The potential for health risks from intrusion of contaminants into the distribution system from pressure transients

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ABSTRACT

The potential for public health risks associated with intrusion of contaminants into water supply distribution systems resulting from transient low or negative pressures is assessed. It is shown that transient pressure events occur in distribution systems; that during these negative pressure events pipeline leaks provide a potential portal for entry of groundwater into treated drinking water; and that faecal indicators and culturable human viruses are present in the soil and water exterior to the distribution system. To date, all observed negative pressure events have been related to power outages or other pump shutdowns. Although there are insufficient data to indicate whether pressure transients are a substantial source of risk to water quality in the distribution system, mitigation techniques can be implemented, principally the maintenance of an effective disinfectant residual throughout the distribution system, leak control, redesign of air relief venting, and more rigorous application of existing engineering standards. Use of high-speed pressure data loggers and surge modelling may have some merit, but more research is needed.

Key words | contamination, distribution system, hydraulic surge, intrusion, pressure, viruses

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DEFINITION OF THE PROBLEM

A pressure transient in a drinking water pipeline is caused by an abrupt change in the velocity of water. This event is sometimes termed 'surge' or 'water hammer'. The energy at any point in the pipeline is composed of kinetic and potential energy. Water will move through a pipe from points of higher energy to points of lower energy regardless of its position. Any change in flow in a pipe (due to valve closure, pipe fracture, or pump stoppage) will result in an exchange of energy between flow and pressure. The change in pressure can be defined by the Joukowsky equation (Thorley 1991):

$$H = \frac{4660}{\left(1 + \frac{M_w}{M_p} * \frac{ID}{th}\right)^{0.5*g}} * (V_i - V_f) \qquad (1)$$

where:

H = pressure increase (ft), where 1 ft = 0.305 m

M_w = bulk modulus of water (psi), where 1 psi = 6.9 kPa

M_p = bulk modulus of pipe materials (psi), where 1 psi = 6.9 kPa

ID = inside diameter of the pipe (in), where 1 inch = 2.54 cm

th = wall thickness of the pipe (in), where 1 inch = 2.54 cm

g = acceleration due to gravity (ft/sec²), 0.305 m/sec²

V_i = initial water velocity (ft/sec), 0.305 m/sec

V_f = final water velocity (ft/sec), 0.305 m/sec.

The magnitude of the pressure change is influenced by the materials of construction, pipe characteristics, and the water velocity. Operational characteristics can further
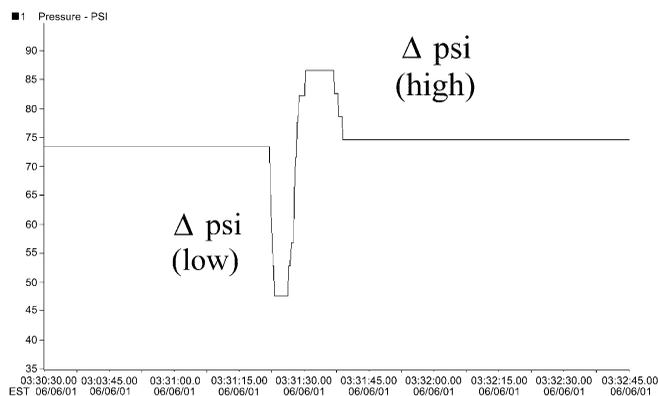
Figure 1 │ A pressure transient (1 psi=6.9 kPa).

affect the significance of pressure transients, including: non-networked and dead-end pipelines, a lack of elevated distribution system storage tanks, undulating topography, entrained air, valve characteristics, and frequent power failures of pumping stations.

For example, consider a pipeline on which an open valve is located at a distance downstream from a reservoir. If the valve is closed instantaneously, water will decelerate to zero velocity and the kinetic energy will be converted into pressure. The transient wave will travel upstream and downstream from the valve and ultimately reach the ends of the pipe. If the pressure wave in the pipe is not relieved (as in a surge tank), it will travel in the reverse direction back to the valve. Because the valve is closed and there is no relief for this flow, a negative pressure wave (suction) will be created at the valve (Simon & Korom 1997). This wave will travel back and forth until the kinetic energy is dissipated by friction. The process will occur both upstream and downstream from the valve. However, the initial pressure will be positive on the upstream side and negative on the downstream side (Simon & Korom 1997).

The analysis of transient flow in large distribution systems or other incompressible fluids requires the solution of the wave equations coupled to the boundary conditions of the flow. A widely used technique is the so-called method of characteristics (Streeter & Wylie 1967) or the wave plan method (Wood *et al.* 1966). Pressure transients can be described as waves (Figure 1), having both a positive and negative amplitude (Simon &

Korom 1997; Funk *et al.* 1999). Because these waves travel through the distribution system, the resulting low or negative pressures may occur in many different locations. The circumstances that produce these pressure waves may commonly occur in every water system. Pressure transients can be caused by main breaks, sudden changes in demand, uncontrolled pump starting or stopping, opening and closing of fire hydrants, power failures, air valve slam, flushing operations, fire flow, feed tank draining and other conditions including venturi effects (Funk *et al.* 1992). As a general rule of thumb, for every 0.3 m/sec (1 ft/sec) of velocity forced to a sudden stop, water pressures increase by 345 to 414 kPa (50 to 60 psi), depending on the pipe materials, topography, etc. The opposite is true for a sudden velocity increase, resulting in an instantaneous low or negative pressure (Kirmeyer *et al.* 2001).

The production of negative pressure transients creates the opportunity for back-siphonage or backpressure of non-potable water from domestic, industrial or institutional piping into the distribution system. These conditions of backflow are more thoroughly addressed in other reviews (USC FCCCHR 1993). Intrusion refers to the flow of non-potable water into mains through leakage points, submerged air valves, faulty seals, or other openings. As such, intrusion is defined as a specialized backflow situation that occurs in an otherwise pressurized system.

MAGNITUDE OF THE RISK

The public health significance of intrusion from a pressure transient depends on the number and effective size of orifices (leaks), the type and amount of contaminant external to the distribution system, the frequency, duration, and magnitude of the pressure transient event, and the population exposed.

Pipe leakage, orifices and location

In the American Water Works Association Research Foundation (AWWARF) report *Pathogen Intrusion into*

Table 1 │ Determination of the intrusion volume (in litres) during a 30 second negative pressure event.

Orifice diameter (mm)	Power loss 0.3 m*	3 m	Main break 0.3 m	3 m	Fire flow 0.3 m	3 m
0.79	0.03	0.30	0.15	0.45	0.15	0.45
3.175	0.75	4.5	2.3	6.8	2.3	6.1
12.7	11.4	68	30	102	30	98
25.4	30	219	87	363	91	329
50.8	49	700	208	1268	174	923

From Kirmeyer *et al.* (2001).

*0.3 m (1 ft) and 3 m (10 ft) refer to the height of the external water table above the pipe.

the Distribution System (Kirmeyer *et al.* 2001), 77% of 26 utilities surveyed had a leak detection programme that used a variety of different leak detection techniques (e.g. leakage correlator, comparison of metered sales, electronic noise detection). The percent of leakage (unaccounted for water) for these utilities ranged from less than 10% to as high as 32%. It is not uncommon for water systems to lose more than 10% of the total water production through leaks in the pipelines (AWWA & AWWARF 1992). In reality it is very difficult to know precisely how much of the unaccounted water is due to leakage unless a significant effort is exerted to track all losses.

Hydraulic modelling can be used to estimate the impact of orifice diameter on the volume of water that could intrude during a negative pressure event (Funk *et al.* 1992, 1999; Kirmeyer *et al.* 2001). Depending on the effective size of the orifice, the external pressure, and the nature of the transient event, the volume of intrusion can range from millilitres to thousands of litres (Table 1).

Pipes located below the water table are subject to pressure from the exterior water (depending on the height of the water table above the pipe), and thus an opportunity exists where water exterior to the pipe could intrude into the pipe under low or negative pressure conditions within the pipe. Utilities were surveyed as to the percentage of mains that are submerged, and the results showed that at least 20% of the systems had pipes below the water table (42% had no information) (Kirmeyer *et al.* 2001). It is assumed that all systems have some pipes below the water table for at least some part of the year.

Water may also intrude into a distribution system by means other than pipelines. It has been speculated that faulty joint seals may leak under certain circumstances when exposed to negative pressures (Grigory 2002). A survey of the percentage of flooded vaults or meter boxes showed that although the rate changed seasonally, approximately 20% of the systems reported between 25 and 75% of meter boxes flooded, with about half of the systems not knowing how much flooding had occurred (Kirmeyer *et al.* 2001). One utility provided pictures of an air valve vault that was flooded with an oily film and a second picture from a short while later when the vault was drained (Figure 2). It is presumed that a pressure transient caused the air valve to open and allowed the water to enter into the distribution system. Engineering standards (Recommended Standards for Water Works 1997) specify that all air release valves (and similar appurtenances) be designed with above-grade-venting (this venting should be tamper-proof to prevent deliberate contamination of the system), or be modified in a way to prevent the flooding of the vault (e.g. via drainage or a pump).

Figure 2 │ Submerged air release valve.

Figure 3 │ Summary of microbial occurrence in water and soil samples.

Presence of contaminants external to the distribution system

Any contaminant exterior to the distribution system may enter potable water supplies during a negative pressure event. Chemical contaminants could include pesticides, petroleum products, fertilizers, solvents, detergents, pharmaceuticals and other compounds. Predominant pesticides in urban areas include atrazine, simazine, prometon and diazinon (Patterson & Focazio 2001). Other studies have detected insect repellants, fire retardants and other industrial chemicals (Koplin *et al.* 2002). If chemical compounds intrude in sufficient concentration or volume, they might result in acute toxicity. Microbial contaminants are a concern because, even with dilution, some microbes (e.g. viruses) could cause an infection with a single organism.

Karim *et al.* (2003) reported on a study that examined 66 soil and water samples collected from eight utilities in six states. The samples were collected immediately adjacent to the drinking water pipelines. The purpose of the study was to determine the presence of microbial contaminants in the soil immediately external to the distribution system. Whenever a main was excavated, samples were collected of either the water or the undisturbed soil next to the pipe. Total coliform and faecal colifo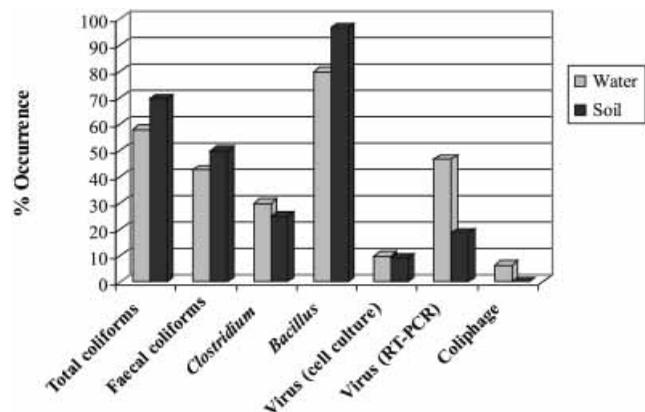rm bacteria were detected in water and soil in about half of the samples, indicating the presence of faecal contamination (Figure 3). Bacillus was found in almost all the samples, which is not a surprise since it is a normal soil organism. Viruses were detected using culturable methods in 12% of the soil and water samples, and by molecular methods in 19% of the soil samples and 47% of the water samples. When these data are combined, 56% of the samples were positive for viruses either in the water or the soil. Sequence analysis showed that these viruses were predominantly enteroviruses (the vaccine strain of Poliovirus), but Norwalk and Hepatitis A viruses were also detected, providing clear evidence of human faecal contamination immediately exterior to the pipe.

In the same study an analysis of the levels of organisms detected showed that they could be quite high; for example, total faecal coliform levels were as high as 10^4 bacteria per 100 g of soil (Table 2). This may not be surprising considering that sewer lines are often located only a few feet away (Figure 4). Engineering standards call for a minimum separation of 3 m (10 ft) between drinking water and sewer pipelines, although separations can be as little as 0.5 m (18 in) if the drinking water pipe is located at a higher elevation than the sewer pipe (Recommended Standards for Water Works 1997). In saturated soil conditions, microbes can move several metres in short periods of time (Abu-Ashour *et al.* 1994). This transport could be aided by water flowing out of the sewer (exfiltration).

Table 2 │ Microbe concentrations in water and soil.

Organism	Water CFU or PFU/100 ml	Soil CFU or PFU/100 gm
Total coliforms	<2–1.6×10^3	<2–1.6×10^4
Faecal coliforms	<2–1.6×10^3	<2–1.6×10^4
Clostridium	0–2.5×10^3	0–1×10^5
Bacillus	0–4.6×10^6	0–1.2×10^8
Phage	0–1×10^4	0

CFU, colony-forming units; PFU, plaque-forming units.

Figure 5 │ Comparison of the Radcom and conventional pressure recorders for measurement of low pressure events (1 psi=6.9 kPa).

The soil and water samples in the study (Karim *et al.* 2003) were randomly collected from urban environments and the location of adjacent sewer lines is not known. More detailed studies could develop better guidelines for the separation of water and sewer mains. The concentration of *Bacillus* spores in soil was as high as 10^8 colony-forming units (CFU) per 100 g of soil, with some of the highest levels associated with samples containing human enteric viruses. It is possible that seepage of sewage stimulated the growth of the soil flora in these locations.

Figure 4 │ Leaky water pipe laid next to a sewer pipe (source: Gary Feeny, Earth Tech. Reprinted from *Opflow* **25**(9), September 1999 by permission. Copyright © 1999, American Water Works Association).
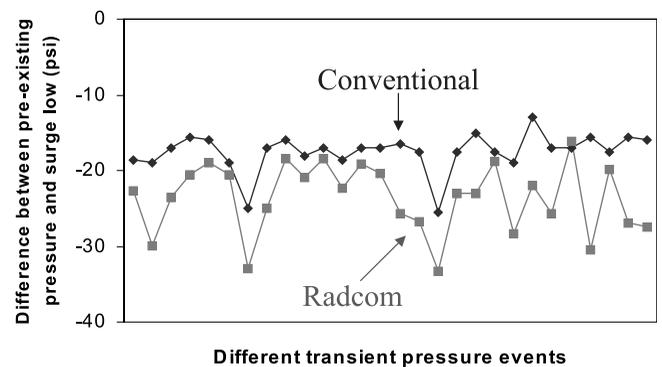
Frequency and magnitude of pressure transient events

Problems with low or negative pressure transients have been reported in the literature (Walski & Lutes 1994; Qaqish *et al.* 1995). Recent research efforts have focused on documenting the frequency and magnitude of pressure transient events to determine whether negative pressure events occur during normal distribution system operations. A high-speed pressure logger (RDL 1071L/3 Pressure Transient Logger, Radcom Technologies, Inc.; Woburn, MA), with a monitoring rate of 1–20 measurements per second and a range from 0 to 2070 kPa (0 to 300 psi), was used to detect negative pressure events. Other manufacturers offer similar equipment.

A comparison of a high-speed electronic data logger to a conventional strip chart recorder showed a good correspondence between the measurements of sudden high pressures, but the Radcom monitor was much more sensitive in capturing the low pressure events, on average showing values 69 kPa (10 psi) lower than those recorded by the conventional recorder (Figure 5).

Application of high-speed pressure loggers to routine operations in approximately 10 systems has shown substantial variability in pressure values, however, negative values have only rarely been observed. Various attempts to examine hydrant flushing with different rates of valve opening demonstrated the production of pressure transients, but none of the events produced negative distribution system pressures (Kirmeyer *et al.* 2001). Additional investigation of hydrant operation is warranted because

hydraulic modelling has suggested that negative distribution system pressures could be produced under certain hydrant flushing circumstances.

Examination of a household tap (Kirmeyer *et al.* 2001) showed large fluctuations with pressures as low as 29.7 kPa (4.3 psi; data not shown). These fluctuations may be due to domestic water use patterns. If there was an external water table of 3 m (10 ft) over the pipe (as in a stream crossing or lowland area), there could be enough external water pressure to cause intrusion. The point is that it is not necessary to have a negative pressure—a low pressure can cause intrusion under certain circumstances.

Pressures were analysed in one system while conducting a routine draw-down test in Spring 2001 (an annual test to verify accuracy of the venturi meters at the water treatment plant). During this test, the main service pumps were shut down at the treatment plant Clearwell and restarted with all flow going through one venturi meter. Two Radcom monitors were installed at high elevation points on a 0.75 m (30 in) main (one was ~4 km (2.5 miles) from the plant, and the other was ~7.25 km (4.5 miles) from the plant), and a third monitor was located about 24 m (80 ft) from the treatment plant's high-service pumps. Pressure readings both near the treatment plant and within the distribution system showed large pressure fluctuations. While the static pressures near the plant ranged between 863 and 1035 kPa (125 and 150 psi), the pressure transients caused by the pump shutdowns resulted in pressures as low as 124 kPa (18 psi) in the plant effluent. However, several miles away in the distribution system these fluctuations resulted in a pressure of minus 69 kPa (− 10 psi) lasting for 16 sec (Figure 6). The valve closure speed for the main service pumps was 20 sec, which may have been too fast, and thus contributed to the pressure transient. A second test was conducted with the valve closure speed slowed to 30 sec, but negative pressures resulted from this second test as well.

Routine pressure monitoring of another distribution system in December 2000 showed a negative pressure event during a power outage at a pumping station that lasted for 24 sec and produced a negative pressure of 30.36 kPa (4.4 psi) (Figure 7). Similarly, a power outage at the treatment plant of another system in July 2001
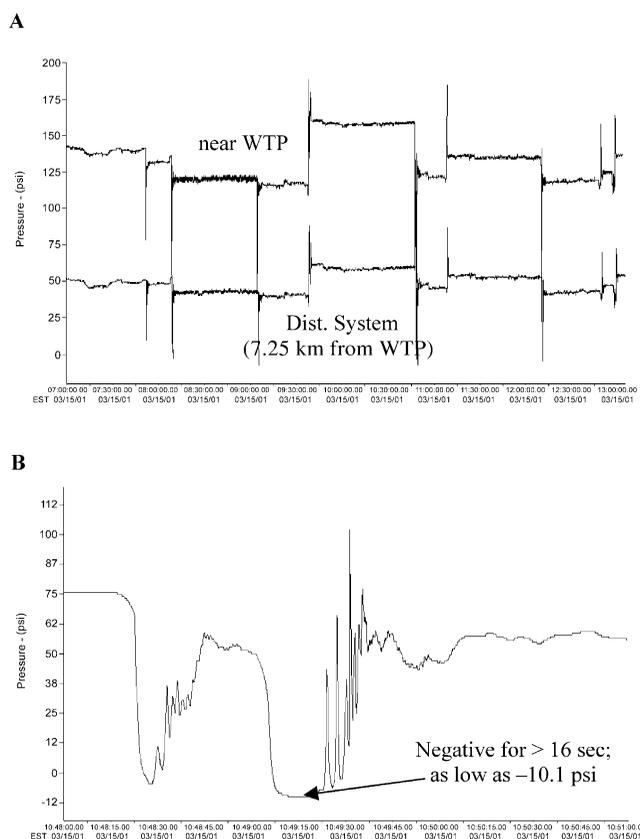

Figure 6 | Pressure recording during a pump draw down test. (A) Pressures near the water treatment plant (WTP) and in the distribution system. (B) Enlargement of one of the distribution system negative pressure events shown in (A), illustrating duration of the negative pressure event. A second recorder in the distribution system showed similar result (1 psi=6.9 kPa).

produced zero pressure for 51 sec in a section of the distribution system (Figure 8).

Based on the above information, it is concluded that transient pressure events occur in distribution systems; that these events can result in negative pressures; that negative pressures provide a potential portal for entry of non-potable water into potable water distribution pipelines; and that faecal indicators and culturable human viruses are present in the soil and groundwater exterior to the distribution system. However, the characteristics of distribution systems that contribute to producing negative pressure transients have not been examined. These characteristics may include the presence of storage tanks, valve closure speed, placement of air relief and other surge
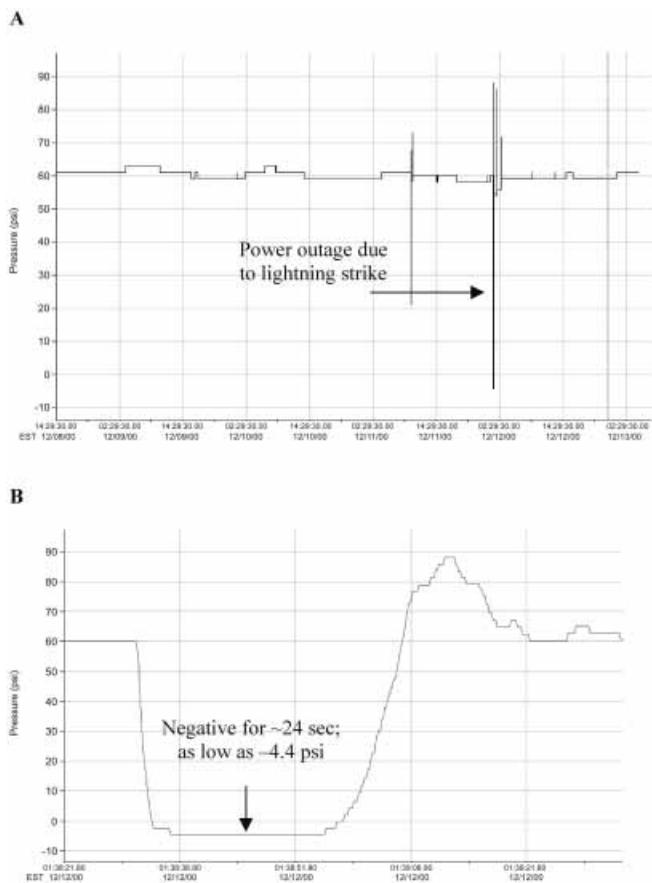
Figure 7 | Distribution system pressure monitoring following a pump station power outage. (A) Daily monitoring data; (B) enlargement of the negative pressure event (1 psi=6.9 kPa).

Figure 8 | Distribution system pressure monitoring following a pump station power outage due to a lightening strike. (A) Daily monitoring data; (B) enlargement of the negative pressure event (1 psi=6.9 kPa).

control devices, pump operation, and shut down procedures. To date, all observed negative pressure events have been related to power outages or other pump shutdowns. More research is needed to better characterize the types of systems (e.g. those without distribution storage, without air or vacuum relief valves, etc.) most prone to negative pressure transient events.

Public health impact

Payment *et al.* (1991, 1997) conducted two epidemiology studies, each suggesting that the distribution system was at least partially responsible for increased levels of gastrointestin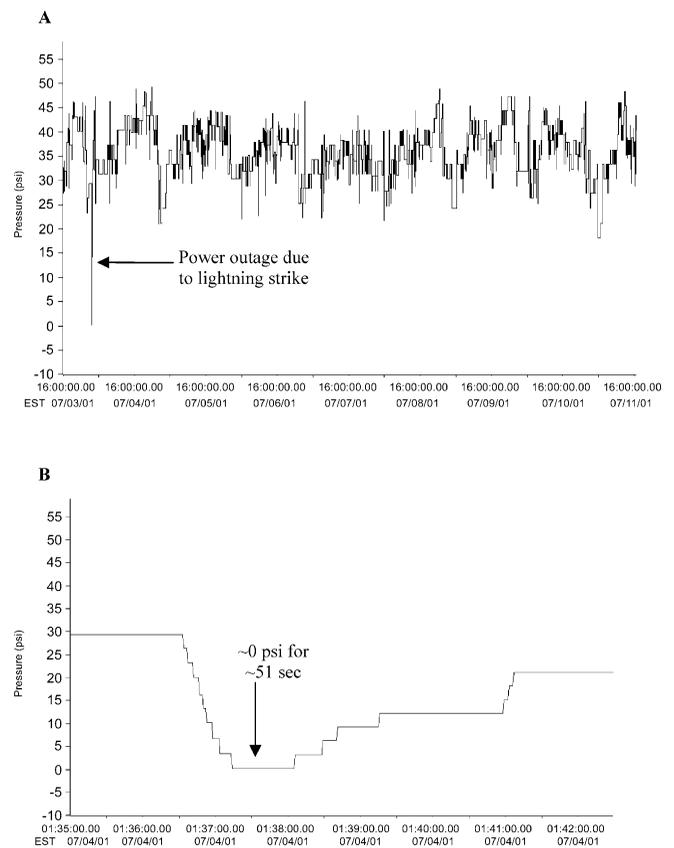al illnesses. The studies examined the health of people who drank tap water, and compared the group to people receiving water treated by reverse osmosis to determine which group had higher levels of gastrointestinal illness. Both studies pointed to the fact that people who drank tap water had increased cases of gastroenteritis. Analysis of the data from these two studies shows that people who lived in zones far away from the treatment plant had the highest risk of gastroenteritis. Transient pressure modelling (Kirmeyer *et al.* 2001) found that the distribution system studied by Payment *et al.* (1991, 1997) was extremely prone to negative pressures, with more than 90% of the nodes within the system drawing negative pressures under certain modelling scenarios (e.g. power outages). The system is located in the Montreal area, and reported many pipe breaks, particularly during the fall and winter when temperature changes place added stresses on

the distribution system pipelines. Although the system employed state-of-the-art treatment, the distribution network maintained low disinfectant residuals, particularly at the ends of the system. Low disinfectant residuals and a vulnerability of the distribution system to pressure transients could account for the viral-like etiology of the illnesses observed.

A double-blinded, randomized, trial was recently completed in Melbourne, Australia, to determine the contribution of drinking water to gastroenteritis (Hellard *et al.* 2001). Melbourne draws its drinking water from a protected forest watershed and has an unfiltered surface water supply using only free chlorine treatment. Free chlorine levels in the distribution system ranged from 0 to 0.94 mg/l, with a median of 0.05 mg/l, and 90% of samples had <0.20 mg/l. Total coliform bacteria were detected in 18.9% of 1,167 routine 100-ml water samples, but faecal coliform bacteria were not detected. Distribution system samples were positive for *Aeromonas* spp (50% of 68 weekly samples), *Campylobacter* (1 occasion) and *Giardia* (2 viable samples by reverse transcriptase-polymerase chain reaction). Six hundred families were randomly assigned to receive either a real or placebo water treatment unit installed on the kitchen faucet. Real units were designed to remove viruses, bacteria, and protozoa using microfiltration and ultraviolet light treatment. Study participants completed a weekly health diary reporting gastrointestinal symptoms during the 68-week observation period. The study found that the water was not a source of measurable gastrointestinal disease (the ratio of illness between the group drinking treated water compared to the normal tap water was 0.99, with a 95% confidence interval of 0.85–1.15; $p = 0.85$). Analysis of 795 faecal specimens from participants with gastroenteritis did not reveal any difference in pathogen detection between the two groups. Pressure transient modelling of the Melbourne system has not been done and specialized pressure monitoring was not performed during the study.

The 1996 amendments to the Safe Drinking Water Act required the US Centers for Disease Control and Prevention (CDC) and the US Environmental Protection Agency (EPA) to conduct epidemiology studies to determine the occurrence of waterborne disease in the US Dr

Jack Colford of the University of California at Berkeley School of Public Health has conducted one of these epidemiology studies in collaboration with the Iowa-American Water Company in Davenport, Iowa. The study began in November 2000, and was completed in June 2002. The study was a randomized, triple-blinded, placebo-controlled, crossover intervention study. The intervention to be tested was household-level treatment of drinking water. The water was treated using a kitchen countertop device that treats tap water with ultraviolet light and microfiltration. Participating households were randomly assigned to two different groups. One group received the active device and the other received an identical-looking placebo device. Half way through the study, 'cross-over' took place: active devices were replaced with inactive devices, and inactive devices were replaced with active devices. The participants, the study staff, and the data analysis team were blinded (unaware of) to which group each household was assigned throughout the study. A total of 456 households residing in Davenport, Bettendorf, Panorama Park, and Riverdale were enrolled.

The American Water Works Association Research Foundation funded American Water to conduct a water quality study in the Davenport area in parallel to the epidemiology study. The study is conducting extensive analysis of the raw water, treatment plant performance, distribution system and household water quality. Seven pressure data loggers (one in each pressure zone) are being used to monitor distribution system pressures to determine if pressure transients are associated with any health impacts that may be observed during the epidemiology study. To date, although fluctuations in pressures have been noted, no negative pressure events have been recorded in the distribution system. Modelling of the distribution system is underway to extrapolate the pressure data to the whole pipe network.

In summary, although there are data to demonstrate that negative pressure events do occur, there are insufficient data to indicate whether these events result in substantial risk to water quality in the distribution system. Direct microbial monitoring of drinking water would be impractical due to the transient nature of the pressure effect, the relatively small volume of intrusion water

(compared to the total volume within the pipe network), and the plug flow nature (i.e. limited dispersion) of water within distribution systems. In addition, a source of microbial contamination (e.g. leaky sewer lines) must be relatively near the pipe system, and the soil must be saturated to allow for microbial transport. These factors may be important variables explaining the disparate epidemiology results and should be factored into any future epidemiological studies.

RISK MITIGATION

The first step in risk mitigation for the issue of transient negative pressures in the distribution system is simply the recognition that the phenomenon does exist. Some have dismissed the issue as being not significant, too brief, or of too small a volume to be an important source of contamination. On-going studies are beginning to document the occurrence of negative transient pressure events within distribution systems, but additional research is necessary. The frequency of negative pressure transients need to be determined, as well as the characteristics of the distribution system that contribute to these events. Studies need to be conducted for groundwater systems, particularly in non-disinfected systems.

Engineering standards require consideration of pressure transients for pipeline and pump design, distribution system network analysis, and valve selection and installation (Table 3). Information on transient analysis and control can be found in standard engineering texts on pump design, pipeline flow, and fluid dynamics (Karassik *et al.* 1976; Thorley 1991; Simon & Korom 1997; Larock *et al.* 2000). Surge control, particularly control of high-pressure events, has typically been thought of in terms of preventing pipe bursts and efforts have been directed at reducing the maximum pressures. Concerns regarding negative pressure transients and their public health implications have not received similar attention. However, mitigation measures are well described and include slow valve closure times, avoiding check valve slam, minimized resonance, air vessels, surge tanks, pressure relief valves, surge anticipation valves, air release valves, combination

Table 3 | Available standards and guidelines for surge and intrusion mitigation.

Existing standards and guidelines

- ANSI/AWWA C510 (Double check valve backflow-prevention assembly)

- ANSI/AWWA C511 (Reduced-pressure principle backflow-prevention assembly)

- ANSI/AWWA C512 (Standard for air release, air/vacuum. and combination air valves for waterworks services)

- *Recommended Standards for Water Works* (10 State standards)

- AWWA Manual M14 *Recommended Practice for Backflow Prevention and CrossConnection Control*

- A WWA Manual M32 *Distribution Network Analysis for Water Utilities*

- AWWA Manual M36 *Water Audits and Leak Detection*

- AWWA Manual M44 *Distribution Valves*: *Selection, Installation, Field Testing, and Maintenance*

- AWWA Manual M51 *AirRelease, Air/Vacuum, and Combination Air Valves*

Abbreviations: ANSI, American National Standards Institute; AWWA, American Water Works Association.

two-way air valves, vacuum break valves, check valves, surge suppressors, and by-pass lines with check valves. A surge tank or standpipe provides water when system pressure decreases and can also absorb pressure increases. Four common types of surge tanks include: pneumatic or closed tank, open standpipe, a feed tank with a check valve, and a bladder tank. If water is stored in the tank for long periods of time the water quality may degrade and proper operation and maintenance is required to avoid poor quality water from entering the distribution system.

Air relief valves and similar appurtenances should be designed to have above-grade venting (at least 0.3 m (1 ft) and be designed to be tamper-proof to avoid deliberate contamination of the system). All below-grade vacuum or air relief valves should be retrofitted to above-grade

venting, or modified in a way to prevent the flooding of the vault (e.g. drainage or pump).

The results of these studies emphasize the need to maintain an effective disinfectant residual in all parts of the distribution system. Although the effectiveness of a residual disinfectant has been debated (Trussell 1999; LeChevallier 1999), critics typically question the effectiveness of a disinfectant residual to inactivate volumes of sewage mixed with drinking water (Snead *et al.* 1980; Payment 1999). For distribution system negative pressure events, the volume of intruded water is a fraction (much less than 1%) of the water within the pipe network, so the opportunity for effective disinfection exists. Unknown is the effect of turbidity, compounds causing a chlorine demand, and limited mixing (in a relatively plug flow condition) on the disinfection efficacy of the residual disinfectant. Chloramine residuals will be particularly ineffective for viruses that intrude into the distribution system, as the *CT* (disinfectant concentration multiplied by the contact time) for preformed chloramines would not be effective for enteric viruses. Studies examining the microbial risk-risk tradeoffs (e.g. disinfection effectiveness for intrusion contaminants compared with biofilms) are needed as many US water suppliers continue to convert from free chlorine to chloramines due to disinfectant by-product regulations.

Efforts to reduce distribution system pipeline leakage are beneficial, not only from a water conservation standpoint, but also to minimize the potential for microbial intrusion into potable water supplies. Leaks are not simply a loss of revenue for a water utility, but the leak is a potential pathway for contamination. The public health benefits of leak control should be recognized and encouraged. Repair of leaking sewer lines should similarly be a top priority, not only to minimize the occurrence of pathogens near drinking water pipelines, but to reduce these sources of contamination being transported to groundwater supplies and receiving streams, particularly under wet weather conditions.

High-speed pressure data loggers would probably benefit distribution system monitoring, as they appear to be more sensitive, particularly for low-pressure events. Additional studies are needed to examine the accuracy of the pressure transducers and determine the appropriate placement of the recorders within the distribution system. Installation of the monitors at high elevation points within the distribution system would seem reasonable, but additional work is needed to identify other useful monitoring locations. The generation of high-quality pressure data would help determine the effect of routine operational practices on distribution system pressures. This monitoring data could evaluate the impact of hydrant operations, pump start-up and shut down procedures, and valve closing speed, among others. This information should be compiled to develop standard operating procedures to minimize low-pressure surges.

Surge modelling can be used to determine the potential vulnerability of a system to negative pressures under a number of worst-case scenarios (e.g. power failure, main break, flushing, etc.). This modelling would be useful especially after addition of new pipelines, interconnections, or changes in distribution system storage or consumption patterns that may have changed original design parameters. Modelling may be able to identify zones of the distribution system most prone to negative pressure events. These areas would then be prioritised for maintenance of a disinfectant residual, leak detection and control, main replacement, and rehabilitation of nearby sewer systems. This engineering analysis can apply surge control techniques, like installation of air relief valves (above grade), surge tanks, and other activities to mitigate negative pressure events.

Personnel training with respect to hydrant and valve operations, and prevention of unauthorized or inappropriate use of hydrants or blow-offs, would be useful so that maintenance and repair crews understand the concerns regarding the potential for intrusion.

INDICATORS

Many States have requirements to maintain minimum distribution system pressures based on conventional pressure recorder data. It would be inappropriate, and possibly impractical, to apply the same guidelines to data collected by electronic pressure loggers. Additional research is needed to evaluate new guidelines based on the

frequency and duration of the event, the concentration and type of residual disinfectant, the proximity of the drinking water main to sewer lines, soil conditions and the level of the water table, and other data that still need to be collected to assess the public health significance of such events.

Additional research is needed to develop guidelines for proper placement of pressure monitors. Distribution system modelling of a power outage suggested that negative pressures may have occurred in locations other than those selected for pressure monitoring. Monitoring locations are often selected based on the availability of land, access, and electrical power or communications; not necessarily because the location is most prone to negative pressures.

Increased microbiological monitoring, particularly using existing methodologies, is not recommended because of the low probabilities of actually detecting an intrusion event. Use of continuous chlorine residual monitors may have some application, but the effectiveness of such an approach needs to be evaluated. Development of new on-line microbial monitoring techniques may have some future application, particularly those related to fibre optic or real-time analysis.

SUMMARY

In summary, it is concluded that transient pressure events occur in distribution systems; that during these negative pressure events pipeline leaks provide a potential portal for entry of groundwater into treated drinking water; and that faecal indicators and culturable human viruses are present in the soil and water exterior to the distribution system. To date, all observed negative pressure events have been related to power outages or other pump shutdowns, although more research is needed to better characterize the types of systems most prone to these events. There is insufficient data to indicate whether pressure transients are a substantial source of risk to water quality in the distribution system. Nevertheless, mitigation techniques can be implemented, principally the maintenance of an effective disinfectant residual throughout the distri-

bution system, leak control, redesign of air relief venting, and more rigorous application of existing engineering standards. Use of high-speed pressure data loggers and surge modelling may have some merit, but understanding the effectiveness of these tools requires additional research. More research is needed and this topic should become a priority for both the USEPA and industry-funded programmes.

ACKNOWLEDGEMENTS

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