Managing risks from virus intrusion into water distribution systems due to pressure transients

Jian Yang, Mark W. LeChevallier, Peter F. M. Teunis and Minhua Xu

ABSTRACT

Low or negative pressure transients in water distribution systems, caused by unexpected events (e.g. power outages) or routine operation/maintenance activities, are usually brief and thus are rarely monitored or alarmed. Previous studies have shown connections between negative pressure events in water distribution systems and potential public health consequences. Using a quantitative microbial risk assessment (QMRA) model previously developed, various factors driving the risk of viral infection from intrusion were evaluated, including virus concentrations external to the distribution system, maintenance of a disinfectant residual, leak orifice sizes, the duration and the number of nodes drawing negative pressures. The most sensitive factors were the duration and the number of nodes drawing negative pressures, indicating that mitigation practices should be targeted to alleviate the severity of low/negative pressure transients. Maintaining a free chlorine residual of 0.2 mg/L or above is the last defense against the risk of viral infection due to negative pressure transients. Maintaining a chloramine residual did not appear to significantly reduce the risk. The effectiveness of ensuring separation distances from sewer mains to reduce the risk of infection may be system-specific. Leak detection/repair and cross-connection control should be prioritized in areas vulnerable to negative pressure transients.

Key words | distribution system, intrusion, pressure transients, QMRA, risk assessment, viruses

Jian Yang (corresponding author)
Mark W. LeChevallier
Minhua Xu
American Water,
1025 Laurel Oak Rd, PO Box 1770,
Voorhees, NJ 08043,
USA
E-mail: *jian.yang@amwater.com*

Peter F. M. Teunis
National Institute of Public Health and the Environment (RIVM),
PO Box 1, 3720 BA Bilthoven,
The Netherlands
and
Hubert Department of Global Health,
Rollins School of Public Health,
Emory University, Atlanta GA,
USA

INTRODUCTION

Pressure transients in water distribution systems, also called water hammer or surge, are pressure waves generated due to pipeline elasticity and water compressibility when a system changes rapidly from one flow condition to another (Walski *et al.* 2007). For a quick estimation of the transient magnitude, every 0.3 m/sec (1 ft/sec) of velocity change can result in a pressure transient of 276 to 414 kPa (40 to 60 psi), depending on the pipe material, the quantities of entrapped air, etc. A pressure wave of this magnitude could raise or drop a system pressure of 414 kPa (60 psi) above 689 kPa (100 psi) or below 138 kPa (20 psi), respectively, which is beyond the recommended ranges for a water distribution system in the United States (Ten State Standards 2007). The pressure wave can propagate throughout a distribution system causing high and low/negative pressures in locations miles away from the origin of the event. Low/negative pressure transients are usually brief and thus are rarely monitored or alarmed. But even for a few seconds, low/negative pressures can create a force driving contaminants from the external soil and water environment into the distribution system. Utility survey results (Kirmeyer *et al.* 2001) showed that at least 20% of the surveyed systems had pipes below the water table and about 20% systems reported 25%–75% of meter boxes flooded during different seasons.

Because pressure transients can propagate throughout a distribution system, the local magnitude of the pressure transients can be complicated by the characteristics of the distribution system and operational activities, including: dead-end or looped pipelines, presence of elevated storage tanks, system topography, pump/valve characteristics and operational procedures, placement of surge

doi: 10.2166/wh.2011.102

control devices, and quantities of entrapped air. The occurrence of pressure transients may be common, as these transients can be caused by routine distribution system operation and maintenance activities such as valve closure, main breaks/repairs, hydrant flushing, and pump start/shutoff (Walski *et al.* 2007). Gullick *et al.* (2004) studied transient occurrences in full-scale distribution systems for extended periods (up to 1.6 years) and observed 15 surge events that resulted in negative pressures. Details about these systems can be found in the project report (Friedman *et al.* 2004). In the study, 40 events were observed with pressures below 138 kPa (20 psi) and negative pressure transients occurred in three of seven full-scale distribution systems. Most negative pressure transients (12 out of 15) were caused by the sudden shutdown of pumps at a pump station because of either unintentional (e.g. power outages) or intentional circumstances (e.g. pump stoppage or startup tests). The duration of pressure transients can be influenced by flow control operations and system characteristics such as presence of storage tanks, entrained air, and pipe leaks, which can significantly dampen transients. Gullick *et al.* (2004) showed that the negative pressures lasted from 1 second to more than 160 seconds in four of eight studied distribution systems. The volume of intrusion can range from milliliters to thousands of liters depending on the effective size of the orifice, external pressure, and the nature of the transient event (Kirmeyer *et al.* 2001). Pilot-scale investigations estimated intrusion volumes up to 50 mL and 127 mL through 3.2 mm (1/8 in) and 6.4 mm (1/4 in) orifices, respectively, when 8.3 L/sec (132 gpm) of flow was brought to a stop with the sudden closure (<1 second) of a 64 mm (2.5 in) ball valve (Boyd *et al.* 2004a, b).

Public health impact

The intrusion of microbial contaminants due to low or negative pressure transients is of great concern because even with dilution, some microbes can cause an infection with a single organism (LeChevallier *et al.* 2003; Teunis *et al.* 2008). Karim *et al.* (2003) examined 66 soil and water samples immediately adjacent to drinking water pipes from eight utilities in six states of the United States (US). About 56% of the samples were found positive for human enteric viruses. In addition, total fecal coliform levels in some soil samples were greater than 1.6×10^4 CFU/100 g of soil, suggesting the sampling locations were potentially under the influence of leaking sewage pipes. An epidemiological study by Payment *et al.* (1997) suggested that the distribution system was at least partially responsible for increased levels of gastrointestinal illnesses. Kirmeyer *et al.* (2001) conducted surge modeling for the distribution system of the epidemiological study and found that the system was extremely vulnerable to negative pressures. More than 90% of the nodes in the system were estimated to draw negative pressures under certain modeling scenarios (e.g. power outages). In the absence of other plausible explanations, low disinfectant residuals and the system vulnerability to negative pressure transients were speculated to contribute to the viral-like etiology of the observed illnesses in the epidemiological study (LeChevallier *et al.* 2003). In April 2002, a *Giardia* outbreak occurred at a trailer park in New York state causing six residents to become seriously ill (Blackburn *et al.* 2004). The contamination was attributed to a power outage, creating a negative pressure transient in the distribution system, which allowed water to enter the system through either a cross-connection inside a mobile home or through a leaking underground pipe that was near sewer crossings.

There are many potential portals in a distribution system for external contamination to enter: leakage points in water mains, submerged air valves, faulty seals or joints, and cross-connections. A survey of over 700 North American distribution systems (Lee *et al.* 2003) indicated that all surveyed systems had locations susceptible to backflow of non-potable water during a low or negative pressure transient. The US Environmental Protection Agency (USEPA) compiled backflow events from 1970 to 2001 and revealed 459 backflow incidents, resulting in 12,093 illnesses (USEPA 2002). Intrusion of microbial contamination is also possible in areas drawing low pressure during a main break or when inadequate sanitary measures are used during main repairs. Nygård *et al.* (2007) conducted a cohort study in Norway and found that households exposed to water from a segment of distribution system with main breaks or maintenance were 1.6 times more likely to report gastrointestinal illness than households unexposed to such distribution system events.

Problem statement

Despite insufficient direct evidence to show pressure transients as a substantial source of risk to waterborne disease, risk mitigation measures can still be implemented. To evaluate the effectiveness of various risk mitigation measures without seeking actual disease occurrence in a population as in an epidemiological study, a quantitative microbial risk assessment (QMRA) can be conducted (Hunter *et al.* 2003). QMRA can infer and compare the risks of infections assuming different mitigation measures were in place. The International Life Sciences Institute (ILSI) Risk Science Institute developed a conceptual framework for assessing the risks of human disease following exposure to waterborne pathogens (ILSI 2000). A few studies have been conducted previously using QMRA to estimate the waterborne disease burden in communities or to assist developing drinking water treatment regulations. Haas *et al.* (1993) used QMRA with Monte Carlo simulations and estimated an annual risk of disease of 0.23 from enteric viruses in drinking water, based on an average concentration of 6×10^{-4} viruses per liter found in the finished drinking water in the Montreal area. Teunis *et al.* (1997) evaluated the risk to customers from ingesting *Cryptosporidium parvum* surviving treatment at a plant in the Netherlands, where the median annual risk of infection from *Cryptosporidium* was estimated to be slightly higher than 10^{-4}. Similar to using the acceptable risk level of 10^{-4} for carcinogens, the USEPA has used an annual acceptable infection risk of $<10^{-4}$ due to drinking water contamination for regulatory purposes (NRC 2006).

There are few published studies using QMRA to assess the health risk associated with pathogen intrusion due to negative pressure transients in water distribution systems. Research is needed to better characterize the risks (e.g. exposed population, risk of infection, spatial heterogeneity, the risk sensitivity, etc.). Research is also needed to guide water utilities to use the QMRA models, identify areas in their systems susceptible to low pressures, and identify best corrective measures to mitigate the risks. This study is part of a research project about developing QMRA models to characterize the risks of infection from microbial intrusion caused by negative pressure transients (LeChevallier *et al.* 2010). The purpose is to apply the QMRA models developed in the project, evaluate the sensitivity of various risk driving factors, and elucidate the effectiveness of various risk mitigation practices for public health protection.

METHODS

Quantitative microbial risk assessment

The QMRA model was previously developed to couple hydraulic and surge modeling with Monte Carlo simulations to obtain risk estimates of the waterborne viral infections (excluding secondary or person-to-person transmission). The most challenging component in the QMRA model was exposure assessment, which involved evaluating the characteristics of intrusion (location, volume, and duration) and the fate of intruded viruses traveling within the distribution system. The risk model is summarized as the following and more details of the QMRA model development are described elsewhere (LeChevallier *et al.* 2010; Teunis *et al.* 2010).

Virus concentrations in sewage

Norovirus was selected in this study as the microbial pathogen for the risk modeling. Virus was selected for the risk modeling because it was found immediately adjacent to drinking water pipes (Karim *et al.* 2003) and can cause acute risk of infection. Virus levels in raw sewage were used as the baseline (the worst case) to estimate the risk of infection, i.e., cross-connection or when water mains are in direct contact with raw sewage. The occurrence of norovirus levels in raw sewage was collected from published data and the virus levels may be highly variable. Pusch *et al.* (2005) and Haramoto *et al.* (2006) reported norovirus levels in sewage of $<1.0 \times 10^6$–1.6×10^9 and 1.7×10^2–2.6×10^6 genome copies per liter, respectively. Qualitative differences between concentrations estimated by different enumeration methods were considered, as culture methods (e.g. most probable numbers per liter – MPN/L) might yield lower estimates than methods based on detection of genetic material (polymerase chain reaction – PCR). Lodder & de Roda Husman (2005) and Ottoson *et al.* (2006) reported norovirus levels in sewage of 5.1×10^3–8.5×10^5 PCR detectable units (PDU) per liter and $<5.5 \times 10^2$–4.5×10^3 MPN/L, respectively. Virus levels were characterized by quantiles of virus concentrations and combined in a two-level "meta-analysis" model, producing a predictive distribution of virus concentrations in sewage. Distributions of virus concentrations were assumed to be lognormal. The median virus concentration was predicted to be 4.9×10^4 PDU/L. The 2.5% and the 97.5% percentiles for norovirus concentrations were estimated to be 4.3×10^{-1} and 4.1×10^8 PDU/L, respectively.

Surge modeling of the studied distribution system

The hydraulic model of the studied distribution system was previously calibrated for 24-hour extended period simulations (EPS), which included 1128 nodes and 1369 pipes, with a total length of 269 km (167 miles) of pipe. The system had a service population of about 33,000. The annual average and maximum day demands were 2.3×10^4 m^3/day (6.0 MGD) and 5.0×10^4 m^3/day (13.3 MGD), respectively. Service pressures ranged typically from 276 to 689 kPa (40 to 100 psi). The system had one pressure gradient, two elevated storage tanks, four wells, and five pump stations (four for the wells and one in the distribution system). Figure 1 shows the hydraulic model of the studied system and the 118 nodes (11%) that were predicted to be susceptible to intrusion (assuming that every model node had a leak for potential intrusion). The transient-producing

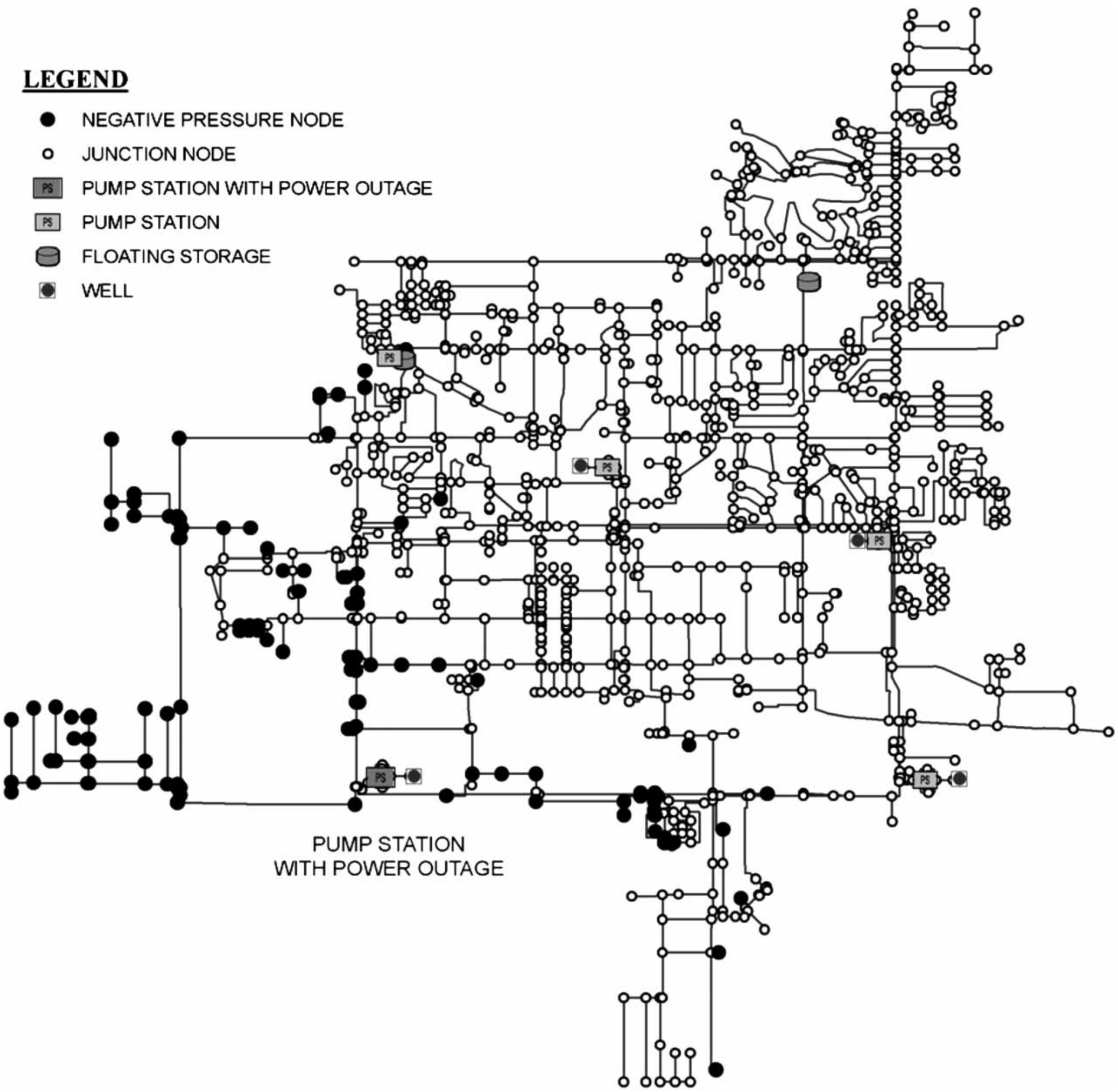

Figure 1 | Hydraulic model and potential intrusion nodes (negative pressure nodes) of the studied distribution system.

event was modeled as a power outage at the southwest pump station under the maximum day demand conditions. InfoSurge (MWH Soft Inc., Pasadena CA, USA) was used to conduct the surge modeling. Transient events due to pump shutdown were simulated for 120 sec. Gullick et al. (2004) observed that most negative pressure events due to transients last less than 2 min. As a worst-case scenario, transient events were analyzed when a maximum flow rate was supplied to the system. The duration of pump shutdown was modeled to be 1 sec. The check valve at each pump was modeled to close within 0.1 sec of sensing reverse flow. The check valve resistance was set to 11 sec^2/m^2 (1 sec^2/ft^2) and a wave speed of 1,100 m/sec (3,600 ft/sec) was assumed for the system. More details of the surge modeling procedure are described elsewhere (Fleming et al. 2006).

Exposure assessment

Upon intrusion, the intruded viruses are suspended and diluted in the local water flow (assuming no attachment/detachment of virus from pipe wall). Assuming an intrusion volume V_{intr} (L, gal) of sewage, containing a concentration C_v (PDU/L) of viruses, enters the system at a location (at node k) where the flow rate is Q_k (L/sec, gpm) so that during a negative pressure duration Δ_1 (sec, min) a volume $Q_k\Delta_1$ (L, gal) passes through the leaking node, the virus concentration c_k (PDU/L) at the intrusion node is

$$c_k = C_v \frac{V_{\text{intr}}}{V_{\text{intr}} + Q_k\Delta_1} \quad (1)$$

EPANET, the hydraulic modeling software developed by the USEPA (Rossman 2000), was used to analyze system hydraulics and virus transport within the system. Hydraulic and water quality simulations were run over a 24 hour period with a hydraulic time step of 0.1 hour (6 min), a water quality time step of 0.01 hour (36 sec), and a report time step of 1 hour. The intrusion event was modeled to occur at the start of the simulation. To study the impact of a disinfectant residual (chlorine and chloramines), an extension of EPANET, EPANET-MSX, was used to simultaneously simulate the disinfectant decay and virus inactivation. EPANET-MSX enabled the modeling of complex reaction schemes between multiple chemical and biological species in the system (Shang et al. 2008). Table 1 summarizes the initial disinfectant demand and decay constants used in the model, which were obtained from the disinfectant decay experiments with 0.1% wastewater intrusion that had total organic carbon (TOC) levels ranging from 4.6 to 54 mg/L. Details about the disinfectant decay experiments can be found in the project report (LeChevallier et al. 2010). Virus inactivation due to a residual disinfectant (either free chlorine or chloramines) was estimated by using the Chick–Watson model, which is described as (Haas 1990):

$$Ln\left(\frac{N_0}{N}\right) = k_i C_d^n T \quad (2)$$

where N is the number of microorganisms after exposure to a disinfectant residual; N_0 is the number of microorganisms before disinfectant additions; k_i is an inactivation constant $(\text{mg Cl}_2\cdot\text{min/L})^{-1}$; C_d is disinfectant residual (mg Cl_2/L); n is the order of inactivation kinetics (assumed to be 1 in this study); and T is exposure time (min). Values for the inactivation constant k_i were derived from a review of CT values, disinfectant concentration multiplied by contact time, from the USEPA Guidance Manual (USEPA 1989). Linear regression of the CT values to the virus log inactivation was conducted using the Chick–Watson model ($R^2 = 0.99$). The inactivation constant values for free chlorine and chloramines were estimated to be 1.6 and 6.4×10^{-3} $(\text{mg Cl}_2\cdot\text{min/L})^{-1}$, respectively.

The consumption of tap water at any node depends on the number of customers receiving water from that node and their individual intake of unheated tap water. The service population at a node was determined by distributing the total population across all system nodes weighted by the water demand allocated at each node. An average service

Table 1 | Free chlorine and chloramine initial demands and decay constants used in the QMRA model

Disinfectant	Decay order	Decay constant without intrusion	Initial demand after intrusion (mg Cl_2/L)	Decay constant after intrusion
Free chlorine	1st	0.055 ($hour^{-1}$)	0.088	0.24 ($hour^{-1}$)
Chloramine	2nd	0.012 $(\text{mg Cl}_2\cdot\text{hour/L})^{-1}$	0.0	0.11 $(\text{mg Cl}_2\cdot\text{hour/L})^{-1}$

population per node was estimated to be 30 people in the studied system. To simulate varying numbers of household members drinking tap water, the Monte Carlo simulation assumed a Poisson-distributed random number of people drinking water at each node, using the service population at the node as the parameter. The USEPA generally employs a volume of 2 L per person per day to estimate drinking water exposure for chemical risk assessment, however, only a fraction of which may be consumed unmodified (e.g. not boiled). In this study, the daily intake of unheated tap water was estimated from a population survey (Teunis *et al*. 1997) and approximated by a lognormal distribution with a median water consumption of 0.18 L. The daily intake volume was assumed to be randomly consumed completely once a day by a customer and at any time of the day.

Risk characterization

After the exposure assessment, a risk model was developed using Monte Carlo simulation programmed in Mathematica (Wolfram Research Inc., Champaign IL, USA). The Monte Carlo simulation was run with 1,000 repetitions. During each Monte Carlo repetition, the following random variables were generated or derived: external virus levels, intrusion volume, intrusion duration, dilution factor, virus levels after dilution, number of customers drinking water at a model node, and individual water intake volume. After estimation of the population exposed and the virus doses consumed, the dose response models were incorporated to estimate the numbers of waterborne infections and the risk of infection. The infectivity of norovirus had been inferred from human challenge studies (Teunis *et al*. 2008) and human dose responses were established in PCR-based units. The dose response model was characterized by a beta-probability distribution of infectivity for a single norovirus particle. The model indicated high infectivity of the virus, e.g., exposure to a single norovirus could cause infection in about 30% of exposed population.

Sensitivity analysis

To elucidate the effectiveness of various mitigation measures for public health protection, a sensitivity analysis was conducted for various operational and controllable risk factors. Risk of infection was estimated under a baseline scenario and a variety of mitigation scenarios for best practice development. Table 2 summarizes the baseline and various mitigation scenarios under which the risk driving factors were varied. The risk factors in the sensitivity analysis included the external virus concentrations, maintaining disinfectant residuals, negative pressure duration, the number of intrusion nodes, and leak sizes. The sensitivity to each contributing factor was evaluated by applying different multipliers or fixing the factor at different values while allowing the other factors to vary throughout their respective ranges.

External virus concentrations

Under the baseline conditions, virus levels external to the distribution system were randomly generated based on virus occurrence levels in raw sewage, i.e. the worst case. Actual virus levels at intrusion locations can be much lower. First, sewer pipes are usually not in immediate

Table 2 | Summary of scenarios in which risk driving factors are varied

Scenarios in which risk driving factors are varied	Conditions
Baseline conditions	1. External virus concentration: random generated; 2. Disinfectant residual: no disinfectant residual; 3. Negative pressure duration: random generated; 4. Number of nodes drawing negative pressure: 11%; 5. Leak sizes: 1.3 mm
1. External virus concentration	Original concentrations $\times 10^{-4}$, $\times 10^{-3}$, $\times 10^{-2}$, $\times 10^{-1}$, $\times 10^{0}$ (baseline), $\times 10^{1}$, and $\times 10^{2}$
2. Maintenance of a disinfectant residual	No disinfectant residual (baseline), 0.5 mg Cl_2/L chloramines, 0.1, 0.2, and 0.5 mg Cl_2/L free chlorine
3. Negative pressure duration	Fixed at 1, 10, 20, 100, 500, and 1,000 sec
4. Number of nodes drawing negative pressures (intrusion nodes)	6.0%, 11% (baseline), 42%, and 85%
5. Leak sizes (intrusion volumes)	0.66 mm, 1.3 mm (baseline), and 2.6 mm (original intrusion volumes $\times 0.25$, $\times 1.0$, and $\times 4.0$)

vicinity of drinking water pipes. A previous survey of 26 utilities showed that 15 (58%) utilities typically used a 3.0 m (10 ft) separation distance and 7 (27%) used a minimum distance of 0.61–1.5 m (2–5 ft) (Kirmeyer *et al.* 2001). The pathogen levels in leaking sewage may be significantly reduced after conveyed to the vicinity of drinking water pipes by natural die-off, groundwater dilutions, soil filtration, etc. Additionally, in the immediate vicinity of drinking water main leaks, a mixture of leaked drinking water and contaminated water may occupy the space around the leaks. Disinfectant residuals in the leaked drinking water, if not exhausted by the environment, may still provide some inactivation of non-chlorine-resistant pathogens. To study the sensitivity of risk to the variation of external virus levels, this parameter was multiplied with a value from 10^{-4} to 10^{2}. Under the scenario with a multiplier of 10^{-4}, the median virus concentration external to the distribution system was as low as 4.9×10^{0} PDU/L.

Maintaining disinfectant residuals

Maintaining a disinfectant residual has been regarded as the final barrier for protecting public health in the event of intrusion or backflow of a contaminant within distribution systems. The US federal regulations (the Surface Water Treatment Rule) require large (>10,000 people) surface water systems to maintain a detectable free or combined residual in 95% of monthly samples, or to demonstrate a heterotrophic plate count less than 500 CFU/mL. However, this requirement provides minimal protection against microbial intrusion and previous studies have not reached consensus on what constitutes an adequate disinfectant residual (Snead *et al.* 1980; LeChevallier *et al.* 1996; Payment 1999; Propato & Uber 2004). The sensitivity analysis evaluated the risk of infection with different disinfectant residuals maintained in the system (listed in Table 2), including the absence of a residual (baseline), 0.5 mg Cl_2/L as monochloramine, 0.1, 0.2, and 0.5 mg Cl_2/L as free chlorine.

Negative pressure duration

If the internal pressures in a system are always maintained greater than the external pressures, there is no physical force to drive intrusion. The objective of pressure transient control is to minimize the rapid and/or extreme fluctuations in flow velocities and to alleviate the severity of the pressure transients. When a negative pressure transient is alleviated (e.g. by adding an elevated/hydropneumatic tank), the duration and the magnitude of negative pressures are reduced. Under the baseline condition, negative pressure durations at intrusion nodes were randomly generated based on the published data with a median about 10 sec and ranging from <1 sec to 165 sec (Gullick *et al.* 2004). To study the sensitivity of risk to the negative pressure duration, this parameter was set at a value of 1, 10, 20, 100, 500, or 1,000 sec.

Number of nodes drawing negative pressures

Another direct outcome of reducing the magnitude of negative pressure transients is the reduced number of nodes experiencing negative pressures. A previous surge modeling study of 16 distribution systems (Fleming *et al.* 2006) predicted susceptibilities to negative pressure during a power outage ranged from 1 to 98% with a median susceptibility of about 30%. These percentages suggested that the risk of infection may vary widely for different distribution systems due to different vulnerability to negative pressures. Table 3 summarizes four different transient-producing events simulated by surge modeling to estimate different percentages of nodes experiencing negative pressures. The estimated percentages of nodes drawing negative pressures ranged from 6.0 to 85%.

Table 3 | Transient-producing events and simulated percent of nodes drawing negative pressures

Transient-producing events	Percent nodes drawing negative pressures
1. Three of the four pumps operating in the southwest well pump station were suddenly shut down	6.0
2. The southwest well pump station was suddenly shut down	11 (baseline)
3. The booster station and the two well pump stations in the south of the system were suddenly shut down	42
4. All five pump stations were suddenly shut down	85

Leak orifice sizes

Kirmeyer *et al.* (2001) found that the most common type of leak/break was circumferential and reported by 18 (69%) of the 26 surveyed utilities. Thirteen utilities also reported longitudinal and circular (pinhole) leaks. For circumferential or circular leaks, the sizes of the leaks were reported to be 3 to 102 mm (1/8 to 4 in). However, for leaks that were not surfaced or observed, the sizes might be much smaller. In this study, the orifice discharge equation was used to estimate an equivalent orifice diameter for all leaks in the studied system.

$$Q = C_f C_{disc} D^2 \sqrt{P} \tag{3}$$

where Q is leakage flow rate (L/sec, gpm); C_{disc} is discharge coefficient; C_f is unit conversion factor (0.111 SI, 29.8 Imperial); D is orifice diameter (cm, in); and P is pressure (kPa, psi). If the system was assumed to have 10% of leakage water (2.3×10^3 m^3/day or 417 gpm), 414 kPa (60 psi) of discharge pressure, 1,128 leaks (one leak per node), and a discharge coefficient of 0.8 at each leak, the equivalent orifice diameter was estimated to be 1.3 mm (0.05 in). The sensitivity of risk to the size of the leak was evaluated under two scenarios: half and twice the estimated equivalent orifice diameter (0.66 mm and 2.6 mm). Under these two scenarios, the intrusion volumes randomly generated at the intrusion nodes were reduced to 25% and increased to 400% of the baseline values, respectively.

Impact of the randomness of risk factors

To compare the contribution from the randomness of individual risk factors to the variation of the infection risk, a fixed sensitivity analysis was also conducted for the risk of norovirus infection. The variation of the infection risk to each contributing factor was evaluated by fixing the risk factor at the respective average value while allowing the other factors to vary throughout their respective ranges. Random factors in the fixed analysis included external virus concentrations, negative pressure duration, the intrusion volume at any node, the number of individual intake events at any node (node population), water consumption during an intake event, and infectivity of the virus.

RESULTS AND DISCUSSION

Risk characterization

Under the baseline conditions, the studied system was estimated to have a median infection risk of 2.1×10^{-4} for norovirus due to a single negative pressure transient event. The variation of the estimated risk was approximately 1.5 logs of magnitude (3.5×10^{-5} to 1.2×10^{-3}) due to the randomness of various risk factors during the Monte Carlo simulations. The median risk level was slightly higher than the USEPA acceptable level of annual infection risk (10^{-4}). If the system had five power outages per year (Grebe *et al.* 1996) and each power outage caused a similar negative pressure transient (118 or 11% nodes drawing negative pressures), the system annual risk of norovirus infection would be 1.1×10^{-3}, or about one order of magnitude higher than the acceptable risk level of 10^{-4}.

External virus concentrations

The variation of external virus concentrations appeared to have no significant impact on the risk of infection (Figure 2(a)). Increasing the external norovirus levels by 2 orders of magnitude was estimated to increase the median risk only slightly (from 2.1×10^{-4} to 2.5×10^{-4}). Decreasing the external virus levels by 4 orders of magnitude had a modest reduction of the median risk (2.1×10^{-4} to 3.4×10^{-5}). These results suggest that mitigation measures target to reduce external virus levels might not be effective. Due to the high infectivity of the selected viruses, low doses of highly infectious viruses may still cause most exposed populations to be infected.

Disinfectant residual maintenance

Maintaining a disinfectant residual had a significant impact on the fate of intruded viruses. Figure 3 shows, under the baseline condition (no disinfectant residual in the system), approximately 94% of intruded viruses were washed out from the system during the 24-hour simulation. With a disinfectant residual of 0.5 mg Cl_2/L as monochloramine or 0.1 mg Cl_2/L as free chlorine, the same rate of virus removal/inactivation was achieved within 12 hours and

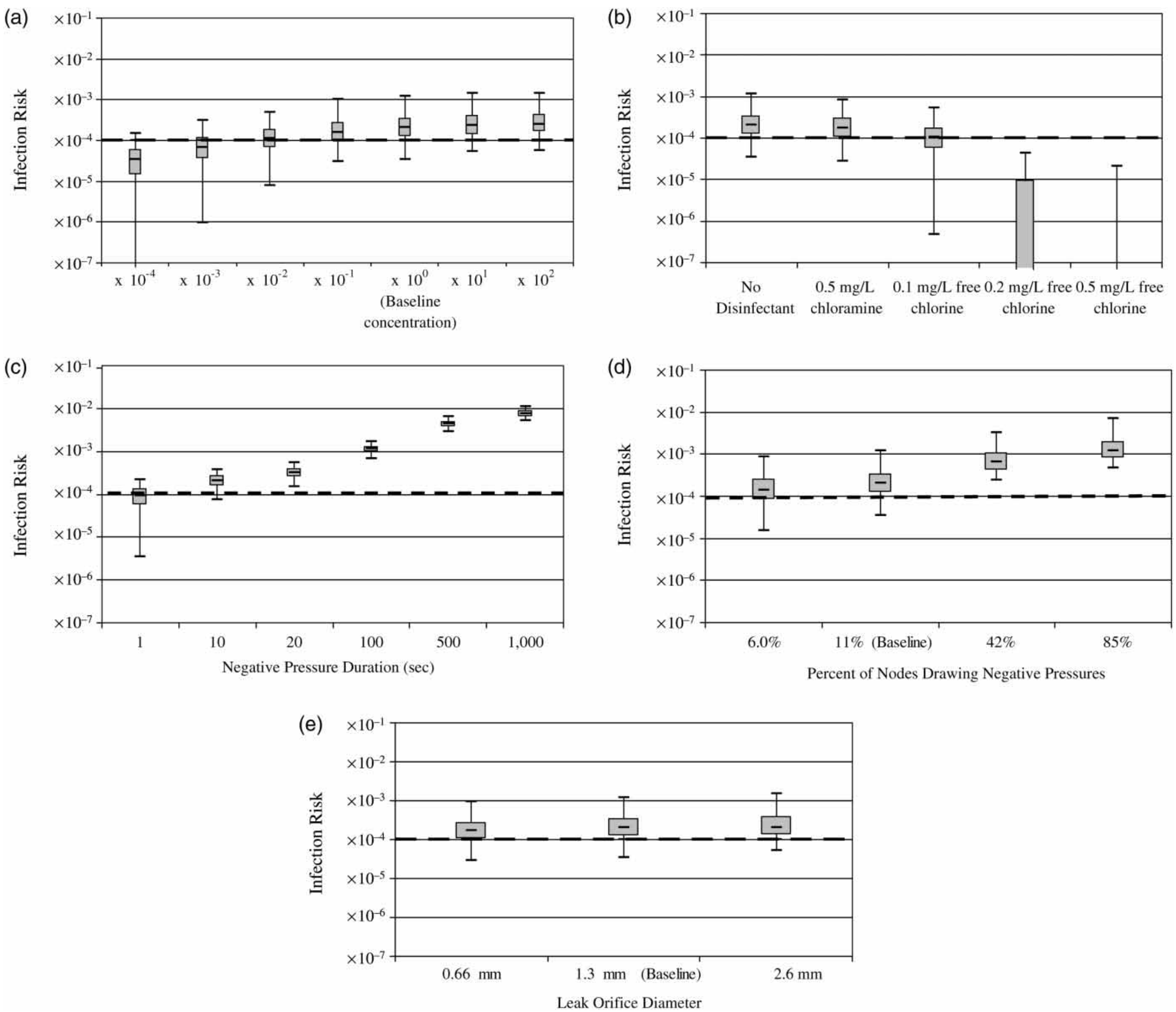

Figure 2 | Impact on the risk of norovirus infection: (a) External virus levels, (b) Disinfectant residual maintenance, (c) Negative pressure duration, (d) Number of intrusion nodes experiencing negative pressures and (e) leak sizes (risk below 10^{-7} not shown).

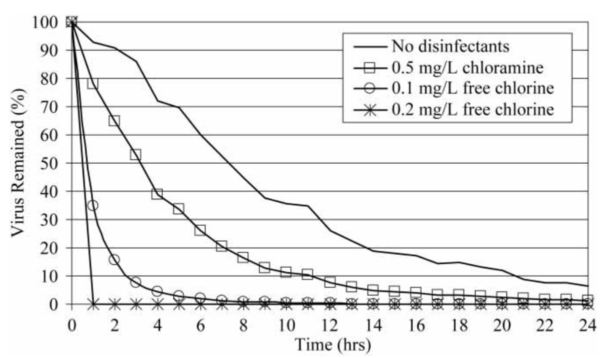

Figure 3 | Comparison of percentages of intruded viruses remained in the system within 24 hours of intrusion.

3 hours, respectively. The intruded viruses were estimated to be completely eliminated within 30 min when a free chlorine residual of 0.2 mg Cl_2/L or higher was maintained in the system (simulation for a free chlorine residual of 0.5 mg Cl_2/L not shown).

The intruded viruses survived from the inactivation would cause infections in the exposed population (Figure 2(b)). Maintaining a disinfectant residual of 0.5 mg Cl_2/L as monochloramine was estimated to have no apparent reduction on the risk of infection despite it inactivated approximately half of the viruses in the system as shown in Figure 3. Similarly, maintaining a free chlorine residual of 0.1 mg Cl_2/L only had a modest reduction on the risk (from 2.1×10^{-4} to 1.1×10^{-4}), despite 95% of viruses removed or inactivated after 4 hours. These results are due to the high infectivity of norovirus, i.e., although a significant portion of norovirus had been removed or inactivated, the remaining norovirus may still cause most exposed populations to be infected. If the system maintained a free chlorine residual of 0.2 mg Cl_2/L or higher, the median risk of infection was reduced to insignificant levels ($<10^{-7}$). This is because a free chlorine residual of 0.2 mg Cl_2/L or higher could overcome the initial chlorine demand of wastewater intrusion and free chlorine is an effective biocide for virus inactivation. The intruded viruses were estimated to be completely eliminated within 30 minutes after entering the system.

Negative pressure duration

The risk of infection was most sensitive to the duration of negative pressure (Figure 2(c)). The median risk with a negative pressure duration of 10 seconds was estimated to be 2.1×10^{-4}. Reducing the negative pressure duration to 1 sec reduced the median risk below the acceptable risk level of 10^{-4} to 9.2×10^{-5}. Increasing the duration from 10 to 1,000 sec increased the median risk of infection by about 2 orders of magnitude. The duration of the negative pressure events influences the amount of sewage entering the system as well as the dilution factor. More importantly, the duration of the negative pressure events determines the probability that a person's consumption of water would coincide with the occurrence of viruses in the distributed tap water. The longer the duration, the more likely that people will be exposed to the contaminated water. Negative pressure events with a prolonged duration may impose significant risk on the exposed population. Although typical low/negative pressure events may not last more than 2 min, longer durations of depressurization (e.g. 500 and 1,000 sec) may occur after a power outage or large water main break. These long periods of depressurization may cause significant risks to public health, which should trigger the issuance of a Boil Water Advisory.

Number of intrusion nodes

Four different transient-producing events were modeled to cause the percentage of nodes experiencing negative pressures from 6.0% to 85% (see Table 3). Figure 2(d) shows the significant impact of the number of intrusion nodes on the risk of norovirus infection. Increasing the percentage of intrusion nodes from 11% to 85% increased the median risk by sixfold (2.1×10^{-4} to 1.2×10^{-3}). Decreasing the percentage of intrusion nodes from 11% to 6.0% reduced the risk about half (2.1×10^{-4} to 1.4×10^{-4}). A large number of nodes experiencing intrusion likely lead to an increased number of customers exposed to the contaminated water, thus causing a significant increase in risk. As the number of intrusion nodes decreases due to surge protection or leak detection/repairs, the risk of infection may be more sensitive to the location of the intrusion and the system hydraulics. Intrusion at locations serving a large number of customers may have much higher risks than intrusion at remote locations with no or few customers.

Leak sizes

Different leak sizes did not appear to significantly affect the risk of infection (Figure 2(e)). The median infection risks of the three different orifice diameters were not significantly different. This insensitivity was probably because the size of the leak only changed the amount of viruses entering/traveling through the system. It was previously shown that the risk of infection was not particularly sensitive to virus concentration (but rather exposure), hence orifice size would also have little impact on risk. One implication of this finding is on how to prioritize leak detection and repair activities. When the purpose of leak detection is to minimize water loss, leak detection and repair activities should be prioritized in areas with big leaks. However, from a perspective of public health protection, the size of the leak is a less critical factor and leak detection/repair should be prioritized in areas vulnerable to negative pressure transients. It should be noted that the minimum risk impact from leakage sizes was estimated under the baseline scenario where no disinfectant residual was maintained. When a disinfectant residual (e.g. free chlorine) is maintained, the impact of the size of the leak may have significant impacts on the stability of the disinfectant residual. Larger leak orifices may allow larger volumes of intrusion, which could exhaust the disinfectant residual and significantly increase the risks of infection to the exposed population.

Impact of the randomness of risk factors

The contribution from the randomness of individual factors to the variation of norovirus infection risk is compared in Figure 4. The strongest influence on the risk variation was due to the variability of the negative pressure duration. All other factors contributed much less. As discussed earlier, the negative pressure duration is highly important because it drives the probability that water consumption would coincide with the occurrence of the contamination slug. In a small system there is a definite chance that intrusion due to negative pressure transients of only a few seconds will not cause any infection because of the low probability that people will drink the water precisely when the slug of contamination is present.

Best practices for risk mitigation

The sensitivity analysis elucidated two primary mechanisms to mitigate risk: 1) reduce the exposure or 2) reduce/eliminate the pathogen concentration at the time/location of water consumption. For pathogens with high infectivity (e.g. viruses), risk mitigation practices that control exposure, (i.e. reduce the probability that people will be exposed to the contamination during a water intake event), are likely to be the most effective.

Optimized pressure management

Reducing the duration or the number of nodes experiencing negative pressures was shown to significantly reduce the risk of infection, indicating that optimized pressure management to control negative pressure transients would be the most effective tool to mitigate risk. Theoretically, if the internal pressure in a system is consistently maintained above the external pressure, there is no physical force to drive intrusion. In reality, short periods of pressure below 138 kPa (20 psi) often go undetected due to a variety of reasons. First, pressure monitoring at susceptible locations within distribution systems (e.g. high elevations) may be less commonly conducted than at convenient sites (pumps and tanks). Second, pressure deficiency analysis under transient conditions is not commonly done in current hydraulic modeling practices. Transient pressures are often not considered during the fire flow analysis. Given these deficiencies in common practices, the optimization of pressure management may require a combination of hydraulic/surge modeling, pressure monitoring, and transient pressure mitigation. Surge models can be used to improve the understanding of how the system may respond to a variety of events that can create rapid changes in flow conditions. Key elements include: 1) causes of transient events; 2) the magnitude and duration, as well as locations of lowest pressures; and 3) monitoring plan for transient pressures. Pressure monitoring within distribution systems can reveal extreme transient pressures, as well as pressures under normal and fire flow conditions. The strategies to control transient pressures may be adopted as either direct action or diversionary tactics (Thorley 2004). The direct action strategies attempt to modify system operations that cause rapid flow condition changes. The diversionary tactics attempt to control the magnitude of the transient that may occur due to unplanned events such as power failures. Common surge protection devices include surge tank, one-way tank, pressure relief valve, surge anticipation valve, air release/vacuum valve, and pump bypass. Surge modeling and pressure monitoring should be conducted to validate the effectiveness of the adopted device and strategies for transient control.

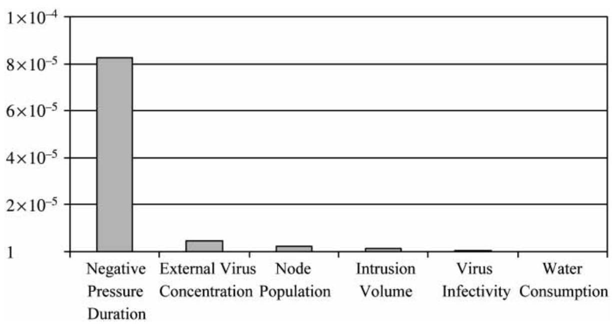

Figure 4 | Contribution of the randomness of individual risk factors to the variation of the risk.

Disinfectant residual maintenance

The risk results in this study demonstrated the importance of maintaining an adequate disinfectant residual as the final barrier for protecting public health in the event of intrusion within the distribution system. To overcome the potential initial demand of the intrusion, a free chlorine residual of

0.2 mg/L or above was needed to significantly reduce the risk of infection. It should be noted that this free chlorine residual was derived for dispersed viruses that are highly infectious (Teunis *et al.* 2008) but easy-to-kill (USEPA 1989; Shin & Sobsey 2008). For chlorine-resistant pathogens (e.g. *Cryptosporidium* or viruses in aggregated or particle-associated forms), maintaining a chlorine residual may not provide additional protection after the pathogen enters the system. This variability in chlorine-resistance may be one reason why previous studies have not reached consensus on recommending what constitutes an adequate disinfectant residual for public health protection (Snead *et al.* 1980; LeChevallier *et al.* 1996; Payment 1999; Thurston-Enriquez *et al.* 2003; Propato & Uber 2004). Chloramine residuals did not appear to have a significant impact on reducing the risk. For utilities that use chloramines as disinfectant residual, other preventive measures (e.g. pressure management and surge protection) should be emphasized to a greater extent to reduce the public health risks.

Leak detection/main repairs

Although this study found the size of the leak orifice not a significant factor influencing the risk from intrusion, leak detection/repair is still an important practice, especially in areas that are vulnerable to negative pressure transients and a chlorine residual is maintained. Leak detection programs are commonly practiced in the US. A previous survey showed that 85% of 26 surveyed utilities had a leak detection program with an unbilled water percentage of total water produced, ranging from less than 10% to 32% (Kirmeyer *et al.* 2001). It should be noted that the goal of leak detection for water loss control or for reducing the risk of infection may have different emphasis. The former strives for reducing the water loss volume, while the latter aims for reducing the most number of leaks at areas susceptible to negative pressure transients. This difference may have a significant impact on the selection and employment of leak detection techniques.

Ensuring separation distance from sewer mains

Ensuring adequate separation distance from sewer mains may reduce pathogen levels and the chlorine demand of the contaminant intrusion into the drinking water pipes. This study suggested that external virus concentrations had little impact on the risk of viral infection when no disinfectant residual was maintained in the system. However, if a disinfectant residual is maintained, ensuring adequate separation distance may reduce chlorine demand of the intruded water and an adequate free chlorine residual is effective to reduce the risk of viral infection. Second, inadequate separation distance may also increase the virus dose during an intake event, which might increase the severity of viral infection (not investigated in this study). Additionally, the impact of pathogen concentration might be important for other microbes such as *Cryptosporidium* and *Mycobacterium*, which are more resistant to chlorine residuals (not investigated in this study). The Ten State Standards (2007) in the US recommend a minimum separation distance between water mains and sewer mains of 3.0 m (10 ft) horizontally for parallel installation and 0.46 m (18 in) vertically for crossings with preference to the water main above the sewer. More research is necessary to determine whether such guidelines are adequate to provide a barrier to protect public health.

Other practices

This study did not evaluate the sensitivity of the infection risk to other mitigation measures such as implementing cross-connection control or flushing. The backsiphonage type of cross-connections can be viewed as similar to leaks under sewage influences, i.e., intrusion may occur when the system pressures drop below the external pressure. Therefore, it is likely that reducing the number of cross-connections in the area susceptible to negative pressure transients may significantly reduce the risk of infection.

Emergency response planning should include protocols to decontaminate distribution system mains that are subject to negative pressure events. A utility may consider boosting disinfectant residuals in the system, issuing a boil water notice, or implementing flushing to remove the intruded contaminants. Boosting disinfectant residuals may not be effective when the viruses have intruded downstream of points of disinfection. A Boil Water Notice can be issued and broadcast only as quickly as administratively possible. Flushing can be effective if administered in time. In this study, the majority of intruded viruses (94%) were washed out from the system within 24 hours. Flushing should start near the sites of intrusion and be limited to the estimated impacted area because flushing far away from the contamination source may encourage further spread of the contaminants. Aggressive flushing may trigger additional low/negative pressures and should be avoided. Generally conventional flushing should be used instead of unidirectional flushing because the location of contamination may be approximate and unidirectional flushing may require significantly more time for valve operations.

Limitations and future research

The QMRA model used in the sensitivity study focused on calculating the risk of infection associated with the ingestion of contaminated water as a result of a single negative pressure transient event. This approach did not address the unique properties of infectious disease transmission such as secondary transmission, acquired immunity and population dynamics (Haas & Eisenberg 2001). Second, the estimated impacts of various risk mitigation measures were specific to the selected distribution system in the study. Mitigation might have different effectiveness when applied to a system with different system configurations and vulnerability to negative pressure transients (e.g. a closed system with no pressure control). Finally, the EPANET modeling tool used in this study applies a plug flow scheme (without dispersion) to calculate constituent transport in the bulk water. The impact of dispersion on pathogen transport may affect the risk of infection in different ways. Dispersion may dilute pathogen concentrations, therefore, lowering the dose during a water intake event. However, dispersion may increase the duration of pathogen presence, which increases the probability of consumption of contaminated water. For intrusion with highly infectious viruses, dispersion may significantly increase the risk of infection. Research on dispersion and the other issues discussed above is needed to improve the development of quantitative microbial risk modeling and assist developing best operation practices to mitigate the risk.

CONCLUSIONS AND RECOMMENDATIONS

The risk of infection from intrusion due to low/negative pressure transients in distribution systems was most sensitive to the duration and the number of nodes experiencing negative pressures, suggesting that optimized pressure management to control negative pressure transients would be the most effective tool to mitigate the risk. Via a combination of hydraulic/surge modeling, pressure monitoring, and transient pressure mitigations, an optimized pressure management program will yield utility-specific best practices such as adding new hydropneumatic tanks/floating storages, upsizing water mains, etc.

Maintaining an adequate free chlorine residual (e.g. 0.2 mg/L or above) is the last defense against the risk of viral infection due to low/negative pressure transients. Maintaining a chloramine residual did not appear to significantly reduce the risk of infection under the studied conditions. For utilities that use chloramines as disinfectant residual, other preventive measures (e.g. pressure management and surge protection) should be emphasized to a greater extent to reduce the public health risks.

Ensuring adequate separation distance from sewer mains, leak detection and repair, and cross-connection control may reduce pathogen levels and chlorine demand of the contaminant intrusion into the drinking water pipes. These practices should be prioritized in area vulnerable to negative pressure transients to reduce the risks of microbial infection. Flushing is simplest and most effective approach to remove contaminants if administered in time.

ACKNOWLEDGEMENTS

This research was jointly sponsored by the Water Research Foundation (project 4152) and the utility subsidiaries of American Water (Voorhees New Jersey, United States). The authors appreciate the cooperation of American Water associates in collection of field data and other distribution system information: Jon L. Jarvis and Philip Bright of West Virginia American Water, and field service representatives from New Jersey American Water. The authors would also extend their thanks to Jian Zhang, Water Research Foundation Project Manager; Christine Moe, Emory University; Boris Lau, Baylor University; Shang Feng, MWH Soft Inc.; and the following Project Advisory Committee: Rehan Sadiq, National Research Council of Canada; Tom Walski, Bentley Systems, Inc.; Daniel

J. Smith, Water District #1 of Johnson County, KS; Dr Joe Eisenberg, University of Michigan; Carel Vandermeyden, Cincinnati Water Works.

REFERENCES

Blackburn, B. G., Craun, G. F., Yoder, J. S., Hill, V., Calderon, R. L., Chen, N., Lee, S. H., Levy, D. A. & Beach, M. J. 2004 Surveillance for waterborne-disease outbreaks associated with drinking water–United States, 2001–2002. In: *Surveillance Summaries*, October 22, 2004. MMWR 2004, Vol. 53 (SS-8), pp. 23–45. Available from: http://www.cdc.gov/mmwr/preview/mmwrhtml/ss5308a4.htm (accessed January 26, 2010).

Boyd, G. R., Wang, H., Britton, M. D., Howie, D. C., Wood, D. J., Funk, J. E. & Friedman, M. J. 2004a Intrusion within a simulated water distribution system due to hydraulic transients. I: Description of test rig and chemical tracer method. *Journal of Environmental Engineering* **130** (7), 774–777.

Boyd, G. R., Wang, H., Britton, M. D., Howie, D. C., Wood, D. J., Funk, J. E. & Friedman, M. J. 2004b Intrusion within a simulated water distribution system due to hydraulic transients. II: Volumetric method and comparison of results. *Journal of Environmental Engineering* **130** (7), 778–783.

Fleming, K. K., Dugandzik, J. & LeChevallier, M. W. 2006 *Susceptibility of Distribution Systems to Negative Pressure Transients #3008*. AWWARF, Denver, Colorado.

Friedman, M., Radder, L., Harrison, S., Howie, D., Britton, M., Boyd, G., Wang, H., Gullick, R., LeChevallier, M., Wood, D. & Funk, J. 2004 *Verification and Control of Low Pressure Transients in Distribution Systems*. AWWA Research Foundation, Denver, Colorado.

Grebe, T. E., Sabin, D. D. & McGranaghan, M. F. 1996 *An Assessment of Distribution System Power Quality. Electric Power Research Institute (EPRI)*. Project 3908 Final Report.

Gullick, R. W., LeChevallier, M. W., Svindland, R. C. & Friedman, M. J. 2004 Occurrence of transient low and negative pressures in distribution systems. *Journal of AWWA* **96** (11), 52–66.

Haas, C. N. 1990 Disinfection. In: *Water Quality and Treatment – A Handbook of Community Water Supplies*, 4th edition (F.W. Pontius, ed.). McGraw-Hill, New York.

Haas, C. N., Rose, J. B., Gerba, C. & Regli, S. 1993 Risk assessment of virus in drinking water. *Risk Analysis* **13** (5), 545–552.

Haas, C. N. & Eisenberg, J. N. S. 2001 Risk assessment. In: *Water Quality: Guidelines, Standards and Health. Assessment of Risk and Risk Management for Water-related Infectious Disease* (L. Fewtrell & J. Bartram, eds). IWA Publishing, London. pp. 161–183.

Haramoto, E., Katayama, H., Oguma, K., Yamashita, H., Tajima, A., Nakajima, H. & Ohgaki, S. 2006 Seasonal profiles of human noroviruses and indicator bacteria in a wastewater treatment plant in Tokyo, Japan. *Water Science and Technology* **54** (11–12), 301–308.

Hunter, P. R., Payment, P., Ashbolt, N. & Bartram, J. 2003 Assessment of risk. In: *Assessing Microbiological Safety of Drinking Water: Improving – Approaches and Methods* (E. Ronchi & J. Bartram, eds). Organisation for Economic Co-operation and Development/World Health Organization, IWA Publishing, London, pp. 79–109.

International Life Sciences Institute (ILSI) 2000 *Revised Framework for Microbial Risk Assessment*. An ILSI Risk Science Institute (RSI) Workshop Report. Available from: http://rsi.ilsi.org/file/mrabook.pdf (accessed January 26, 2010).

Karim, M., Abbaszadegan, M. & LeChevallier, M. W. 2003 Potential for pathogen intrusion during pressure transients. *Journal AWWA* **95** (5), 134–146.

Kirmeyer, G. J., Friedman, M., Martel, K., Howie, D., LeChevallier, M., Abbaszadegan, M., Karim, M., Funk, J. & Harbour, J. 2001 *Pathogen Intrusion into the Distribution System*. AWWA Research Foundation and American Water Works Association, Denver, Colorado.

LeChevallier, M. W., Welch, N. J. & Smith, D. B. 1996 Full-scale studies of factors related to coliform regrowth in drinking water. *Applied and Environmental Microbiology* **62**, 2201–2211.

LeChevallier, M. W., Gullick, R. W., Karim, M. R., Friedman, M. & Funk, J. E. 2003 The potential for health risks from intrusion of contaminants into the distribution system from pressure transients. *J. Water & Health* **01** (1), 3–14.

LeChevallier, M. W., Teunis, P. F. M., Xu, M., Yang, J. & Fleming, K. K. 2011 *Managing Distribution System Low Pressures to Protect Water Quality*. Water Research Foundation, Denver, Colorado.

Lee, J. J., Schwartz, P., Sylvester, P., Crane, L., Haw, J., Chang, H. & Kwon, H. J. 2003 *Impacts of Cross-Connections in North American Water Supplies*. AWWA Research Foundation. Denver, Colorado.

Lodder, W. J. & de Roda Husman, A. M. 2005 Presence of noroviruses and other enteric viruses in sewage and surface waters in The Netherlands. *Applied and Environmental Microbiology* **71** (3), 1453–1461.

National Research Council (NRC) 2006 *Drinking Water Distribution Systems: Assessing and Reducing Risks*. National Academy Press, Washington, District of Columbia.

Nygård, K., Wahl, E., Krogh, T., Tveit, O. A., Bøhleng, E., Tverdal, A. & Aavitsland, P. 2007 Breaks and maintenance work in the water distribution systems and gastrointestinal illness: a cohort study. *Int J. Epidemiol*. **36**, 873–880.

Ottoson, J., Hansen, A., Bjorlenius, B., Norder, H. & Stenstrom, T. A. 2006 Removal of viruses, parasitic protozoa and microbial indicators in conventional and membrane processes in a wastewater pilot plant. *Water Research* **40** (7), 1449–1457.

Payment, P., Siemiatycki, J., Richardson, L., Renaud, G., Franco, E. & Prevost, M. 1997 A prospective epidemiological study of gastrointestinal health effects due to the consumption of drinking water. *Intern. J. Environ. Health Res.* **7**, 5–31.

Payment, P. 1999 Poor efficacy of residual chlorine disinfectant in drinking water to inactivate waterborne pathogens in distribution systems. *Can. J. Microbiol.* **45** (8), 709–715.

Propato, M. & Uber, J. G. 2004 Vulnerability of water distribution systems to pathogen intrusion: How effective is a disinfectant residual? *Environmental Science & Technology* **38**, 3713–3722.

Pusch, D., Oh, D. Y., Wolf, S., Dumke, R., Schroter-Bobsin, U., Hohne, M., Roske, I. & Schreier, E. 2005 Detection of enteric viruses and bacterial indicators in German environmental waters. *Archives of Virology* **150** (5), 929–947.

Rossman, L. A. 2000 *EPANET Version 2 Users Manual*. EPA Drinking Water Research Division, Cincinnati, Ohio. Available from: http://www.epa.gov/NRMRL/wswrd/dw/epanet.html (accessed 12 April 2011).

Shang, F., Uber, J. G. & Rossman, L. A. 2008 Modeling reaction and transport of multiple species in water distribution systems. *Environ. Sci. & Tech*. **42** (3), 808–814.

Shin, G. A. & Sobsey, M. D. 2008 Inactivation of norovirus by chlorine disinfection of water. *Water Research* **42** (17), 4562–4568.

Snead, M. C., Olivieri, V. P., Kawata, K. & Kruse, C. W. 1980 The effectiveness of chlorine residuals in inactivation of bacteria and viruses introduced by post-treatment contamination. *Water Res.* **14**, 403–408.

Ten State Standards 2007 *Recommended Standards for Water Works. Great Lakes - Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers*. Water Supply Committee of the Great Lakes. Available from: http://10statesstandards.com/waterstandards.html.

Teunis, P. F. M., Medema, G. J., Kruidenier, L. & Havelaar, A. H. 1997 Assessment of the risk of infection by *Cryptosporidium* or *Giardia* in drinking water from a surface water source. *Water Research* **31** (6), 1333–1346.

Teunis, P. F., Moe, C. L., Liu, P., Miller, S. E., Lindesmith, L., Baric, R. S., Le Pendu, J. & Calderon, R. L. 2008 Norwalk virus: how infectious is it? *Journal of Medical Virology* **80** (8), 1468–1476.

Teunis, P. F., Xu, M., Fleming, K. K., Yang, J., Moe, C. L. & LeChevallier, M. W. 2010 Enteric virus infection risk from intrusion of sewage into a drinking water distribution network. *Environmental Science & Technology* **44** (22), 8561–8566.

Thorley, A. R. D. 2004 *Fluid Transients in Pipeline Systems*. 2nd edition. D. & L. George, Ltd., Herts, England.

Thurston-Enriquez, J. A., Haas, C. N., Jacangelo, J. & Gerba, C. P. 2003 Chlorine inactivation of adenovirus Type 40 and feline calicivirus. *Applied and Environmental Microbiology* **69**, 3979–3985.

USEPA 1989 *Guidance manual for compliance with the filtration and disinfection requirements for public water systems using surface water sources*. Science and technology branch criteria and standards division, Office of drinking water: Appendix E.

USEPA 2002 Potential contamination due to cross-connection and backflow and the associated health risks: an issue paper. Standards and risk management division, Office of Water, Available from: http://www.epa.gov/safewater/disinfection/tcr/pdfs/issuepaper_tcr_crossconnection-backflow.pdf (accessed January 26, 2010).

Walski, T. M., Chase, D. V., Savic, D. A., Grayman, W. M., Bechwith, S. & Koelle, E. 2007 *Advanced Water Distribution Modeling and Management*. Haestad Methods, Inc, Watertown, Connecticut.

First received 8 June 2010; accepted in revised form 2 January 2011. Available online 18 April 2011