SUMMARY DOCUMENT
STATE OF RESEARCH ON HIGH-PRIORITY DISTRIBUTION SYSTEMS ISSUES

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Disclaimer

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1. INTRODUCTION AND BACKGROUND

The Research and Information Collection Partnership (RICP) is a working group formed by recommendation of the Total Coliform Rule Distribution System Advisory Committee (TCRDSAC) to identify specific high-priority research and information collection activities and to stimulate water distribution system (DS) research and information collection. The TCRDSAC further recommended that this research and information collection agenda include short, medium, and long term research and information needs that support EPA's Third Six-Year Review of existing regulations with distribution system components, except for the Total Coliform Rule for which revisions were already being recommended (USEPA, 2008). The current RICP partners are the U.S. Environmental Protection Agency (EPA) and the Water Research Foundation (WRF).

1.1. Objective of the Research and Information Collection Partnership and the Steering Committee

The EPA and the WRF, hereafter called "partners", signed a memorandum of understanding (MOU) in January 2009, which formed the RICP. The TCRDSAC Agreement in Principle (AIP) specified that the RICP was to ―establish a science-driven, mutually-agreed-upon, strategically-focused, decision-relevant research and information collection agenda that encompasses short, medium, and long term research and information needs (US EPA, 2008). The objective of the RICP was to stimulate distribution system research and information collection from all interested parties.

The TCRDSAC AIP also specified that the RICP form a steering committee. The role of the steering committee was to review and accept the products of the RICP. The steering committee was selected to provide a broad perspective on the relevant drinking water distribution system issues. The RICP steering committee members included individuals from EPA, water utilities, and state regulators, as well individuals who shared perspectives from small water utilities, public health, and environmental advocacy groups. For a full list of steering committee members, see Appendix.

1.2. Distribution System Research and Information Collection Priorities

The TCRDSAC identified DS research and information collection priorities, and classified them in two tiers depending on the extent to which information was available demonstrating direct impacts on public health. The priorities consist of the following:

Tier One (Documented Health Outcomes)

1. Cross connections and backflow of contaminated water.
2. Contamination due to storage facility design, operation or maintenance.
3. Contamination due to main installation, repair or rehabilitation practices.
4. Contaminant intrusion due to pressure conditions and physical gaps in distribution system infrastructure.

Tier Two (Suspected Health Outcomes)

5. Significance and control of biofilm and microbial growth.
6. Nitrification issues that lead to public health effects.
7. Accumulation and release of contaminants from DS scales and sediments.

1.3. The Process

The partners followed a multi-year process to develop this product. The process involved the following steps: identification and publication of high priority research and information collection needs (USEPA and WRF, 2010); annual meetings of the steering committee to discuss research and information collection activities; communication and public involvement; implementation and analysis.

1.3.1. Identification of High-Priority Research and Information Collection Needs

Based on a three-year research effort with industry experts, the RICP developed the document titled, *Priorities of the Distribution System Research and Information Collection Partnership*. The Priorities document identifies 10 high-priority research and information collection topics that are all classified as Tier One priorities (USEPA and WRF, 2010):

1. Best Practices to Minimize Risks Associated with Cross-Connections and Backflow
2. Contaminant Entry from Breaches in Storage Facilities
3. Estimation of Contaminated Water Volumes and Contaminant Concentrations Introduced into Distribution Systems Due to Backflow Events from Unprotected Cross-Connections Based on Model Predictions and Field and Pilot-Scale Experiments
4. Quantitative Microbial Risk Assessment (QMRA) to Evaluate Exposure to Pathogens through Drinking Water Distribution Systems
5. Epidemiological Studies of Health Effects Associated with Low or Negative Pressure Events in Distribution Systems
6. Survey of Distribution System Pressure Management Practices
7. Characterize Propagation of Pressure Events through Water Distribution Systems to Improve Pressure Management Approaches
8. Best Practices for Minimizing Risks Associated with Storage Facilities
9. Survey of Large Drinking Water Utility Distribution Systems
10. Targeted Surveys to Obtain Information on State and Local Regulations, Policies, Manufacturing Practices, and Guidelines for Distribution Systems

1.3.2. Annual Meetings

The TCRDSAC AIP specified that the RICP steering committee meet at least once per year over the duration of the research and information collection partnership. The partners and steering committee met 8 times between April 2009 and April 2010, prior to finalizing the Priorities document in May 2010. Eleven additional meetings and teleconferences were held between May 2010 and March 2016.

1.3.3. Communication and Public Involvement

The partners and steering committee members periodically disseminate results of research and information collection efforts through public meetings and conference proceedings. In April 2013, the RICP steering committee partnered with the EPA National Center for Environmental Research's Science to Achieve Results (STAR) Grant Progress Review to hold a public meeting with updates from STAR grantees and other scientists working on research related to the priorities identified by the RICP. In November 2014, the RICP steering committee organized a Special Topic Session at the American Water Works Association (AWWA) Water Quality Technology Conference. The session included an overview of the RICP and presentations from scientists working on RICP priority research. In June 2016, the RICP will present the results from this report at the AWWA Annual Conference and Exposition.

1.3.4. Summary of Analyses Conducted

The RICP steering committee undertook a number of analytical activities to assess distribution system research and information collection needs. Initial RICP meetings and analyses revealed that challenges related to better understanding and addressing possible public health impacts from potential degradation of drinking water quality in distribution systems were greater than initially expected. Thus, the RICP underwent the analytical activities in Section 1.3.1 to develop a list of the 10 highest priority research and information collection needs.

More recent RICP steering committee analysis activities include a literature review and gap analysis to identify remaining research gaps and information needs. This report summarizes those activities, including research findings from papers published between 2010 and 2014, preliminary results from research projects that were underway when the literature review was conducted in 2014, and a limited number of highly relevant papers that were published during the revision process. The report is organized by the 10 high priority distribution system issues with sub-sections describing the scope of research studies, research findings, analysis of research needs and information gaps, and conclusions.

The analysis of research gaps and information needs, summarized in Tables 1-10, was conducted based on the availability of new research and information as of August 2014. For each of the 10 high priority topics, specific research objectives that were identified in the RICP Report (EPA and WRF, 2010) are listed in Tables 1-10 and used to further assess the degree to which a research topic gap may have been met. The tables also include suggested approaches for filling the research gaps that were first identified by EPA and WRF (2010). The following terms are used to assess each research objective:

- "Not Met" indicates that no new information was provided for the project's literature review. It is possible that relevant research or information exists, but it was not compiled and synthesized or provided when this report was developed. It is also possible that new research or information collection exists on the topic, but it is not relevant to targeted outcomes.
- "Partially Met" means that some new research was conducted or information provided that could be a step toward addressing an information gap, or addresses a partial objective of the research need.
- "Fully Met" typically indicates that additional research was conducted, confirming industry understanding of fairly well-established principles. Combined with the body of information available prior to 2010, it seemed reasonable to conclude that additional new research/information would not be needed for the particular objective. The degree to which a particular objective is fully met will vary depending on the target product (e.g., regulation, guidance, industry standard).

2. NEW INFORMATION AND REMAINING GAPS FOR THE 10 PRIORITY RESEARCH AREAS

2.1. BEST PRACTICES TO MINIMIZE RISKS ASSOCIATED WITH CROSS-CONNECTIONS AND BACKFLOW

The purpose of this research area is to identify and describe best practices for minimizing contamination via cross-connections and backflow. Such research could provide information regarding the cost-effectiveness of best practices as well as barriers to implementation of best practices (USEPA and WRF, 2010).

2.1.1. Description of Ongoing and Recently Completed Research Projects

Multiple sources have published guidance or articles describing best practices for minimizing risks associated with backflow events. In 2012, the Rural Community Assistance Corporation issued a guide describing best practices for cross-connection control, targeted to systems serving fewer than 3,300 people (RCAP, 2012). Burlingame et al. (2011) describe pathways for contamination within the DS, including cross-connections and pressure conditions or intrusion. Adamus (2013) discusses best practices to prevent cross-connections in high-hazard facilities, including elements to be included in utility cross-connection control programs. Raucher et al. (2014) took a closer look at boil water advisory implementation, an action utilities might implement in response to a backflow event. This study compiled existing information on boil water advisory implementation, such as benefits, costs, and factors which may influence effectiveness of the action.

An AWWA survey captured some information on cross-connection control and backflow management at selected utilities in the United States. In 2011, AWWA conducted a pilot survey of nine utilities serving more than 50,000 customers focusing on DS activities and issues. The cross-connection and backflow portion of the survey reviewed the number and types of connections in the systems, cross-connection control program elements, and number of backflow prevention assemblies. However, the survey report was not finalized and results are not available for citation. More information on this survey can be found in Section 2.9.

Research that may lead to improving industry practices has been conducted to identify factors associated with occurrence of backflow events and cross-connections. Schneider et al. (2010) conducted research to identify the most effective technologies for rapidly detecting backflow events at residential service connections. The authors developed a risk matrix and conducted surge modeling to identify DS locations that may have more potential for backflow events. The WRF is supporting an ongoing project using flow meters to better understand the frequency of backflow and to identify conditions that can promote backflow (Schneider et al., 2012, 2014). In 2013, Schneider et al. (2014) conducted accuracy testing of new meters, collected information on 14,000 reverse flow events registered by meters, and developed a classification system for reverse flow events. The outcome of this research (not yet available) will include guidance for reducing the occurrence of conditions that can contribute to backflow events.

2.1.2. Key Findings from Relevant Publications

Researchers noted that one reason for the difficulty in identifying backflow events and associated factors is the lack of utility data. Schneider et al. (2010) found that backflow events were not necessarily observed in areas predicted to be associated with low or negative pressures, and some did occur in areas that were thought to be less vulnerable. The investigators noted difficulty in assessing risk factors because of a lack of clear, detailed backflow event documentation.

WRF Project 3022 concluded that backflow of water from residential connections to the DS is probably more widespread than currently thought (Schneider et al., 2010). However, the authors indicated that installation of backflow prevention assemblies on every residential connection would be cost-prohibitive and that this measure should be confined to service connections where backflow could be a public health concern. This study also included development of a protocol for responding to backflow events detected by utilities.

WRF Project 4384 (Schneider et al., 2014) reported a similar frequency of reverse flow events (1.5% per month) in residential water meters as WRF Project 3022 (Schneider et al., 2010). Schneider et al. (2014) found that new positive displacement meters were largely accurate over the expected flow range but some of the other meter types tested were not accurate over the full flow range.

Raucher et al. (2014) developed a framework for conducting a risk-based analysis of the efficacy of boil water advisories, identifying information gaps and research priorities.

2.1.3. Research Gaps and Information Needs

Five research objectives identified in the RICP document (USEPA and WRF, 2010) are used to assess research and information needs on best practices to minimize risks with cross-connections and backflow events (Table 1). Three of these research objectives have been partially met and two have not been met.

2.1.4. Conclusions

Research conducted from 2010 to 2014 resulted in new guidance and information on preventing and responding to backflow events and characterizing risk factors. Multiple organizations have published information on best practices for minimizing risks associated with backflow events. Researchers noted that one reason for the difficulty in identifying backflow events and associated factors is the lack of utility data. Topics that require additional research include documentation of backflow events; compilation of existing resources; evaluation of training programs; and implementation of cross connection control programs.

Table 1. Gap Analysis for Research Topic CC1: Best Practices to Minimize Risks Associated with Cross Connections and Backflow

	Not Met	Partially Met	Fully Met	Explanation	Suggestions for Filling Gaps
Objective 1: Compile existing materials that document best practices that are used by a range of different audiences (e.g., utility personnel, plumbers) to diagnose, prevent and mitigate backflow contamination risk factors, including cross connection hazard surveys, elements of effective cross-connection control programs and responses to contamination events. Information related to implementation costs and barriers to implementation will also be compiled.					
Compilation of available materials	X			– Ranked as "Not Met" because there is no indication from the information provided for review that the significant quantities of existing information from already available resources have been compiled in one location by any group/organization since 2010.	Compile available literature, references, manuals, training materials, industry surveys, interviews and site visits, and existing cross connection and backflow materials.
Objective 2: Provide a single reference resource for industry personnel to evaluate cross connection and backflow related risk factors, and risk mitigation options (including costs and potential implementation obstacles). Risk factors are those factors which potentially contribute to the occurrence of backflow (e.g., unstable operating pressures).					
Development of a single reference resource Ultimate goal is development of "State of Knowledge" synthesis document.	X			– Numerous resources available prior to 2010 regarding cross connection risk factors. – Ranked as "Not Met" because there is no indication that a single reference resource has been developed from the materials compiled and referenced above, since 2010.	Provide a comprehensive review and summary of key existing information and knowledge from available materials on potential risk factors.
Costs and implementation obstacles	X			– Ranked as "Not Met" because no new information related to costs and implementation barriers was provided for review.	Update existing guidance information with current costs to correct potential cross connections and install backflow prevention assemblies. Provide a comprehensive review and summary of existing information on barriers to implementation and strategies to overcome these barriers.

	Not Met	Partially Met	Fully Met	Explanation	Suggestions for Filling Gaps
Additional information related to risk factors		X		– Adamus (2013) describes high hazard facilities with respect to cross connections. – Schneider et al. (2010) developed a risk matrix for utilities to use as a tool in their own systems. However, the study does not make use of the tool to assess backflow vulnerability (relies on modeling instead). The authors indicate difficulty in developing the risk matrix due to lack of clear data collected for backflow events. – Schneider et al. (2010) reported backflow measurements in locations not consistently associated with a risk of vulnerability to low or negative pressures. – Schneider et al. (2014) reported a similar frequency of reverse flow events (1.5% per month) in residential water meters as WRF Project 3022 (Schneider et al., 2010) – Burlingame et al. (2011) on contamination pathways in DS included a brief description of cross connection and backflow.	Develop tool that can assist utilities in evaluating risks.
Objective 3: Evaluate attributes of effective training programs provided to water utilities, plumbers, etc. and provide a resource from which training materials could be developed.					
Evaluation of training programs	X			– Numerous training resources available prior to 2010 regarding cross connection risk factors. – Ranked as "Not Met" since no indication that these resources have been evaluated since 2010.	Evaluate available training materials. Develop a glossary with illustrations, definitions, etc., that can be used by the water industry and others to promote dialog and to more fully characterize cross connections and backflow.
Objective 4: Determine key barriers to development, implementation and enforcement of cross connection control and backflow prevention programs, and provide cast study examples of how these barriers have been overcome.					
Determine key barriers to implementation	X			No new information for 2014 literature review.	Provide case study examples of how some systems have overcome key barriers to development, implementation, and enforcement of cross connection control and backflow prevention programs.
Case studies	X			No new information for 2014 literature review.	

	Not Met	Partially Met	Fully Met	Explanation	Suggestions for Filling Gaps
Objective 5: Develop strategies to quantify and benchmark the effectiveness of Best Practices used by utility personnel, plumbers, etc. and document case studies of successful programs.					
Metrics and benchmarking	X			No new information for 2014 literature review.	Provide easy to use examples and case studies of cross connection and backflow risk-related regulations, standards, policies, certification programs, ordinances, key program elements, codes and best practices. Provide comparative costs and constraints for adoption of risk evaluation, prevention and mitigation measures. Applies to Objectives 3 and 4 as well.
Case studies	X			No new information for 2014 literature review.	
Responses to cross connection events		X		– Schneider et al. (2010) developed protocol for responding to backflow events detected by utilities. – RCAP (2012) has 6 bullet list of responses to backflow events.	
Effective programs			X	– Numerous resources available prior to 2010 regarding effective program elements. – Adamus (2013) discussed cross connection control best practices including cross connection prevention in high hazard facilities. – Small system guidance (RCAP, 2012) has a brief section depicting cross-connection control assemblies, some training on risk assessment, and case studies.	Not applicable

2.2. CONTAMINANT ENTRY FROM BREACHES IN STORAGE FACILITIES

The purpose of research in this area is to compile data to help water utilities and regulators better understand and predict health risks associated with contaminant entry through structural breaches in storage facilities (USEPA and WRF, 2010). Data are needed on the frequency and relative magnitude of contamination events at storage facility hatches, vents, covers, roofs, and sidewalls. Other research needs include the factors that contribute to the contamination events and the types of contaminants.

2.2.1. Description of Ongoing and Recently Completed Research Projects

Although contamination events may be occurring at finished water storage facilities, only one recently published paper on such an event was found. Ailes et al. (2013) investigated the causative factors, health effects, and economic impacts of a large *Salmonella* outbreak that occurred in 2008 in the Alamosa, Colorado, municipal water supply, an unchlorinated groundwater source. The authors conducted interviews with local, state and non-governmental agencies, health care facilities, and schools, as well as a postal survey of the 8,746 residents.

Industry standards and guidance are available to help utilities develop programs and practices to prevent or respond to contaminant entry due to a storage facility breach. AWWA Standard G200, *Distribution Systems Operation and Management* (AWWA, 2010) describes requirements for storage facility inspection programs. AWWA Standard C652-11 *Disinfection of Water-Storage Facilities* (AWWA, 2011b) describes required disinfection procedures following inspection, maintenance, or construction of a new storage facility. Oberoi (2013) illustrated how Charleston Water System in South Carolina meets AWWA Standard G200. Washington State developed guidelines to improve the sanitary protection of stored water (Washington State DOH, 2010a and 2010b). Storage facility inspections are required by regulation or statute in 16 states and are included in sanitary surveys or sanitary survey requirements in 32 states (USEPA and Cadmus, 2013).

2.2.2. Key Findings from Relevant Publications

Investigations of a *Salmonella* outbreak in the Alamosa municipal water supply concluded that the likely cause was the municipal water system and, specifically, a storage tank that had numerous cracks and entry points (Ailes et al., 2013). Of 1,732 residents who provided survey responses, 369 reported diarrheal illness during the outbreak, and 108 reported possible long-term health impacts (e.g., skin problems, arthritis or other joint problems, urinary tract problems, eye pain or redness, abscess, bowel perforation, septic arthritis, endocarditis). The total cost of the outbreak was estimated to be $2.6 million, including costs to residents, businesses, schools, health care facilities, and agencies.

2.2.3. Research Gaps and Information Needs

Four research objectives are used to assess research and information needs on contaminant entry from breaches in storage facilities as listed in Table 2. Two of these research objectives have been partially met and two have not been met.

2.2.4. Conclusions

Industry standards and guidance are available to aid in preventing contaminant breaches in finished water storage facilities. Many training resources are available but additional training workshops are needed to provide information to utilities on finished water protection and DS optimization. Literature is lacking on utility case studies of storage facility contamination events. Research studies should be conducted to assess storage facility contamination and pathogen occurrence under various operating conditions.

Table 2. Gap Analysis for Research Topic Con3: Contaminant Entry from Breaches in Storage Facilities

	Not Met	Partially Met	Fully Met	Explanation	Suggestions for Filling Gaps
Objective 1: Enhance the understanding of effectiveness of various storage breach-related risk mitigation measures, costs, and implementation obstacles.					
Availability of state and industry standards and guidance		X		– Oberoi (2013) provided a detailed overview of AWWA Standard G200, Distribution Systems Operation and Management, and illustrated how Charleston Water System in in South Carolina meets this voluntary standard. – Storage facility inspections are required by regulation or statute in 16 states and are included in sanitary surveys or sanitary survey requirements in 32 states (USEPA and Cadmus, 2013). – Washington State developed guidelines to improve the sanitary protection of stored water (Washington State DOH, 2010a and 2010b), troubleshoot coliform contamination, and implement emergency disinfection procedures at small systems (Washington State DOH, 2010c and 2011). – Ailes et al. (2013) identified critical control measures including comprehensive inspections of storage facilities, identification of system deficiencies as part of sanitary surveys, and adequate resource allocation to address system deficiencies in a timely manner. – EPA's contractor surveyed nine state primacy agencies to document current state requirements and practices on finished water storage monitoring, as well as to identify available resources and guidelines (Cadmus, 2013).	Collect guidance information from all state primacy agencies.
Availability of training programs		X		– Available resources include WRF webcasts on demand, Partnership for Safe Water Distribution System Optimization Program, operator training programs, Effective Utility Management program.	Conduct utility training workshops to promote distribution system optimization and finished water protection.
Identification of costs and implementation barriers		X		Ailes et al. (2013) investigated the causative factors, health effects, and economic impacts of a large *Salmonella* outbreak due to a storage tank in Alamosa, Colorado.	Need more investigative studies to further characterize costs and implementation barriers. Determine if deficiencies are being identified in sanitary surveys and/or storage tank inspections, and whether repairs are completed in a timely manner.

	Not Met	Partially Met	Fully Met	Explanation	Suggestions for Filling Gaps
Objective 2: To characterize storage breach entry pathways, causes, sizes, mechanisms, durations, and frequencies of occurrence.					
Occurrence of structural breaches (e.g., poorly sealed hatches, unprotected vents, tears in covers, holes, structural cracks) from sanitary survey and inspection reports.	X			No new information for 2014 literature review.	Conduct observational studies (i.e., utility case studies) of storage facilities to evaluate the potential for animal access. Compile data from sanitary surveys, inspection reports and Centers for Disease Control and Prevention (CDC) data on WBDOs.
Objective 3: Measure contaminants in bulk and stored water, and sediments within storage facilities.					
Monitoring and source tracking to determine relative magnitude of contamination from structural breaches.	X			No new information for 2014 literature review.	Identify potential pathogen sources of contaminants that might gain entry to storage facilities (e.g., birds). Delineate possible storage contamination scenarios and relative risks including animal access.
Occurrence of water quality events (e.g., total coliform positive caused by structural breach (Frequency, number of events, geographic distribution, system size).	X			No new information for 2014 literature review.	Conduct sampling studies following total coliform positive and other water quality events connected to storage facilities; Complete Revised Total Coliform Rule assessments following total coliform positive events.

	Not Met	Partially Met	Fully Met	Explanation	Suggestions for Filling Gaps
Objective 4: Estimate the extent to which pathogen accumulation, growth, or die-off occurs due to storage conditions or operations (e.g., fill/draw, mixing, stratification, disinfection effectiveness, entrapment in sediments or biofilms, temperature) to develop predictive models to estimate release from storage into the distribution system.					
Full-scale studies of pathogen occurrence under various operating conditions	X			No new information for 2014 literature review.	Summarize scientific literature on environmental pathogen occurrence, growth, survival rates, and disinfection susceptibility in finished water storage tanks. Develop and implement plans to characterize and sample storage systems with a range of potential vulnerabilities to external contamination. Estimate pathogen concentrations in different types of storage facilities and underground finished water reservoirs, and the extent to which accumulation, amplification, release, or die-off occurs due to storage conditions or operations.
Pilot-scale studies of pathogen occurrence under various operating conditions	X			No new information for 2014 literature review.	Estimate the effects of mixing on the dispersion of pathogens in the stored water.
Laboratory studies of pathogen occurrence under various operating conditions		X		EPA conducted Computational Fluid Dynamics (CFD) modeling and sediment analyses from 25 tank locations to determine effects of sediment resuspension on metals, organics, and pathogens (Murray et al., 2014).	Conduct targeted sampling and laboratory testing of storage conditions that impact pathogen viability (e.g., disinfectant type and concentration, stratification, temperature, biofilms, or solids accumulation).

2.3. ESTIMATION OF CONTAMINATED WATER VOLUMES AND CONTAMINANT CONCENTRATIONS INTRODUCED INTO DISTRIBUTION SYSTEMS DUE TO BACKFLOW EVENTS FROM UNPROTECTED CROSS-CONNECTIONS

The purposes of this research area are to determine the magnitude and duration of pressure reductions that could introduce contaminants to drinking water via an unprotected cross-connection and to estimate the potential volume of contamination that could enter the DS in this manner (USEPA and WRF, 2010).

2.3.1. Description of Ongoing and Recently Completed Research Projects

The information available on this topic area is very limited. In reviewing the recent and ongoing research, the industry appears to be conducting research on event detection, frequency of events, and some measurement of backflow volume, but not the magnitude and duration of pressure events that could introduce contaminants through unprotected cross-connections.

The AWWA DS survey asked nine utilities whether they recorded the number of backflow events, how events are detected, and the number of backflow events that occurred within the last 10 years. The survey included detailed questions such as type of contaminant associated with the event, whether backflow events occurred within customer plumbing or reached the DS, and if the pressure difference was caused by backpressure or backsiphonage. Final survey results are not available for citation. LeChevallier et al. (2014) conducted an investigation of pressure management practices and monitoring which included a survey and 20 case studies (on systems ranging in size from 1,000 customers to 175,000 customers), one of which involved backflow monitoring.

Researchers have investigated water quality monitoring methods that may have implications for backflow detection. Schneider et al. (2010) investigated the most effective technologies for rapidly detecting backflow events at residential connections. The authors compared water quality monitoring for conductivity, pH, oxidation-reduction potential, and free chlorine using direct hydraulic meters. Hambly et al. (2010) investigated the use of fluorescence spectroscopy versus monitoring water quality parameters and excitation-emission matrix (EEM) spectra from a recycled water treatment plant and locations within a dual DS over 12 weeks to determine which approach was more effective at detecting contamination.

The WRF is supporting an ongoing project that is studying the use of flow meters to better understand the frequency of backflow events and to identify the conditions that can promote backflow (Schneider et al., 2014). This project will determine the ability of flow meters to measure reverse water flows accurately and examine factors associated with measured backflow events, such as pressure measurements and seasonality. WRF intends this project to contribute significantly to industry data on backflow frequency (Schneider et al., 2012, 2014). Until a final report is available, it is difficult to determine, from the available work plan, how much data on backflow volumes will be provided.

The Centers for Disease Control and Prevention (CDC) periodically publishes data on reported waterborne disease outbreaks, including potential causative factors such as deficiencies in water treatment or water distribution. Data for outbreaks reported in the years 2009 and 2010 were published in 2013 (CDC, 2013a).

2.3.2. Key Findings from Relevant Publications

Schneider et al. (2010) determined that the backflow sensing meter is the best available technology for detecting backflow occurrence. Results from this study focus on reporting frequency of recorded events instead of volumes, although some volume-specific information was presented. For example, during the investigation, backflow events of at least one gallon occurred at 1.6 percent of meters each month on average (698 of 42,735 monthly meter reads). Five percent of the 10,313 meters included in this study detected the occurrence of a backflow event. The investigators found that while online water quality monitors can detect small changes in parameters (e.g., free chlorine and oxidation-reduction potential), the technology is not suitable for determining the public health effects of backflow events because the current data processing features cannot identify changes in water quality caused by backflow from those caused by normal variations. Finally, the investigators concluded that further investigation is needed to develop more complete information on the frequency of backflow events and the related water volumes (Schneider et al., 2010).

A case study developed by LeChevallier et al. (2014) included pressure and backflow monitoring within a pressure zone at the same utility studied by Schneider et al. (2010). Two pressure events occurred during the monitoring period, both of which coincided with a main break. During both pressure events, six backflow monitors registered backflow at the same time, indicating that multiple services were affected by each event. Volume measurements were considered to be unreliable.

Hambly et al. (2010) concluded that the EEM method could be used to detect lower contamination levels of recycled water in drinking water systems than measurement of conductivity. Using statistical analyses, the authors found that detection of contamination could occur at a 45 percent contamination rate of recycled water in drinking water using EEM compared to a 70 percent contamination rate using conductivity.

CDC (2013a) identified two distribution system-associated outbreaks (one used an unchlorinated ground water supply) resulting from cross-connections. The etiological agents were *Giardia intestinalis* and *Campylobacter jejuni*. Information on contaminant volumes and concentrations were not provided.

2.3.3. Research Gaps and Information Needs

Three research objectives are used to assess research and information needs for estimating contaminant volumes and concentrations that enter DSs due to backflow as listed in Table 3. Two of these research objectives have been partially met and one has not been met.

2.3.4. Conclusions

Limited information is available on the contaminated water volume and concentration of contaminants that can enter the DS during a backflow event. The industry appears to be conducting research on event detection and the frequency of backflow events. More research is needed to document the occurrence of unprotected cross connections. Key information needs include: estimates of contaminant concentrations associated with backflow events; assessment of pressure changes that can cause backflow or backsiphonage; and nationwide estimates of backflow occurrence and backflow volume.

Table 3. Gap Analysis for Research Topic Con4: Estimation of Contaminated Water Volumes and Contaminant Concentrations Introduced into Distribution Systems Due to Backflow Events from Unprotected Cross-Connections

	Not Met	Partially Met	Fully Met	Explanation	Suggestions for Filling Gaps
Objective 1: To determine the magnitude and duration of pressure reductions under which contaminated water could be introduced to the DS through unprotected cross-connections.					
Magnitude and duration of pressure reductions in the distribution system.		X		– LeChevallier et al. (2014) investigated the use of optimized and baseline pressure monitoring at 20 utilities and developed case studies describing the experience. One case study involved a combination of pressure and backflow monitoring and measured two backflow events coinciding with two main breaks. – LeChevallier et al. (2011b) conducted pressure monitoring at a utility for 40 days at six locations. Reporting focuses on whether a correlation can be found between pressure and water quality, does not provide detail describing pressure changes. – Ranked as "Partially Met" because LeChevallier et al. (2014) capture pressure information for 21 utilities. The degree to which these utilities represent the universe of utilities is not clear.	Identify three “representative” physical distribution configurations to be used in subsequent analyses. Develop information on magnitude and duration from utility records/literature related to systems similar to the three representative configurations.
Documentation of or estimate of presence of unprotected cross-connections.	X			– Ranked as "Not Met" because the AWWA survey is very small and final results are not available.	Review existing utility records and literature to identify the number of unprotected cross-connections per service connection.
Development of estimates of pressure changes which could introduce contaminated water through unprotected cross-connections.	X			No additional new information provided for review in the area of pressure changes that could result in backsiphonage or backflow through unprotected cross-connections. LeChevallier et al. (2014) discusses backflow through residential service meters, not necessarily unprotected cross-connections.	Use existing or newly developed models to calculate the magnitude and duration of backsiphonage and backflow events needed to draw a contaminant through service plumbing and past service connections into the three representative distribution systems.

	Not Met	Partially Met	Fully Met	Explanation	Suggestions for Filling Gaps
Objective 2: To estimate the potential frequency and volume of contamination that may be occurring nationwide through unprotected cross-connections.					
Estimate of backflow occurrence and/or volume.		X		– Research since 2010 has focused on methods for detection of backflow occurrence: Schneider et al. (2010) and Hambly et al. (2010). – Schneider et al. (2010) concluded that further investigation is needed to develop more complete information on the frequency of backflow events and related water volumes. – Schneider et al. (2010) reported that 1.6% of meters detected backflow events of more than one gallon each month. Results of this study focused on backflow detection frequency.	Use models discussed above to calculate frequency and volume of events. Conduct sensitivity analyses on characteristics such as flow rate, pipe length, etc. using the models described above.
Estimate of backflow occurrence and/or volume nationwide.	X			No information describing a national estimate of backflow occurrence or volume provided for review.	Relate modeled information to national statistics on distribution system configurations, unprotected cross-connections, and other key characteristics.
Objective 3: To estimate the contaminant concentration in the contaminant sources (if feasible).					
Estimate of contaminant concentration.	X			Ranked as "Not Met" since no new information on specific contaminants or contaminant concentrations associated with backflows provided for review.	Estimate contaminant concentrations in sources from which backflow contaminants originate. Conduct more detailed review of data collected by CDC during waterborne disease investigations.

2.4. QUANTITATIVE MICROBIAL RISK ASSESSMENT (QMRA) TO EVALUATE EXPOSURE TO PATHOGENS THROUGH DRINKING WATER DISTRIBUTION SYSTEMS

The purpose of this research area is to develop a tool that can be used to estimate relative risks of exposure to DS pathogens and the effectiveness of risk management strategies for preventing and controlling microbial risks (USEPA and WRF, 2010).

2.4.1. Description of Ongoing and Recently Completed Research Projects

Besner et al. (2011) reviewed a conceptual model that describes the elements needed to develop a QMRA model for intrusion into DSs. The review addressed both model input parameters and population exposure methods.

The research team for WRF Project 4307, *Effective Microbial Control Strategies for Main Breaks and Depressurization*, conducted laboratory studies to evaluate pathogen removal from various flushing and disinfection practices and developed a QMRA model for main break and adverse pressure events (Kirmeyer et al., 2014). Researchers evaluated the effectiveness of drinking water disinfection and operational practices in mitigating public health risk and identified parameters that could be used to quantify the level of control achieved.

The project *Water Infrastructure Sustainability and Health in Alabama's Black Belt* includes a prospective cohort study following 900 households for 18 months in rural Alabama to collect information on household water quality and health outcomes (Brown et al., 2012, 2013). Water quality data collected during the epidemiological investigation will be used in QMRA models and compared with epidemiological data (i.e., self-reported health symptoms). The QMRA model will be used to assess transmission pathways for waterborne pathogens and to identify risk mitigation strategies. Based on interviews of 897 households and initial data collection through July 2013, the research team decided to suspend household-based sampling and instead expand the scope and scale of system-level, dead-end sampling for more detailed microbial molecular identification of indicators and pathogens (Brown et al., 2013).

Borchardt et al. (2012) investigated the association between acute gastrointestinal illness (AGI) incidence and quantitative real-time polymerase chain reaction (qPCR) measures of enteric viruses in tap water in 14 Wisconsin communities served by non-disinfected groundwater. As part of this study, Lambertini et al. (2012) evaluated the effect of intrusions into DSs on endemic AGI.

The research team for WRF Project 4152, *Managing Distribution System Low Transient Pressures for Water Quality* (LeChevallier et al., 2011b), developed an expansive QMRA model based on hydraulic, water quality, and surge modeling data.

Researchers in Massachusetts compared daily numbers of hospital admissions for elderly people with AGI to drinking water quality metrics over 11 years (Beaudeau et al., 2014). The utility serving the study population provided disinfected unfiltered surface water. Data were controlled for weather, seasonality, and time trends. During the study period, the utility switched its disinfection method from chlorination to ozonation; changes in risk associated with this treatment modification were evaluated.

As part of the Water and Health Trial for Enteric Risk Study, Lambertini et al. (2012) attempted to quantify human enteric viruses directly entering non-disinfected drinking water DSs and to estimate the fraction of endemic AGI from distribution system contamination, using the QMRA model.

Schoen and Ashbolt (2011) developed a mathematical model to simulate exposure to *Legionella* from inhalation of shower aerosols containing biofilm-associated *Legionella* bacteria. The purpose of the model was to predict *Legionella* densities that would result in infection from inhalation during showering.

Buse et al. (2012) summarized current methods used to identify and quantify *Legionella* and described engineered water system characteristics that are believed to be conducive to *Legionella* growth. The authors discussed the use of these parameters as they relate to QMRA models. Buse et al. (2012) investigated the maximum potential release of *L. pneumophila* from a single infected trophozoite. Buse and Ashbolt (2011) investigated the effect of premise plumbing temperatures on growth of five different *L. pneumophila* strains within free-living amoebae.

Under EPA STAR Grant R834870, Nguyen et al. (2013) at the University of Illinois Urbana-Champaign studied adhesion and release of *Legionella pneumophila* from biofilms in real time. The effects of biofilm roughness and drinking water flow hydrodynamics were identified (Janjaroen at al., 2013). These results could provide information for estimating the risk of *Legionella pneumophila* infection as a function of exposure time.

2.4.2. Key Findings from Relevant Publications

Brown et al. (2013) reported initial results on analysis of household reported water service conditions and health symptoms. Households reporting poor water service (e.g., intermittent service, low water pressure, poor taste, odor, or odd color) were more likely to report gastrointestinal (GI) symptoms and individual symptoms (e.g., diarrhea, vomiting) compared to households that reported satisfactory water service.

Besner et al. (2011) emphasized that the occurrence of intrusion events requires adverse pressure conditions (e.g., low or negative pressure in the system or elevated pressures external to the system), along with presence of outside contamination and a pathway for contaminant entry.

Borchardt et al. (2012) found that communities and time periods with the highest virus measures also had the highest reported AGI incidence, particularly for norovirus genogroup I and certain types of enteroviruses. The study estimated the percentage of AGI attributable to viruses in tap water at 6 percent to 22 percent, depending on virus exposure. The investigation concluded that protecting source water quality and providing groundwater disinfection when needed could reduce AGI burden from groundwater drinking water sources. Lambertini et al. (2012) determined that virus intrusions into non-disinfected drinking water DSs can contribute to endemic AGI.

LeChevallier et al. (2011b) reported that risk levels of infection were slightly higher than EPA's threshold for acceptable levels of annual infection risk if one negative pressure event per year occurred in the study systems. The most critical parameters in determining infection risk were the concentration of viruses, individuals' water intake, and duration of negative pressure events. Risk of infection was most sensitive to the duration of the negative pressure event and the number of intrusion nodes. Based on the results of this research effort, the authors concluded that the most effective practice to reduce health risks from intrusion due to negative pressure is to maintain distribution system pressures higher than external pressures at all times. Maintaining a chlorine residual of 0.2 mg/L is a secondary preventive measure that can be utilized to reduce infection risk.

Beaudeau et al. (2014) found that the risk of AGI attributable to drinking water was likely reduced when the unfiltered utility switched from chlorination to ozonation. The data also suggested that low water temperature and increased turbidity may be associated with higher hospital admissions for AGI in elderly people.

Schoen and Ashbolt (2011) successfully demonstrated use of a model to help identify system-specific critical conditions (e.g., water temperature, available nutrients) that may result in pathogen infection in humans exposed to aerosols through biofilm presence in in-premise plumbing.

Buse and Ashbolt (2011) found that the temperature conditions and species of amoeba host appear to have an important impact on the growth of human-pathogenic *Legionella*. Buse et al. (2012) found that a concentration of 1 to 75 infected amoebae may represent a pathogenic *Legionella* concentration.

Janjaroen et al. (2013) found that biofilm roughness facilitated the accumulation of *Legionella pneumophila* and *E. coli* on biofilms by enhancing the interception between bacteria and biofilms. Meanwhile, biofilm roughness protected pre-adhered *Legionella pneumophila* from detachment under flow shear stress, thus reduced the release of *Legionella pneumophila* to water phase.

2.4.3. Research Gaps and Information Needs

Four research objectives are used to assess research and information needs for QMRA studies to evaluate exposure to pathogens through DSs as listed in Table 4. Three of these research objectives have been partially met and one has not been met.

2.4.4. Conclusions

Recent research projects have developed or are developing QMRA and other types of models to assess DS risks; however, no models have been published specifically to address RICP research objectives. Additional research is needed to refine and validate QMRA models, to standardize modeling practices, and to educate researchers, engineers, and the regulatory community on modeling techniques.

Table 4. Gap Analysis for Research Topic Hea1: Quantitative Microbial Risk Assessment (QMRA) to Evaluate Exposure to Pathogens through Drinking Water Distribution Systems

	Not Met	Partially Met	Fully Met	Explanation	Suggestions for Filling Gaps
Objective 1: Develop models that will enable quantification of risks as sufficient information becomes available.					
Develop and refine existing models to characterize potential pathogen exposure. Use model to identify data that can reduce model uncertainties. Develop an adaptive tool to estimate relative risks of exposure to DS pathogens and evaluate risk management strategies.		X		− No models developed specifically to meet RICP objectives. − WRF Project 4307, *Effective Microbial Control Strategies for Main Breaks and Depressurization*, evaluated pathogen removal from various flushing and disinfection practices and developed a QMRA model for main break and adverse pressure events. − WRF Project 4152, *Managing Distribution System Low Transient Pressures for Water Quality* developed an expansive QMRA model based on hydraulic, water quality, and surge modeling data. − Several studies investigate parameters likely to be used as inputs for QMRA models. − A project in Alabama includes a prospective cohort study to collect information on household water quality and health outcomes (Brown et al. 2012, 2013). Water quality data collected during the epidemiological investigation will be used in QMRA models and compared with epidemiological data.	Begin development of adaptive QMRA tool. Use existing research to validate model and identify data needs. Develop larger scale models. Obtain results from existing QMRA models if available (status of some projects listed here is unknown).

	Not Met	Partially Met	Fully Met	Explanation	Suggestions for Filling Gaps
Objective 2: Depending on available and sufficient information, quantify magnitude of exposure to pathogens associated with distribution systems and identify sources of microbial contamination (bulk water, biofilms, cross-connection, infrastructure breaches or failures), fate and transport factors (growth, die-off, interactions with internal surfaces and biofilms), and potential public health concerns.					
Evaluate scenarios under which contamination events result in pathogen exposure through public water systems. Apply dose-response models to estimate pathogen densities of concern.		X		– Borchardt et al. (2012) investigated association between AGI and measures of enteric viruses in tap water. – Researchers in MA evaluated AGI and water quality metrics – Schoen and Ashbolt (2011) simulated exposure to *Legionella* through shower aerosols. – Buse and Ashbolt investigated in-premise plumbing temperatures on growth of *L. pneumophila.* – A project in AL includes a prospective cohort study to collect information on household water quality and health outcomes. Water quality data collected during the epidemiological investigation will be used in QMRA models and compared with epidemiological data. – EPA STAR grant R834870 investigated the role of disinfectant exposure on biofilm mechanical properties and related release of biofilm associated pathogens.	Continue to investigate and develop case studies where contamination events have occurred. Conduct field simulations to further study sources of microbial contamination. Continue to research dose-response relationships between typical DS pathogens and disease. Conduct statistical analysis of frequency and magnitude of contamination events for different DS vulnerabilities. Determine factors controlling biofilm properties under relevant conditions of drinking water distribution systems, including frequency of use and varied various disinfectant concentration. Develop data analytic tools to predict exposure of pathogens based on real-time imaging of pipe surface.

	Not Met	Partially Met	Fully Met	Explanation	Suggestions for Filling Gaps
Objective 3: Apply QMRA to identify approaches to optimize monitoring and improve the ability to diagnose, prevent, and manage microbial risks.					
Use QMRA to define optimal drinking water system conditions. Use QMRA to evaluate design and management outcomes.		X		– WRF Project 4307, *Effective Microbial Control Strategies for Main Breaks and Depressurization*, evaluated pathogen removal from various flushing and disinfection practices and developed a QMRA model for main break and adverse pressure events. – WRF Project 4152, *Managing Distribution System Low Transient Pressures for Water Quality,* developed an expansive QMRA model based on hydraulic, water quality, and surge modeling data. – Several studies investigate parameters likely to be used as inputs for QMRA models.	Continue to apply and validate QMRA models at different system types and geographic locations. Obtain results from existing research projects, if possible.
Objective 4: Integrate QMRA into the design and implementation of pathogen-related studies to provide a common framework for interpreting data and evaluating the extent to which management options are effective at reducing health risks associated with exposure to water from distribution systems.					
Integrate QMRA into pathogen related studies.	X			– Besner et al. (2011) reviewed a conceptual model that describes the elements needed to develop a QMRA model for intrusion into DSs. The review addressed both model input parameters and population exposure methods.	Continue to standardize QMRA modeling practices. Communicate QMRA practices and objectives to researchers in public health and engineering fields.

2.5. EPIDEMIOLOGICAL STUDIES OF HEALTH EFFECTS ASSOCIATED WITH LOW OR NEGATIVE PRESSURE EVENTS IN DISTRIBUTION SYSTEMS

The purpose of this research area is to obtain information on the incidence and severity of adverse health effects occurring among customers who are impacted by low or negative pressure events in water DSs (USEPA and WRF, 2010). The information can inform estimates of both baseline risks and reduction in those risks resulting from mitigation.

2.5.1. Description of Ongoing and Recently Completed Research Projects

The Centers for Disease Control and Prevention (CDC) periodically publishes data on reported waterborne disease outbreaks, including potential causative factors such as deficiencies in water treatment or water distribution. Data for outbreaks reported in the years 2009 and 2010 were published in 2013 (CDC, 2013a).

In February and March of 2010, the CDC and the Alabama Department of Public Health conducted an investigation in response to a January 2010 event during which 18,000 residents in two predominantly rural counties in Alabama experienced loss of access to municipal water for up to 12 days (CDC, 2011). Using a stratified random sample, investigators conducted a household survey with the goal of assessing the extent of the water emergency and its effect on public health. The primary outcomes of interest were AGI and acute respiratory illness (ARI).

Shortridge and Guikema (2014) attempted to assess whether a statistical relationship exists between main breaks in municipal drinking water DSs and GI, as estimated by Internet search volume for terms related to GI illness. The study compared weekly Internet search volume for symptoms of GI with main break counts in two cities in the United States while controlling for seasonal patterns, climatic fluctuations and other environmental factors.

Ercumen et al. (2014) conducted a meta-analysis to investigate whether distribution deficiencies are associated with endemic GI in water system customers in the United States as well as other developed and developing countries. The authors acknowledge significant heterogeneity among study settings and water system characteristics, even within study subgroups.

A study conducted in Gothenburg, Sweden (Malm et al., 2013), investigated whether there was increased frequency of contact with the city's Health Call Center regarding GI symptoms when deficiencies were reported in the drinking water treatment facility (failure of chlorine disinfection) or DS (pump station failure, main breaks). For each period of disruption, the number of calls by customers to the Health Call Center regarding GI symptoms was compared to calls during a control period (without disruptions in drinking water facility function).

Researchers at Emory University are investigating the relationship between emergency department visits for GI, distribution water quality, and distribution characteristics in the metro Atlanta area (Moe et al., 2013). One research objective was to refine the data set developed during a previous study; this effort is complete and a publication describing the analysis is forthcoming. Currently, researchers are collecting and analyzing data using an automated monitoring and sampling device strategically placed in areas that have historically demonstrated vulnerability to main breaks.

As part of WRF Project 4390 – *Epidemiological Study of Health Effects Associated with Low Pressure Events in Drinking Water Distribution Systems*, CDC researchers will design a prospective cohort study to collect data from households receiving drinking water from three to five selected utilities located across the United States (CDC 2013b). Utilities will be recruited based on a history of low and/or negative pressure events. Researchers will use data collected during the study to evaluate whether individuals exposed to low or negative pressure events in the water DS are at an increased risk for AGI or ARI. Researchers have conducted an initial pilot study (Friedman, 2014). A multi-site follow-up study has begun.

2.5.2. Key Findings from Relevant Publications

From 2009 to 2010, 33 reported waterborne disease outbreaks were associated with 1,040 cases of illness, 85 hospitalizations, and nine deaths (CDC, 2013a). The most frequently identified causal deficiencies in the drinking water-associated outbreaks were *Legionella* in plumbing systems (57.6 percent), untreated ground water (24.2 percent), and DS deficiencies (12.1 percent). The majority of outbreaks occurred in community water systems (75.8 percent), with 92.6 percent including reports of AGI and 57.6 percent including reports of ARI. Five outbreaks were attributed to distribution deficiencies (four were solely attributed to a distribution deficiency and one was attributed to untreated ground water and a distribution deficiency). Three of these outbreaks occurred in systems that used an unchlorinated ground water supply. Two of the distribution system-associated outbreaks (one used an unchlorinated ground water supply) resulted from cross-connections (CDC, 2013a).

The CDC (2011) found a significantly higher prevalence of AGI among Alabama residents who experienced loss of both water service and water pressure (adjusted odds ratio (AOR) 2.6), as well as significant dose response relationships for the duration of both the loss of service ≥ 7 days (AOR 2.4) and loss of pressure ≥ 7 days (AOR 3.5) and 3-6 days (AOR 2.8). Although statistically significant findings were not observed for ARI, researchers did find that reporting of ARI increased with increasing duration of pressure loss.

Shortridge and Guikema (2014) demonstrated a positive relationship between the number of main breaks and Internet search volume for terms related to GI. The study indicated that Internet search data could be useful in identifying GI outbreaks in situations where monitoring of doctor and hospital visits may only capture a small percentage of cases.

Malm et al. (2013) did not find a statistically significant increase in calls to the city's Health Call Center related to GI symptoms during or after disruption of function at the drinking water treatment facility (e.g., failure of chlorine disinfection) or in the distribution system (e.g., pump station failure, main break).

Ercumen et al. (2014) concluded that tap water consumption has a statistically significant association with endemic GI in DSs that experience both temporary outages (relative risk 3.26, 95 percent confidence interval 1.48–7.19) and chronic outages in intermittently operated DSs (odds ratio 1.61, 95 percent confidence interval 1.26–2.07).

2.5.3. Research Gaps and Information Needs

Three research objectives are used to assess research and information needs related to epidemiological studies of health effects associated with low or negative pressure events in DSs as listed in Table 5. All three of these research objectives have been partially met.

2.5.4. Conclusions

The CDC and other researchers have conducted a number of studies to establish a relationship between DS low or negative pressure events and GI or acute respiratory illnesses. Additional research is needed to establish a common set of definitional criteria of pressure events for use in epidemiological studies; to evaluate risk measures; and to correlate risk with pressure management strategies. Utilities need to develop baseline assessments of their vulnerability to contaminant intrusion considering operational conditions (e.g., the magnitude and duration of low or negative pressure events), potential contaminant pathways (e.g., faulty seals, points of leakage), and GI and acute respiratory illness prevalence in their customer population.

Table 5. Gap Analysis for Research Topic Hea2: Epidemiological Studies of Health Effects Associated with Low or Negative Pressure Events in Distribution Systems

	Not Met	Partially Met	Fully Met	Explanation	Suggestions for Filling Gaps
Objective 1: Identify rates of adverse health effects, including GI illness, and other diseases occurring in customers consuming drinking water in periods following known low or negative pressure events.					
Develop method and approach for full epidemiology study (goal to assess whether low pressure events increase incidence of AGI/ARI). Research survey designs.		X		– In 2010, the CDC and the Alabama Department of Public Health conducted a household survey in AL to assess a water emergency and its effect on public health. The primary outcomes of interest were AGI and ARI. – A study conducted in Sweden (Malm et al., 2013), investigated whether there was increased frequency of contact with the city's Health Call Center regarding GI symptoms when deficiencies were reported in the drinking water treatment facility. – WRF Project 4390, *Epidemiological Study of Health Effects Associated with Low Pressure Events in Drinking Water Distribution Systems*, CDC will design a prospective cohort study. Data collected will evaluate if exposure to low or negative pressure events in the DS increases risk for AGI or ARI. – Borchardt et al. (2012) investigated association between AGI and measures of enteric viruses in tap water. – Researchers in MA evaluated AGI and water quality metrics. – Other studies using secondary data to investigate the relationship between water quality and AGI/ARI.	Review existing studies for alignment with research goals. Evaluate how to increase the sensitivity of such studies to detect events that may be significant but not currently detected.
Research approaches to identify pressure events.	X			Researchers at Emory University are collecting and analyzing data using an automated monitoring and sampling device strategically placed in areas that have historically demonstrated vulnerability to main breaks.	Increase focus on identification of pressure events as part of epidemiology study efforts.
Objective 2: Develop estimates of risk measures (e.g., relative risks, odds ratios) to differentiate the potential for these adverse health effects between customers consuming water affected by low pressure events and those not affected.					
Determine appropriate risk measures.		X		Use of relative risk, odds ratios and adjusted odds ratios can be reviewed in the studies meeting Objective 1.	Once study design is determined, evaluate most appropriate risk measure.

	Not Met	Partially Met	Fully Met	Explanation	Suggestions for Filling Gaps
Objective 3: Develop estimates of potential reduction in the risk associated with the most common pressure management strategies to reduce the system's vulnerability to intrusion events (e.g., the extent to which reductions in pressure events would reduce AGI and possible strategies for achieving this)					
Provide quantitative estimates on the degree of risk attributed to low or negative pressure events in the DS.		X		– CDC (2011) found a significantly higher prevalence of AGI among Alabama residents who experienced loss of both water service and water pressure (AOR 2.6), as well as significant dose response relationships for the duration of both the loss of service ≥ 7 days (AOR 2.4) and loss of pressure ≥ 7 days (AOR 3.5) and 3-6 days (AOR 2.8). – Ercumen et al. (2014) concluded that tap water consumption has a statistically significant association with endemic GI in DSs that experience both temporary outages (RR = 3.26, 95% CI1.48–7.19) and chronic outages in intermittently operated DSs (OR 1.61, 95% CI 1.26–2.07).	Estimate the potential risk reduction for the most common pressure management strategies.
Conduct baseline assessment of system vulnerabilities.	X			No new information for 2014 literature review.	Work with utilities to develop baseline vulnerability assessments.

2.6. SURVEY OF DISTRIBUTION SYSTEM PRESSURE MANAGEMENT PRACTICES

The purpose of this research area is to assess pressure management practices in drinking water DSs to determine the prevalence of specific high risk DS attributes causing low or negative pressures. The approach suggested by the RICP (USEPA and WRF, 2010) included surveying 400 to 600 utilities on elements of DS pressure management, such as presence of surge protection infrastructure and frequency of main leaks and breaks.

2.6.1. Description of On-going and Recently Completed Research Projects

Recent research has incorporated surveys on aspects of pressure management on a smaller scale than that outlined by the RICP (USEPA and WRF, 2010). The majority of information currently available in this topic area focuses on pressure monitoring (rather than pressure management strategies) and occurrence of main breaks and leaks.

LeChevallier and Yang (2010) proposed to develop a smaller-scale industry survey on pressure management practices and pressure monitoring equipment to be used as a "beta-test" of elements recommended by the RICP (USEPA and WRF, 2010). This research included case studies on optimizing pressure management, integrating pressure management with other distribution system activities, and development of best practices (LeChevallier et al., 2014). In another study, LeChevallier et al. (2011a) surveyed 47 utilities to determine the amount of effort utilities put towards pressure management for the purpose of preventing the occurrence of low or negative pressure transients. The survey focused on system operating pressures, pressure monitoring, cost and application of hydraulic models, and main break frequency. The AWWA DS survey asked nine utilities about leak detection and repair practices, with a few queries on main breaks and repairs.

Erickson et al. (2015) conducted a survey of state primacy agencies and utilities regarding minimum pressure standards, enforcement methods, and distribution system structure, operations, monitoring, and procedures in response to low pressure events. Thirty-three primacy agencies participated in an initial survey and 11 of these agencies participated in a follow-up interview. Eight utilities were also interviewed.

In 2011, WRF issued a request for proposals for multiple projects to develop a picture of current industry practices and improve industry understanding and practices for responding to main break events. In response, investigators have recently completed surveys focused on main breaks. A survey completed by Kirmeyer et al. (2014) on main break events and practices included 27 utilities in the United States and the UK. It is unclear if other aspects of pressure management were included in the survey.

In 2011, the Partnership for Safe Water launched a voluntary DS optimization program to guide water utilities through data collection, self-assessment, and peer review processes (AWWA, 2011a). The program requires use of secondary disinfection and requires the utility to meet operating goals for disinfectant residual, pressure maintenance, and main break frequency.

2.6.2. Key Findings from Relevant Publications

Survey results describing pressure management strategies, such as pressure control valves with design and operational criteria, were not described in the currently available research. Results for the small-scale survey (LeChevallier et al., 2014) indicated that the majority of responding utilities conduct pressure monitoring at convenient locations instead of locations targeted based on potential for pressure transients, and they do not conduct pressure monitoring in every pressure zone. Most pressure monitors are calibrated annually or not at all and are unable to capture short-duration events.

LeChevallier et al. (2011a) also determined that pressure monitoring occurs at conveniently located sites instead of areas which are at risk for pressure transients. The investigators reported that 65 percent of 47 utilities experienced at least one water hammer event during the year before the survey, and 30 percent of utilities reported one negative pressure event during the same period of time. Utilities reported an average of 4.7 power outages per year, with some reporting more than 10 per system per year. Approximately 13 percent of systems reported no floating storage facilities, and 51 percent indicated more than 4 floating storage facilities.

Supervisory control and data acquisitions systems are most often used to determine system operating pressures (36 percent) followed by hydrant flow tests (28 percent). Locations with pressures <35 psi were typically high elevation areas. The median and average numbers of breaks per 100 miles per year were 20 and 34, respectively. Forty (85 percent) of 47 utilities used hydraulic models as engineering and planning tools. The costs of creating and maintaining models are also discussed. The study included pressure monitoring at low and high pressure locations concurrent with water quality monitoring to evaluate whether low pressure areas were prone to poor water quality.

Survey findings on main break frequency are helpful in understanding the frequency of low or negative pressure events. A recent survey by Kirmeyer et al. (2014) reported that utilities experienced an average of 0.3 main breaks per mile per year, with a median of 0.18 main breaks per mile per year. The maximum number reported in the survey was 1.4 main breaks per mile per year. The authors indicated that there is a seasonal pattern with the majority of main breaks occurring during the winter.

While most states have a standard for maintaining a minimum system pressure of 20 psi, state policies varied on when utilities should issue a boil water advisory or report a low pressure event to the state (Erickson et al., 2015).

In 2013, AWWA reported that 125 utilities in 40 states had enrolled in the Partnership for Safe Water's DS optimization program and a number of utilities had submitted Phase III self-assessment reports for review (AWWA, 2013). In 2014, seven water utilities received Director's Awards for completing Phase III of the DS optimization program (AWWA, 2014a).

2.6.3. Research Gaps and Information Needs

Three research objectives are used to assess research and information needs related to DS pressure management practices as listed in Table 6. Of these three research objectives, two have not been met, and one has partially been met.

2.6.4. Conclusions

Recent research has incorporated surveys on aspects of pressure management on a smaller scale than that outlined by the RICP (USEPA and WRF, 2010). The majority of information currently available in this topic area focuses on pressure monitoring (rather than pressure management strategies) and occurrence of main breaks and leaks. Representative, valid, and accurate surveys are needed to document DS management practices in order to develop a comprehensive national database.

Table 6. Gap Analysis for Research Topic Pres1: Survey of Distribution System Management Practices

	Not Met	Partially Met	Fully Met	Explanation	Suggestions for Filling Gaps
Objective 1: Identify 400-600 utilities to participate in survey. Sur1 may be used to identify the sampling frame of utilities for such a survey.					
Conduct survey of distribution system management practices.		X		– Smaller scale surveys have been conducted. One survey (LeChevallier et al., 2014), as part of ongoing research has been developed to "beta-test" elements recommended by the RICP. – Surveys on this topic have included 9 utilities (AWWA survey, final results not available for citation), 35 utilities (Kirmeyer et al., 2014), 36 utilities (LeChevallier et al. 2014), and 47 utilities (LeChevallier et al., 2011b). Erickson et al. (2015) surveyed primacy agencies and 8 utilities specifically on low pressure events. – Smaller scale surveys report on relevant information such as pressure monitoring practices (LeChevallier et al., 2011b and 2014), occurrence of water hammer and negative pressure events, power outages, hydraulic modeling, and main break occurrence. Kirmeyer et al. (2014) reported on main break frequencies. Erickson et al. (2015) looked at low pressure event management.	Develop large-scale survey to capture distribution system management practices, including pressure management. Use information from previous surveys to facilitate development. Determine how to capture information with the appropriate level of detail.
Objective 2: Generate a comprehensive information base characterizing the diversity of distribution system infrastructure and operation related to pressure and pressure management in the US.					
Develop a comprehensive pressure management information base.	X			Ranked as "Not Met" because the smaller scale survey conducted (LeChevallier et al., 2014) has not been converted into or merged with Comprehensive Information Bases such as the Community Water System/Infrastructure Survey (2006), nor has the Community Water System Survey been updated.	See above.
Objective 3: Assess the prevalence of pressure-related distribution system attributes that may increase the risk of low or negative pressures.					
Using a comprehensive information base, analyze occurrence of practices or infrastructure which may increase the risk of low or negative pressures.	X			– Ranked as "Not Met" since the comprehensive information base referenced in Objective 2 has not been developed, and thus, the data have not been analyzed. – No information provided on occurrence of practices or infrastructure prevalence with respect to a utility survey. – LeChevallier et al. (2014) focuses on developing recommendations for reducing the risk of pressure variation or problematic pressure scenarios. This report includes best management practices to optimize pressure monitoring and management in distribution systems and could be an input to the comprehensive information base, along with already available industry guidance.	See above.

2.7. CHARACTERIZE PROPAGATION OF PRESSURE EVENTS THROUGH DISTRIBUTION SYSTEMS TO IMPROVE PRESSURE MANAGEMENT APPROACH

The purpose of this topic area is to research risk and mitigation factors associated with the propagation of pressure events through the DS to protect public health from intrusion-related contamination (USEPA and WRF, 2010). The RICP encourages using both field and surge modeling to evaluate implementation of pressure management strategies.

2.7.1. Description of Ongoing and Recently Completed Research Projects

Much of the recent research has focused on occurrence of pressure events and estimating intrusion volumes based on variables associated with intrusion risk (e.g., pressure magnitude and duration). Fewer studies have been focused on understanding the propagation of pressure events. Besner et al. (2011) developed a conceptual model of intrusion events to detail the current understanding, assumptions, and questions associated with pressure events; the conceptual model was used in developing a QMRA model. Ebacher et al. (2012) used a combination of computer modeling and field work in a full-scale DS serving 380,000 people to evaluate the sensitivity of estimated intrusion volumes to the following parameters: external head of untreated water on leakage orifices and air vacuum valves; leakage rate; and diameter of air vacuum valve outlet orifice. Schneider et al. (2010) developed a risk matrix using data from past backflow events, and conducted surge modeling to identify DS locations that may be susceptible to low or negative pressure transients; the five surge models represented a range of system sizes from 4,265 to 190,000 service connections.

Collins et al. (2012) investigated pressure events that may result when a pipe is under static pressure and a valve is suddenly opened. This research was conducted in two laboratory pipeline networks. Mansour-Rezaei et al. (2013) modeled contaminant intrusion and movement through a drinking water DS as a result of a pressure event using a Lagrangian-based contaminant transport model with an Eulerian-based transient hydraulic model to study contaminant intrusion and propagation in two water DSs described in the literature. The researchers looked at two scenarios: valve closure and pump failure. The investigators evaluated the usefulness of this modeling approach as a tool for assessing the vulnerability of DSs during pressure events.

Jung et al. (2011) used multi-objective optimization modeling in designing a distribution system to minimize the impacts of pressure transients and cost while also considering steady state conditions. The authors described the modeled conditions used to trigger a pressure transient and track the pressure wave through the distribution system. The paper illustrated the proposed design approach with a case study on the New York City tunnel system. LeChevallier et al. (2014) summarized a case study in which a utility used surge modeling to determine occurrence and mitigation of pressure transients after a pump failure occurs.

2.7.2. Key Findings from Relevant Publications

Collins et al. (2012) reported that negative pressures were measured for several seconds after the sudden valve opening event, and a low pressure event was followed by rapidly increasing pressures. The authors determined that effective protection from pressure events relies on understanding the cause of the event and controlled operations, such as taking adequate time to close and open valves.

With respect to investigating the variables used to analyze pressure events, Besner et al. (2011) concluded that it is unclear whether the duration of a pressure event or the magnitude of the pressure change has a greater impact on intrusion. The sensitivity analyses conducted by Ebacher et al. (2012) showed that the head of untreated water on air vacuum valves was the most influential of the four factors studied. The authors indicated modeled intrusion through the air vacuum valves was significant and should be considered a potential point of contamination. The authors recommended that water utilities inspect air vacuum valves and ensure drainage of vaults prone to flooding. Ebacher et al. (2012) pointed out the importance of understanding factors influencing intrusion.

Schneider et al. (2010) used surge modeling to assist in identifying locations susceptible to backflow events. Using backflow detecting meters, the researchers determined that backflow events occurred in many areas other than those identified by surge modeling.

Researchers have also observed the interdependence between the pressure event and the intrusion volume. Both Collins et al. (2011) (in research focused on estimating intrusion volume, not pressure events) and Ebacher et al. (2012) note that an increase in the intrusion flow rate will dampen the pressure transient, decreasing intrusion volume.

Researchers also pointed out practical results from their investigation and available data. Besner et al. (2011) noted that, with respect to reported contamination events, it is difficult to clearly identify the causative pressure event. Mansour-Rezaei et al. (2013) concluded that their proposed model provided a tool for evaluating the vulnerability of a water DS during contaminant intrusion events. The results were then used for hazard and vulnerability evaluations of the systems, although the proposed model does not take into account mass transport caused by diffusion, dispersion, or degradation. The investigators put forth two preliminary conclusions: 1) intrusion volumes would usually be small and intrusion would most likely only occur during a worst-case scenario that involves multiple failures; and 2) if contamination occurred and detailed system data (e.g., pressure data) were not available, it would be difficult to attribute any illness to the intrusion event.

Jung et al. (2011) showed that pipe diameter is a significant design consideration for controlling pressure transients.

2.7.3. Research Gaps and Information Needs

Four research objectives are used to assess research and information needs related to characterization of the occurrence and propagation of pressure events in DSs as listed in Table 7. Of these four research objectives, three have been partially met and one has been fully achieved.

2.7.4. Conclusions

Much of the recent research has focused on estimating intrusion volumes and appears to be less focused on understanding the propagation and characterization of pressure events. Other researchers have been working to develop a better understanding of the variables involved in estimating intrusion risk, volume, and pressure magnitude and duration, but not specifically the propagation of pressure events. Additional laboratory-scale studies are needed to investigate the magnitude and duration of pressure events. Further research is needed on field monitoring and modeling techniques to evaluate changes in pressure management practices.

Table 7. Gap Analysis for Research Topic Pres2: Characterize Propagation of Pressure Events through Distribution Systems to Improve Pressure Management Approach

	Not Met	Partially Met	Fully Met	Explanation	Suggestions for Filling Gaps
Objective 1: Promote further understanding of risk and mitigation factors associated with pressure events by generating field and modeled data on the occurrence and propagation of pressure events through water distribution systems.					
Field investigations of occurrence and propagation of pressure events.		X		– Several field studies have been completed to promote further understanding of occurrence of pressure events. – While new field information demonstrating the occurrence of pressure events has been developed, no new information was provided on propagation of pressure events. – Ebacher et al. (2012) used field investigations in combination with computer modeling to evaluate the sensitivity of intrusion volumes to external head on leakage orifices and air vacuum valves; leakage rate; and diameter of air vacuum valve outlet orifice. – LeChevallier et al. (2014) developed case studies with optimized and baseline monitoring conducted side-by-side at 20 utilities ranging in size from 1,000 to 175,000 customers. Monitoring was conducted in pressure zones, and not necessarily system-wide. Hydraulic modeling was also used. – LeChevallier et al. (2011b) conducted pressure monitoring at a utility for forty days at six locations. Reporting focused on whether a correlation can be found between pressure and water quality. Authors noted that pressure transients are recorded due to normal pump operations, but report did not provide detail describing pressure changes or system size. – Collins et al. (2012) discussed impacts of pipe material on wave propagation, but studied only plastic pipe under laboratory-scale conditions.	More field studies demonstrating propagation of pressure events under varying design and operational scenarios are needed.

	Not Met	Partially Met	Fully Met	Explanation	Suggestions for Filling Gaps
Computer modeling or conceptual modeling investigations of occurrence and propagation of pressure events.			X	– Ranked as "Fully Met" since several computer modeling studies have been completed which promote further understanding of occurrence and propagation of pressure events. – Mansour-Rezaei (2013) studied contaminant intrusion and movement under two scenarios: valve closure and pump failure. Part of this effort included evaluating the modeled systems for hazard and vulnerability to intrusion. – Besner et al. (2011) developed a conceptual model of intrusion events to review the current state of understanding of variables involved in pressure events. – Schneider (2010) used surge modeling in 5 systems representing a range of system sizes to identify areas with low to negative pressures for the purpose of selecting sites to monitor for backflow occurrence and determined that backflows did occur in areas other than those identified by surge modeling. – See Ebacher et al. (2012) and LeChevallier et al. (2014) above. – Jung et al. (2011) used multi-objective optimization modeling to consider both steady state and transient pressure conditions in designing a distribution pipe network and illustrated the approach using the New York City tunnel system, a large system study.	Not applicable
Laboratory-scale investigations of occurrence and propagation of pressure events.		X		– Ranked as "Partially Met" since only one additional study was provided for review, and the study evaluated only one cause of transients. – Collins et al. (2012) investigated pressure events that may result when a pipe is under static pressure and a valve is suddenly opened. This research determined that effective protection from pressure events relies on understanding the cause of the event and controlled operations.	Conduct laboratory-scale analysis to determine which characteristics may affect magnitude and duration of pressure events.
Objective 2: Implement changes expected to eliminate or minimize pressure events (or the area of distribution system impacted by pressure events) and generate field and modeled data on the occurrence and propagation of pressure events under the new conditions (e.g., hydrant, valve, pump or storage structural or operational changes, or main repair procedural or operational changes).					
Implement changes expected to eliminate or minimize pressure events and generate field and modeled data under the new conditions.	X			Ranked as "Not Met" since no new information provided for review. For example, LeChevallier et al. (2014) focused on monitoring for pressure events and improved monitoring for capturing pressure events. This study did not focus on implementation or assessment of effectiveness of distribution system modifications on pressure management. Collins et al. (2012) recommends slower valve opening and closing speeds to minimize transients but did not study impacts of valve operating speeds.	Evaluate the impacts of changes through field monitoring. Concurrently, assess the use of modeling as a predictive tool for studying pressure management efforts.

	Not Met	Partially Met	Fully Met	Explanation	Suggestions for Filling Gaps
Objective 3: Evaluate the effectiveness of the changes in eliminating or minimizing pressure events.					
Evaluate the effectiveness of the changes in eliminating or minimizing pressure events.	X			No new information for 2014 literature review.	Evaluate results of activities described under Objective 2.
Objective 4: Describe the use, application and limitations of surge models as tools in pressure management.					
Describe the use, application, and limitations of surge models.		X		– Ranked as "Partially Met" since the studies may have used models as part of the research but did not necessarily focus on or evaluate limitations of surge modeling. – Mansour Rezaei (2013) evaluated usefulness of modeling approach for assessing DS vulnerability during pressure events. – Ebacher et al. (2012) used a surge model as part of a sensitivity analysis, this effort also includes uncertainty associated with intrusion volume estimates and aspects of modeling. – LeChevallier et al. (2011b and 2014) apply surge modeling to investigate pressure events. – Schneider et al. (2010) use surge modeling to identify areas with low to negative pressures for the purpose of selecting sites to monitor for backflow occurrence and determined that backflows did occur in areas other than those identified by surge modeling.	Compile pressure monitoring data to illustrate and explain causes of pressure events and the value and limitations of surge modeling to evaluate pressure events and management strategies.

2.8. BEST PRACTICES FOR MINIMIZING RISKS ASSOCIATED WITH STORAGE FACILITIES

The purpose of this research area is to identify and characterize best practices for finished water storage that can be used to mitigate potential contamination exposure concerns (USEPA and WRF, 2010). Research findings will help water utilities diagnose potential problems, understand the conditions that could lead to a contamination event, and implement cost-effective measures to reduce risks.

2.8.1. Description of Ongoing and Recently Completed Research Projects

Air stripping has recently been applied to finished water storage facilities to reduce trihalomethanes and improve stored water quality (Reed et al. 2013). Mixers can be installed to eliminate dead-zones where water is stagnant and to help meet DBP regulations (Fiske, 2014; Bleth, 2010). Manufacturers have developed appurtenances (e.g., flap valves) to improve protection of stored finished water. Murray et al. (2014) researched contaminant resuspension mechanisms in storage tank sediments.

Online water quality monitoring systems are being developed and implemented to improve the detection of contamination events in the water DS including contamination at storage facilities. Compared to grab sampling, online monitoring can be cost-effective and provide sufficient data over time and location to identify contamination events before they reach the consumer (Rosen and Bartrand, 2013). Philadelphia Water Department and CH2M Hill (2013a) developed guidance on siting online water quality monitoring stations using hydraulic models, operator system knowledge, site assessments, and EPA's Threat Ensemble Vulnerability Assessment—Sensor Placement and Optimization Tool (TEVA-SPOT). Philadelphia Water Department and CH2M HILL (2013b) measured the following parameters at each site: pH, conductivity, combined chlorine, oxidation reduction potential, temperature, turbidity, and ultraviolet light adsorption. Gottshall (2014) recommended monitoring the following storage variables: fill and draw cycles, seasonal operating changes, pump station activations, and water age parameters. Thompson (2013) explained how Smart Grid technology is being used to integrate real-time data from various sources (water quality laboratory, maintenance department, supervisory control and data acquisition system, customer complaint database) to help operators make important decisions when managing contamination events.

As discussed in Section 2.2.1, Ailes et al. (2013) conducted an investigation after a large *Salmonella* outbreak in the Alamosa, Colorado, municipal water supply, an unchlorinated groundwater source. Based on survey findings and other information revealed in the investigation, the authors determined the critical control measures that could help minimize contamination risks at the system's finished water storage facilities.

2.8.2. Key Findings from Relevant Publications

New near-laminar-flow active mixing technologies have been developed to completely mix finished water storage facilities to help address thermal stratification and improve stored water quality (Bleth, 2010). New mixer technology can circulate up to 10,000 gallons per minute to water depths of 100 feet and tank radius of 800 feet.

Philadelphia Water Department and CH2M Hill (2013a) described the three types of TEVA-SPOT model simulations needed to select monitoring locations in the DS. The EPANET simulation was used to define the time and duration of contaminant release, the contaminant mass released, and the locations of contaminant release. The health impact simulation applied hydraulic modeling (EPANET) simulation results to determine potential health impacts to the population served based on specified contaminant properties. The sensor placement simulation determined sensor locations that would minimize the mean population exposed to contaminants using four defined contamination scenarios. Field surveys were conducted to check the feasibility of installing sensors at specific locations.

After investigating a large Salmonella outbreak in Alamosa, Colorado, Ailes et al. (2013) identified critical control measures for reducing the risks of outbreaks including comprehensive inspections of storage facilities, identification of system deficiencies as part of sanitary surveys, and adequate resource allocation to address system deficiencies in a timely manner.

2.8.3. Research Gaps and Information Needs

Four research objectives are used to assess research and information needs related to best practices for minimizing risks associated with finished water storage facilities as listed in Table 8. Of these four research objectives, two have not been met, and two have been partially achieved.

2.8.4. Conclusions

Ongoing and recently completed research projects show that utilities are investing in technologies (e.g., air stripping, mixing, online water quality monitoring) and installation of appurtenances (e.g., flap valves) to improve stored water quality. Information needs include potential risk factors, lessons learned (i.e., utility case studies), best practices, and costs of storage facility maintenance and risk mitigation.

Table 8. Gap Analysis for Research Topic Stor1: Best Practices for Minimizing Risks Associated with Storage Facilities

	Not Met	Partially Met	Fully Met	Explanation	Suggestions for Filling Gaps
Objective 1: Document the elements of effective storage best practices currently in use. Information related to implementation costs and other barriers to implementation will also be compiled.					
Collect and summarize information on potential risk factors, storage related contamination events and lessons learned.		X		- After investigating a large *Salmonella* outbreak in Alamosa, Colorado, Ailes et al. (2013) determined the likely source was animal contamination of a storage tank that was in poor condition. Potential risk factors include the frequency of tank inspections and routine maintenance, and the time it takes to correct deficiencies found during inspections or sanitary surveys. - Murray et al. (2014) are investigating sediment resuspension mechanisms in storage facilities.	Review literature and summarize potential risk factors, incorporate information from Sections 2.2, 2.4 and 2.6 of RICP report. Reach out to utilities and local governments to gather information on frequency of tank inspections, types of storage-related deficiencies identified in sanitary surveys, and available funding for tank inspections and maintenance.
Collect information on storage best practices and implementation costs.		X		– Air stripping has recently been applied to finished water storage facilities to reduce trihalomethanes and improve stored water quality (Reed et al., 2013). – Rosen and Bartrand (2013) reported that online water quality monitoring can improve detection of contamination events in the DS. – Thompson (2013) describes how Smart Grid technology can help integrate water quality monitoring data. – Gottshall (2014) provided information supporting the monitoring of several specific storage variables. – Active mixing technologies can reduce water age and improve stored water quality (Bleth, 2010; Fiske, 2014). – Manufacturers are designing new appurtenances (e.g., flap valves) that improve protection of stored water quality.	Work with manufacturers and industry organizations to develop implementation cost estimates. Continue to communicate with utilities to understand best storage practices.

	Not Met	Partially Met	Fully Met	Explanation	Suggestions for Filling Gaps
Objective 2: Provide a single reference resource for evaluation of storage facility design, operations or maintenance-related risk factors, and risk mitigation options (including costs, and other potential implementation obstacles).					
Compile relative costs of components of existing storage facility maintenance and provide comparative costs and constraints for adoption of risk minimization or mitigation measures	X			No new information for 2014 literature review.	Additional research needed which focuses on cost versus technical aspects of storage facility maintenance and adoption of risk mitigation measures. Compile available information into single reference source.
Provide examples and case studies of storage risk-related regulations, standards, policies, and BPs		X		− The Philadelphia Water Department and CH2MHill (2013a) developed guidance on siting online water quality monitoring stations. − After investigating a large *Salmonella* outbreak in Alamosa, Colorado, Ailes et al. (2013) identified critical control measures including comprehensive inspections of storage facilities, identification of system deficiencies as part of sanitary surveys, and adequate resource allocation to address system deficiencies in a timely manner.	Continue to work with utilities and local governments to identify and compile case studies.
Develop a glossary with illustrations, definitions, units of measure, etc., that can be used to characterize storage physically and operationally, including relative costs of storage alternatives	X			No new information for 2014 literature review.	This will be a compilation of the information gathered under the other suggested tasks.

	Not Met	Partially Met	Fully Met	Explanation	Suggestions for Filling Gaps
Objective 3: Determine key barriers to development, implementation and enforcement of storage related best practices, and provide case study examples of how these barriers have been overcome.					
Identify barriers to storage related best practices	X			No new information for 2014 literature review.	Work with systems providing case studies under other tasks to identify barriers to implementation. Work with local and state governments to identify barriers to development and enforcement of storage related best practices.
Provide case study examples of how some systems have overcome key barriers to development, implementation and enforcement of storage related best practices.	X			No new information for 2014 literature review.	
Objective 4: Develop strategies to quantify and benchmark the effectiveness of BPs and document case studies of successful programs.					
Consider development of cost-benefit analysis of storage best practices.	X			No new information for 2014 literature review.	Need additional quantitative data regarding storage best practicess including comparative water quality data, public health data and fiscal data.
Document successful ongoing storage best practice programs.	X			No new information for 2014 literature review.	Follow up with systems providing case study info to benchmark best practice programs.

2.9. SURVEY OF LARGE DRINKING WATER UTILITY DISTRIBUTION SYSTEMS

The purpose of this research area is to collect information on baseline system operating conditions and management practices; prevalence of risk factors that could contribute to pathogen intrusion, other system contamination, or other public health risks; and use of risk management strategies (USEPA and WRF, 2010). The survey ideally would include 400 to 600 water utilities that serve more than 50,000 people each.

2.9.1. Description of Ongoing and Recently Completed Surveys

Two survey instruments were developed to collect information identified by the RICP (USEPA and WRF, 2010). The AWWA conducted a pilot utility survey focused on main breaks/replacements, cross connections/ backflow, finished water storage facilities, risk management strategies, and general utility information in 2011. The goal of this pilot was to evaluate the feasibility of such a survey by assessing response rate and data availability, not to obtain survey data for a statistically representative cross-section of utilities. The AWWA Utility Survey was sent to 38 water utilities serving at least 50,000 people; nine utilities responded. Among the responding utilities, the reported level of effort to provide all the desired information (which was not provided by most utilities) ranged from 6 to 170 hours, with differences depending upon how much readily available information the utility already had versus the need to gather and organize additional information to respond to the specific survey instrument questions. In the survey lead's opinion, the pilot indicated that a significant effort would be needed to further refine the survey instrument and to collect the desired information from a large enough sample size for the results to be statistically representative of a cross section of utilities (Personal communication from Jeffery Rosen to RICP March 9, 2012). The WRF Project 4321 survey (LeChevallier et al., 2011a) focused on pressure management, and was The WRF 4321 distributed to 330 water utilities. The WRF 4321 survey received responses from 36 utilities, including some small utilities.

The American Society of Civil Engineers' Report Card for America's Infrastructure (ASCE, 2013) is an assessment conducted every four years by the ASCE Report Card Advisory Council. The Council is composed of 33 civil engineers who spend a year reviewing available data, surveys, and reports; interviewing stakeholders and industry leaders; and developing a summary report on infrastructure condition, capacity, and trends. Infrastructure across the United States is evaluated with an A-F grading system based on the following criteria: capacity, condition, funding, future need, operations and maintenance, public safety, resilience, and innovation.

EPA's Drinking Water Infrastructure Needs Survey (DWINS) is a comprehensive national assessment of the 20-year capital improvement need for public water system infrastructure and is conducted every four years. The 2011 needs estimate (USEPA, 2013) is based on new survey data from 885 systems serving >50,000 people.

AWWA's annual utility performance benchmarking survey gives utilities an opportunity to compare their current performance with their peers and identify appropriate performance goals. Performance indicators pertinent to DS research topics include the following: water main renewal/replacement rates, DS water loss rates, planned maintenance hours as a percentage of total hours for planned and corrective maintenance, number of customer service complaints per 1,000 accounts, and training hours per employee. The number of utilities providing performance data varies by the indicator and the year. For example, water main renewal/replacement rates were provided by 25 utilities in 2012 as compared to 50 utilities in 2006 (Mercer, 2014). Participating utilities include all sizes, from those serving <10,000 to those serving >500,000 people.

2.9.2. Key Findings from Relevant Publications

The 2013 ASCE Report Card gave drinking water infrastructure an overall D grade, indicating poor, at-risk conditions. "The infrastructure is in poor to fair condition and mostly below standard, with many elements approaching the end of their service life. A large portion of the system exhibits significant deterioration. Condition and capacity are of significant concern with strong risk of failure" (ASCE, 2013). Further, ASCE reports there is currently an $84 billion funding gap between total needs and funding available to upgrade all water and wastewater infrastructure to a B grade or a state of good repair.

The 2011 DWINS (USEPA, 2013) estimates a total capital improvement need of $284.5 billion for distribution, transmission, and storage facilities in the U.S. states and territories for years 2011 through 2030. The estimated need for transmission and distribution projects ($247.5 billion) is the largest category of need (64.4 percent of the total) and has increased since the 2007 DWINS. It primarily includes water main replacement and rehabilitation projects to address aging infrastructure.

2.9.3. Research Gaps and Information Needs

Six research objectives are used to assess research and information needs related to surveys of large drinking water utility distribution systems as listed in Table 9. Of these six objectives, two have not been met, three are partially met and one has been fully met.

2.9.4. Conclusions

Two survey instruments have been developed to collect information to address this research topic. The AWWA Utility Survey focused on main breaks/replacements, cross connections/backflow, finished water storage facilities, risk management strategies, and general utility information, while the WRF Project 4321 survey (LeChevallier et al., 2011a) focused on pressure management. Initial survey distributions were completed to assess survey response rate and data availability/accessibility, but further survey distributions are required to obtain survey data for a statistically representative cross-section of utilities. National surveys conducted by ASCE and EPA every four years provide comprehensive assessment of infrastructure needs.

Table 9. Gap Analysis for Research Topic Sur1: Survey of Large Drinking Water Utility Distribution Systems

	Not Met	Partially Met	Fully Met	Explanation	Suggestions for Filling Gaps
Objective 1: Identify drinking water distribution and storage systems at public water supplies to target for surveys conducted in this project area.					
Identify systems to target for surveys.		X		– Two survey instruments were developed and submitted to collect information identified by the RICP (AWWA survey and WRF Project 4321 survey). – The AWWA survey was distributed to 38 utilities, 9 responses were received. – The WRF survey was submitted to 330 water utilities, responses received from 36 utilities.	In the future may want to pursue a statistically significant sample population and higher response rate. More work is needed on how to increase the response rate through identifying targeted surveys.
Objective 2: Identify key variables related to the type, quantity, and condition of distribution system infrastructure elements that may contribute to increased public health risks in distribution systems.					
Identify key variables related to distribution elements that may contribute to public health risks from distribution systems.		X		– The 2013 ASCE Report Card indicated poor, at-risk conditions for drinking water infrastructure nationwide. They noted age as cause of significant system deterioration. – The 2011 DWINS (USEPA, 2013) estimates a total capital improvement need of $284.5 billion for distribution, transmission, and storage facilities in the U.S. states and territories for years 2011 through 2030, with key projects being water main replacements needed due to age. – AWWA utility surveys and WRF survey provide additional information on distribution system management at specific systems which can be tied to system performance.	Compare infrastructure and system performance/public health data to evaluate variables that may contribute to public health risks.
Objective 3: Assess the prevalence and use of various risk management strategies on distribution systems.					
Assess prevalence and use of risk management strategies for distribution system operation.	X			– Ranked as "Not Met" because the AWWA Utility Survey was very small and results cannot be cited or referenced. – The WRF Project 4321 survey (LeChevallier et al. 2011b) focused on pressure management.	Continue to work with utilities to gather information on use of risk management strategies.

	Not Met	Partially Met	Fully Met	Explanation	Suggestions for Filling Gaps
Objective 4: Provide baseline information on distribution system conditions, operations, and management practices.					
Compile baseline information on distribution system conditions, operations and management practices.		X		– Two survey instruments were developed and submitted to collect information identified by the RICP (AWWA survey and WRF Project 4321 survey). – The WRF survey had an 11% response rate (36 surveys received of 330 water utilities invited). This survey contained questions on pressure management, although it was intended to assess response rate and data availability, rather than collect statistically significant data. (LeChevallier et al., 2011b)	Continue to review data from AWWA's annual Utility Benchmarking Survey and identify other ongoing or recent surveys which could contribute to baseline distribution dataset. More work is needed on how to increase the response rate through identifying targeted surveys.
Objective 5: Identify additional research and information collection needs.					
Use survey data to improve understanding of key DS issues (e.g., vulnerability to contamination, effectiveness of programs).	X			– The AWWA survey was distributed to 38 utilities and 9 responses were received. Survey focused on main breaks/replacements, cross connections/backflow, finished water storage, risk management strategies and utility information. – Ranked as "Not Met" because the survey was small and results cannot be cited or referenced.	Compile and analyze results from the existing surveys and determine information collection needs that might still exist to meet the 6 survey data objectives listed under this task. Identify surveys under development for opportunities to potentially fill these information needs.
Objective 6: Identify a subset of utilities with varied infrastructures, distribution system conditions, and/or water quality conditions to assist in construction of a representative sample for subsequent distribution system related research and information collection projects.					
Identify a pool of utilities with varied infrastructures, DS conditions, and/or water quality conditions. Use info to identify a representative sample for subsequent research and information collection projects.		X		– AWWA survey was distributed to 38 utilities, 9 responses were received. – WRF survey was submitted to 330 water utilities, responses received from 36 utilities. – The 2013 ASCE Report Card indicated poor, at-risk conditions for drinking water infrastructure nationwide. They noted age as cause of significant system deterioration. – The 2011 DWINS (USEPA, 2013) estimates a total capital improvement need of $284.5 billion for distribution, transmission, and storage facilities in the U.S. states and territories for years 2011 through 2030, with key projects being water main replacements needed due to age.	Use sampling frames from existing surveys to identify subsets of utilities with varied infrastructure characteristics.

2.10. TARGETED SURVEYS ON STATE AND LOCAL REGULATIONS, POLICIES, MANUFACTURING PRACTICES, AND GUIDELINES FOR DISTRIBUTION SYSTEMS

The purpose of this research topic is to evaluate the extent to which DS risk management and mitigation practices are implemented by states or through manufacturing, installation, or inspection programs (USEPA and WRF, 2010).

2.10.1. Description of Ongoing and Recently Completed Projects

As discussed in Section 2.8, EPA surveyed the 50 states and the District of Columbia to collect baseline information on storage facility inspections as part of a rulemaking effort (USEPA and Cadmus, 2013). Survey information included the mechanism for conducting inspections (e.g., required by regulation, guidance, or as part of sanitary surveys), inspection and cleaning frequencies, requirement for cleaning, inspector qualifications, and recommended corrective actions for addressing significant deficiencies.

EPA's contractor surveyed nine state primacy agencies to document current state requirements and practices on finished water storage monitoring, as well as to identify available resources and guidelines (Cadmus, 2013). Cadmus collected survey information via phone interviews in March 2013. State primacy agencies were selected following a review of state primacy agency websites, current literature, and existing state drinking water regulations.

Erickson et al. (2015) conducted research on state policies related to water system pressure management and surveyed all 50 primacy agencies, receiving 33 responses.

Missouri Department of Natural Resources collected information on low pressure events at five utilities over the period April 2014 to March 2015 using criteria (e.g., types of main breaks) developed by Kirmeyer et al. (2014) but findings were not publicly available for this report.

LeChevallier et al. (2011a) conducted a utility survey on pressure management practices in water DSs. The survey included questions on state requirements for pressure maintenance and monitoring. Survey respondents represented 21 states.

Several states have developed guidance on addressing significant deficiencies and sanitary defects to help public water systems meet requirements of sanitary surveys and the Revised Total Coliform Rule (Hawaii Safe Drinking Water Branch, 2014; Minnesota Department of Health, 2013). Washington State developed guidelines to improve the sanitary protection of stored water (Washington State DOH, 2010a and 2010b), troubleshoot coliform contamination, and implement emergency disinfection procedures at small systems (Washington State DOH, 2010c and 2011).

In New York State, Van Houten (2010) developed a pilot training program for sanitary survey inspectors to address an increasing number of public water system failures. The program involved 12 students who were current public health sanitarians and technicians at six local health departments in western New York. Health department managers participated in a feedback meeting halfway through the pilot training program. The program was well received by local health departments in western New York (Van Houten 2010). An analysis of final exams showed that students increased their knowledge base on conducting sanitary surveys.

Matichich et al. (2014) collected survey information from 17 water utilities on current performance benchmarking metrics and practices for effective utility management and used results to develop a benchmarking framework and tool. They found that five of the ten attributes of effectively managed water utilities can be directly associated with DS management: product quality, customer satisfaction, operational optimization, infrastructure stability, and operational resiliency.

AWWA standards are used as industry guidelines and benchmarks. Some of the AWWA standards pertinent to the RICP research priorities include the following:

- G200-09 Distribution Systems Operation and Management (AWWA, 2010),

- C651-14 Disinfecting Water Mains (AWWA, 2014b), and
- C652-11 Disinfection of Water-Storage Facilities (AWWA, 2011b).

EPA has several research programs to develop guidelines and tools to help utilities improve infrastructure management programs:

- EPA's Aging Water Infrastructure Research Program has conducted state of the technology reviews and developed guidance on condition assessment technologies and rehabilitation methods for drinking water systems (Murray, 2013).
- EPA and the Water Environment Research Foundation have a cooperative agreement to co-fund research projects (Royer, 2013) including development of decision support tools (e.g., Asset End of Life Reinvestment Decision Tool INFR2R11) and a national database for documenting life cycle cost and performance of technologies for condition assessment, pipe location, and rehabilitation (www.waterid.org).

Several ongoing WRF-funded research projects are developing guidelines on implementing risk management methodologies for DS protection:

- WRF 4451, Utility Risk Management Methodologies for Buried Assets with Improved Triple Bottom Line Understanding of Pipe Failures.
- WRF 4553, Guidance and Strategies for Determining When it is Cost Effective to Use Condition Assessment Technologies on High Consequence Water Mains.

2.10.2. Key Findings from Relevant Publications

Storage facility inspections are required by regulation or statute in 16 states and are included in sanitary surveys or sanitary survey requirements in 32 states (USEPA and Cadmus, 2013).

Finished water storage facility monitoring requirements based on a survey of nine state primacy agencies (Cadmus, 2013) include:

- Seven of nine states require monitoring at finished water storage facilities.
- Seven of nine states require bacteriological sampling for new tanks before they are placed into service, and six of the seven also require bacteriological sampling for existing tanks. The two states in the survey which do not have bacteriological sampling requirements consider the activity a recommended "best practice."
- Two of the nine states surveyed require sampling for VOCs after tank painting or coating, and one state also requires VOC sampling before new tanks are placed into service. A third state recommends VOC sampling in the event that the first fill of water is not wasted after tank painting or coating.
- None of the states interviewed had documented requirements or recommendations for routine finished water storage monitoring. Microbial contaminants and VOCs were the primary water quality parameters considered, and disinfectant residual was also described as a potential monitoring parameter as a best practice or during isolated water quality events.

Most states have some requirements for pressure maintenance, according to a recent utility survey with respondents in 21 states (LeChevallier et al., 2011a). Ninety-five percent of survey respondents reported that a 20 psi pressure must be maintained during fire flow, while only 68 percent reported that 20 psi must be maintained during other emergency conditions. The allowable pressures during normal operations varied widely. Only 2 of 21 states (Wisconsin and California) require pressure monitoring in the DS.

Major revisions to AWWA Standard C651 (AWWA 2014b) included expanded guidance for disinfecting after water main repair; addition of a spray disinfection method for transmission mains; changes in bacteriological sampling requirements for new mains; and an increased flushing rate for scour flushing. The revisions were based on science-based guidelines developed by several research projects including Kirmeyer et al. (2014) and Reilley and Burlingame (2013).

2.10.3. Research Gaps and Information Needs

The analysis of research gaps and information needs (Table 10) shows that three research objectives have not been met; three are partially complete; and one has been fully addressed.

2.10.4. Conclusions

Several surveys have recently been completed to collect information from state primacy agencies or utilities on state regulations, policies, and guidelines. No surveys have been conducted on manufacturing practices related to DS issues (e.g., failure rates of backflow prevention assemblies, trends in tank design). Several states are actively developing guidelines to improve DS practices and to help utilities identify and address sanitary defects. Additional research and information collection are needed to improve understanding of fire department practices for operating hydrants; DS inspection practices; implementation issues with cross connection control programs; and current trends in finished water storage facility design.

Table 10. Gap Analysis for Research Topic Sur4: Targeted Surveys to Obtain Information on State and Local Regulations, Policies, Manufacturing Practices and Guidelines for Distribution Systems

	Not Met	Partially Met	Fully Met	Explanation	Suggestions for Filling Gaps
Objective 1: Evaluate inspection practices and results (e.g., plumbing/backflow prevention assemblies, main installations, storage).					
Review and analyze available data and literature.		X		– Data and information related to inspection practices is available from state guidance documents and procedural documents, state training programs, state optimization programs as well as industry standards.	Consolidate information from various state sources into single database. Continue to collect manufacturer information.
Develop surveys to fill information gaps.		X		– USEPA and Cadmus (2013) surveyed all 50 states and D.C. at the direction of EPA to collect baseline information on storage facility inspections. – Cadmus (2013) surveyed nine states to document current state requirements and finished water storage monitoring practices. – Three additional studies (Erickson et al., N.D., LeChevallier et al., 2011b and Matichich et al., 2014) collected information on state policies related to pressure management, utility pressure management practices and performance benchmarking metrics, respectively.	Review ongoing surveys for possible opportunities to collect information related to storage facility inspection practices. Collect data on significant deficiencies from sanitary surveys and sanitary defects from Revised Total Coliform Rule assessments.
Objective 2: Evaluate certification requirements for inspecting distribution system components (storage tanks, backflow prevention assemblies, new construction, main repair, etc.).					
Review and analyze available data and literature.		X		Data and information related to DS inspection certification requirements is available from state guidance documents and procedural documents, state training programs, state optimization programs as well as industry standards.	Work with utilities to understand who typically conducts DS inspections.
Develop surveys to fill information gaps.		X		USEPA and Cadmus (2013) surveyed all 50 states and D.C. to collect baseline information on storage facility inspections including information on DS inspector qualifications.	Determine completeness of inspector certification requirement information in USEPA and Cadmus (2013) data set.
Objective 3: Evaluate fire department practices for operating and maintaining hydrants and level of coordination with water utilities.					
Review and analyze available data and literature.	X			No new information for 2014 literature review.	May need to reach out to municipalities or fire departments to collect this information.
Develop surveys to fill information gaps.	X			No new information for 2014 literature review.	

	Not Met	Partially Met	Fully Met	Explanation	Suggestions for Filling Gaps
Objective 4: Evaluate the extent to which backflow prevention assemblies are used and failure frequency (manufacturers).					
Review and analyze available data and literature.	X			No new information for 2014 literature review.	Review AWWA and other industry standard documents as well as manufacturer reports for applicable information.
Develop surveys to fill information gaps.	X			No new information for 2014 literature review.	
Objective 5: Evaluate trends in storage tank types, configurations, construction materials, and ages (tank fabricators and designers).					
Review and analyze available data and literature	X			No new information for 2014 literature review.	Review ongoing surveys for any data related to storage tank infrastructure. Contact manufacturers to collect data on current trends.
Develop surveys to fill information gaps.	X				
Objective 6: Estimate the frequency of state and/or local sewer leak and breaks and repair strategies that might impact water distribution systems (wastewater utilities and municipalities).					
Review and analyze available data and literature.		X		– The Partnership for Safe Water launched a DS optimization program in 2011 which requires enrolled utilities to meet operating goals for break frequency. 125 utilities in 40 states are enrolled in this DS optimization program. – EPA's Aging Water Infrastructure Research program has developed guidance on rehabilitation methods for drinking water systems.	May need specific data collection effort to target leak and break rates for states and specified localities and collect data on prevalent repair strategies.
Develop surveys to fill information gaps.		X			
Objective 7: Compare requirements in state laws, regulations, policies, and industry standards/guidelines concerning distribution systems.					
Review and analyze available data and literature.		X		– Surveys described under Objectives 1 and 2 include significant information regarding states' laws, regulations and polices related to distribution systems. Erickson et al. (2015) are developing an analysis which will assess how well various regulations for water quality monitoring address public health risks from low/negative pressure events. – Applicable AWWA Standards include G200-09, C651-05 and C652-11.	Use existing data to build comparative analysis of outcomes as a result of varying laws, regulations, polices and adoption of standards.
Develop surveys to fill information gaps.			X		

3. SUMMARY OF FINDINGS

This report provides information on recent research findings and additional research needs for 10 high priority distribution system issues. It is based on literature published between 2010 and 2014 and uses the same project areas described in the RICP's 2010 report (EPA and WRF, 2010). The analysis of research gaps and information needs, summarized in Tables 1-10, was conducted based on the availability of new research and information as of August 2014. Specific research objectives identified in the 2010 Report are listed in Tables 1-10 and were used to assess the degree to which a research gap may have been met.

During the period 2010 to 2014, new guidance and best practices information were developed for several priority distribution system topics:

- Preventing and responding to backflow events and characterizing risk factors;
- Minimizing risks associated with backflow events;
- Preventing contaminant breaches in finished water storage facilities; and
- Identifying and addressing sanitary defects.

However, the degree to which these studies are applicable to other system sizes and different system configurations must still be determined.

Some remaining research gaps are due in part to a lack of utility data. The following types of utility data are needed:

- Case study documentation of backflow events including data on associated causative factors, contaminated water volume, concentration of contaminants, and operational conditions (e.g., magnitude and duration of pressure reduction events);
- Baseline assessment of vulnerability to contaminant intrusion including information on illness rates and the types of potential pathways to the distribution system (e.g., damaged or missing insect screens on tank vents and overflow pipes).
- Frequency of occurrence of unprotected cross connections and backflow events;
- Case study documentation of storage facility contamination events including data on operational conditions at the time of contamination, risk factors, costs of storage facility maintenance and risk mitigation, best practices, and lessons learned; and.
- Issues with implementing cross connection control programs.

Other research gaps remain because some of the objectives outlined in the RICP's 2010 report (EPA and WRF, 2010) were quite prescriptive. For example, additional research on the occurrence of pressure events was conducted, but not on the propagation of pressure events. Thus the research objective of "….generating field and modeled data on the occurrence and propagation of pressure events…." was only partially met.

Several gaps remain because available information has not been compiled into a single reference document. For example, the need for single reference documents covering best practices for cross-connection control and storage facility risk mitigation strategies were identified in the RICP's 2010 report. This information undoubtedly exists and has been further developed since 2010, but it has not yet been compiled and reviewed.

Nationwide surveys are needed to collect additional information for a statistically representative cross-section of utilities on the following topics:

- Pressure management strategies;
- Propagation and characterization of pressure events;

- Distribution system management practices;
- Occurrence of unprotected cross connections and backflow events;
- Risk management strategies; and
- General utility information.

Surveys are needed to collect information from equipment manufacturers and fire department staff:

- Information on manufacturing practices related to distribution system issues (e.g., failure rates of backflow prevention assemblies, trends in tank design).
- Fire department practices for operating hydrants; DS inspection practices; implementation issues with cross connection control programs;

Although many training resources are available, additional training is needed for utility staff on the following topics:

- Finished water protection in storage facilities;
- Distribution system optimization; and
- Modeling techniques for using quantitative microbial risk assessment (QMRA) to assess distribution system risks;

The effectiveness of existing training programs should be evaluated.

Other research needs include modeling, laboratory and field studies. Modeling work is needed to develop an adaptive QMRA tool to estimate the relative risks of exposure to distribution system pathogens and evaluate risk management strategies. Additional modeling is needed to refine and validate existing QMRA models and to standardize QMRA modeling practices. Research is needed to further develop modeling techniques to evaluate changes in pressure management practices. Laboratory-scale studies are needed to investigate the magnitude and duration of pressure events. Field studies are needed on pressure monitoring methods and practices.

4. CONCLUSION

4.1. Results of Research and Information Collection Partnership (RICP)

The Research and Information Collection Partnership (RICP) has identified several high priority research and information collection needs. This report shows that there is a better understanding of public health impacts and mitigation techniques from potential degradation of drinking water quality in distribution systems since the inception of the RICP in 2009. Many research and information collection activities have been completed. Yet, many activities are still underway and others remain unaddressed.

Each section of this review identified information gaps and whether those were met, partially met, or not met during the tenure of the RICP. Key conclusions from this review include:

1. Best Practices to Minimize Risks Associated with Cross-Connections and Backflow

There is new guidance and information on preventing and responding to backflow events and characterizing risk factor (e.g., RCAP's *Protecting Water Quality by Optimizing the Operations and Maintenance of Distribution Systems*). Multiple sources have published information on best practices for minimizing risks associated with backflow events. Researchers noted that one reason for the difficulty in identifying backflow events and associated factors is the lack of utility data.

Topics that require additional research include documentation of backflow events; compilation of existing resources; evaluation of training programs; and implementation of cross connection control programs.

2. Contaminant Entry from Breaches in Storage Facilities

Industry standards and guidance are available to aid in preventing contaminant breaches in finished water storage facilities (e.g., AWWA Standards G200 and C652-11). Many training resources are available but additional training workshops are needed to provide information to utilities on finished water protection and DS optimization. Literature is lacking on utility case studies of storage facility contamination events.

Research studies should be conducted to assess storage facility contamination and pathogen occurrence under various operating conditions.

3. Estimation of Contaminated Water Volumes and Contaminant Concentrations Introduced into Distribution Systems Due to Backflow Events from Unprotected Cross-Connections Based on Model Predictions and Field and Pilot-Scale Experiments

Limited information is available on the contaminated water volume and concentration of contaminants that can enter the distribution system during a backflow event. The industry is conducting research on event detection and the frequency of backflow events.

More research is needed to document the occurrence of unprotected cross connections. Key information needs include: estimates of contaminant concentrations associated with backflow events; assessment of pressure changes that can cause backflow or backsiphonage; and nationwide estimates of backflow occurrence and backflow volume.

4. Quantitative Microbial Risk Assessment (QMRA) to Evaluate Exposure to Pathogens through Drinking Water Distribution Systems

Recent research projects have developed or are developing QMRA and other types of models to assess DS risks; however, no models have been published specifically to address RICP research objectives.

Additional research is needed to refine and validate QMRA models, to standardize modeling practices, and to educate researchers, engineers, and the regulatory community on modeling techniques

5. Epidemiological Studies of Health Effects Associated with Low or Negative Pressure Events in Distribution Systems

The CDC and other researchers have conducted a number of studies to establish a relationship between DS low or negative pressure events and GI or acute respiratory illnesses.

Additional research is needed to establish a common set of definitional criteria of pressure events for use in epidemiological studies; to evaluate risk measures; and to correlate risk with pressure management strategies.

Utilities need to develop baseline assessments of their vulnerability to contaminant intrusion considering operational conditions (e.g., the magnitude and duration of low or negative pressure events), potential contaminant pathways (e.g., faulty seals, points of leakage), and GI and acute respiratory illness prevalence in their customer population.

6. Survey of Distribution System Pressure Management Practices

Recent research has incorporated surveys on aspects of pressure management on a smaller scale than that outlined by the RICP (USEPA and WRF, 2010). The majority of information currently available in this topic area focuses on pressure monitoring (rather than pressure management strategies) and occurrence of main breaks and leaks.

Representative and accurate surveys are needed to document DS management practices in order to develop a comprehensive national database.

7. Characterize Propagation of Pressure Events through Water Distribution Systems to Improve Pressure Management Approaches

Much of the recent research focuses on estimating intrusion volumes and appears to be less focused on understanding the propagation and characterization of pressure events. Other researchers have been working to develop a better understanding of the variables involved in estimating intrusion risk, volume, and pressure magnitude and duration, but not specifically the propagation of pressure events.

Additional studies are needed to investigate the magnitude and duration of pressure events. Further research is needed on field monitoring and modeling techniques to evaluate changes in pressure management practices.

8. Best Practices for Minimizing Risks Associated with Storage Facilities

Ongoing and recently completed research projects show that utilities are investing in technologies (e.g., air stripping, mixing, online water quality monitoring) and installation of appurtenances (e.g., flap valves) to improve stored water quality.

Additional information is needed to characterize the relative risks of different potential risk factors, lessons learned (i.e., utility case studies), best practices, and costs of storage facility maintenance and risk mitigation.

9. Survey of Large Drinking Water Utility Distribution Systems

Initial survey instruments were completed to assess survey response rate and data availability/accessibility, but further survey distributions are required to obtain survey data for a statistically representative cross-section of utilities. National surveys conducted by ASCE and EPA every four years provide an assessment of infrastructure needs.

10. Targeted Surveys to Obtain Information on State and Local Regulations, Policies, Manufacturing Practices, and Guidelines for Distribution Systems

Several surveys have recently been completed to collect information from state primacy agencies or utilities on state regulations, policies, and guidelines. No surveys have been conducted on manufacturing practices related to DS issues (e.g., failure rates of backflow prevention assemblies, trends in tank design). Several states (e.g., Colorado, Hawaii, Minnesota) are actively developing guidelines to improve DS practices and to help utilities identify and address sanitary defects.

Additional research and information collection are needed to improve understanding of fire department practices for operating hydrants; DS inspection practices; implementation issues with cross connection control programs; and current trends in finished water storage facility design.

4.2. Application of Information on the State of Research on High Priority Distribution Systems Issues

The information produced by the RICP was intended to provide information to improve public health protection by the drinking water community (e.g., regulations, guidance, industry standards). While this information will be used to inform future efforts at EPA, including those undertaken as part of EPA's Regulatory Reviews, it will also benefit public health through non-regulatory means such as enhanced State sanitary surveys, new or improved industry standards, improved State employee and system operator training, as well as improved policy. Specific examples of improvements from RICP-related research include ANSI/AWWA C651-05 "Disinfecting Water Mains". This standard was updated in 2015 using the information obtained from WRF project 4307 "Effective Microbial Control Strategies for Main Breaks and Depressurization". This is an excellent example of how research led to an industry standard that can be used broadly, such as in construction contracts and in State guidelines, for response to main breaks and installations to better protect public health. Another example can be found in the paper *Critical Review and Rethinking of USEPA Secondary Standards for Maintaining Organoleptic Quality of Drinking Water* (Dietrich and Burlingame, 2015). This paper reviewed the EPA standards for aesthetic parameters which can impact on public acceptance and trust, which affect public health. These standards should be updated periodically to ensure they stay current with advances in treatment technologies and changing public expectations.

4.2.1. EPA's Third Six-Year Review

The Safe Drinking Water Act (SDWA) requires EPA to review each national primary drinking water regulation at least once every six years and revise them, if appropriate. As part of the "Six-Year Review," EPA evaluates any publicly available data and information in a range of areas, including health effects, contaminant occurrence and exposure, treatment technologies, and implementation issues to determine if any regulatory revisions are needed. Revisions must maintain or strengthen public health protection.

The third Six Year Review, which is scheduled to be completed by the end of 2016, includes review of the Surface Water Treatment Rule (SWTR) residual disinfectant requirements in the distribution system, Interim Enhanced Surface Water Treatment Rule (IESWTR) (sanitary survey requirements) and the Ground Water Rule (GWR) (sanitary survey requirements). The purposes of these disinfectant residual requirements are to i) ensure that the distribution system is properly maintained and identify and limit contamination from outside the DS when it might occur, ii) limit growth of heterotrophic bacteria and *Legionella* within the DS, and iii) provide a quantitative limit, which if exceeded, would trigger remedial action. The purpose of the existing sanitary survey requirements, which include consideration of distribution system vulnerabilities, is to identify water system deficiencies that could pose a threat to public health, and to allow for correction for such deficiencies to prevent such threats. The extent to which there is new information that can be used to enhance the realization of these objectives, i.e., meaningful opportunity to identify and prevent distribution system vulnerabilities, will help inform the basis for a review decision.

If under EPA's Third Six-Year Review, EPA makes a determination to revise any of the existing standards, EPA would develop a proposed rule considering all the available data. In such a case, EPA may decide to pursue further collaboration among stakeholders to inform the development of such a rule.

4.2.2. How Has the Information Gathered During the RICP Informed Third Six-Year Review?

a. What do summary findings inform relative to the Six-Year Review?

EPA is examining information from the 10 high priority research and information collection project areas in the context of the six-year review. As part of the Six-Year Review effort, EPA is considering information generated during the RICP related to the effectiveness of sanitary survey and corrective action requirements under existing drinking water regulations (e.g., information generated from the topic area Contaminant Entry from Breaches in Storage Facilities).

b. What are the summary findings shortfalls?

The overarching shortfall is the limited new information that has become available to inform the frequency and magnitude of distribution system vulnerability events (e.g., backflow events, storage tank breaches), their associated risk implication, and costs for preventing such events from occurring. The generation of such information and its compilation on a national basis would help inform meaningful opportunities for enhanced public health protection through revised regulation. There has been a challenge with coordinating a national effort to prioritize or focus research funding on RICP issues. Ongoing communication and coordination is still needed fulfill the research needs identified by the RICP. Venues other than the RICP, discussed below, are helping to address the RICP priority areas. However, there should be ongoing discussion on how to better coordinate and prioritize all the various ways that drinking water research is conducted and funded.

4.2.3. Other Initiatives that Complement RICP in Supporting Distribution Risk Management Decision Making

a. AWWA's Partnership for Safe Water – Distribution System Optimization Program

The Partnership for Safe Water (PSW) launched a distribution system optimization program (DSOP) in 2011. At the end of 2015 the DSOP included 157 participating utilities. This program, and related optimization guidance, was built around results of the Water Research Foundation Project 4109, *Criteria for Optimized Distribution Systems,* which was published in 2010. The DSOP is designed to encourage continuous improvement through adjusting operational procedures.

The DSOP focuses on three key distribution system performance indicators, with each indicator representing a different distribution system integrity. These integrities, along with the indicator by which they are quantitatively represented, are: water quality integrity (e.g., disinfectant residual), hydraulic integrity (e.g., pressure management), and physical integrity (e.g., main breaks and leaks). Optimization goals have been identified for each of these indicators and guidance has been provided on methods and approaches to achieve optimization. Utilities participating in the program complete a comprehensive self-assessment of distribution system operations. The self-assessment is used to identify performance-limiting design factors around which an action plan for improvement is developed and implemented. The DSOP is expected to evolve over the coming years as knowledge and experience is gained by the utility subscribers. The focus to date has primarily been on measurement and reporting of disinfectant residual and disinfectant by-product (DBP) data.

The PSW program includes submission of an annual data summary, and progress is tracked by comparing current data to the utility's initial baseline data submission. Fifty-one utilities reported DSOP data for the 2014 – 2015 reporting period on disinfectant residual and DBPs. Fewer than 20 utilities have reported data for pressure management and breaks. From the reporting utilities, the most common action plan items for greater optimization have been increased monitoring, optimizing flushing, improving leak detection and updating standard operating procedures. Some utilities have also reported that the increased communication amongst different groups prompted by the DSOP has been extremely valuable

b. EPA's technical assistance Distribution System Optimization Program

EPA's Area-Wide Optimization Program (AWOP) began development of its distribution system optimization program in 2005. AWOP is utilized by State drinking water primacy agencies to provide compliance and technical assistance to water systems and support core drinking water program activities. The overall focus of the optimization program is on optimizing water system operations to improve distribution system water quality and public health protection. This is currently measured using water quality parameters such as disinfection byproduct formation, disinfectant residual concentrations, pH, temperature and other indicators of nitrification. AWOP "tools" include water system evaluation and operator training approaches intended to assess and improve distribution system water quality. Once a system is evaluated and a water quality concern is identified, primary approaches for improving water quality include managing tank operations (e.g., reducing turnover time, while encouraging good mixing – either operationally or mechanically – to improve water quality), proactive flushing (e.g., generally through the use of automatic flushers, intended to improve water quality), and rerouting water (when/if possible). Baseline water quality data are often collected to document the impact of these activities on water quality. Additionally, this program has a strong focus on the importance of sampling to represent distribution system water quality and sample analysis (e.g., chlorine residual) using proper technique; this is reflected in both evaluation and technical assistance (i.e., operator training) activities.

EPA's optimization program is similar to the PSW's DSOP in that both programs have a water quality focus. However, the EPA program does not include hydraulic or physical metrics such as pressure and water main breaks. Additionally, the EPA's program is intended to be implemented at water systems by state AWOP teams in a facilitated manner, whereas the PSW's program utilizes a self-assessment approach. Historically, AWOP efforts have focused on small-to-medium sized water systems, while larger systems tend to be better able to implement the PSW self-assessment. That being said, there are systems of all sizes in AWOP states that very successfully utilize the PSW's program. Additionally, there are systems that are members of the PSW who also participate in their state's AWOP by providing data, attending training, or other activities.

4.2.4 New Developments Regarding DS RICP Prioritization

a. Increasing Concern of Pathogen Growth in DS

Given recent information that estimated annual hospitalization costs (excluding mortality, disability, and other related costs) attributed to pathogens that can grow in biofilm exceed $900 million per year, (Collier et al., 2012), there may be opportunities for substantial cost savings and increase in public health protection if such incidence can be reduced through better risk management. A fundamental question is to what extent these risks might be reduced through actions within premise plumbing or improved quality of the water being delivered to the household or institution premise plumbing situation. A closely related issue pertains to the disinfectant residual in the distribution system and defining its purpose, improving its measurement, and determining the residual levels that can meet the appropriate purpose(s) that are assigned to it.

b. Premise plumbing

Premise plumbing is the portion of the water distribution system beyond the property line and in-buildings (e.g., hospitals, schools). Addressing premise plumbing issues is particularly challenging. Because a water system's responsibility to deliver potable water ends at the water meter, the favorable environment that promotes the growth of various organisms in premise plumbing may be largely outside of utilities' operations and management control. Also, the unique features (e.g., low disinfectants residuals, stagnation, and warmer temperature) of premise plumbing tend to allow opportunist pathogens to multiply and persist in premise plumbing systems. In 2014, WRF developed a focus area on waterborne pathogens in distribution and plumbing systems to address this important public health concerns. WRF project 4606, *Research Plan for Management of Emerging Pathogens in Distribution Systems and Premise Plumbing*, (LeChevallier et al., 2015) identified the 15 most pressing research needs concerning pathogens in premise plumbing systems. WRF project 4664 *Customer Messaging on Plumbing Systems Issues* is underway to develop messages for the water community to communicate with different audiences about the potential risks of opportunistic pathogens in plumbing systems and the most appropriate measures to minimize risk. Another research need identified under WRF project 4606 is a risk-based model for opportunistic pathogens in premise plumbing to develop for exploring control strategies to keep below a QMRA "tolerable" risk threshold.

c. EPA's *Legionella* Document

To help address concerns for *Legionella*, EPA is developing the document, *Technologies for Legionella Control in Premise Plumbing Systems: Scientific Literature Review*. EPA released a draft of this document for public comment in October 2015 (USEPA, 2015). The draft document provides a summary of the current body of knowledge that evaluates the effectiveness of different approaches to control for *Legionella* in a building's premise plumbing systems. In the draft document EPA summarizes available publications on multiple control technologies including: Risk management approaches (including temperature control, chlorine, monochloramine, chlorine dioxide, copper-silver ionization, ultraviolet light, and ozone). The draft document also discusses other control technologies that are often used for emergency remediation: superheat-and-flush, hyperchlorination and point of use filtration.

The target audience of the document includes, but is not limited to, primacy agencies, facility maintenance operators, facility owners, and technology developers and vendors. The agency expects the final document to improve public health by helping the targeted audience make science-based, risk management decisions regarding treatment and control of *Legionella* in buildings. EPA expects to publish the document in 2016.

4.3 Next Steps

Publication of this document is the final product agreed to by the RICP steering committee. Hence, with the document's publication, the formal partnership agreed to under the 2009 MOU which formed the RICP ends. However, all steering committee members acknowledge the need for continued research, information collection, and collaboration on distribution system issues. The partners and steering committee members recognize the benefits of continuing to partner through other available vehicles (e.g., Partnership for Safe Water). As opportunities for collaboration arise, the steering committee members intend to engage with the research and utility communities to fill the greatest number of research gaps identified in this document.

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APPENDIX

RICP Steering Committee Members

Nicholas Ashbolt, *U.S. Environmental Protection Agency*, 2009 - 2013

Joan Brunkard, *Centers for Disease Control and Prevention*, 2009 – 2010

Gary Burlingame, *Philadelphia Water Department*, 2009 - 2016

Stephen Estes-Smargiassi, *Massachusetts Water Resources Authority*, 2009 - 2016

Cindy Forbes, *California Environmental Protection Agency*, 2009 – 2016

David Gute, *Tufts University*, 2009 - 2016

Mark LeChevallier, *American Water*, 2009 - 2016

Audrey Levine, *U.S. Environmental Protection Agency,* 2009 – 2013

Stig Regli, *U.S. Environmental Protection Agency,* 2009 – 2016