Application of pressure monitoring and modelling to detect and minimize low pressure events in distribution systems

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ABSTRACT

A variety of normal water distribution system operations will result in pressure fluctuations that can possibly lead to the occurrence of relatively brief (transient) low or negative pressures at various locations of the system, thus creating the potential for backsiphonage or backpressure of non-potable water from external sources into the distribution system, including contaminated water around leaking pipes. Extensive pressure monitoring of a single distribution system using seven electronic data loggers for 1.4 years found only nine occasions when distribution system pressures were less than 138 kPa (20 psi). No negative pressures were observed. Evidence showed that most low pressure events were caused by pump shutdowns. Distribution system modelling suggested that negative pressures (<0 kPa) were possible when the water treatment plant pumping station lost power. The model simulations suggested that protection against low pressures is possible by installing hydro-pneumatic tanks downstream of the pumping stations. Modelling results suggested that air/vacuum valves did not offer reliable protection against low pressures in the system.

Key words | distribution system, intrusion, modelling, monitoring, pressure, surge

INTRODUCTION

Protection of water quality in the distribution system is the last treatment barrier and one of the most important objectives for a community water system. Meeting this objective is not a simple task given the large lengths of pipeline and the many opportunities for contamination. To protect the distribution system, utilities focus on cross connection control, maintaining a positive pressure (typical US regulations require maintenance of a pressure of 20 psi (138 kPa) or greater), minimizing leaks and performing hygienic repairs, proper distribution system maintenance and flushing, and maintenance of an effective disinfectant residual, among others (Kirmeyer et al. 2000). Monitoring of distribution system water quality typically relies on the measurement of disinfectant residuals and total or fecal coliform bacteria, or Escherichia coli (Kirmeyer et al. 2002).

Although the potential for intrusion of viruses and other contaminants during negative pressure transients has recently been recognized (Walski & Lutes 1994; Kirmeyer et al. 2001; LeChevallier et al. 2003a; Karim et al. 2003; Friedman et al. 2004), distribution system monitoring programmes do not typically include viral indicators.

The current project was part of an epidemiological study conducted in response to the 1996 amendments to the US Safe Drinking Water Act requirements that directed the US Centers for Disease Control and Prevention (CDC) and the US Environmental Protection Agency (EPA) to implement a series of epidemiological studies to determine the occurrence of waterborne disease in the US. The study was performed in collaboration with the Iowa American Water Company in Davenport, Iowa, and the epidemiological results will be...
presented elsewhere. The American Water Works Association Research Foundation funded American Water to conduct a water quality study in the Davenport area in parallel to the epidemiological study (LeChevallier et al. 2002). The primary objective of the project was to characterize raw water, treatment plant, distribution and household tap water quality with respect to microbes, water quality indicators and physicochemical parameters so as to provide a context for interpreting the public health data generated by the epidemiological study. The purpose of this paper is to describe the distribution system pressure monitoring results and to highlight the benefit of hydraulic surge modelling.

METHODS

Iowa American Water Company, Quad Cities District

The Iowa American Water Company, Quad Cities District, East River Station treatment plant serves 45,800 customers (about 130,000 people) in the cities of Davenport, Bettendorf, Riverdale, Panorama Park and portions of Scott County along the Mississippi River in east-central Iowa. Raw water from the Mississippi River is treated in the East River Station plant in two Superpulsator clarifiers and two conventional flocculation-sedimentation basins and filtration through 20 granular activated carbon filter/adsorbers. Free chlorine is used as a primary disinfectant and is converted to chloramines by the addition of anhydrous ammonia after filtration. The treatment plant is located at an elevation of 174 m (571 feet). Iowa American is a voluntary member of the USEPA 'Partnership for Safe Water' and received the Director's Award in 2001 for producing outstanding water quality. An extensive analysis of the treatment plant and distribution system water quality showed that the utility met or surpassed all state and federal standards for potable water (LeChevallier et al. 2002, 2003b).

The distribution system (Figure 1) includes more than 871 km (541 miles) of mains and 5,053 hydrants and varies in elevation from 172 m to 263 m (565 feet to 862 feet) above mean sea level. There are two sets of distributive pumps at the treatment plant. The main service pumps discharge at an average of 772 kPa (112 psi) to pressure zone #3. Zone #3 includes higher elevations along the river bluff, and is the larger and faster-growing part of the system. A booster pump in zone #1 transfers water to zone #4, and another pumps to an elevated tank. A booster pump next to that tank pumps water regularly (i.e. every day) from that tank into zone #3 (monitoring site #3 is located downstream from this tank and booster station). Four other booster stations in zone #3 are used to supply water to the remaining four other pressure zones (zones #2, 5, 6 and 7, which are located in outlying areas of the municipality). In total, there are five discharge stations in zone #3 that transfer water to another pressure zone, and two discharge stations in zone #1. In addition, there are four storage facilities in zone #3, one in zone #1, and one in zone #5.

Pressure monitoring

The electronic pressure monitor used was a high-speed, single-channel pressure transient data logger (Model RDL 1071L/3 Pressure Transient Logger; Radcom Technologies, Inc., Woburn, Massachusetts). The units were placed at indoor locations where they could be connected to a fire line so as to collect distribution system pressures without exposure to freezing conditions (Figure 2). The electronic pressure monitors were installed and set up according to manufacturer's instructions. The monitors were zeroed to atmospheric pressure upon each installation, and also each time the pressure transducer connection link to a distribution system pipe was disconnected. The recorders were set to take one reading per second at a tolerance of ±27.6 kPa (±4.0 psi). With this setting, the monitor recorded new pressure readings only if the values changed by more than ±27.6 kPa (±4.0 psi). This enabled about a week’s worth of data to be collected before the recorder memory became full and no further data would be recorded. The clock time used by the logger was periodically calibrated by use of a connection to a personal computer. The times were used to relate the pressure data to distribution system events.

A summary of the pressure monitoring programme is presented in Table 1, and the monitoring locations are shown in Figure 1. There were two phases of pressure monitoring for this project. For the primary phase one monitor was installed...
in each of the seven separate pressure zones from March 2001 to June 2002. This monitoring programme was intended to record general pressures in each zone. Selection of the monitoring locations within each zone was not necessarily based on surge study criteria, but instead was based primarily on considerations of site accessibility, freezing and security due to the extended period of monitoring and the desire to download data from each site once a week. These monitoring site ID numbers match the pressure zone ID numbers (i.e. site #1 was in zone #1, etc.).

The second monitoring phase lasted from June through October 2002. For the full period monitors continued reading pressures only at sites #3 and #7 (other locations from phase I were no longer monitored). In addition, for approximately one month from September through October, three additional monitors were used in pressure zone #3. This zone had shown the greatest propensity for low pressures based on earlier monitoring. The three additional monitors were placed at locations that model predictions suggested would exhibit negative pressures in the event of a power outage at the water treatment plant.

Hydraulic model development

Data from the existing Iowa American Water Company, Davenport District steady-state Cybernet model was
converted by researchers at the University of Kentucky to the steady-state KYPipe2000 format, and then to Surge2000 model format. Surge2000 is a combined steady and non-steady state (transient) hydraulic surge model. The Davenport model comprises 1,703 pipes, 1,146 nodes, 12 supplies, 30 pumps, and includes 15, 20, 30, 41, 61, and 61-cm (6, 8, 12, 16, 24 and 24-inch) mains (thus is skeletonized leaving out pipes smaller than 15 cm (<6 inches). Water demand data used 1999 results. The two steady-state models were aligned and compared, and the data for the models were in good agreement. It was concluded that the Pipe2000 model was virtually identical to the Cybernet model and the pressures agreed within \( \pm 6.9 \text{ kPa} (\pm 1 \text{ psi}) \).

A schematic of the Pipe2000 model is shown in Figure 1.

The base model calibration was performed using the Pipe2000 optimized calibration module, and included a comparison of model predictions and field measurements of residual pressures before and during fire flow tests. Transient magnitudes were not compared in this calibration. For six of these fire flow tests, the static pressure head obtained in the test corresponded well to the model residual pressures and were used to optimize the model. The other 11 fire test results were considered not valid because some other condition was different: either the elevations were incorrect or some other boundary condition was not accounted for (e.g. pump status, tank level, etc.).

When comparing the model with static field pressure measurements from before the fire flow test, the model provided pressures for those six locations within a maximum difference of 27.6 kPa (4 psi) of the field data, and averaged a difference of 15.2 kPa (2.2 psi). When comparing the model with field measurements taken during the fire flow tests for the six locations, residual pressures predicted by the model were within a maximum difference of 62 kPa (9 psi) of the field data, and averaged a difference of 43 kPa (6.3 psi). Additional calibration procedures are described by LeChevallier et al. (2002).

Calibration is affected by the demands and measured fire flows and the values used always have some uncertainty. An accuracy of 10% was assumed for these parameters. This allows the calibration to utilize this uncertainty when making adjustments. For example, pipes assigned Hazen Williams coefficients differing by 10% were

<table>
<thead>
<tr>
<th>Site no</th>
<th>Days of available data</th>
<th>Dates monitored</th>
<th>Description of monitoring</th>
<th>No. of pressure events</th>
<th>Observed pressure range (min–max) (kPa)</th>
<th>Observed pressure range (min–max) (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>428</td>
<td>19/3/01–3/6/02</td>
<td>Zone #1</td>
<td>0</td>
<td>200–661</td>
<td>29–96</td>
</tr>
<tr>
<td>2</td>
<td>439</td>
<td>22/3/01–3/6/02</td>
<td>Zone #2</td>
<td>0</td>
<td>186–524</td>
<td>27–76</td>
</tr>
<tr>
<td>3</td>
<td>438</td>
<td>15/3/01–11/10/02</td>
<td>Zone #3</td>
<td>7</td>
<td>65.4–462</td>
<td>9.5–67</td>
</tr>
<tr>
<td>4</td>
<td>508</td>
<td>23/3/01–3/6/02</td>
<td>Zone #4</td>
<td>1</td>
<td>138–737</td>
<td>20–107</td>
</tr>
<tr>
<td>5</td>
<td>432</td>
<td>16/3/01–3/6/02</td>
<td>Zone #5</td>
<td>0</td>
<td>303–710</td>
<td>44–103</td>
</tr>
<tr>
<td>6</td>
<td>439</td>
<td>15/3/01–3/6/02</td>
<td>Zone #6</td>
<td>0</td>
<td>214–613</td>
<td>31–89</td>
</tr>
<tr>
<td>7</td>
<td>506</td>
<td>16/3/01–11/10/02</td>
<td>Zone #7</td>
<td>0</td>
<td>214–723</td>
<td>31–105</td>
</tr>
<tr>
<td>10</td>
<td>32</td>
<td>9/9/02–11/10/02</td>
<td>High point in zone #3</td>
<td>0</td>
<td>165–606</td>
<td>24–88</td>
</tr>
<tr>
<td>11</td>
<td>32</td>
<td>9/9/02–11/10/02</td>
<td>High point in zone #3</td>
<td>1</td>
<td>96–441</td>
<td>14–64</td>
</tr>
<tr>
<td>12</td>
<td>32</td>
<td>9/9/02–11/10/02</td>
<td>High point in zone #3</td>
<td>0</td>
<td>248–558</td>
<td>36–81</td>
</tr>
</tbody>
</table>

Note: Data collected at rate of one reading per second with a tolerance setting of \( \pm 27.6 \text{ kPa} (\pm 4.0 \text{ psi}) \).
assigned new values that also differed by 10%. The results of a hydraulic calculation showed that the differences caused by the adjusted Hazen Williams values were very small and the pressures varied by 13.8 kPa (2 psi) or less. The Davenport distribution system operates with relatively small head loss under baseline conditions and, for this situation, the sensitivity to Hazen Williams coefficient values was relatively small.

**Davenport Surge2000 model**

The calibrated KYPipe2000 model was utilized to create the Surge2000 model. A wave speed of 914 ms$^{-1}$ (3,000 feet s$^{-1}$) was assigned to all pipes, which is a reasonable value for metal and reinforced pipes with a small amount of entrained air. Additional modifications were made to the model to prepare it for use in transient modelling. A non-reopening check valve was designated for each pump to assure that, during the modelling of transient events, water was not allowed to flow back through closed pumps. In addition, two pressure reducing valves (PRVs) were modelled to provide the correct residual pressures in the adjacent lower pressure zones.

Before modelling surge events, it was necessary to assure that the Surge2000 model was initially balanced and capable of holding the initial steady state conditions. To prove this, a ten second transient analysis was carried out with no transient producing conditions specified. Pressures did not vary during this analysis (results showed the maximum/minimum pressures obtained by the transient analysis for the ten second run and the maximums and minimums were all identical). This is an important verification check for surge models, and in this case it verified that the model started with balanced conditions and no surges would be initiated without additional user input.

A preliminary sensitivity analysis of select model parameters showed that wave speed had significantly greater effect on the magnitude of pressure transients than did the overall demand factor, and significant variation in the global demand factor appeared to have relatively minor effects on the magnitude of surges (also supported by model data presented later in Table 3). The effect of wave speed on surge magnitude was greatest when the wave speed was 914 ms$^{-1}$ (3,000 feet s$^{-1}$).

**RESULTS AND DISCUSSION**

**Monitoring programme**

A summary of the pressure monitoring parameters is presented in Table 1. During a combined 3,286 days of pressure monitoring, totalling 2.839 × 10$^8$ data points, only nine occasions were observed where distribution system pressures were less than 138 kPa (20 psi), and no negative pressures were observed.

A summary of the nine occasions where distribution system pressure over the 19-month study period was less than 138 kPa (20 psi) is shown in Table 2. In each case a pressure below 138 kPa (20 psi) was observed in only one pressure zone, though at times pressure transients were simultaneously experienced in some, or all, of the other pressure zones. Pressure zone #3 (the high service zone) experienced the most frequent surges as a result of routine pump shutdowns or power failures (Table 2). In addition, separate pipe breaks in two pressure zones caused pressures there to drop below 138 kPa (20 psi). Other than these events at these particular sites, no pressures below 138 kPa (20 psi) were detected at any of the monitoring sites in the Davenport distribution system during the 18-month study period. The recorded pressures were above 186 kPa (27 psi) during the full monitoring period at sites #1, #2, #5, #6 and #7, and the results for these sites are not further discussed.

**Regular pump operations (events #1, #2, and #4)**

While all pump shutdowns (either normal operations or as a result of power outages) caused transients (e.g. the many large downward surges shown in Figure 3), not many resulted in pressures less than 138 kPa (20 psi) (Table 2). Nevertheless, regular pump shutdowns often resulted in pressures less than 207 kPa (30 psi), and on occasion pressures less than 158 kPa (20 psi), including events #1, #2 and #4 (Table 2). An example is shown for event #2 in Figure 3, where many similar pressure drops caused by regular pump shutdowns are evident, though only rarely did the pressure drop below 138 kPa (20 psi) (which it did during event #2). Since they are routine, events #1, #2 and #4 are not discussed further.
Table 2 | Observed pressures less than 138 kPa (20 psi)

<table>
<thead>
<tr>
<th>Event No.</th>
<th>Date</th>
<th>Monitoring site ID number</th>
<th>Initial pressure, kPa (psi)</th>
<th>Minimum pressure, kPa (psi)</th>
<th>Pressure differential, kPa (psi)</th>
<th>Time &lt; 20 psi (s)</th>
<th>Suspected cause of surge</th>
<th>Figure no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17/5/01</td>
<td>3</td>
<td>353 (51.3)</td>
<td>119 (17.3)</td>
<td>234 (34.0)</td>
<td>8</td>
<td>Pump shutdown*</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>31/7/01</td>
<td>3</td>
<td>344 (49.9)</td>
<td>137 (19.9)</td>
<td>207 (30.0)</td>
<td>7</td>
<td>Pump shutdown*</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>2/8/01</td>
<td>3</td>
<td>351 (51.0)</td>
<td>65 (9.5)</td>
<td>286 (41.5)</td>
<td>19</td>
<td>Power outage (lightning)</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>2/9/01</td>
<td>3</td>
<td>349 (50.7)</td>
<td>126 (18.3)</td>
<td>223 (32.4)</td>
<td>1–2</td>
<td>Pump shutdown</td>
<td>–</td>
</tr>
<tr>
<td>5</td>
<td>10/8/01</td>
<td>4</td>
<td>491 (71.2)</td>
<td>136 (19.8)</td>
<td>354 (51.4)</td>
<td>43 min</td>
<td>Hole bored in service line</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>4/6/02</td>
<td>3</td>
<td>332 (48.2)</td>
<td>94 (13.7)</td>
<td>238 (34.5)</td>
<td>15</td>
<td>Power outage (lightning)</td>
<td>–</td>
</tr>
<tr>
<td>7</td>
<td>2/7/02</td>
<td>3</td>
<td>357 (51.8)</td>
<td>61 (8.8)</td>
<td>296 (43.0)</td>
<td>27</td>
<td>Power outage</td>
<td>–</td>
</tr>
<tr>
<td>8</td>
<td>2/7/02</td>
<td>3</td>
<td>307 (44.5)</td>
<td>104 (15.1)</td>
<td>205 (29.7)</td>
<td>10</td>
<td>Generators stop</td>
<td>–</td>
</tr>
<tr>
<td>9</td>
<td>25/9/02</td>
<td>11</td>
<td>401 (58.2)</td>
<td>101 (14.7)</td>
<td>300 (43.5)</td>
<td>55 min</td>
<td>Main break</td>
<td>–</td>
</tr>
</tbody>
</table>

*Assumed the cause was pump shutdowns based on comparison of pressure pattern to the regular pattern of transients resulting from pumps going on and off.

Figure 3 | Effect of scheduled and inadvertent pump shutdown on pressure in the high service zone (site #3) (1.0 psi = 6.9 kPa).

Event #2: regular pump shutdown (137 kPa; 19.9 psi)
Event #3: power outage (65.4 kPa; 9.5 psi)
Pump shutdown from power failure (events #3, #6, #7 and #8)

In other studies of pressure variations (Gullick et al. 2004; Friedman et al. 2004), most of the significant downward transients were caused by pumps turning off. One such event is shown in Figure 3 as event #3 (2 August 2001), where a power outage occurred for 6 minutes at the treatment plant (due to a lightning strike), shutting the high service pumps down. The pump at the Ripley booster station near site #3 apparently also lost power. The pressure at site #3 dropped from 351 kPa (51.0 psi) to 65.4 kPa (9.5 psi) for 19 seconds (Figure 3). Monitors at the other locations recorded some small pressure variations, but not substantially different from the normal variations recorded on a routine basis. It is possible that only site #3 was largely affected by the power outage due to the shutdown of the booster pump sending water to site #3, and that the other monitoring sites were located in other pressure zones not affected by that particular booster pump. Even though the pumps at the water treatment plant directly feeding pressure zone #1 (site #1) lost power, that pressure zone is in a low-lying area along the river, and the lack of elevation rise may have contributed to minimizing the resulting hydraulic surge. Furthermore, as explained later in this paper, locations other than the specific monitoring sites may have experienced larger pressure drops (as was predicted by the model to occur in zone #3).

Not all power outages resulted in pressures less than 138 kPa (20 psi). For example, out of 20 power outages that occurred between April 2001 and September 2002, three resulted in measured pressures under 138 kPa (20 psi) (all at site #3), and the low pressures monitored for the other 17 power outages were all above 138 kPa (20 psi).

Another power outage caused by a lightning strike occurred at the water treatment plant on 4 June 2001, shutting off the transmission pumps (event #6). Site #3 was the only monitoring location where the pressure dropped below 138 kPa (20 psi) (it went from 332 kPa (48.2 psi) down to 94 kPa (13.7 psi), and stayed below 138 kPa (20 psi) for 15 seconds).

Event #7 was another sudden power outage that shut down the pumps at the treatment plant (2 July 2002). In that case the pressure at site #3 went from 357 kPa (51.8 psi) down to 60.6 kPa (8.8 psi), and stayed below 138 kPa (20 psi) for 27 seconds. During the power outage the generators came on and the pumps restarted. When the generators shut down and regular power was restored there was another transient pressure event (because the pumps shut down when the generators did), which is referred to as event #8. In that case the pressure at site #3 went from 307 kPa (44.5 psi) down to 104 kPa (15.1 psi), and stayed below 138 kPa (20 psi) for 10 seconds.

Break in service line (event #5)

The pressure event shown in Figure 4 apparently occurred when a contractor inadvertently drilled a hole through a 5-cm (2-inch) water service line in pressure zone #4 on 10 August 2001 (the exact nature of the hole was not determined). The pressure dropped from 491 kPa (71.2 psi) to 136 kPa (19.8 psi) and stayed at 136 kPa (±27.6 kPa) (19.8 psi ±4.0 psi) for 43 minutes before slowly increasing to normal. This 5-cm line is about 6 m long, and the hole was drilled at about the midpoint of it, approximately 3 m from a 41-cm (16-inch) main, which is between the curb and the sidewalk. Three 2.5-cm (1-inch) lines (corporations) are connected to the main within a 1.2 m area, and these three lines tie into a Siamese connection going into a roadway box. The 5-cm line that had the hole comes out from this roadway box (and is the only pipe to do so). Site #1 showed a pressure drop at this time, although it was no larger than the normal pressure variation at this site. No discernible pressure changes occurred at sites #2, 3, 6 or 7 (no data was available for site #5, as the flow through the pipe with that meter was shut off at that time by the property owner).

Main break (event #9; 25 September 2002)

Event #9 was caused by a break in a main transmission line very close to the monitor at site #10 located in the high service zone (zone #3). While a pressure decrease was recorded at this site (minimum of 167 kPa (24.3 psi)), a more significant pressure drop with a low of 97 kPa (14.1 psi) was measured at site #11, located within the same pressure zone. Site #10 is located upstream from the break and site #11 is located downstream, and thus the larger pressure drop was observed at site #11. At site #11...
the pressure dropped suddenly to 97 kPa (14.1 psi), and then stayed at 125 kPa (18.2 psi) for approximately 55 minutes. The sustained 55-minute period of low pressure was due to a new steady state flow condition being established in the system because of closed valves. This low pressure event could be seen only very slightly at site #3 and not at all at site #12, both of which are located within the same pressure zone as the main break (zone #3).

Modelling programme

A total of three types of events were modelled: a power failure at a pump station (modelled after event #3), a main break (modelled after event #5), and an imposed fire flow demand (a hypothetical scenario). The causes for event #3 and event #5 could be clearly defined and were therefore appropriate for modelling. Using these three scenarios the modelling analysis focused on examining the effects of various systems components (such as hydro-pneumatic tanks, pumps and air/vacuum valves) on surge magnitude. A total of 16 modelled scenarios were simulated, as outlined in Table 3.

Modelling a power outage

A total of five different model scenarios were performed to replicate surges caused by the event #3 power outage. Since it was not known exactly how many pumps were in service at the time of the lightning strike, the number of pumps in service was varied in the model (cases 1 and 2 in Table 3). Because there were indications that the Ripley booster station feeding zone #3 from zone #1 (Figure 1) may have also lost power, a modelling scenario was performed with this station either on or off (cases 1 and 3). The system demand was also varied (cases 1, 1a and 1b), and used the 1999 average day demand as a base value.

For each of the scenarios modelling the event #3 power outage (case studies #1, 1a, 1b, 2 and 3), the calculated pressures matched reasonably well with the observed pressures monitored at six of the seven recording stations (e.g. see Table 4 for results from case studies 1a, 2 and 3). As an example of agreement between field data and model results, Figure 5 shows that the model output (case #1 in Table 3) matched very closely the observed low-pressure transient at the location of largest recorded pressure change (site #3). It is noted that the model did not predict quite as well the rate of the subsequent rise back up in pressure. Pressures at site #7 were not well replicated, possibly due to inaccurate information in the model about booster pump #2 characteristics (site #7 is immediately downstream of that pump). Although it is likely that the model could more accurately replicate the scenario given more detailed information about actual field conditions, in this exercise...
### Table 3 | Modelling cases for surge analysis

<table>
<thead>
<tr>
<th>Case study</th>
<th>Event type (real event #)</th>
<th>Number of pump trips</th>
<th>Global demand factor</th>
<th>Hydro-pneumatic tank?</th>
<th>Result</th>
<th>Number of model nodes with negative pressures</th>
<th>Total time† node pressures were below zero (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Power outage (#3)</td>
<td>5 pump trip (1 MS, 3 HS, booster #1)</td>
<td>1.0</td>
<td>No</td>
<td>132</td>
<td>541</td>
<td></td>
</tr>
<tr>
<td>1a</td>
<td>Power outage (#3)</td>
<td>5 pump trip (1 MS, 3 HS, booster #1)</td>
<td>1.5</td>
<td>No</td>
<td>118</td>
<td>476</td>
<td></td>
</tr>
<tr>
<td>1b</td>
<td>Power outage (#3)</td>
<td>5 pump trip (1 MS, 3 HS, booster #1)</td>
<td>0.5</td>
<td>No</td>
<td>140</td>
<td>601</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Power outage (#3)</td>
<td>7 pump trip (2 MS, 4 HS, booster #1)</td>
<td>1.0</td>
<td>No</td>
<td>154</td>
<td>1,041</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Power outage (#3)</td>
<td>4 pump trip (1 MS, 3 HS)</td>
<td>1.0</td>
<td>No</td>
<td>108</td>
<td>381</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Power outage (#3)</td>
<td>All pumps (1 MS, 3 HS, all boosters)</td>
<td>1.0</td>
<td>No</td>
<td>124</td>
<td>503</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Power outage (#3)</td>
<td>7 pump trip (2 MS, 4 HS, booster #1; with hydro-pneumatic tanks)</td>
<td>1.0</td>
<td>Yes</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Power outage (#3)</td>
<td>All pumps (1 MS, 3 HS, all boosters; with hydro-pneumatic tanks)</td>
<td>1.0</td>
<td>Yes</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Power outage (#3)</td>
<td>7 pump trip (case 2) with air/vacuum valves</td>
<td>1.0</td>
<td>No</td>
<td>116</td>
<td>377</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Power outage</td>
<td>Booster #2 only</td>
<td>1.0</td>
<td>No</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Power outage</td>
<td>Booster #3 only</td>
<td>1.0</td>
<td>No</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Main break/leak (#5)</td>
<td>Leak near site #4 (4 seconds to establish)</td>
<td>1.0</td>
<td>No</td>
<td>32</td>
<td>392</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Main break/leak (#5)</td>
<td>Leak near site #4 (50 seconds to establish)</td>
<td>1.0</td>
<td>No</td>
<td>1</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Imposed fire flow</td>
<td>Demand imposed in 3 seconds (9,084 l min⁻¹)</td>
<td>1.0</td>
<td>No</td>
<td>19</td>
<td>197</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Imposed fire flow</td>
<td>Demand imposed in 30 seconds (9,084 l min⁻¹)</td>
<td>1.0</td>
<td>No</td>
<td>1</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Imposed fire flow</td>
<td>Demand imposed in 3 seconds with air valve (9,084 l min⁻¹)</td>
<td>1.0</td>
<td>No</td>
<td>19</td>
<td>196</td>
<td></td>
</tr>
</tbody>
</table>

MS = main service pumps; HS = high service pumps.

†Total time is the cumulative value for all nodes with negative pressures.
the exact actual operating conditions and system configuration that would replicate the scenario could not be determined. This was especially true at monitoring site #7 which had a surge magnitude that was, at best, 345 kPa (50 psi) larger than the field observed surge magnitude.

Importantly, though no negative pressures were recorded by any of the monitors, for all five scenarios (case studies 1, 1a, 1b, 2, 3) three principal areas of the distribution system were projected to experience negative pressures. However, the monitoring stations were not located in the affected zones (see boxed areas in Figure 6). The output for these three case studies varied only slightly in the number of nodes that experienced negative pressures (Table 3).

In an attempt to validate the model predictions, for approximately one month during September–October 2001, three pressure monitors were placed on fire hydrants within the areas in pressure zone #3 that the model predicted would have the lowest pressures after a power outage (boxed areas in Figure 6). However, no negative pressure events were detected during that period.

In order to assess the potential for shutdown of the individual booster pump stations to cause pressure transients, additional simulations were performed where just the pumps at booster stations #2 or #3 were turned off (cases 8 and 9). In both instances no negative pressure nodes resulted.

The data from these modelling scenarios (cases 1–4 in Table 3) indicate that the loss of power to the pumps at the water treatment plant could result in significant distribution system low pressures (<0 kPa). The number of pumps initially running and the level of demand appeared to have little effect on the generation of low pressures (Table 3). It also appeared that power failures that do not affect the water treatment plant would generally not cause low pressures (cases 8 and 9 in Table 3).

Case 2 was used as a base when developing and comparing surge mitigation techniques (hydro-pneumatic...
tanks and air/vacuum valves; see sections below) because this scenario resulted in the largest transients and would provide the most conservative estimate of the protection provided by modelled surge control devices.

**Analysis of effect of hydro-pneumatic tanks.** Protection against down-surges due to pump trips can often be provided by hydro-pneumatic tanks (air vessels) located just downstream from the pumping station. To assess this potential effect, model simulations were performed where two hydro-pneumatic tanks were added, one immediately downstream of the main service pumps and the other immediately downstream of the high service pumps at the water treatment plant. The hydro-pneumatic tanks were modelled as closed 6-m (20-foot) diameter tanks with 3 m (10 feet) of water and 3 m (10 feet) of air initially in the tanks. These two simulations were cases 5 and 6 (for the power outage of event #3), and are compared with cases 2 and 4, respectively.

The model predicted that installation of hydro-pneumatic tanks downstream from the water treatment plant pumping station provided complete protection from negative pressure transients due to a power outage. Specifically, with the addition of hydro-pneumatic tanks in case 5, the number of nodes predicted by the model to experience negative pressures dropped from 154 to 0 (Table 3). For case 6, a similar effect on the development of negative pressures was observed, where all 124 nodes that experienced negative pressures without the hydro-pneumatic tanks remained at positive pressure with the addition of hydro-pneumatic tanks (Table 3). As an example, as shown in Figure 7, the modelled pump trip (case 2) produced a large pressure drop at site #1 (372–393 kPa (54–57 psi)) when no hydro-pneumatic tanks were present, but with hydro-pneumatic tanks present (case 5) a pressure drop of only 76 kPa (11 psi) resulted at site #1, and it occurred much more slowly.

**Analysis of effect of air/vacuum valves.** A modelling exercise was performed to evaluate the effectiveness of air/vacuum valves for reducing low pressures and intrusion following a major pump trip event. Thirteen air/vacuum
valves (10-cm orifice (4-inch)) were modelled at elevated locations in regions where low pressures were predicted. Figure 8 shows the locations of the simulated air/vacuum valves. A 10-cm (4-inch) orifice was modelled to ensure that the full potential effect of the air/vacuum valves was realized. A modelling scenario where all seven pumps were tripped (case 2) was repeated with the air valves installed (case 7); however, the results showed that the presence of the air/vacuum valves provided little protection from the development of low or negative pressures.

In addition, overall throughout the modelled system, 154 nodes reached a negative pressure after a power outage without the air/vacuum valves, and with the valves added 116 nodes reached negative pressure (Table 3). This notable but still relatively small benefit from the air/vacuum valves was experienced even though the air/vacuum valves were activated as shown in pressure traces (Figure 9).

Furthermore, at most of the locations examined, the pressure drops remained basically the same despite the use of the 13 hypothetical air/vacuum valves dispersed throughout the distribution system. In each of these cases the minimum pressure during the surge was above 0 kPa (0 psi), and thus the air/vacuum valves would not be effective since they are designed to open only when the pressure in the pipe falls below atmospheric pressure. Because of this operational feature, brief negative pressures can occur at air/vacuum valve sites since the valve will not open until the pressure has already dropped below 0 kPa. Such an occurrence is shown in Figure 9.
In conclusion, although the addition of air/vacuum valves can be used to reduce the duration of negative pressures, air/vacuum valves do not respond to low pressures (e.g. from 0 to 138 kPa (0–20 psi)), and thus in many locations little benefit was gained from addition of these valves.

One potential problem associated with the use of air/vacuum valves is an elevated surge pressure due to the ‘air slam’ when air is expelled from the valve. This is shown in the simulated pressure traces for the sites of three of the valves in Figure 9. This result shows a surge pressure of over 1,034 kPa (150 psi) due to the ‘air slam’ when the air is expelled from one of the locations (the valve at location AIR-8).

Another potential drawback of air/vacuum valves is that they present a potential route of access for contaminants to enter a distribution system, either inadvertently or via intentional vandalism or terrorism. Such valves should include an above-grade vent and be placed in secure locations to lessen the risk of contamination through this route.

Modelling a sudden leak in pipe

Two modelling scenarios were examined to simulate the leak that occurred in the 5-cm (2-inch) pipe near monitoring site #4 (event #5). As detailed previously, a contractor inadvertently drilled a hole through the pipe, and this apparently was the cause of a recorded pressure drop at site #4 from 482 kPa (70 psi) to 138 kPa (20 psi). Cases #10 and #11 (Table 3) modelled the initiation of the leak by imposing a sudden demand with the leak rate increasing from zero to peak flow in 4 seconds and in 50 seconds, respectively (the model simulations assumed the pipe was sheared all the way through). The model determined that a flow of 15,140 l min$^{-1}$ (4,000 gpm) through the pipe puncture would be required to produce the recorded drops in pressure – a flow rate that is excessive for a 5-cm (2-inch) line. In reality the 345-kPa (50-psi) drop may have occurred in part because of a shorter time of acceleration and in part because of other variables not fully accounted for.

For modelling both cases (#10 and #11) the pressure drops from an initial value of around 482 kPa (70 psi) to a final value of around 138 kPa (20 psi). However, the more rapidly the leak develops (4 seconds compared with 50 seconds), the greater the initial pressure drop will be. Therefore, it is possible that a rapid puncture of a distribution system line may have resulted in the observed pressure variations, and that under certain circumstances such a rapid rupture could cause negative pressures at various distribution system locations. Figure 10 shows that the low-pressure locations for the 4-second scenario were downstream of the electronic pressure monitoring location. At the faster rate (4 seconds for leak development) the model predicts that 32 nodes (Figure 10) would experience negative pressures for a total of 392 seconds, and at the slower rate (50 seconds for leak development) the model predicted that only one node would experience a negative pressure for a total of 7 seconds.
Modelling hydrant operations (fire flows)

The Surge2000 model was used to examine several hypothetical scenarios (cases 12–14, Table 3) related to hydrant use to examine the vulnerability of the distribution system to negative pressure transients from the operation of fire hydrants under emergency situations. It is important to note that there was no evidence of pressure events due to hydrant activity, but because the area of the distribution system affected by hydrant use may be limited, these activities may not have been observed at the fixed monitoring locations used in this study.

Event #5 (hole drilled in pipe) illustrates the situation where a rapid demand in the system could cause negative pressures. Although this event was modelled as a pipe break, turning on a fire hydrant would produce the same response. If a fire pump were used to increase the fire flow, even lower pressures would result. The situation would be more severe when the hydrant is at a lower elevation than the adjacent regions of the distribution system.

A simulated hydrant startup was modelled in a vulnerable area of the distribution system (cases 12–14; Table 3). The hydrant location highlighted is in the lowest elevation part of that region in an area of looped pipes (Figure 11). A steady state calculation for a fire flow of 9,084 l min\(^{-1}\) (2,400 gpm) at the location will lower the pressure at the hydrant to 138 kPa (20 psi) while the adjacent locations are at higher pressures.

A surge analysis was performed for a 3-second and a 30-second hydrant startup. As shown in Table 5 (case 12), a 3-second startup produces transient negative pressures at 19 nodes in the model. Assuming that these locations have leaks and are submerged within the water table, the model also predicts the potential for intrusion of approximately 1 gallon (3.78 l) during the operation of the hydrant (LeChevallier et al. 2002 provides details on the calculation of intrusion). Figure 11 shows that the low pressures are predominantly associated with locations near the hydrant. Initiating the flow from the hydrant over a 30-second period dramatically reduced the number of nodes experiencing negative pressure.
of nodes experiencing low pressures and the potential for intrusion (Table 5).

An analysis was also performed to evaluate the effectiveness of inserting an air/vacuum valve at a high spot in the vicinity of the hydrant startup (Figure 11). The elevation of the simulated air/vacuum valve location is approximately 9.1 m (30 feet) above the hydrant. Data presented in Table 5 show that even though the air/vacuum valve was activated, it did little to reduce low pressures and the potential for intrusion in the region.

### Table 5 | Model simulations of hydrant operations

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Description</th>
<th>Number of nodes experiencing a negative pressure</th>
<th>Total time of negative pressure (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>Hydrant opening in 3 seconds</td>
<td>19</td>
<td>197</td>
</tr>
<tr>
<td>13</td>
<td>Hydrant opening in 30 seconds</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>14</td>
<td>Hydrant opening in 3 seconds with addition of air valve</td>
<td>19</td>
<td>196</td>
</tr>
</tbody>
</table>

*Simulations were performed for a hydrant at model node #5975 at a flow of 9,084 l min⁻¹ (2,400 gpm).

**MODELLING CONCLUSIONS**

The following conclusions were reached during the surge modelling exercise:

**General conclusions of model applications:**

- A well-calibrated hydraulic surge model can be used to reasonably accurately simulate the occurrence of pressure transients under a variety of operational scenarios.
A model can be used to determine optimal mitigation measures.

**Model variable sensitivity analysis:**
- During the sensitivity analysis, it was shown that wave speed had significantly greater effect on the magnitude of pressure transients than did the overall demand factor.
- The effect of wave speed on surge magnitude was greatest when the wave speed was 914 m s\(^{-1}\) (3,000 feet s\(^{-1}\)).
- Significant variation in the global demand factor appeared to have relatively minor effects on the magnitude of surges.

**Power outages and means of surge control:**
- It appears that the Davenport distribution system may experience negative pressures in certain locations when the water treatment plant pumping station loses power. The number of pumps initially running at the water treatment plant and the level of demand appear to have little effect on the generation of low pressures due to this situation.
- Although negative pressures were not recorded where the field monitors were located during observed power failures in the system, the model predicted that negative pressures may have occurred elsewhere in the system during the events. No pressure monitors were located during a power outage in the regions that were predicted by the model to experience negative pressure surges.
- It also appears that power failures that do not affect the water treatment plant pumps will generally not cause low pressure surges.
- It is possible to provide protection against low pressures due to a power outage by installing hydro-pneumatic tanks downstream from the affected pumping stations. The model predicted that the addition of two closed hydro-pneumatic tanks 6 m (20 feet) in diameter, with 3 m (10 feet) of water and 3 m (10 feet) of air, would prevent negative surges from occurring in the distribution system after a power outage at the water treatment plant.
- Air/vacuum valves, however, would not appear to offer reliable protection against low pressures in this system. Air/vacuum valves protect the system to some degree against negative surges by opening when the pressure in the pipe drops to below 0 kPa (atmospheric pressure). Air/vacuum valves can cause a spike in pressures due to ‘air slam’ of the valves, and also can be a potential route for contaminants to enter a distribution system if they are not properly vented and secured.

**Sudden demands:**
- The surge analysis modelling showed that a high flow leak that develops rapidly can produce low and negative pressures. Also, rapid opening of fire hydrants can produce a similar situation.
- The rate at which a sudden demand (e.g. main break, fire flow) is imposed has an impact on the magnitude of the pressure downsurge initially created.

**Future research**
The next logical step in the research process is to better determine the frequency of negative pressure transients in drinking water systems, as well as the characteristics of distribution systems that contribute to increased vulnerability to negative pressure events. Furthermore, research is needed to identify means to lessen the magnitude of surges to reduce the risk of contamination of water supplies, and to provide guidance to utilities for developing and using hydraulic surge models for identifying system areas most susceptible to negative pressures, and to identify corrective measures. American Water is currently performing surge modelling for a variety of distribution systems in order to address these issues in research funded by the American Water Works Association Research Foundation and the New Jersey Department of Environmental Protection.

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REFERENCES


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