38 min (pH 6, ORP +804 mV, total Cl 0.6 mg/L. free Cl 0.36 mg/L). Another pumping run depleted the well in 1:21 hr.

Pumping resumed on June 26 at pH 6.2, ORP = +307 mV and total/free Cl < 0.1 mg/L and pumping conducted through two depletion cycles. Two samples were collected (at 19:56 and 20:03) for total coliform after total and free chlorine dropped below detection. Both were positive.

The well was revisited on July 16, pumped dry through two cycles (pH 5.6-5.9 and ORP dropping to +336 mV). Pumping was resumed upon recovery and a total coliform sample collected at 14:22 (free Cl 0.08 mg/L, pH 5.8, ORP +326 mV). This TC was negative, as was a second sample collected after several more drawdown cycles on July 17. However, samples taken in late August and September 3 were positive for TC.

Bogey C (74-ft 2-in. drilled well)

As noted, Bogey C (immediately adjacent to the well tested at 419 Bogey, on the same property as Bogey D (following) and across the street from Bogey A) is a deeper drilled well with distinctly different water quality characteristics. It tested TC negative prior to disinfection testing despite long sitting open.

Disinfection testing was conducted June 25-27, 2002. The drop pipe was removed. A well bore volume of 7.5 gal. was calculated. To make a 200-mg/L well bore solution, a solution was made using 8 gal. of water from the Parrish (419 Bogey) well (TC negative), to which was added two oz. (fluid) of 6 % NaOCl solution and 0.5 oz. of 20 % muriatic acid, then another 0.5 oz. of sodium hypochlorite solution. This solution was poured down the well at 11:18, then the well pressurized to 10 pounds per square inch (psi) at 11:28 and released at 11:32. This pressurization and relaxation cycle was continued through 12:35. A bailed sample from the water table surface at 12:42 showed ORP in the disinfection range of +774 mV but total chlorine was 10 mg/L.

At 12:59, a bailed sample from the bottom of the well provided water quality of +60 mV and total Cl = 0.61 mg/L (free Cl = 0.56 mg/L), while a sample from the surface was ORP = +679 mV and total Cl = 10 mg/L. The solution was stratified with Cl floating.

At 13:50, a second 8-gal. solution was mixed: 0.5 oz. of 20 % muriatic acid, 2 oz. 6 % sodium hypochlorite, then 0.5 oz. of hypochlorite. This solution was poured to the well bottom through a garden hose. A bailer sample taken at mid depth at 14:23 yielded ORP = +723 mV and total Cl = 10 mg/L and one from the bottom yielded ORP = +759 mV and total Cl = 50 mg/L.

A bailer was used to pull water up repeatedly from the bottom to mix chlorine through the water column to various depths. At 14:38, a bailer sample taken at mid depth yielded ORP = +656 mV and total Cl = 2.27 mg/L (free Cl = 2.05 mg/L).

A third 8-gal. solution was mixed at 15:34 and dosed to the bottom and mixed through as before. A bailer sample taken from mid depth at 15:50 yielded ORP = +829 mV and total Cl = 25 mg/L at pH 6.8. A sample bailed from the bottom yielded ORP = +750 mV (disinfection zone) and free Cl = 1.47 mg/L at pH 6.3 (predominantly HOCl). At 16:20, a fourth 8-gal solution was mixed and tremied in as before, then mixed. This time, from the bottom to top of the water column, ORP was above +900 mV and total Cl $\geq$ 200 mg/L.

A sample taken July 17, 2002 for total coliform was negative, and water conditions still deviated from the pretreatment ambient values (ORP = +326 mV, pH 5.8). This may simply reflect that the well was cleaned and disinfected in contrast to its abandoned condition after years of use.

Samples taken August 1, 2002 were positive for TC. It was hypothesized that this was a contamination from water, obtained from 419 Bogey, used to prime the jet pump to take the sample. The well at 419 Bogey had previously tested negative and was considered bacterially safe, although nitrates were elevated. However, samples taken September 3 were also positive, possibly due to residual biofouling (water was discolored).

Bogey D (24-ft bored well)

Bogey D was the most impaired of the Edgecombe County wells. Its water quality as tested in early June was strongly discolored and biofouled, total coliform results positive, and the well pumped dry quickly. As with the others in the area on abandoned properties, it had been unused for almost three years.

During the June 14-16, 2002, disinfection test, treatment began with filling two 32-gallon plastic trash cans with clean well water. In each container, 0.5 ounce of 20 % muriatic acid was added to the water, lowering pH to 5.4, followed by 0.5 ounce of 46 % $Ca(OCl)_2$, making a 100-mg/L disinfecting solution in the 32-gal. containers, with a solution pH of 6.9. The 24-in. concrete top was removed and a large soft brush was used to scrub the sides with disinfecting solution, as described in the procedure. Next, 6 oz. of muriatic acid was added to the water column, then 6 (volume) oz. of powdered $Ca(OCl)_2$, mixed thoroughly with the brush. The resulting solution was approximately 100 mg/L. The pH was dropped from 6.8 prior to treatment to 5.9 and ORP increased from +169 to the disinfecting range of +800. Temperature, conductivity and hardness all increased considerably. The dirty water was then removed from the water column and the well permitted to recharge.

Redox potential remained high in the disinfecting range (above +733) and pH low (6.0) during the first 12-minute pumping on June 15, when the well pumped dry (to the foot valve at 27 ft) again (15:22 to 15:34) from a starting SWL of 12.5 ft. Pumping was resumed at 17:12 (SWL 17.8 ft) and continued for two hours. On recovery, the ORP remained in the disinfecting range and pH below ambient (6.1 to 6.3) through shutdown (PWL at 20 ft).

On June 16, pumping was resumed after a full water level recovery to 10 ft BTC from a low of 20.3 ft the prior evening. ORP dropped from the initial value of +720 mV to +357 mV in 24 min, and continued to drop. Some slight cement dissolution was expected as pH was initially 6.5, then stabilized at 6.1.

Three total coliform samples collected during this last pumping event after ORP dropped to +320 mV (at 29, 33, and 43 min. of pumping) were all positive. When sampled on July 17, total coliform was negative. However, when sampled again on August 1 and September 3, TC results were positive.

Based on repeat samples in the area, shallow ground water remains in an impaired condition with detectable nitrates and some total-coliform positive results. Bogey A (with a leak at 12 ft) was apparently disinfected (based on achievement of disinfecting chlorine content and ORP). However, TC-containing water returned to the well. Long-term safety of such a well as this would require repair of the 12-ft leak. Based on June tests, disinfection of Bogey D would be termed unsuccessful, however, July samples were negative, indicating that residual effects repressed bacteria responding positively to the Colilert test. However, a return to positive results in August illustrate that apparently successful disinfections can be temporary.

Bogey C was already coliform negative, however, the demonstration illustrated chlorine solution behavior in such wells. As discussed by Holben (2002), and repeated by survey respondents (Section 3), obstructions in such wells make solution mixing and contact very difficult. However, even with the in-well equipment pulled, chlorine solutions stratify. The treatments demonstrated how such impediments to chlorination can be overcome, but also how results can be temporary.

5.2.2 Pender County

Tests on these wells were inconclusive as the impaired conditions of wells made feeding chlorine solutions difficult. The experience in accessing and restarting the wells was an exercise in the tasks needed to restart flooded wells. In this case, wells were in poor operational condition at the time of abandonment, with very poor hydraulic connections in the wells with the aquifers, making the pumps unable to pump very much water. Under these conditions, such wells may typically be impossible to disinfect. Total coliform results were negative, however, BART results suggest the presence of very high numbers of bacteria including potential enterics. The ground water is significantly impaired.

5.2.3 Chlorine Solution Modifications

In testing subsequent to the initial Edgecombe County treatments (Table A.5), NaOCl was substituted for $Ca(OCl_2)$ in bored well treatments. Due to a desire to explore a less hazardous acidifying alternative, common distilled white vinegar (5 % acetic acid by volume) was substituted for 20 % muriatic acid in the final treatment tests. The final solution (to make a 32-gal. Solution) was 10 oz. of 6 % NaOCl, 10 oz. of 5 % acetic acid in locally available water (219 Bogey) to make a solution with a pH of approximately 5.9.

6 Conclusions and Recommendations

6.1 Conclusions and Observations

Disinfection methods selected and tested on both shallow bored wells and 2-inch wells in Edgecombe and Pender counties were successful in achieving disinfecting conditions in wells:

1. Solutions made and applied achieved disinfecting ORP and chlorine residual levels. Maintaining target total chlorine values in the treated two-inch wells required repeated treatment.
2. Acidification aids in forming optimal disinfecting solutions (favoring HOCl) in ambient well water encountered. This was accomplished with small amounts of acid, and can be done safely by trained personnel.
3. However, the use of available muriatic acid products poses both safety and handling difficulties. A typical solution of 20 % muriatic acid sold for mortar cleaning can cause serious injury if mishandled or inhaled. Opened containers vent HCl vapor even when reclosed, posing an inhalation hazard and damaging equipment. The use of available low-concentration acetic acid (white distilled vinegar) or hydroxyacetic acid (both of which have better biofilm-removing and buffering properties than does HCl) is encouraged instead, even though a somewhat larger volume of acidifier (10 oz. in 32 gal.) would be needed for the water types used. The amount would vary depending on water characteristics.
4. Mixing was required to distribute disinfecting solutions through water columns, echoing IAGP (1997), Holben (2002) and other literature.
5. Disinfecting solutions and residual water quality effects can be persistent.
6. Although $Ca(OCl)_2$ is more easily stored for long periods (if stored cool and dry), drops to well bottoms better, and is favored by some (Wise, 2001) for higher organic content water, it is our experience that solutions are harder to regulate. Mixing in even a little too much makes a solution very "hot" (excessively high OCl in solution). Sodium hypochlorite is easier to use in mixing solutions. $Ca(OCl)_2$ is also known to leave clogging Ca-carbonate and -sulfate solids in carbonate- and sulfate-rich waters such as limestone (e.g., Mansuy, 1999; Hanson, 2001; Holben, 2002), and thus may pose problems for Castle-Hayne wells.
7. The treatment program in Edgecombe County was conducted successfully using off-the-shelf equipment and solutions, and mimicked the disaster-relief scenario, but demonstrated that expertise and time are required to assemble the proper equipment and solutions, and to apply them to make these procedures work, and also that impaired water can make disinfection temporary.
8. The experience with the impaired Pender County wells illustrates that some wells would be almost impossible to disinfect and should be slated for replacement.

A strategic conclusion based on this research is that, in the context of coastal NC and similar settings, it may be best to think of well disinfection as first an emergency response task and second as a technical task. That is, specific methodology recommendations are secondary to developing and implementing a Private Water Supply Disaster Relief or Emergency Response Plan to respond rapidly with equipment and training, and having people available to respond effectively locally.

However, technique and solution characteristics impact treatment effectiveness. Based on surveys and discussions the team had with well owners, and reflecting testing results (also literature, e.g., Holben, 2002):

1. Two inch wells, typically equipped with in-line jets on deep well settings, were reported to be very difficult to impossible to treat by homeowners, as chlorine was difficult to force to the bottom. People had to pull the pump ejectors and typically pellets were required to get to the bottom. Granular calcium hypochlorite floated. However, deeper wells tapping confined areas of the Castle-Hayne aquifer came out mostly unscathed (TC-negative), especially those equipped with sealed 2-in in-line jet pumps. Nearby shallower (not pressurized) 2-in wells were often reportedly contaminated.

2. Some installations observed are prone to contamination that could have been prevented by better protection and design.

3. Only a few wells of our sampled population were TC positive now (all in Edgecombe County), with only one *E. coli* positive (a bored well in Edgecombe County). Ground water contamination by bacteria, if it occurred, did not appear to be lingering over a large area, but was locally present, as in the Edgecombe County neighborhood tested. Detectable nitrate was also very rare, also found only in shallow Edgecombe County wells.

4. In a related observation, TC negative results could easily be "false negatives" if taken from water highly affected by or adjacent to chlorinous water. ORP values should be well below the disinfection range (for these wells, < +350 mV) before samples are taken.

5. In talking with well owners, the people thought that competent help was essential to rapidly restore potable well function. However, many expressed frustration about their perception that they were left on their own to restore their water supplies. However, it must be noted that many public health people provided valuable assistance in a dedicated fashion during the Hurricane Floyd flooding. This was a very large-scale disaster that also required personnel who could have typically responded to well problems to be assigned to other emergency tasks. Public health response capabilities were simply overwhelmed.

6. Experience shows that restoring pump function is a primary function of well disaster response. One big problem mentioned by NC well owners and public health personnel was the difficulty of restarting and fixing/replacing jet pumps, which are electrically powered. Air-cooled motors were subject to shorting out and controls fouled when immersed.

6.2 Recommendations

Well disinfection field tests in this current work demonstrate the value of proper equipment and expertise in treating the types of wells that are the subject of this study. A logical recommendation that proceeds from that experience is that future response to large-scale well flooding should involve improved coordination with well contractors, who have the equipment and experience necessary to properly disinfect wells. For an event of Hurricane Floyd scale, it would probably be necessary to supplement professional help with trained volunteers. In the future, a well-executed Private Water Supply Disaster Relief or Emergency Response Plan that a) more effectively mobilizes professional help and b) trains and equips larger numbers of people to reactivate, clear and disinfect wells properly should improve the process of restoring their water supplies.

6.2.1 General North Carolina Recommendations

1. A Private Water Supply Emergency Response Plan should be drafted and implemented in counties affected by Hurricane Floyd, a near-maximum event from the standpoint of water well impact, historically.
2. Treat well disinfection response as an emergency response task first, technical task second.
3. While rapid, imperfect action may be better than delayed, overly elaborate reaction, technique is important, and proper techniques are teachable and achievable.
4. Emphasize restoring pump function and pumping wells clear for several bore volumes to several hours (or more if severely affected by dirty water) as a first step, then go to disinfection. Based on experience, a pattern of pumping about two hours, allowing recovery, then repeating is most effective.
5. Conduct "trained responder" training to better respond in the future, using the experience of this project as a basis.
6. Mobilize professional well contractor capabilities on a reserve basis to be available in such emergencies.
7. In preparation for a future large-scale inundation event such as a large hurricane, reemphasize prevention in North Carolina, starting as soon as possible. Based on survey responses, observations during the field phase, and other experience nationally (e.g., IAGP, 1997 and Holben, 2002), the following are recommended: a) Wells in flood zones should be minimized or if necessary, completed above the 1999 flood altitude and protected, b) Wells should be properly sealed to resist contamination. c) As shallow bored wells are very difficult to protect and restore, their phase-out in flooding zones is recommended (with incentives to do so).

6.2.2 National Recommendations

As such disaster events and need for appropriate response are common events in the United States (and elsewhere in the world), this study's field testing program can be extrapolated to additional wells, and other hydrogeologic, social and climate settings.

1. Conducting a larger-scale study could provide a statistical-analysis capacity superior to that which could be applied to these tests. Time available and difficulty associated with locating wells for this study limited the numbers that could be effectively visited, although a representative sample of affected well types was tested. The repeatability of experience with Bogey C (stratification, high chlorine demand) should be assessed.
2. Treatment methods described for the Midwest and other settings where larger-diameter drilled wells are more common should be tested on a scale larger than IAGP (1997) to test the effects of depth, pump settings, water quality and other parameters.

3. Treatment method suitability for other difficult conditions (great depth, high and very low temperatures, remote locations) should also be assessed.
4. Using field-compatible water quality analytical methods to develop profiles of water quality is beneficial in identifying potentially vulnerable areas, wells and ground water that is more difficult to disinfect, and for providing a way to recognize aquifer-scale water quality impacts after an event such as a major flood. The relatively simple and low-cost methods employed in this study are capable of reliably providing information necessary to develop such profiles.
5. Finally, national training, availability and market penetration of reference materials, and extrapolation to Developing World situations can be assessed in light of the need, and the capacity of the United States to be a technical leader in reducing suffering associated with contaminated water around the world.

6.3 Epilogue: Recommendations for NC Prevention and Emergency Response

While the following recommendations are not direct outcomes of the work reported in this report, they proceed from discussions the project team has had during its execution and from review of Holben (2002), a model well disinfection manual for state use summarized in the literature review (Section 2). These recommendations are provided for further consideration.

6.3.1 Develop a County-by-County Emergency Response Plan for Private Water Supplies

At the time this report was being written, the State of North Carolina was in the process of developing Emergency Response Plans to better deal with such mass disasters in the future. As part of this process, the Division of Environmental Quality is formulating a plan for water well response. We recommend that the following be included.

1. In each county/district of local government environmental health, train and equip response teams who can evaluate, help and equip wells as needed. It is best that this include experienced well and pump service contractors, and other experienced experts such as hydrogeologists. Include them in disaster preparedness planning and writing the plan. A training program for "trained responders" in North Carolina can be a model for the nation.
2. Include training of "big box store" and local hardware store people in pump and chemical selection. Homeowners are very likely to turn to these stores for supplies and equipment after a flood. However, plumbing supplies staffs are typically not trained and experienced in well disinfection.
3. Draft and supply fact sheets with detailed recommendations for well disinfection, with versions in both English and Spanish, given recent immigration patterns in eastern North Carolina.
4. Have wells spotted and located on county GIS plat maps. Have these maps stored in hard copy somewhere safe.
5. Impacts of such events cannot be understood using regulatory total coliform and nitrate data alone. Sample and map ambient water quality county-by-county before the next disaster. The suite of physical-chemical and microbial ecology parameters used in this study provides a basis for understanding an ambient baseline condition, and the information can be gathered with minimal facilities under field conditions by trained people. With such an ambient

baseline recorded, deviations can be recognized, even if basic regulatory parameters are negative or inconclusive.

6. The plan should include a well triage strategy for use in the event of an emergency:
   a. Start with a rapid survey (aided by having wells finely located). Have teams trained in 1) evaluation and expedient fixes (pump repair) and 2) human interaction (customer relations).
   b. Accurately mark and bypass 2-in. deep wells with in-line jets, and 2-in. jetted or driven wells. Have people pump them, but leave treatment or replacement to an equipped contractor. Pulling is fraught with difficulties.
   c. Instruct people on how to treat shallow bored wells.
   d. Recruit and train (and certify as in CPR) "neighborhood helpers" - those people found in any neighborhood or community who are capable, helpful and competent in fixing things, who others look to for this. Train them to safely and effectively deal with the well problems that do not require contractor equipment, such as jet pump repair or shallow well disinfection. Similar training should be supplied to employees in stores providing plumbing and pool-spa chemical supplies. Both safety and effectiveness must be emphasized.
7. Equip response teams as follows:
   a. A supply of pump sets for circulating chlorine and pumping, equipped as needed (hoses, valves, fittings) and working. Include a generator, instructions, etc.
   b. As only $Ca(OCl)_2$ has a lengthy shelf life (when stored cool and dry), keep some of this on hand in various forms for use until trucks can bring in sodium hypochlorite. Include any associated treatment chemicals such as vinegar for acidizing. Rotate stocks semiannually.
   c. Teams should also be equipped with and trained to use well water testing equipment similar to that used in this study - maintained, calibrated, and with fresh batteries. Testing should be part of triage and follow up.

6.3.2 National Recommendations

1. Based on the sometimes weak knowledge of literature expressed by survey respondents (Section 3), training and better market penetration of effective publications (some multilingual) should be reviewed by the NGWA and improved as needed.
2. If the "trained responder" program were successful in North Carolina, it could be expanded nationally and adapted internationally. This can begin with recommended procedures, formatted for both U.S. and international use. Follow up can include the development of training programs for well disinfection, designed for public health personnel and well-treatment contractors.

7 General Recommendation for Emergency Well Disinfection

Section 6.3 of the report outlines a recommended state Emergency Response Plan (ERP) for large-scale inundation events. In North Carolina and other states that may be affected by such large-scale events, FEMA should take steps to assure that the well inundation ERP, including the following provisions, is drafted and its provisions implemented.

7.1 Planning for a Potential Large-Scale Inundation Event

The following is a set of recommendations for planning and implementing a program of returning water supply wells inundated by flood to potable status. Implementing these activities will require coordination among county departments and among local jurisdictions, the state, and supporting federal agencies such as FEMA, and also with the private sector. An appropriate organizational umbrella under which this process could operate is state/county emergency management.

1. In each county/district of local government environmental health, teams will be trained and equipped to evaluate, help and conduct needed immediate repairs of wells as needed to restore private water supply function and potability. The team should include government environmental health staff, private-sector personnel experienced in well and pump service, and other people with specific knowledge of local ground water quality and occurrence, such as hydrogeologists. The teams need to be trained in both a) evaluation and expedient fixes (pump repair) and b) human interaction (customer relations). Private sector teams members should be on retainer or standing purchase order.
2. These teams in turn should train a) retail workers, such as those working in hardware stores and home-improvement superstores who work with pumps, plumbing, and chemical selection and b) "neighborhood helpers" - those people found in any neighborhood or community who are capable, helpful and competent in fixing things - to assist people with basic pump repair and well disinfection. Train them to safely and effectively deal with the well problems that do not require contractor equipment, such as jet pump repair or shallow well disinfection, the specifics of safety issues, and water sampling. Such trained personnel, upon passing a practical examination, would be awarded a limited-time certification in emergency water supply assistance. The local environmental health agency would maintain and publicize a current list of stores with such certified personnel available. Certified neighborhood helpers would identify themselves to emergency response personnel and neighbors, and be known to well ERP team members. All such responders must be insured or otherwise protected under state “good Samaritan” provisions to the extent appropriate.
3. Draft and supply simply worded and illustrated fact sheets with detailed recommendations for safe pump function restoration, well flushing, and well disinfection, with versions in both English and widely used secondary languages such as Spanish.
4. In support of activities triggered under the local well restoration ERP:
    a. Have wells spotted and located on county GIS plat maps, with a database of essential well characteristics (type, depth, diameter). Hard-copy maps and GIS electronic file backups should be generated regularly, made available to the well response teams, and stored safely in case of emergency.

b. Collect data on hydrogeology (aquifer tapped by wells, protective layers, water tables) and a suite of physical-chemical and microbial ecology parameters that provides a basis for understanding an ambient baseline condition. With such an ambient baseline recorded, deviations from the expected hydrogeochemical profile of a well can be recognized, even if basic regulatory parameters are negative or inconclusive. Include this hydrogeochemical data in the GIS database and as map layers for use by the well ERP team.
c. The plan should include a well triage strategy for use in the event of an emergency, as follows:
   1) Start with a rapid survey (aided by having wells finely located) to assess the situation and to formulate a response.
   2) Accurately mark and bypass 2-in. deep wells with in-line jets, and 2-in. jetted or driven wells, and other wells requiring specific training and equipment to restore. Have people pump them, but leave treatment or replacement to an equipped contractor.
   3) Instruct people on how to treat shallow bored wells.
   4) Sample wells for total coliform once restored to function and pumped. Certified helpers would supplement environmental health in this.
   5) Plan and implement follow-up testing and additional response, such as ordering and assisting impaired well replacement.

5. Equip response teams as follows:
   a. A supply of pump sets for circulating chlorine and pumping, equipped as needed (hoses, valves, fittings) and working. Include a generator, tools, parts and instructions to install functional systems on typical installations. Provide and periodically update reliable telephone numbers for troubleshooting and installation assistance.
   b. As only $Ca(OCl)_2$ has a lengthy shelf life (when stored cool and dry), keep some of this on hand in various forms for use until trucks can bring in sodium hypochlorite. Include any associated treatment chemicals such as vinegar for acidizing. Rotate stocks semiannually. Have on hand measuring cups and laminated sheets with information on dosing volumes for wells by diameter and depth.
   c. Well water testing equipment similar to that used in this study - maintained, calibrated, and with fresh batteries – and sampling supplies for (limited) onsite and laboratory analysis of TC, nitrates, and selected other contaminants. Testing should be part of triage and follow up.
6. Local environmental health jurisdictions should aggressively work to reduce the number of substandard and unsafe private water supplies vulnerable to flooding inundation.
   a. Begin a public information campaign to educate well owners and users about safe and unsafe or vulnerable water supplies and how they can be tested and improved.
   b. Deficiencies in specific well and pump installations (poorly designed, vulnerable to inundation or damage during credible flooding events, or otherwise unsafe in addition to not meeting state rules) identified during mapping efforts should be called to the attention of property owners and responsible parties, with procedures and schedules for resolution provided.
7. This inspection and response plan should have a regular review and revision cycle with measurable goals set.

7.2 Immediate Response and Prioritizing Follow-up Response

1. Determine that an emergency exists, assess its magnitude and implement the well restoration ERP elements appropriate to the emergency.
2. Broadcast instructions for safely restoring well function and activate the network of certified well responders and professional contractors. Make instructions for disinfection that can be attempted by well owners and contacts for assistance available to affected residents.
3. As soon as it is safe, well ERP teams begin the reconnaissance to determine necessary responses for specific wells and assign them to the appropriate responders. Use the predetermined well designations from disaster-preparedness inspections (Section 7.1).
    a. Inform residents of the response plan and schedule. Provide a point of contact for residents, and assist them as needed in obtaining emergency potable and wash water.
    b. In a site visit:
        1) Identify and record (narrated video or by photography with notation) problems for follow up later.
        2) As soon as possible, restore well function and instruct residents to pump wells several hours to clear contamination.
        3) Sample for contamination parameters.
        4) If analysis results indicate that contamination has occurred (or may have occurred), implement disinfection as follows.

7.3 Emergency Disinfection Methods

While disinfection procedures are somewhat specific to the individual well's dimensions, design and conditions, the following are general requirements of emergency disinfection in response to inundation.

1. As needed, restore pump function as needed and pump inundated wells clear for several hours to clear dirt and flood water contaminants. Do not pump flush water through treatment and distribution systems, but discharge from the first flushing tap. The time required is dependent on well size, aquifer hydraulic conductivity, and flood water depth and quality. As few as three hours and as many as 24 may be needed, and reasonable numbers should be determined for local conditions.
2. In a clean mixing tank or container, mix a solution with 100 mg/L (ppm) chlorine, maximized for hypochlorous acid: In the appropriate volume (one well bore volume – determine by well diameter, depth, and depth to water level) of clean water, acidify with white distilled food-grade vinegar or more concentrated food-grade acetic acid to approximately pH 5.9 (varies according to water pH and buffering capacity). Then mix in the sodium hypochlorite solution (generally 5-12 %) volume needed to make a 100-ppm solution. Adjust pH as needed to pH 6.5 or less. Alternative: Use powdered or granular calcium hypochlorite for chlorine and muriatic or sulfamic acid for acidifier. People conducting this mixing must be trained in the specific chemical safety issues of these chemicals and mixtures and their use and be equipped to avoid injury and to respond to spills.
3. Drain or pump to the bottom of the well.

4. Start agitation or pumping to pull solution upward throughout the water column.
5. Allow to react up to 24 hr.
6. Pump off to waste, avoiding environmental harm, until measured total chlorine is <0.2 mg/L.
7. Conduct water system disinfection per state rules or recommendations.
8. After one week, test for total coliform bacteria and nitrates. In the interim, instruct residents to boil water for drinking and cooking. Exception: Boiling should be avoided if a history of high nitrates exists, substitute filtration.
9. If wells are substandard at inspection, or do not respond to treatment, follow up with action to require replacement or repair, and provide the appropriate assistance to make this happen.

Specific steps for a 2-in in-line jet well)

1. Pump clear 3 well volumes or fresh ground water by parameters
2. Mix in large plastic tubs: vinegar for acidifying and sufficient NaOCl to treat 2 well volumes
3. Pull in-well pipe and jet (inspect and clean)
4. Displace in chlorine solution: Air used to displace solution downward and a bailer to pull solution upward through the water column
5. Wait 24 hr
6. Reinstall pump components and hook up jet pump
7. Pump off to clear
8. Pump one well volume + after Cl is < 0.2 mg/L and test for TC and ion parameters.
9. In one week, test for indicator parameters.

Specific steps for a bored well:

1. In clean, new 32-gallon plastic trash cans, mix vinegar and NaOCl or $Ca(OCl)_2$ to make a well-bore volume of 100-mg/L solution, and permit residues to settle.
2. Pump well down and clear.
3. Dose with chlorine solution and brush well walls
4. Let refill if slow to respond after emptying
5. Recirculate with jet pump
6. Wait 24 hr
7. Pump clear (to < 0.2 mg/L by chlorine test kit)
8. Pump more than one well volume, then test for indicator parameters

Follow up

1. Take steps to replace vulnerable and substandard well water supplies, with specific plans, goals and schedules, developed through consultation with the public, regulatory officials, stakeholders, and funding sources, and prevent installation of at-risk private water supplies in the future.
2. Review the well restoration ERP and its implementation and make adjustments needed.

The above recommended protocols should be viewed as being preliminary and subject to review and revision by the implementing agencies.

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Note: On-line citations are referenced by the URL where they were encountered, which may change.

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Appendices

Note: In the submitted report, the following had some information on private property, which has been obscured here. That information (and the spreadsheets) can be made available to those with legitimate interest upon request. Contact info@groundwaterscience.com

Appendix A

A.1 Identification and characteristics of wells tested
A.2 Latitude and longitude of sampled and tested wells (reserved)
A.3 Water quality data for wells tested (Microsoft Excel™ spreadsheet)
A.4 BART results for wells tested (Microsoft Excel™ spreadsheet)
A.5 Results of disinfection of wells, Edgecombe County (Microsoft Excel™ spreadsheet)
A.6 Results of disinfection of wells, Pender County (Microsoft Excel™ spreadsheet)

Appendix B

Attached documents

A.1. Identification and characteristics of wells tested

County	Neighborhood	Dia.	Depth	Construction	Pump type
Edgecombe	Bogey	24		bored	shallow jet
Edgecombe	Bogey	24		bored	shallow jet
Edgecombe	Bogey	24		bored	shallow jet
Edgecombe	Bogey	24		bored	shallow jet
Edgecombe	Bogey	24	24.7	bored	shallow jet
Edgecombe	Bogey	24	75	drilled	DW jet
Edgecombe	Bogey	24		bored	shallow jet
Pender	Croomsbridge	2		drilled	inline jet
Pender	Croomsbridge	2		drilled	inline jet
Pender	Croomsbridge	2		drilled	inline jet
Pender	Croomsbridge	4		drilled	submersible
Pender	Croomsbridge	2		drilled	inline jet
Pender	N Whitestocking	2		drilled	inline jet
Pender	N Whitestocking	2		drilled	inline jet
Pender	N Whitestocking	2		drilled	inline jet
Pender	N Whitestocking	2		drilled	inline jet
Pender	N Whitestocking	2		drilled	inline jet
Pender	River Bend	4"	~250	drilled	submersible
Pender	River Bend	2"	~80	drilled	inline jet
Pender	River Bend	2"	~80	drilled	inline jet
Pender	River Bend	4"	~250	drilled	shallow jet
Pender	River Bend	2"	~80	drilled	inline jet
Pender	River Bend	4"	~250	drilled	shallow jet
Pender	River Bend	2"	~80	drilled	inline jet
Pender	River Bend	2"	~250	drilled	
Pender	River Bend	2"	~250	drilled	inline jet
Pender	River Bend	4"	~350	drilled	submersible
Pender	Lower Whitestocking	2"	~250	drilled	inline jet
Pender	Lower Whitestocking	2"	~250	drilled	inline jet
Pender	Lower Whitestocking	2"		drilled	inline jet
Pender	Lower Whitestocking	2"		drilled	inline jet
Pender	Lower Whitestocking	2"		drilled	inline jet
Pender	Lower Whitestocking	2"		drilled	inline jet