Susceptibility of Potable Water Distribution Systems to Negative Pressure Transients

Prepared by:
Kala K. Fleming, Rich W. Gullick,
Joseph P. Dugandzic, Mark W. LeChevallier
American Water, Voorhees, NJ 08043

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Division of Science, Research & Technology
P.O. Box 409
Trenton, NJ 08625

and

American Water
1025 Laurel Oak Rd
Voorhees, NJ 08043

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EXECUTIVE SUMMARY

The operating conditions of drinking water systems are rarely at a true steady state. All systems will at some time be started up, switched off, or undergo other rapid flow changes. Previous research has established that the pressure waves generated by these disturbances can propagate throughout the distribution system, creating low and negative pressures in several locations, and that the low or negative pressures created can provide an opportunity for intrusion of non-potable water. The occurrence of low and negative pressure transients (also called surges) may also contribute to pipe fatigue and eventual pipe failure if stress fluctuations of sufficient magnitude and frequency occur. Investigating pressure transients improves understanding of how a system may behave in response to a variety of events such as power outages, routine pump shut downs, valve operations, flushing, firefighting, main breaks and other events that can create significant rapid, temporary drops in system pressure.

RESEARCH PROJECT

This report assesses characteristics of distribution systems that contribute to the occurrence of low and negative pressures (using hydraulic modeling), examines the occurrence of transient low and negative pressures in distribution systems and identifies mitigation strategies for minimizing the occurrence and impact from negative pressure transients. Specifically, this research project was designed to encompass the following major objectives and tasks:

1. <u>Distribution System Selection</u>: Select four distribution systems that allow a range of distribution system characteristics to be examined.

2. <u>Surge Model Development and Analysis</u>. Develop computer models that allow actions resulting in sudden changes of flow (that result in hydraulic transients) to be examined.

3. <u>Distribution System Pressure Monitoring</u>: Use surge modeling predictions to locate pressure monitors in the most vulnerable (to low or negative pressure) distribution system areas.

4. <u>Recommendations for Surge Monitoring and Mitigation:</u> Develop recommendations when using surge models to optimally locate pressure monitors, and develop recommendations for minimizing the occurrence of and impacts from negative pressure transients.

Distribution System Selection

Five distribution systems that represent a range of utility operations were selected for surge modeling. The factors that were considered in selecting the distribution systems included the following:

- system size (system delivery and/or population served);
- operating pressure;
- number, size, location and operation of pumps;
- variations in distribution system configuration;
- variations in topography/elevation;
- presence/absence of distribution storage facilities;
- presence of air/vacuum relief valves, surge tanks, air vessels, and other related features.

Surge Modeling Procedure

Calibrated Extended Period Simulation (EPS) models were used to provide initial and boundary conditions (during high flow periods) for the surge models developed for each system. At least three key simulations were performed for each system: 1) complete loss of pumping (e.g., a power outage), 2) a major main break in a key trunk line, 3) opening a hydrant to fire flow. Additionally, rapid fluctuation of a pressure reducing valve (PRV) was simulated if the system included a PRV as a part of the system design.

Surge Modeling Results

In the absence of surge mitigation, each distribution system that contained a pumping station was susceptible to negative pressures if a pumping failure occurred. The following observations were also noted for individual systems:

*Impact of system size***.** System size did not seem to have a significant effect on the occurrence of low and negative pressures in the distribution system. For example, a complete loss of pumping power in a system with 509 miles of main caused negative pressures in approximately 10% of the system, while complete loss of pumping power in another system with 60 miles of main resulted in negative pressures in nearly 70% of the system.

Impact of pump capacity and downstream velocities. Increasing the flow brought to a stop in individual systems increased the predicted percentage of locations with negative pressures when complete loss of pumping power occurred. Power loss at pump stations with downstream velocities less than 1.5 ft/s generally did not result in negative pressures in most of the systems examined. Conversely, the shutdown of pump stations with downstream velocities greater than 3 ft/s almost always created negative pressures in the areas surrounding the station, as long as floating storage facilities or other surge mitigation was absent.

Impact of distribution system configuration and topology. Low and negative pressures were more prevalent at or near dead ends. Low and negative pressures were also more prevalent in regions where local elevations were greater than 30 to 40 ft above immediate surroundings.

Impact of distribution system storage facilities. In general, the presence of floating storage was found to be significant in helping to reduce the impact of low/negative pressure transients.

*Impact of surge relief***.** Installing appropriately sized air vacuum valves reduced negative pressures by as much as 40% in some systems. Hydropneumatic tanks provided the most dramatic reductions in negative pressures, however. For most of the systems examined in this study, if the main downstream of the pump station was 24 inches or smaller, the installation of one 1,000-gal hydropneumatic tank was sufficient to prevent negative pressures when a power outage occurred. Systems with larger mains required larger hydropneumatic tanks to prevent negative pressures from occurring if power was lost at the pump station. Pump bypass piping installed at booster stations was effective in preventing transients when power loss occurred at the stations.

Distribution System Pressure Monitoring

Pressure monitoring was conducted in the field for two systems. Several high-speed, pressure data loggers (RDL1071L/3 Pressure Transient Logger, RADCOM Technologies, Inc., MA) were used to monitor the pressures. The sample rate used for each monitor in each system was 1 sample per second so that data could be collected continuously for up to three weeks. Telog monitors (HPR-31 Hydrant Pressure Recorder, Telog Instruments, Inc, NY) were also used for pressure comparisons. The monitors were placed in each system based on surge modeling predictions of the areas that would be most susceptible to low or negative pressure transients when the most likely transient producing event - a pump shut down - occurred. The findings are summarized below:

- Negative pressures were not detected in the two distribution systems monitored. However, low pressures (pressure < 20 psi) were measured in three locations in one system and in one location in the other. The lowest pressure measured in either system was 1.1 psi.

- Calibrated EPS models produce surge models that can adequately assess distribution susceptibility to low and negative pressures. However, the predicted pressures were lower than observed in the field. This occurs primarily because the initial and boundary conditions used during field monitoring corresponded to initial and boundary conditions for lower flow conditions than used during surge modeling. Additionally, the timing of transient producing events (pump shutdown for example) and the wave propagation speed are estimated.

- The trend in the model and field transient pressures was very similar for the two systems examined.

Recommendations for Surge Monitoring and Mitigation

The following recommendations are made for water utilities to consider as part of their surge monitoring and mitigation programs:

- Calibrated EPS models that have been developed can be used to *identify* susceptible surge monitoring locations as described in this report. However, pressure monitoring should be performed for a few of the locations to verify the susceptibility of the locations that have been predicted to be vulnerable to low and negative pressures.

- To best understand the impact of surge in individual systems, the use of calibrated surge models is recommended. If field verification will be performed, then it would be ideal if the model was calibrated so that tank levels, pumping rates and other boundary conditions match the field conditions on the day data is collected.

- A calibrated EPS model does not equal a calibrated surge model. Once boundary conditions have been verified, critical parameters such as pump inertia, and valve closure times should be verified.

- Vulnerable areas identified via modeling should be prioritized for maintenance of a disinfectant residual, mitigation via surge control, leak detection and control, and cross connection control and backflow prevention.

- Slowing the rate at which a flow control operation occurs will reduce the magnitude of the surge produced. Increasing pump inertia, slowing the opening and closing of fire hydrants, prolonging valve opening and valve closing times, and avoiding complete pumping failure by putting a major pump on a universal power supply are all direct actions that can be taken for surge control.

- Installing standpipes or hydropneumatic tanks near pump stations is effective for surge mitigation. One way feed-tanks, which only allow flow into the pipe system, can be installed anywhere along the line to reduce negative pressures. However, the final choice for surge protection should be based on the initial cause and location of the transient disturbance(s), the system itself, the consequences if remedial action is not taken, and the cost of the protection measure(s).

DEFINITION OF TERMS

Buried Storage Tank. A buried storage tank has more than 10% of the total tank and piping capacity below the ground surface and may or may not float on the system depending on its elevation. If the HGL in the tank is below the HGL in the system, and water must be pumped from the tank to deliver water to the distribution system, the tank is referred to as a pumped buried storage tank.

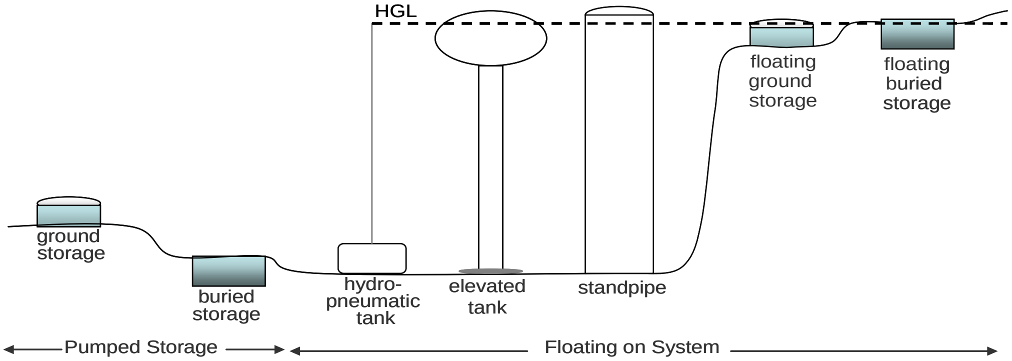
Elevated Storage Tank. An elevated storage tank has a supporting structure which elevates its lower operating level to provide additional head. Most elevated storage tanks are designed to float on the system.

Floating Storage Tank. A tank is said to "float" on the system if the hydraulic grade elevation inside the tank is the same as the HGL in the water distribution system immediately outside of the tank.

Ground Storage Tank. A ground storage tank has ground surface elevation with more than 90% of the total tank and piping capacity above ground and may or may not float on the system, depending on its elevation. If the HGL in the tank is below the HGL in the system, and water must be pumped from the tank to deliver water to the distribution system, the tank is referred to as a pumped ground storage tank.

Head. The total energy associated with a fluid per unit weight of the fluid. Fluids possess energy in three forms. The amount of energy depends on the fluid's movement (*kinetic energy*), elevation (*potential energy*), and pressure (*pressure energy*). In most water distribution applications, the elevation and pressure head terms are much greater than the velocity head term, so the velocity head term is often ignored.

Hydraulic Grade Line (HGL). The sum of the elevation head and pressure head. The HGL corresponds to the height that water will rise vertically in a tube attached to the pipe and open to the atmosphere.



Hydropneumatic Tank (also air vessel or closed surge tank). A hydropneumatic tank is one that is filled with both compressed air and water. Because the water in the tank is pressurized, the HGL is higher than the water. The water surface elevation in a tank typically equals the HGL in the tank, but in a hydropneumatic tank the HGL is the sum of the pressure recorded at the tank (converted to head) plus the elevation of the pressure gage used to measure the pressure. Hydropneumatic tanks serve the same function as open surge tanks, but respond faster and can operate over a wider range of pressure fluctuation. Smaller tanks are used primarily to reduce pressure transients. Larger capacity hydropneumatic tanks can also be designed to lengthen the off cycle time for supply pumps, providing water to customers for a period of time after a power failure (if no emergency generator exists, or if one does exist, for the time it takes for the generator to come on line).

Junction. A junction is node in a distribution system model where pipes connect. Customer demands are typically represented at this point. However, it is possible to have a junction with zero customer demands. The term "node" is used interchangeably with "junction" in this report.

Node. A node is a distribution system model representation of features at specific locations within the full-scale system. Drinking water distribution models have many types of nodal elements, including junction nodes where pipes connect, storage tank and reservoir nodes, pump nodes, and control valve nodes.

Pumped Storage Tank. A pumped storage tank is one that needs a pump to deliver water from the tank to the distribution system, and a control valve to gradually fill the tank without seriously affecting pressure in the surrounding system.

Reservoir. In terms of distribution system modeling, a reservoir represents a boundary node in a model that can supply or accept water with such a large capacity that the hydraulic grade of the reservoir is unaffected and remains constant. It is an infinite source, which means that it can theoretically handle any inflow or outflow rate, for any length of time, without running dry or overflowing.

Standpipe or Open Surge Tank. A standpipe (or open surge tank) is a flat bottomed cylindrical tank with a shell height greater than its diameter. The relatively small tank is located such that the normal water level elevation is equal to the hydraulic grade line elevation. The tank feeds the system by gravity, and the outflow of water from the tank controls the magnitude of low-pressure transients that can be generated following a pump shutdown. The tank can also prevent high pressures by serving as temporary storage for excess liquid.

CHAPTER 1
INTRODUCTION

OVERVIEW

The purpose of this project was to determine which distribution system characteristics influence the susceptibility of distribution systems to low or negative pressure transients. Pressure transients, also called “surge” or “water hammer”, are pressure waves caused by abrupt changes in water velocity. The pressure wave generated can propagate throughout the distribution system causing low or negative pressures in locations several miles away from the origin of the event. The presence of low or negative pressures in the distribution system, even for a few seconds, can create the opportunity for contamination present in the external environment to intrude into the distribution system. Persistent pressure fluctuations can also contribute to weakening distribution system piping.

Typical events that may cause abrupt changes in velocity include: controlled or uncontrolled pump starting or stopping; valve opening or closing; sudden changes in customer demand (opening and closing of fire hydrants, etc); changes in boundary pressures (adjustments in the water levels at reservoirs, pressure changes in tanks, etc); changes in transmission conditions (pipe break or line freezing) and pipe filling or draining. In general, any disturbance in the water that causes a change in mean flow conditions will initiate a sequence of transient pressures in the distribution system.

Because it had generally been thought that the many junctions in distribution systems dissipated transient pressures to the point where surge was not a significant issue, transient pressures were only addressed in large transmission mains. As a result, other distribution system characteristics that may contribute to producing low or negative pressure transients have not been well examined. The presence/absence of storage tanks, placement of air relief and other surge control devices and pump operation procedures are all factors that may affect the occurrence and severity of low or negative pressure transients in the distribution system.

This project builds upon the work done in previous AWWARF projects - *Pathogen Intrusion into the Distribution System* and *Verification and Control of Pressure Transients in Distribution Systems* – by addressing the gap that exists in understanding the distribution system characteristics that contribute to producing negative pressure transients. The specific research objectives are outlined later in this chapter.

BACKGROUND

The functional requirements of a distribution system are to deliver water (1) that meets the regulatory requirements in terms of contaminants that might affect health and is aesthetically acceptable to the customer in terms of taste, color and odor, (2) in the quantity and at the pressures required by the customer and fire protection, and (3) of the correct quality and quantity on a continuous basis with minimum service interruption (Heavens and Gumbel, 2002). The occurrence of pressure transients is inevitable and may threaten the ability of the distribution system to meet its functional requirements depending on the severity and frequency of the pressure fluctuations that occur. The operating conditions of drinking water systems are rarely ever at a true steady state. All systems will at some time be started up, switched off, or undergo other rapid flow changes such as those caused by hydrant flushing. Previous research has established that the pressure waves generated by these disturbances can propagate throughout the distribution system creating low and negative pressure in several locations, and that the low or negative pressures created can provide an opportunity for intrusion of non-potable water. The occurrence of low and negative pressure transients (also called surges) may also contribute to pipe fatigue and eventual pipe failure if stress fluctuations of sufficient magnitude and frequency occur.

Walski and Lutes (1994) provided one of the earliest reported accounts of the effects of negative pressure surges in the distribution system. The study was initiated when customers located in a high elevation area (steady-state pressures of 25-40 psi) of an Austin, Texas system complained of occasionally being out of water while others complained of hearing sputtering water or air-horn sounds when they turned their water on. After eliminating malfunctioning air-release valves and water theft from hydrants as culprits for the low pressures and excess air in the pipes, the complaints were attributed to the transient low pressures created with routine shutdown of pumps and valve operation.

The potential for backflow of contaminants into the distribution system has increased the concern over the occurrence of negative pressures in the distribution system. Gullick et al. (2004) studied intrusion occurrences in full-scale distribution systems and observed 15 surge events that resulted in a negative pressure. Most were caused by the sudden shutdown of pumps at a pump station because of either unintentional (e.g., power outages) or intentional (e.g. pump stoppage or startup tests) circumstances. In the AWWARF Report - *Verification and Control of Pressure Transients in Distribution Systems* - Friedman et al. (2004) demonstrated that negative pressure transients can occur, and that the intruded water can travel downstream from the site of entry, in three of seven full-scale distribution systems. Locations with the highest potential for intrusion were sites experiencing leaks and breaks, areas of high water table, and flooded air-vacuum valve vaults. Pilot-scale investigations, conducted as a part of the same study, estimated intrusion volumes of up to 50 mL and 127 mL through 1/8" and ¼" orifices, respectively, when 132 gpm of flow was brought to a stop with the sudden closure (less than 1 second) of a 2 ½" ball valve (Boyd et al. 2004a, 2004b).

Pressure Transients

Flow is considered steady when pressure and flow do not vary with time, or when fluctuations are small with respect to mean flow values and the mean flow values are static. Any disturbance in the water, generated during a change in the mean flow conditions, will initiate a sequence of transient pressures (waves) in the water distribution system. The terms "water hammer", "transient flow", and "surge" describe the unsteady flow of fluids in pipes. The elastic theory used to describe water hammer, assumes that changing the momentum of a liquid will cause expansion or compression of the pipe and liquid. The consequence of this is that a flow changes initiated at one point in the system does not impact everywhere else in the system at exactly the same instant in time.

The pressure waves created by velocity changes depend on the elastic properties of the pipe and liquid, and they propagate throughout the distribution system at speeds that depend directly on these elastic properties. Abrupt changes in velocity convert the kinetic energy carried by the moving fluid (now brought to a stop) into strain energy in the pipe walls, causing a "pulse wave" of abnormal pressure to travel from the disturbance into the pipe system (Boulos et al. 2004 and 2005). The hammering sound that is sometimes heard indicates that a portion of the fluid's original kinetic energy has been converted not only into pressure, but also into an acoustic form. This acoustic energy release as well as other energy losses (including fluid friction), causes the transient pressure waves to gradually decay until new steady pressures and velocities are established (Figure 1-1).

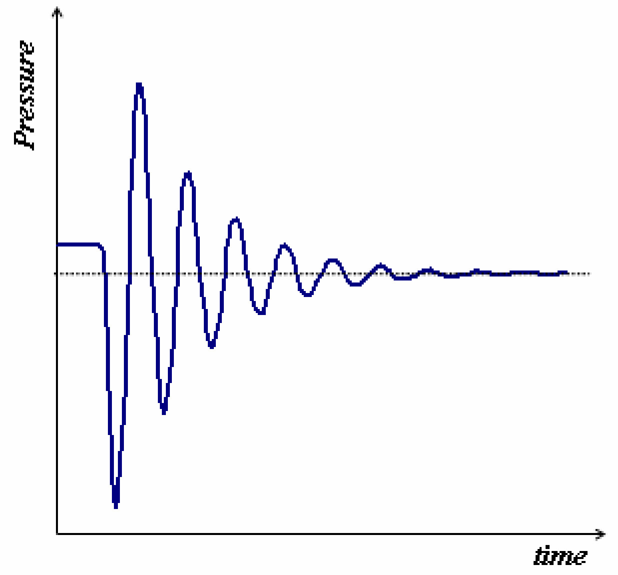


Figure 1-1 Evolution of a transient pressure wave

The Joukowsky equation (Thorley, 2004) provides an estimate of the maximum change in head (*ΔH*) created when water with velocity *V* is brought to a sudden stop:

$$\Delta H = \pm \frac{c}{g} \Delta V \qquad \text{Equation 1.1}$$

where *c* is the acoustic wave speed and *g* is acceleration due to gravity. The negative sign represents a propagation traveling upstream and the positive sign represents a propagation traveling downstream. A general expression for the wave speed is:

$$c = \sqrt{E_f / \rho (1 + K_R E_f D / E_c t_l}) \qquad \text{Equation 1.2}$$

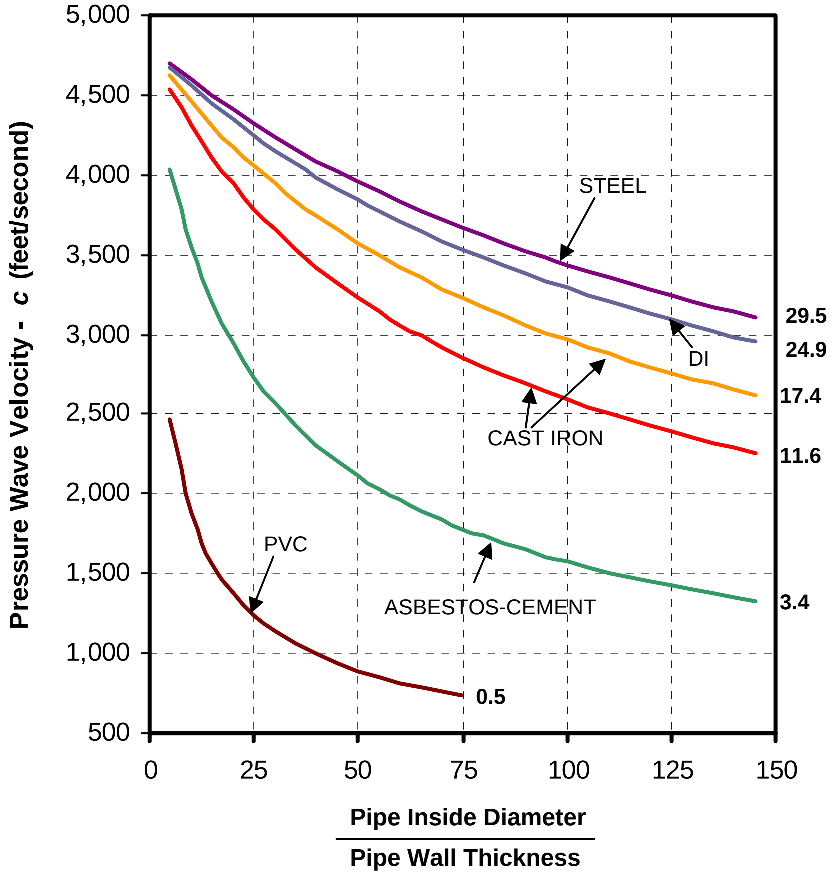
where E_f and E_c are the elastic modulus (Young's Modulus - measure of material stiffness) of the fluid and conduit, respectively; *D* is the pipe diameter; ρ is liquid density; t_l is the pipe thickness; and K_R is the coefficient of restraint for longitudinal pipe movement. K_R for a pipe that is completely restrained can be expressed as:

$$K_R = \frac{D}{D + t_1} + (1 - \mu_P^2) + \frac{2t_1}{D}(1 + \mu_p) \qquad \text{Equation 1.3}$$

where μ_p is Poisson's ratio (elastic constant that is a measure of the compressibility of material perpendicular to applied stress). Table 1-1 lists the Young's modulus and Poisson's ratio of common pipe materials. A plot of wave propagation speeds for water flowing in a completely restrained circular pipe for a variety of pipe materials is shown in Figure 1-2.

Table 1-1
Physical properties of common pipe materials

Material	Young's Modulus, E_c		Poisson's Ratio, μ_p
	Pa x 10^9	PSI x 10^6	
Aluminum	69	10.0	0.33
Asbestos Cement	23-24	3.3-3.5	-
Cast Iron	80-170	11.6-24.7	0.24-0.27
Concrete	14-30	2.0-4.4	0.1-0.15
Reinforced Concrete	30-60	4.4-8.7	-
Ductile Iron	172	24.9	0.30
Polyethylene	0.7-0.8	0.1	0.46
PVC	2.4-3.5	0.3-0.5	0.46
Steel	200-207	29.0 – 30.0	0.30



*Number to the right of curves indicates E_c value (Table 1-1), in PSI, that was used to construct the curve.

Figure 1-2 Pressure wave velocity for water in round pipes with different diameters and thicknesses and K_r equal to 0.91 (adapted from Thorley, 2004 and Wood and Boulos, 2005a).

Since typical values of c/g are often 100 seconds or more, the Joukowsky equation predicts large values of head rise. For every 1 ft/sec (0.3 m/s) of velocity forced to a sudden stop, downstream head can decrease up to 138 ft (42 meters) or 60 psi (414 kPa) depending on the pipe materials, topography, etc. It is important to note that the presence of even small quantities of air can significantly reduce the wave propagation speed. Several other factors, intrinsic to a distribution system, including steady and unsteady fluid friction, network demands, leaks, loops and intersections will also help to reduce the magnitude of pressure wave generated (Karney and Filon, 2003). Loops and intersections will reduce the magnitude of the transient generated since they tend to fragment a coherent pressure signal into a multitude of scattered pieces.

Accounting for non-instantaneous flow changes. The Joukowsky equation provides a worst case estimate of surge magnitude, since the flow change is considered to occur instantaneously. For a more realistic assessment, solving conservation of mass and conservation of momentum equations is required to account for non-instantaneous flow changes that are fast enough to generate a surge and the effect of hydraulic losses.

If x is the distance along the pipe centerline, t is time, rapidly varying pressure and flow conditions in pipe networks can be described by the continuity equation

$$\frac{\partial H}{\partial t} = -\frac{c^2}{gA}\left(\frac{\partial Q}{\partial x}\right) \qquad \text{Equation 1.4}$$

and the momentum (Newton's second law) equation

$$\frac{\partial H}{\partial x} = -\frac{1}{gA}\left(\frac{\partial Q}{\partial t}\right) + f(Q) \qquad \text{Equation 1.5}$$

Where H is the pressure head (pressure/specific weight), Q is the volumetric flow rate, c is the acoustic wave speed in the pipe, A is the cross-sectional area, g is the acceleration due to gravity, and $f(Q)$ represents a pipe-resistance term that is a non linear function of flow rate. A transient flow solution can be obtained by solving Equations 1.4 and 1.5 along with the appropriate initial and boundary conditions. However, except for very simple applications that neglect or greatly simplify the boundary conditions and the pipe resistance term, it is not possible to obtain a direct solution. When pipe junctions, pumps, surge tanks, air vessels, and other components that routinely need to be considered are included, the basic equations are further complicated, necessitating the use of numerical techniques.

Both Eulerian and Lagrangian computer schemes are commonly used to approximate the solution of the governing equations (Boulos et al. 2005, Wood et al., 2005b). Eulerian methods update the hydraulic state of the system in fixed grid points as time is advanced in uniform increments while Lagrangian methods update the hydraulic state of the system at fixed or variable time intervals at times when a change actually occurs. Each approach assumes that a steady state hydraulic equilibrium solution is available that gives initial flow and pressure distribution throughout the system. Boulos et al. (1990), Niessner (1980), and Ames (1979) provide reviews of the different numerical transient-flow solutions.

Assumptions and approximations. The computer-based numerical solutions that describe time-varying flows are derived from the application of conservation laws of mass, linear momentum and, sometimes energy. In most cases, the approach used assumes the flow is one-dimensional, meaning that any changes in the direction perpendicular to the axis of flow are negligible. As a result, flow velocity and pressure are assumed to be uniform over the flow cross-section, although they can vary with both time and axial position. In addition, obtaining a transient-flow solution from Equation 1.4 and equation 1.5 will involve the following assumptions and approximations:

- The flows are of low Mach number (*Ma*, see abbreviations list), i.e. $v<<<c$ so that $\mathrm{dx/dt} = v \pm c \cong \pm c$
- Although density changes occur, they are small, i.e. the flow is only slightly compressible
- Inertial effects in the pipe and duct walls are negligible.

Transient Pressure Mitigation

Industry and engineering standards require consideration of pressure transients for pipeline and pump design, distribution system network analysis, and valve selection and installation (Table 1-2). 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; Larock et al. 2000; Simon and Korom, 1997; Thorley 2004). 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 traditionally received similar attention. However, mitigation measures are well described and include surge tanks, slow valve closure times, avoiding check valve slam, minimized resonance, air vessels, pressure relief valves, surge anticipation valves, air release valves, combination two-way air valves, vacuum break valves, check valves, surge suppressors, and by-pass lines with check valves.

Table 1-2
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 Cross-Connection Control*
• AWWA 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 *Air-Release, Air/Vacuum, and Combination Air Valves*

Potential Impacts of Low or Negative Pressures in the Distribution System

Contaminant Intrusion

Leakage points in water mains, submerged air valves, cross-connections and faulty seals or joints can all serve as entry portals for external contaminants when the external pressure from water surrounding a distribution system main exceeds the water pressure inside the main. Low or negative pressure surges create a temporary situation for this to occur, allowing chemical and microbial contaminants to enter the distribution system.

*Intrusion of chemical contaminants***.** Chemical contaminants that could potentially enter the distribution system during an intrusion event include pesticides, petroleum products, fertilizers, solvents, detergents, pharmaceuticals, and other compounds. Predominant pesticides in urban areas include atrazine, simazine, prometon, and diazinon (Patterson and Focazio, 2001).

*Intrusion of microbial contaminants***.** The intrusion of microbial contaminants is of even greater concern because even with dilution, some microbes (e.g., viruses) could cause an infection with a single organism. Karim et al. (2003) found human enteric viruses in 56% of soil and water samples collected immediately adjacent to drinking water pipelines. In addition, total coliform and fecal coliform bacteria were detected in water and soil in about half of the samples, indicating the presence of fecal contamination. This is especially notable in that any water leaking from the pipes was chlorinated (however, residual chlorine was rarely detected in the aqueous environmental samples).

Pipe Failure

Although much of the focus on negative pressure transients is currently directed on the potential for backflow, the impact of fluctuating pressures on the physical integrity of the distribution system is also a concern. The physical integrity of the distribution system has been defined as its ability to handle external and internal stresses such that the physical material of the system does not fail (Male and Walski, 1991). Pipe failure due to material fatigue can arise if stress fluctuations of sufficient magnitude and frequency occur in the distribution system. Low pressure fluctuations, greater than those occurring under normal operating pressures, create stresses and strains that can slowly fatigue and weaken distribution system piping. Additionally, the collapse of thin walled pipes or even reinforced concrete sections is possible if vacuum conditions are created. Cavitation can also occur during low pressure transient events. If the local pressure in distribution system pipe is lowered to vapor pressure at the ambient temperature, then gas within the water is gradually released and the water starts to vaporize. When the pressure recovers, water enters the cavity caused by the gasses and collides with whatever confines the cavity (i.e. another mass of water or a fixed boundary), resulting in a pressure surge. In this case both vacuum and strong pressure surges are present, a combination that may result in substantial damage.

Evidence of Public Health Implications

Although low water pressure in distribution systems is a well-known risk factor for outbreaks (Hunter, 1997), there is insufficient data in the literature of indicate whether intrusion from pressure transients poses a substantial source of risk to water quality. However, the research to date provides several examples where an association between disease outbreaks and the occurrence of low and negative pressure transients can be made:

- Low water pressure and frequent power outages were found to contribute to widespread contamination of multi-drug resistant typhoid fever in the city of Dushange, Tajikistan, in 1997 (Mermin et al., 1999).

- Payment et al. conducted two epidemiology studies (Payment et al, 1991; Payment et al, 1997), each suggesting that the distribution system was at least partially responsible for increased levels of gastrointestinal 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 Payment's data shows that people who lived in zones far away from the treatment plant had the highest risk of gastroenteritis. Transient pressure modeling (Kirmeyer et al., 2001) found that the distribution system studied by Payment was extremely prone to negative pressures, with more than 90 percent of the nodes within the system drawing negative pressures under certain modeling 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.

- From 1981 to 1998, the CDC documented 57 waterborne outbreaks related to cross-connections, resulting in 9,734 detected and reported illnesses (Craun and Calderon, 2001). A cross-connection is any unprotected actual or potential connection or structural arrangement between a potable water system and any other system through which it is possible to introduce substances other than the potable water with which the system is supplied (FCCCR, 1993). Cross-connections have traditionally been thought of as physical connections to distribution system piping, but leaking joints and pipes also provide a route for entry of non-potable water. If a cross-connection exists, and the pressure in the distribution system is lower than pressure exerted by liquid outside of the system, then backflow, the undesirable reversal of flow into the distribution system, may occur. The pressure differential that allows backflow, may occur because the pressure in the distribution system drops and becomes lower than the pressure of liquid external to the system (backsiphonage), or may occur if the pressure of liquid external to the system increases (backpressure). As long as the pressure within the distribution system is lower than the pressure exerted by liquid external to the distribution system, then backflow is possible. A survey of over 700 North American distribution systems (Lee et al., 2003), found that 65% had cross-connections that were susceptible to backflow via backsiphonage, while 35% of the systems had cross-connections that were susceptible to backflow that could be induced via backsiphonage and backpressure. This means that all of the systems surveyed were susceptible to the introduction of non-potable water through backsiphonage, which could occur with a low or negative pressure transient.

- 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). Contamination was attributed to a power outage, which created a negative pressure transient in the distribution system. This 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.

- A case-control study conducted in England, February 2001 to May 2002, suggested a strong association between self-reported diarrhea and reported low water pressure events (Hunter et al., 2005).

PROBLEM STATEMENT

As discussed previously, pressure transients can cause pipe fatigue and eventual pipe failure or can result in the intrusion of external contamination when the pressure of water surrounding the water main exceeds the internal pressure. However, the characteristics of distribution systems that contribute to producing low or negative pressure transients have not been well examined. Potential distribution system characteristics that may contribute to the occurrence of pressure transients include the following:

- operating pressure
- pump operation
- variations in distribution system configuration
- variations in topography/elevation
- presence/absence of distribution storage facilities
- presence of air/vacuum relief valves, hydropneumatic tanks (air vessels), and other related features.

To date, most observed negative pressure events where the cause was known were related to power outages or other pump shutdowns or valve operation (Walski et al., 1994; Friedman et al., 2004; Gullick et al., 2005). Nonetheless, more research is needed to better characterize the types of systems most prone to negative pressure transient events (e.g., those systems without distribution storage, without air or vacuum relief valves, etc.). Furthermore, research is needed to identify means to lessen the magnitude of surges to reduce the risk of contamination of the 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.

RESEARCH OBJECTIVES

The research project included four primary objectives:

1. Distribution System Selection: Select five distribution systems that allow a range of distribution system characteristics to be examined.

2. Surge Model Development and Analysis. Develop computer models that allow actions resulting in sudden changes flow (that result in hydraulic transients) to be examined for each system.

3. Distribution System Pressure Monitoring: Use surge modeling predictions to locate pressure monitors in the most vulnerable distribution system areas.

4. Recommendations for Surge Monitoring and Mitigation: Develop recommendations when using surge models to optimally locate pressure monitors, and develop recommendations for minimizing the occurrence of low or negative pressure transients.

CHAPTER 2
SELECTION OF DISTRIBUTION SYSTEMS

INTRODUCTION

Five distribution systems that represent a range of utility operations were selected for surge modeling. The factors that were considered in selecting the distribution systems included the following:

- system size (flow rate and/or population served)
- operating pressure
- pumping capacity and operation
- variations in distribution system configuration
- variations in topography/elevation
- presence/absence of distribution storage facilities
- presence of air/vacuum relief valves, hydropneumatic tanks (air vessels), and other related features.

System size

In general, the larger the distribution system, the greater is its complexity. This increased complexity may increase the likelihood for transient producing events. Larger pumps and mains, more complex distribution system topology and topography and the presence of fast closing valves are all factors that can increase the potential for transients.

Operating pressure

Lower operating pressures may increase distribution susceptibility to low or negative pressure transients. The lower the initial steady state pressure is, the lower the minimum pressure will be when a low pressure surge is generated. Surge magnitude, once established at initiation, is not diminished simply because the surge travels into an area with low static pressures. Subtracting a given surge magnitude from a relatively low initial pressure will, of course, result in an even lower minimum pressure at the subject location.

Pumping capacity and operation

With increased pumping capacity, the potential for larger initial low pressure transients in the distribution system exists only if larger initial velocities exist. Based on the Joukowsky equation which estimates the maximum change in head (ΔH) created when water with velocity V is brought to a sudden stop (Equation 1.1), for every 1 ft/sec (0.3 m/s) of velocity forced to a sudden stop, downstream head decreases 115 to 138 ft (35 to 42 meters) or 50 to 60 psi (345 - 414 kPa) depending on the pipe materials, topography, etc. This means pump stations with multiple pumps may increase distribution system vulnerability to low/negative pressure transients, as increasingly higher flows (corresponding to increasingly higher velocities) enter the distribution system. Kerr and Brush (1949) proposed the following questions for assessing the seriousness of surges in transmission mains:

- Are there any high spots on the profile of the transmission main where the occurrence of a vacuum can cause a parting of the water column when a pump is cut off?
- Is the length of the transmission main less than 20 times the head on the pumps (both values expressed in feet)?
- Is the maximum velocity of flow in the transmission main in excess of 4.0 ft/sec?
- What is the natural rate of slowing down of the water column if the pump is cut off? Will the column come to rest and reverse direction of flow in less than the critical surge wave time of the transmission main?
- Are there any quick-closing automatic valves set to open or close in less than 5.0 seconds?
- Will the pump be tripped off before the discharge valve is full closed?
- Are there booster stations on the system which are dependent on the operation of the main pumping station under consideration?
- Are there any quick closing automatic valves used in the pumping system that are inoperative with the failure of pumping system pressure.

They suggested that an increasing number of "YES" answers increases the risk of having serious surges occur in the system.

Variations in topology

Distribution system configurations may be generally classified as branching, gridiron, or a combination of the two. A branching system evolves if distribution mains are extended along streets as the service area expands and can be constructed faster and with less material than the gridiron system. However, the "dead ends" prevalent in branching systems reduce their reliability as water is prevented from being circulated throughout the system. The gridiron system, where each pipe section is fitted to at least one other pipe section, has the hydraulic advantage of delivering water to any location from more than one direction, thereby avoiding dead ends.

Street patterns, topography, development, and treatment and storage facilities dictate a distribution system's design. Although it is advantageous to have all water users located within a grid system, it is often impractical to do so. Water is generally delivered to a remote water user, or a small group of users, by a single distribution main. Therefore, while the majority of the water users are served within a gridiron system, the outlying water users are typically served by mains branching away from the gridiron system.

Once a transient is generated, a well gridded system is more likely to reduce the severity of a transient. When a pressure wave of magnitude ΔH comes to a junction, it is transmitted with a head of $T_i\,\Delta H$, to all other connected pipes and reflects back to the initial pipe with a head value of $R_i\,\Delta H$ (Wood et al., 2005). T_i, the transmission coefficient, is defined as:

$$T_i = \frac{2/F_i}{\sum_j (1/F_j)}$$

where the summation j refers to all pipes connecting at the junction and $F = c/gA$ where c is the propagation speed of the pressure wave, g is the acceleration due to gravity and A is the pipe cross-sectional area. R_i, the reflection coefficient, is T_i -1.

The transmission coefficient, T_i, can range from 0 to 2 with the corresponding reflection coefficients ranging from -1 to 1. A dead end can be considered a two-pipe junction with $A_{dead\ end} = 0$. This gives a $T_i = 2$ and $R_i = 1$, which means that the wave is reflected positively from the dead end. On the other hand, for a reservoir connection, $A_{reservoir} = \infty$ giving $T_i = 0$ and $R_i = -1$, which means that a negative reflection occurs at a reservoir. A negative reflection is the most desirable occurrence since it reduces the magnitude of the initial wave. With the positive reflection that occurs at a dead end, a pressure wave is reflected with the same head as the incident wave.

Variations in topography

Tank overflow elevation typically determines the limits of the pressure zone that can be served. Once a “floating” storage facility has been constructed, the limits of the hydraulic grade line within a pressure zone are fixed. The only way to change these limits would be to replace, raise, or lower the existing tank (Walski et al., 2001). The pressure at any point is determined by the difference in tank level and the point of interest in the distribution system (except when tank is filling and the HGL slopes toward the tank). This means locations in the distribution system at higher elevations will have lower water pressure than customers at the lower elevations in the same pressure zone. With lower operating pressures, it means a transient producing event that occurs in close proximity to an area with significant elevation changes has a better opportunity at creating low/negative pressures in the more elevated portion of that distribution system.

Presence of Distribution Storage Facilities

Distribution storage tanks serve three basic purposes: providing a level of emergency water supply during production interruptions, accommodating fire-fighting incidents, and equalizing operating pressures. In areas with flat topography, the tanks may be elevated above ground, on towers, to provide adequate water pressure, or ground-level storage tanks with booster pumping may be used. When flow is brought to a sudden stop, water on the upstream side of the flow control event decreases in velocity causing a pressure increase. On the downstream side of the flow control, however, water starts to pull away from the location of the stopped water creating low/ negative pressures. Sensing the drop in pressure, water from the elevated storage tank takes over as the energy source to maintain the forward motion of the flow, and as the driving pressure falls, the flow is also allowed to decelerate in a controlled manner.

Presence of combination air release /vacuum relief valves

Air release/ vacuum valves are surge protection devices normally installed at high points in a pipeline and are intended to prevent low/negative pressure by drawing air into the pipe when the pressure drops below 0 psi (atmospheric pressure). Air is expelled from the valve when the line pressure exceeds 0 psi. However, rapid expulsion of air could lead to air slams, which can create excessive secondary pressure surges (Lingireddy et al., 2004). Another potential drawback of air/vacuum valves is that they present a potential route of access for contaminants to enter the distribution system either inadvertently or via intentional vandalism or terrorism. The AWWA Steel Pipe Manual recommends air valves at the following points along a pipeline (AWWA, 2004):

- High Points: Combination Air Valve
- Long Horizontal Runs: Air Release or Combination Valve at 1250 to 2500 ft. (380 to 760M) intervals
- Long Descents: Combination Air Valve at 1250 to 2500 ft. (380 to 760M) intervals
- Long Ascents: Air/Vacuum Valve at 1250 to 2500 ft. (380 to 760M) intervals
- Decrease in an Up Slope: Air/Vacuum Valve
- Increase in a Down Slope: Combination Air Valve

Presence of surge protection (hydropneumatic tanks, pump bypass line)

Hydropneumatic tanks (air vessels) are pressurized vessels containing both water and air. Their effect depends primarily on location, vessel size, entrance resistance, and initial gas volume and pressure, and must be designed properly to be effective (Wood et al., 2005). Hydropneumatic tanks serve the same function as elevated storage but respond faster and can operate over a wider range of pressure fluctuation. The tanks are normally positioned at pump stations to provide protection against a loss of power to the pump.

Pump bypass lines have a check valve that prevents back flow from the pump discharge to the suction side. They are activated when the pump suction head exceeds the discharge head and are most effective in a system where a significant pump suction head is available (such as a booster pump station). Thorley (2004) recommends installing a pump bypass line as a cheaper alternative to the hydropneumatic tank (air vessel) where the pump is discharging against a low static head or at a booster station.

Presence of pressure reducing valves

Pressure-reducing valves (PRVs) are placed in pipelines to keep the pressure downstream, at the outlet, at a constant value regardless of the difference in pressure at the valve inlet. Figure 2-1 shows a pressure reducing valve equipped with an adjustable, 2-way, pressure-reducing pilot. The needle valve [1] continuously allows flow from the valve inlet into the upper control-chamber [2]. The pilot [3] senses downstream pressure. If the downstream pressure rises above the pilot setting, the pilot throttles, enabling pressure in the upper control-chamber to accumulate, causing the main valve to throttle closed, decreasing downstream pressure to pilot setting. If the downstream pressure falls below pilot setting, the pilot releases accumulated pressure, and the main valve modulates open. The integral orifice between the lower control-chamber and valve outlet moderates valve reactions. The needle valve controls the closing speed. The downstream cock valve [4] enables manual closing.

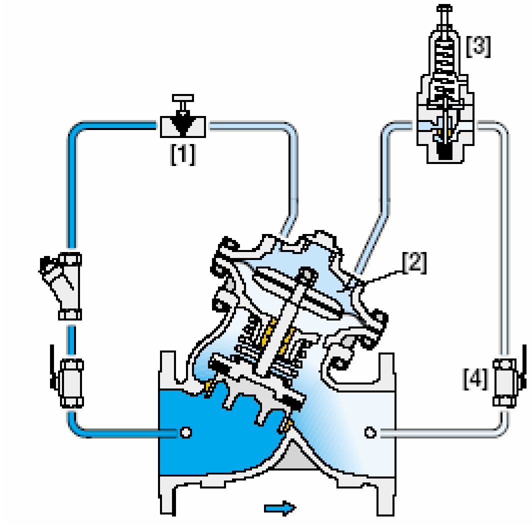


Figure 2-1. Pressure reducing valve (Bermad Waterworks model 720)

SYSTEMS SELECTED FOR MODELING

Five (5) distribution systems that represent a variety of configurations and characteristics were selected for surge modeling (Table 2-1).

Table 2-1
Characteristics of Distribution Systems Selected for Surge Modeling

#	Avg. MGD	Source Type[a]	Elevation Variation	# of Pressure Zones	Service Pressure (max/min psi)		# of floating storage tanks	Primary reasons for selecting system?
1	3.0	GW	Flat	1	130	35	3	flat, 10 inputs into 1 pressure zone
2	12.0	GW	Flat	1	90	40	7	flat, 18 inputs into 1 pressure zone
3	41.0	Both	Moderate	6	110	40	19	multiple inputs; several long, 54-in branching mains
4	39.0	Both	Moderate	13	220	25	17	multiple inputs, complex system
5[b]	29.9	SW	Flat	1	140	25	18	large, no floating storage

[a] SW = surface water; GW = ground water; "Both" indicates system is fed by both groundwater and surface water.
[b] System 5 is located in New York.

System 1

System 1, a medium-sized system located in a relatively flat part of New Jersey, serves approximately 30,900 people with 14,320 service connections. 73% of the connections are residential, 26% are commercial, and 1% are other connections (there are no industrial customers). The distribution system operates as one pressure gradient with customers at elevations ranging from approximately 5 to 35 feet mean sea level (msl) and ground surface elevations generally ranging from 5 to 10 feet msl. Annual average day demand is 3.06 mgd, and the historic record for maximum day usage is 9.65 mgd (1999 data).

The system model skeleton shown in Figure 2-2 includes the 9 pumps that were active during a high demand day (10.1mgd peak hour flow supplied) in 2003, 2 elevated storage tanks and 1 ground storage facility. It also includes 397 junctions and 624 pipes, with a total of 60 miles of pipe. Pipe diameters in the model range from 4- to 24-inches inches with pipe materials including cast iron, concrete, ductile iron, asbestos cement, welded steel, galvanized iron and PVC.

System 2

System 2, a medium-sized system located in a relatively flat part of New Jersey, serves approximately 83,000 persons with 31,100 service connections. 89% of the connections are residential, 9% are commercial, and less than 2% are industrial, fire and other customers. The distribution system operates as one pressure gradient with customers at elevations ranging from approximately 5 to 75 feet mean sea level (msl).

The system model skeleton shown in Figure 2-3 includes the 18 pump stations that were active during a high demand day (23.6 mgd peak hour flow supplied) in 1999 and 7 elevated storage tanks. It also includes 1,733 junctions and 2,570 pipes, with a total of 410 miles of pipe. Pipe diameters in the model range from 2- to 16-inches. All pipes are ductile iron. There are no valves or hydro-pneumatic tanks in the system.

System 3

System 3, a medium-sized system located in a moderately hilly part of New Jersey, provides an average of 41 mgd to approximately 91,200 customers. Approximately 90% of the customer base is residential, 8.4% is commercial, and 1.6% are industrial, fire and other customers. The distribution system is divided into six pressure gradients with ground surface elevations ranging from approximately 0 to 210 feet msl.

The system skeleton model shown in Figure 2-4 includes the 24 pump stations that were active during a high demand day (68.5 mgd peak hour flow supplied) in 2001, 14 elevated storage tanks, 4 standpipes, 6 flow control valves and 5 pressure regulating valves. It also includes 2,684 junctions and 3,939 pipes, with a total of 780 miles of pipe. Pipe diameters in the model range from 4- to 54-inches. All pipes are ductile iron.

System 4

System 4, a medium-sized system located in a moderately hilly part of New Jersey, provides an average of 39.0 mgd to approximately 75,700 customers. Of the total customer base, approximately 85% are residential accounts, 13% are commercial accounts, and the remainder is classified as industrial, fire or “other” accounts. The distribution system is divided into thirteen pressure gradients with ground surface elevations ranging from approximately 80 to 1,025 feet msl.

The system skeleton model shown in Figure 2-5 includes the 18 pump stations that were active during a high demand day (71.5 mgd peak hour flow supplied) in 2000, 14 elevated storage tanks, 4 standpipes, 5 flow control valves, 4 pressure regulating valves and 10 throttle control valves. It also includes 2,684 junctions and 3,939 pipes, with a total of 509 miles of pipe. Pipe diameters in the model range from 2- to 36-inches. All pipes are ductile iron.

System 5

System 5, a medium-size system (average 29.9 mgd) located in a relatively flat part of New York, has elevations ranging primarily from 3 to 60 feet MSL. The system model skeleton is shown in Figure 2-6 and key features are labeled. The model includes 2,088 nodes and 3,397 pipes, with a total of 409 miles of pipe. Pipe diameters in the model range primarily from 4 to 72 inches.

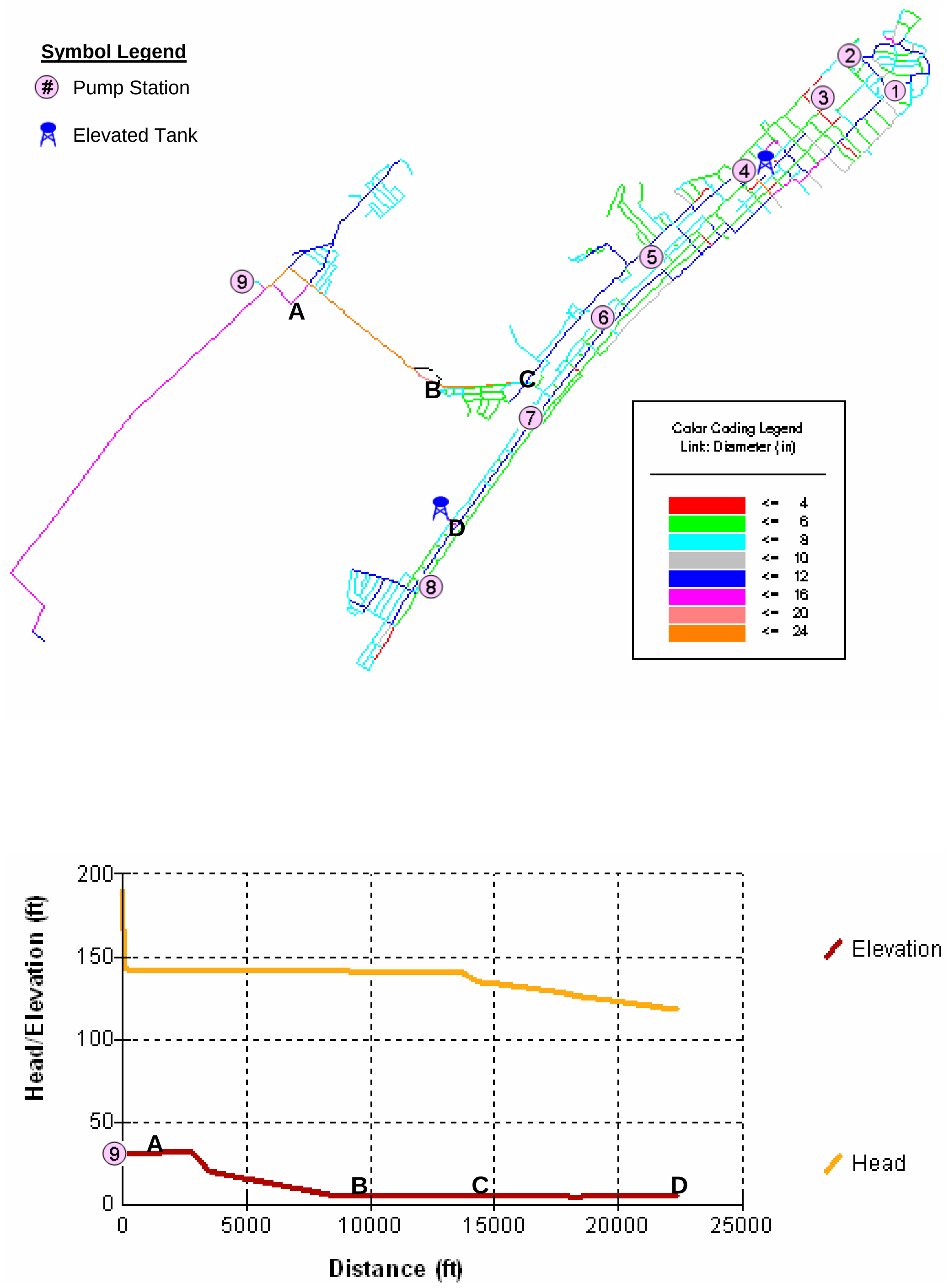


Figure 2-2 Hydraulic model for System 1 *(a)*. The hydraulic profile starting from pump station #9 to the elevated tank at location D is shown *(b)*.

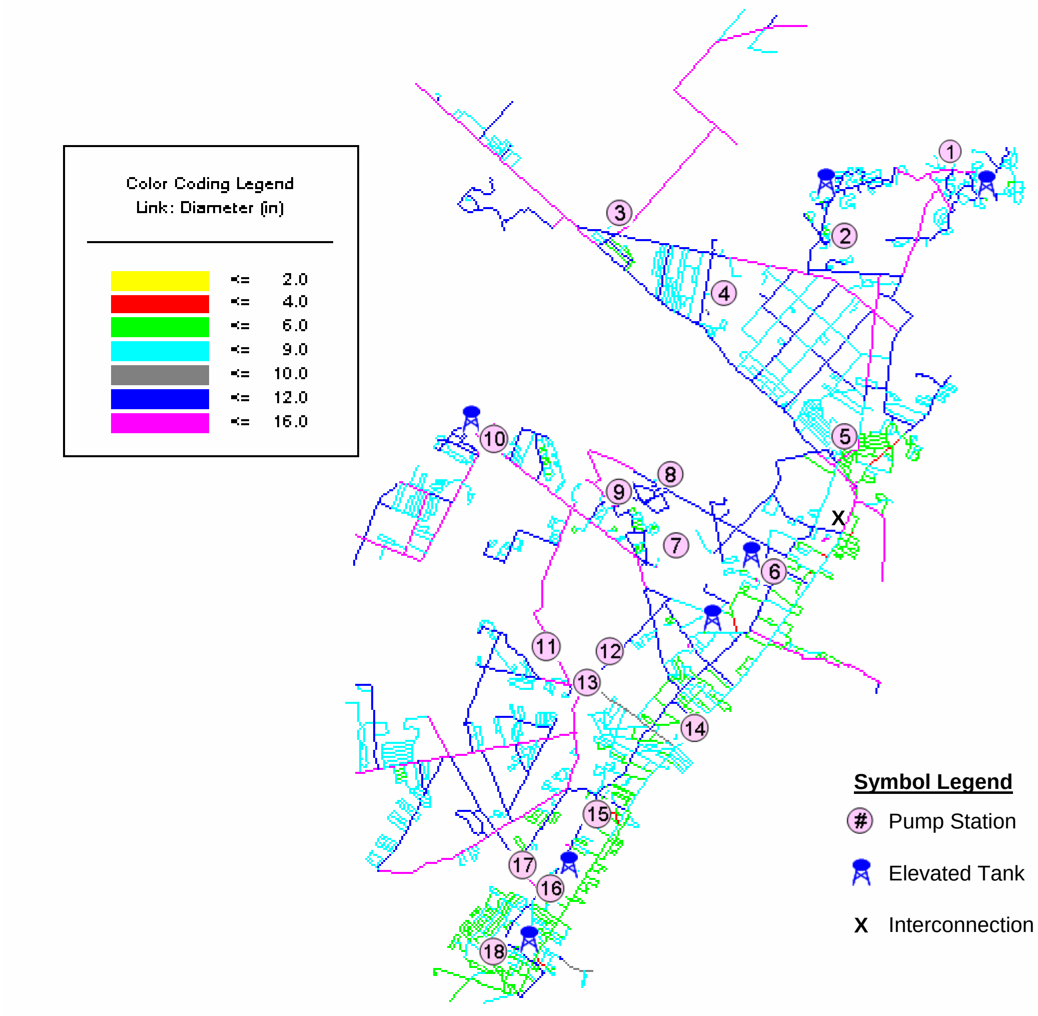


Figure 2-3 Hydraulic Model for System 2

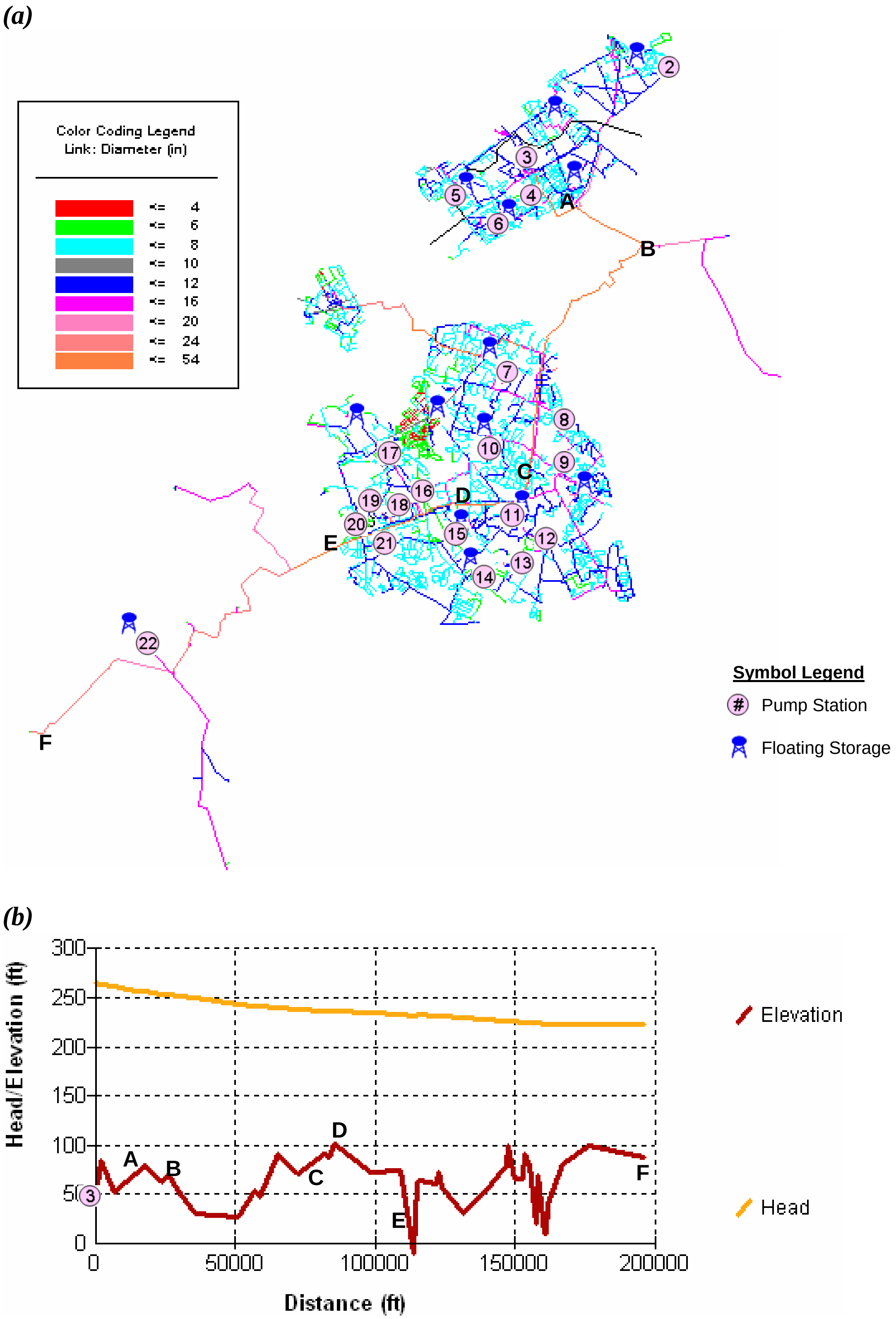


Figure 2-4 Hydraulic model for System 3 *(a)*. The hydraulic profile starting from pump station #3 to location F is shown *(b)*.

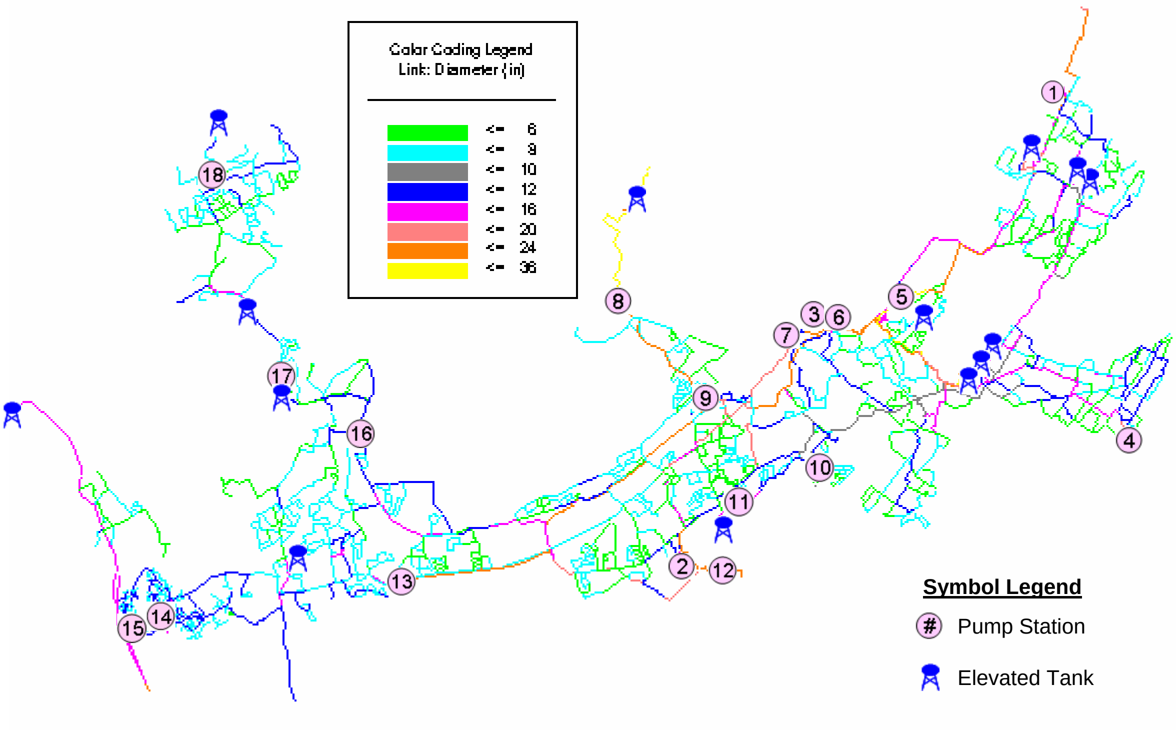


Figure 2-5 Hydraulic model for System 4

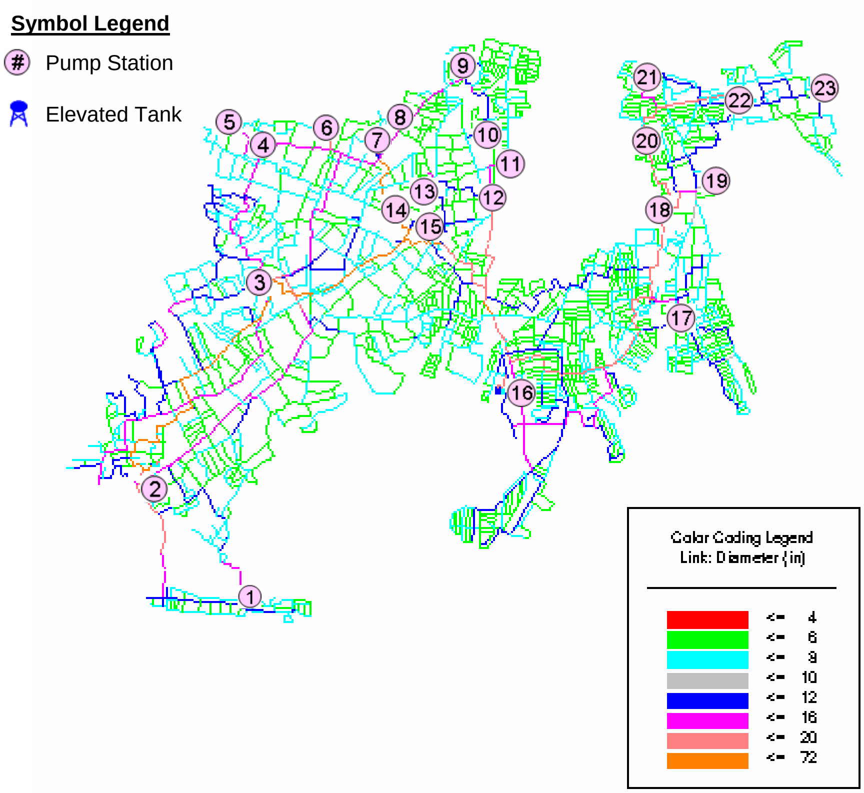


Figure 2-6 Hydraulic model for System 5.

CHAPTER 3
PROJECT DESIGN & METHODS

This Chapter describes the methodology used to develop surge models and the methodology used in analyzing transient events for the distribution systems examined in this research. The methodology used for pressure monitoring is also described.

INTRODUCTION

As outlined in Chapter 1, because of the complex nature of distribution systems, the use of transient analysis software is essential for a full assessment of how abrupt changes in flow will impact pressure changes throughout the distribution system. Before the transient analysis is possible, however, a calibrated steady-state or extended period simulation (EPS) model is necessary to provide initial and boundary conditions for the transient simulation.

A steady-state model simulation predicts behavior in a water distribution system during a hypothetical condition where the effects of all changes in the operation have stopped. With this approach, the conservation of mass (solved at each node) and conservation of energy (around each loop) equilibrium expressions are solved using an iterative scheme (e.g. Newton-Rhapson) based on known static demand loading and operating conditions (AWWA, 2005, Boulos et. a.l 2005). While the steady-state assumption simplifies the analysis of a water distribution system and is a useful tool to size pipelines and supply facilities, an EPS analysis provides significantly more information about system operating characteristics and how the water system responds to changing demand (AWWA, 2005).

Extended-period simulations capture pressure and flow changes as customer demands vary over time, as pumps cycle on and off, and as tank levels change using a series of steady state simulations linked by an integration scheme for the differential equation describing storage tank dynamics. The simulation begins with an initial set of tank levels, a given demand distribution and duration, and a set of operation decisions. At the first time step, a steady state simulation is completed to determine the pressure and flow distribution including flow rates into and out of tanks. Using the tank flow rates and demand duration, a mass balance calculation is completed to update the tank levels. The new tank levels are then used as the fixed grade node elevations for the next steady state hydraulic analysis and time step. The new demands may be changed between time steps. Many hydraulic analysis models allow operation conditions to be altered based upon the hydraulic condition, such as a pump being turned on or off as a function of a tank's water level. The resulting tank flows are again used to update the tank water levels and the process is repeated until the entire simulation duration is completed. Additional discussion addressing EPS model development can be found in several texts that address computer modeling of water distribution systems (AWWA 2005, Boulos et al. 2005, Walski et al. 2001).

Table 3-1
Comparison of assumptions for Steady-state, EPS and transient flow models

Steady State or EPS Model	Transient Model
Steady or gradually varying turbulent flow	Rapidly varying or transient flow
Incompressible, Newtonian, single-phase fluids	Slightly compressible, two phase fluids (vapor and liquid) and two-fluid systems (air and liquid)
Full pipes	Closed-conduit pressurized systems with air intake and release at discrete points

SURGE MODELING PROCEDURE

Surge models were developed and transient events were analyzed for each system using a standard set of procedures as outlined below:

- Develop a calibrated, 24-hour EPS model.
- Determine when maximum flow, to and from storage, occurs.
- Use the initial and boundary conditions (tank levels, pump status – on/off, etc) determined for this time to investigate low/negative pressures that develop from the standard scenarios outlined in Table 3-2.

EPS Model Calibration and Verification

As recommended by the USEPA for the System Specific Studies part of the Initial Distribution System Evaluation component of the Stage 2 D/DBP Rule (USEPA, 2001), the EPS models were calibrated hydraulic models intended for detailed distribution system design, and included:

- Approximately 50 percent of total pipe length in the distribution system
- Approximately 75 percent of the pipe volume in the distribution system
- All 12-inch diameter and larger pipes
- All 8-inch and larger pipes that connect pressure zones, influence zones from different sources, storage facilities, major demand areas, pumps, and control valves, or are known or expected to be significant conveyors of water
- All 6-inch and larger pipes that connect remote areas of a distribution system to the main portion of the system
- All storage facilities with realistic controls applied to govern the open/closed status of the facility
- All active pump stations with realistic controls applied to govern their on/off status
- All active control valves or other system features that significantly affect the flow of water through the distribution system

Water demand data was assigned to at least half of the nodes to assure that model represented actual customer demands. The demand data will include domestic water use, large commercial and industrial users, unaccounted for system water losses, and diurnal and seasonal trends. The models were calibrated using field data on pressures, flows, and tank water levels (assumed accuracy of 10%) in the systems under known conditions, and adjusted (e.g., pipe roughness factors, tank/pump operational settings, etc.) to agree with field data.

A calibrated computer model was defined as a model of the existing distribution system that was calibrated to within ± 5 psi pressure and ± 5% flow at all recorded points for the calibration conditions. Simulated storage tank levels were required to be within +/-2 feet of actual at the end of 24 hours.

Transient Analyses

Steady-state and calibrated EPS models were used to provide initial and boundary conditions (tank levels, pump on/off status, etc) for the surge models developed for each system. A common set of surge scenarios were modeled for each system: 1) complete loss of pumping (e.g., a power outage), 2) a major main break in a key trunk line, and 3) opening a hydrant to fire flow, and 4) rapid pressure reducing valve fluctuations. Table 3.1 summarizes the approach to simulate these transient producing events. The wave speed used in all models was estimated to be 3,600 ft/s unless otherwise specified. The model was used to predict the propagation of pressure transients through each system. Each simulation was run for at least 120 seconds.

Every pipe system has a characteristic time period, $T = 2L/c$, where L is the longest possible path through the system and c is the pressure wave speed. This period is the time it takes for a pressure wave to travel the pipe system's greatest length two times. The rule of thumb recommendation for surge analysis is that the run duration equals or exceeds T. If the path length in one of the larger systems used in this study, System 3 (Figure 2-4), is overestimated at 200,000 feet, then a wave speed of 3,600 ft/s would necessitate a minimum runtime of 110 seconds. On this basis, the 120 second run time used for all systems should be adequate.

Table 3-2
Modeling approach used to simulate surge producing events or surge mitigation

Surge events/ Surge mitigation	Description
demand change	Rapid change in demand simulated at node in system with greatest demand. In a two-minute simulation, demand drops to zero in two seconds (after two seconds of holding initial conditions); then after 30 seconds, the demand is increased to double the original demand in 2 seconds. The doubled demands are held until 60 seconds have elapsed, then the demand returns to initial level in 2 seconds and remains at the initial level for the remaining time.
hydrant opening	At least one hydrant, located near the pump station predicted to cause the most negative pressures, was simulated for each system. The hydrant was ramped up to the available fire flow in 5s.
hydropneumatic tank	Closed hydropneumatic tank – compressor provides air; air to water ratio was 1:5
main break	Modeled as a rupture disk with an outflow resistance that corresponds to the size of the break.
pump shut down	Shut down simulations only performed for pumps that are on at time when maximum flow is being supplied to the system. Each pump was shut down in 1 second. The check valve on each pump was modeled to close within 0.1s of sensing reverse flow. Check valve resistance = 1 s^2/ft^5; resistance = headloss /($flow^2$)
air vacuum valve	Includes two orifices of different diameters: • the intake orifice is sized as outlined in Appendix C • the outtake orifice ranges from ~ ½ intake size to full intake size
valve opening/ closing	Valve goes from fully open to fully closed after two seconds, then reopens fully after 60 seconds. Linear acceleration used in both cases.

PRESSURE MONITORING PROCEDURE

Problems with low or negative pressure transients have been reported in the literature for several years (Walski and Lutes, 1994; Qaqish et al., 1995). Recent research efforts have focused on documenting the frequency and magnitude of pressure transient events using high-speed, electronic, pressure data loggers (Friedman et al., 2004; Gullick et al., 2005). These high speed loggers are required for distribution system monitoring since pressure transients may last only for seconds and may not be observed by conventional pressure monitoring. High-speed pressure data loggers can measure pressure transients at a sampling rate up to 20 samples per second allowing measurement of sudden changes in pressure.

The traditional approach to placement of pressure monitors has been to locate the monitors in areas suspected of being susceptible to low pressures and/or large pressure transients based on operator experience and familiarity with the system and based on proximity to logical areas of the distribution system that may be vulnerable to transients such as – high elevations or in the vicinity of flushing operations or pump stations. With this approach, however, it is possible miss critical monitoring locations (Friedman et al., 2004). The primary purpose of field monitoring was to determine if low/negative pressure transients would be detected in areas identified as being vulnerable.

Pressure monitoring was conducted in System 1 and System 2. Several high-speed, pressure data loggers (RDL1071L/3 Pressure Transient Logger, RADCOM Technologies, Inc., MA) were used to monitor the pressures in both distribution systems. Each RADCOM data logger had the capacity to record up to 20 samples per second with a data storage capacity of 2 million readings. However, the sample rate used for each monitor in each system was 1 sample per second so that data could be collected continuously for up to three weeks. Telog monitors (HPR-31 Hydrant Pressure Recorder, Telog Instruments, Inc, NY) were also used for pressure comparisons.

Monitoring locations in each system were selected based on hydraulic and surge modeling results. The monitors were placed in each system based on modeling predictions of the areas that would be most susceptible to low or negative pressure transients when the most likely transient producing event – a pump shut down - occurred. Figure 3-1 and Figure 3-2 show monitor placement at fire hydrants throughout the two systems.

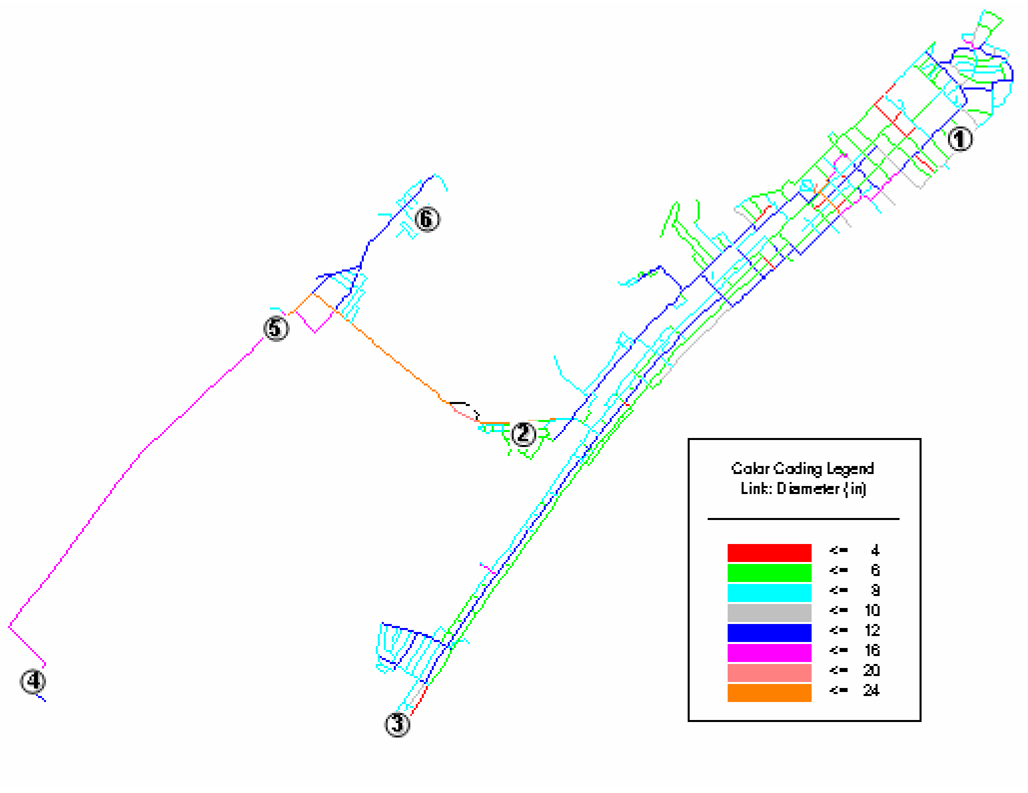


Figure 3-1 Pressure monitoring locations in System 1. Five RADCOM and four Telog pressure monitors were available for the field study. RADCOM and Telog monitors were placed at hydrants near Locations 1, 2 and 4. An additional Telog monitor was placed at Location 6 and only RADCOM monitors were placed at Locations 3 and 5.

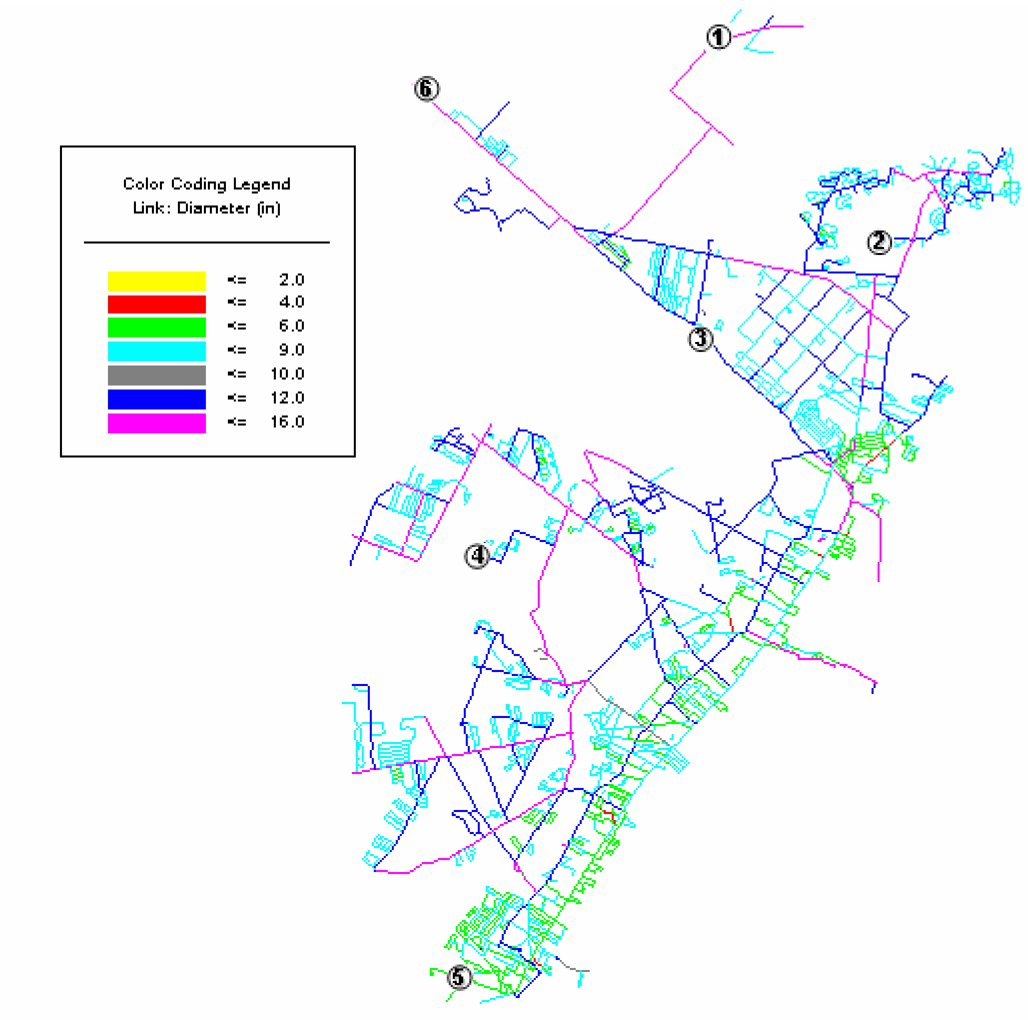


Figure 3-2 Pressure monitoring locations in System #2. Five RADCOM and four Telog pressure monitors were available for the field study. RADCOM and Telog monitors were placed at hydrants near Locations 1, 3 and 5. An additional Telog monitor was placed at Location 6 and only RADCOM monitors were placed at Locations 2 and 4.

CHAPTER 4
QUALITY ASSURANCE

The quality assurance objectives of this research were to ensure surge models were developed from calibrated extended period simulation (EPS) models and to ensure surge simulations were performed in a consistent manner so that the results could be used to identify those system factors that lead to greatest susceptibility for low and negative pressures from surge events.

For the most part, calibration of the EPS models should provide for a fairly well calibrated surge model. However, since parameters such as wave speed are estimated, adjusting this parameter may be necessary to provide a good match between field and surge model results. Pressure monitoring was performed in two (2) systems for approximately two weeks in at least one susceptible location. Selection of the pressure monitoring locations was based on surge modeling results. Field data was then compared to model results, and wave speeds and pump shutdown times were adjusted until a good match was found between the field and model data.

Surge Modeling Software

H2OSURGE (MWHSoft, Pasadena, CA) was used for surge modeling. Previous research has demonstrated the comparable accuracy of the commercially available computer modeling package (Boulos et al. 1990, Wood et al. 2005). The model output showed the results of simulations of transient pressure events, and included analysis of the location and magnitude of low and negative pressure events under a variety of system conditions.

Surge Analysis Procedures

To perform the transient surge analyses, additional input to the EPS models was required, including: pump data such as rated head, speed and inertia, as well as the operating conditions of check valves, tanks (reservoir, feed and surge tanks), pressure relief valves, and surge anticipation valves. To assure that the surge model was initially balanced and holding the initial steady state conditions, a ten second transient analysis was performed with no transient producing conditions specified. Once this was ensured, several transient events were simulated in each system as outlined in Table 3-2.

Pressure Monitoring Procedures

The electronic pressure monitor used was a high-speed single-channel pressure transient datalogger (Model RDL 1071L/3 Pressure Transient Logger; RADCOM Technologies, Inc., Woburn, MA). These monitors are capable of recording up to 20 pressure readings per second. The RADCOM monitor components (Figure 4-1) include the datalogger, a 0 – 20 Bar (approximately -15 to +275 psig) pressure transducer, a brass quick-coupling/threaded connector for fastening the transducer cable to a fitting on a distribution system pipe, and a detachable handheld keypad with connecting cables for programming the monitor and downloading data to a personal computer. The pressure monitors were connected to the distribution system pipes of interest via a connection to a 2 ½” hydrant opening.

Figure 4-1 RADCOM electronic pressure monitor assembly

The project team has extensive experience with these pressure data loggers, as they are the same type as were employed by the investigators in three other research projects (AwwaRF projects on *Pathogen Intrusion into the Distribution System*, *Field-Testing of Surge Modeling Predictions to Verify Occurrence of Distribution System Intrusion*, and *Infectious Disease Associated with Drinking Water from Surface Water Sources*).

The monitors are factory-calibrated and are reported to not require calibration in the field. Where possible, the RADCOM electronic pressure monitors were installed next to Telog monitors (HPR-31 Hydrant Pressure Recorder, Telog Instruments, Inc, NY) in order to verify the accuracy of the RADCOM monitor. Similar, previous testing of the RADCOM monitors has shown them to be reliable and relatively accurate. Additional laboratory testing of the accuracy of one of these RADCOM pressure monitors showed excellent accuracy (Friedman et al, 2004).

Two specific settings for the RADCOM monitors are of particular note: (1) the rate at which readings are taken (up to 20 readings per second), and (2) the tolerance setting. The RADCOM monitors use data compression to minimize the amount of memory used; if a reading is within the set tolerance range from the most recent reading stored, then the logger does not store the new reading (and thus no memory is used) and will instead assign the prior reading to that data point upon decompression of the data after downloading. A new reading is stored in memory only if its pressure differs from the most recently stored value by at least the amount of the data tolerance setting (e.g., +/- 3.0 psi). In other words, for a series of consecutive and identical readings, the first reading is assumed to be precise, and the subsequent readings are assumed to be equal to the value of the first reading plus or minus the value of the tolerance setting.

The pressure monitoring rates and tolerance settings used for each individual case were selected to provide the most specific data possible (i.e., the most readings at the lowest tolerance setting practical) given the characteristics of the monitoring situation and the datalogger memory capacity. In all cases, one reading per second was obtained at a tolerance of +/- 2.0 psi to +/- 4.0 psi which enabled up to about three week's worth of data to be collected before the monitor memory became full. The dataloggers also record the clock time for each pressure reading. The clock time used by the logger was periodically calibrated. The times were used to relate pressure data to distribution system events.

Sample Custody Procedures

There were no environmental (water, air, soil, sediment, etc.) samples collected during this project, and thus no sample custody procedures were applicable.

Analytical Procedures

No analytical tests were performed as part of this project.

Data Quality Requirements

Data collection by the RADCOM electronic pressure monitors is controlled by settings established when the monitor is connected to a distribution system pipe. The monitor can record pressures between 0 and 20 Bar (approximately -15 to +275 psig). The lowest data tolerance setting possible is +/- 0.71 psi. Additional precision can be obtained by programming the monitor to collect as many readings as possible over time (a maximum of 20 per second). While these are the optimum conditions in terms of obtaining the most accurate pressure data (20 readings per second at +/- 0.71 psi), the settings were balanced with considerations for how often data will be downloaded at each monitoring site. Since several weeks of pressure monitoring were performed, a setting of one reading per second at a tolerance of +/- 2.0 psi to +/- 4.0 psi was used.

Calibration Procedures and Preventive Maintenance

The electronic pressure monitors were installed and set up according to the manufacturer's instructions. The monitors are factory-calibrated and are reported to not require calibration in the field. No particular preventative maintenance for the monitors is necessary.

Quality Control Checks

No analytical testing was performed as part of this project, and thus no quality control samples were used.

Documentation, Data Reduction, and Reporting

Pressure data was downloaded from the RADCOM monitors to a portable personal computer using the data download lead and portable keypad, along with the appropriate RADCOM software (RADLOG for Windows). Each file was labeled according to the utility's name, a system-specific hydrant number, and the date of the data download.

Documentation:

The participating utilities reported information related to the nature of normal field operations performed during the monitoring periods, and any unusual occurrences. This latter information included the status of pump operations, power outages that may have shut off pumps, flushing operations (including flow rate and duration), other system demand data and sudden high demands, breaks in pipes, and other information as appropriate. This information was used to ensure the model conditions were set appropriately for comparison of model output to the field pressure data.

Data Reduction and Reporting:

The pressure data was plotted using the RADCOM data software and Excel, and both steady-state pressures and the larger surge events were compared to model simulations. The wave propagation speed was the primary parameter that was adjusted in order to fit the surge model results to the field data.

Data Validation

All pressure monitoring data was reviewed by the Principal Investigator prior to use. Any apparent data anomalies were investigated. Note that short-term (transient) excursions from the normal system pressures were what we are looking for (hydraulic surge events), and thus data was only discarded if there was a reason for its fallibility (e.g., if flow to the pipe with the monitor was stopped during the period in question).

Performance and Systems Audits, and Project Operations and Responsibility

Collection and review of all pressure monitoring data and surge modeling was performed by the Principal Investigator. Co-Principal Investigator Joseph P. Dugandzic, Senior Planning Engineer for American Water, ensured calibrated EPS models were available for surge analysis. Co-Principal Investigator Dr. Mark LeChevallier, Director of Innovation and Environmental Excellence for American Water, provided oversight and quality assurance review of all these activities, project progress, and all deliverables. Dr. Don Wood, Project Advisor, provided input on the modeling approach used for the project and provided a technical review of the final report.

CHAPTER 5
RESULTS AND DISCUSSION

This Chapter summarizes the findings of the four key simulations performed for all five models, discusses the impact of distribution system characteristics on the occurrence of low/negative pressures and presents the findings of field pressure monitoring.

SUMMARY OF KEY SIMULATIONS

Three key simulations were performed for each system: 1) complete loss of pumping (e.g., a power outage), 2) a major main break in a key trunk line, 3) opening a hydrant to fire flow. Additionally, rapid fluctuation of a pressure reducing valve (PRV) was simulated if the system included a PRV as a part of the system design.

Complete loss of pumping power. Table 5-1 summarizes how the distribution systems would be impacted if a complete loss of pumping power occurred when, 1) most of the floating storage facilities are delivering flow to the distribution system and when, 2) most of the floating storage facilities are being filled. For most of the systems examined, demands were higher and pumping was near maximum levels when most of the floating storage facilities were delivering flow to the distribution system. This time was generally in the morning, between 5 am and 9 am or in the afternoon between 5 pm and 6 pm. Demands were near minimum levels when the most volume was entering the floating storage facilities (11 pm to 2 am), but pumping was near maximum levels again so that there was enough flow to fill the tanks. Analysis using steady state initial and boundary conditions was also performed.

With a complete loss of pumping power, systems with more storage tanks per miles of main were less susceptible to negative pressure transients (Table 5-1). While all systems had several vulnerable points with the loss of pumping power, three of the five systems experienced negative pressures in less than 20% of the system during the first two minutes of simulation. However, negative pressure locations combined ranged from 7% to 98% in the five systems. The least affected system (System 4) experienced negative pressures in less than 10% of system nodes. System 5, which has no floating storage facilities, was predicted to experience negative pressures in more than 95% of the system if a complete loss of pumping power occurred. Table A1 summarizes the flow conditions in the systems before complete loss of pumping power occurred. System 1 experienced higher than expected negative pressures when a complete loss of pumping power occurred. This system was the only one included in the study where more than 85% of the system operated at steady state pressures less than 60 psi. In a complementary study funded by the AWWARF, that investigated 12 additional distribution systems, another system that showed higher than expected negative pressures with complete loss of pumping power was also operated with more than 85% of the systems at steady state pressures less than 60 psi.

Table 5-1
Distribution characteristics and corresponding summary of nodes with pressure less than 0 psi when complete pumping failure occurs in each system. Wave speed = 3,600 ft/s; check valve on each pump closes in 0.1 second.

System #	Total main length (mi)	*Floating storage		Total # nodes	† Negative Pressure Nodes					
					under steady state start conditions		EPS @ time of max flow ***from*** storage		EPS @ time of max flow ***to*** storage	
		#	1 facility per X miles of main		#	Percent negative	#	Percent negative	#	Percent negative
1	60	3	20	415	284	68%	0	0	282	68%
2	410	7	59	1,765	241	14%	242	14%	327	19%
3	747	17	44	2,777	488	18%	453	16%	424	15%
4	509	18	28	1,679	116	7%	135	8%	172	10%
5	†† 409	0	NA	2,182	2134	98%	2,133	98%	2,110	97%

* Includes standpipes and elevated tanks that are active when maximum flow is being supplied to the system.
† Negative pressures occurred within the first two minutes of simulation for all systems examined.
†† System 5 has no floating storage, but 3 pumped storage tanks. Analysis was performed when the most flow was being delivered to and from the pumped storage facilities.

Major Main Break in Key Trunk Line. With a major main break along a key trunk line negative pressures were observed at locations as far as 5 miles away. Nodes located more than 30 to 40 ft above the immediate surroundings were more susceptible to low and negative pressures. Locations at or near dead ends were also typically affected. Overall, a main break along a key trunk line could have significant impact, similar to loss of pumping power, if it occurred along a main fed by a major pump station.

Opening a hydrant to fire flow. Opening a hydrant to the available fire flow along a key trunk line similarly had the most impact on nodes of local elevation greater than 30 to 40 ft above the immediate surroundings and locations at or near dead ends or closed valves. If the hydrant was ramped up to the available fire flow in 5 seconds, the impact could be as severe as observed with complete loss of pumping power, if it was located along a main connected to pump station supplying a significant portion of the flow to the distribution system. In System 4 hydrant flushing along a major main was predicted to result in 126 nodes with negative pressures. Complete loss of power in the same system resulted in as much as 197 nodes with negative pressures.

The impact of rapid demand changes was investigated at the highest demand node in several systems as described in Table 3-2. Maximum demands at single nodes in each system were as high as 1,200 gpm. Increasing the demand up to two times the demand at the nodes (in two seconds) had little impact as far as creating negative pressure surges in the system was concerned. None of the systems examined drew negative pressures as a result of the rapid demand change.

Rapid PRV Closure on/near a major main. Of the five systems examined, three used pressure reducing valves (PRVs) to control pressure downstream of an interconnection or to control pressure between different pressure zones. With rapid PRV fluctuations between the PRV's current set point down to 5 psi in the eight systems, pressure transients were generated, but downstream pressures were never less than 20 psi as a result of the fluctuations. The PRVs examined ranged in diameter from 12 inches to 20 inches. In System 3, when the setting on a 20-inch PRV just downstream of pump station #3 was adjusted from 100 psi to 5 psi, in 1 second, the lowest downstream pressure that resulted was approximately 40 psi.

EFFECTS OF DISTRIBUTION SYSTEM CHARACTERISTICS

Distribution System Configuration

In general, dead ends or locations near dead ends were more susceptible to negative pressures when transient producing operations such as pump shutdown or valve opening and closing occurred in the system. However, the proportion of dead ends in a system did not appear to be a significant factor on a system wide basis, when overall system vulnerability to low and negative pressures was being considered.

Distribution System Topology/Elevation

Systems with areas of local elevation greater than 40 to 50 ft above immediate surroundings were more likely to have low or negative pressures after a flow control operation. However, the distribution system predicted to have the lowest susceptibility to negative pressures (System 4) when complete loss of pumping power occurred, was classified as moderately hilly. Systems classified as moderately hilly have elevation differences greater than approximately 60 feet but less than 150 feet per pressure zone, while systems classified as hilly have elevation differences greater than 150 feet in each pressure zone. System 5, which was predicted to be the most susceptible to negative pressures with complete loss of pumping power, is classified as flat since the elevation differences in the system is less than 60 feet.

Elevated storage

In general, the presence of elevated storage was found to be significant in helping to reduce the impact of low/negative pressure transients. In addition to the benefits described previously, floating storage facilities provide beneficial effects when individual transient-producing events occur. As long as the transient event (pump shutdown, main break, hydrant flushing) occurred within less than one mile of elevated storage no (or very few) low/negative pressures were noted.

Pumping capacity and velocity downstream of the pump station

Increasing the amount of flow brought to a stop in each system, increased the predicted percentage of negative pressures when complete loss of pumping power was simulated as shown in Table A1(Appendix A). This was expected since pumping higher flows through pipes of the same diameter increases the velocity through the pipes. This in turn will cause larger velocity changes and larger corresponding changes in pressure. No general correlation was found, however, when comparing that amount of flow brought to a stop between different systems.

The water velocity leaving pumps stations affected the susceptibility of surrounding areas. Areas in close proximity to pump stations where the water velocity was greater than 3 ft/s, more than 200 ft down stream of a pump station, were more likely to experience low and negative pressures. Areas near pump stations with downstream velocities less than 2 ft/s were generally less susceptible to low and negative pressures with a loss of pumping power. However, the presence of elevated storage and well gridded mains played a significant role in mitigating the impact of water velocities. No low or negative pressures were predicted for System 2 when water with velocity of 3 ft/s was brought to a sudden stop when pump station #10 lost pumping power (Appendix B, Table B4, Run #11). An elevated tank located 150 ft away was the likely source of protection. In the same system, when pump station #11 lost pumping power (Appendix B, Table B4, Run #12), negative and low pressures were expected to occur in 34 and 119 nodes respectively.

Presence of air/vacuum valves

The presence of appropriately sized air/vacuum valves helped to reduced negative pressures in the systems. In System 3, if five 4-inch air-vacuum valves are installed at the high points between pump station #3 and location D (Figure 2-4), negative pressures are reduced by 16% (488 to 408). Decreasing the air outlet size to 2 inches decreases the negative nodes to 395, while using air valves with a 5-inch inlet and outlet reduced the negative nodes further to 384 (21% decrease). The installation of the five air valves reduced the negative pressures due to power loss at pump station #3 alone by 40%.

Presence of hydropneumatic tanks and pump bypass lines

The addition of an appropriately sized hydropneumatic tank just downstream of pump stations can significantly reduce the severity of low pressure surges on downstream nodes. In System 1, negative pressures occurred in 61 locations with loss of pumping power at pump station #9. The installation of a 100-gal hydropneumatic tank (5 to 1 water-to-air ratio), on the 16-in main just downstream of the pump station (Figure 2-2), was sufficient to maintain pressures above 0 psi for the first 60 seconds after power loss. A 500-gal vessel was necessary to maintain pressures above 20 psi at all locations in the system. In System 3, with a steeper profile and a larger main (54-inch) downstream of pump station #3 (Figure 2-4), a 10,000 gallon hydropneumatic tank was required to eliminate the negative nodes that resulted when power was lost at the pump station. For most of the systems examined in this study, if the transmission main downstream of the pump station was 24 inches or smaller, the installation of one 1000-gal hydropneumatic tank at individual pump stations was sufficient to prevent negative pressures when a power outage occurred. Main diameter, length, slope, and flow velocity factor significantly in the sizing of hydropneumatic tanks. Stephenson (2002) and Thorley (2004) provide a comprehensive review of the steps involved for manually sizing hydropneumatic tanks (air vessels). It should be noted however, that the manual approach only provides an estimate of adequate vessel sizing. Computer analysis is recommended for additional confirmation and optimization.

All booster stations included in the different systems, were designed with a pump bypass. Significant low or negative pressures were not observed for any booster pump stations, with loss of pumping power, as long as all other facilities were functioning normally.

PRESSURE MONITORING SUMMARY

Pressure monitoring was conducted in System 1 and System 2 to verify that the locations predicted to experience low or negative pressure were actually susceptible to transients. The surge models used to predict vulnerable distribution system locations were developed using maximum day model scenarios. Although a surge model developed using maximum-day flow conditions will likely overestimate the magnitude of low or negative pressures if the flows in the at the time of monitoring are lower that those used in the model, the purpose of pressure monitoring was to gauge the usefulness of a worst-case, uncalibrated surge model (developed from calibrated EPS model) in providing information about the vulnerable locations in each distribution system.

System 1

Pressure monitors were placed in System 1 to capture the low pressure transients that were predicted to occur when pump #9 shuts off as indicated in Figure B1 (Appendix B). Five RADCOM and four Telog pressure monitors (Table 5-2) were available for the field study. RADCOM and Telog monitors were placed at hydrants near Locations 1, 2 and 4 (Figure 3-1). An additional Telog monitor was placed at Location 6 and only RADCOM monitors were placed at Locations 3 and 5. Monitoring sites 1, 2 and 3 served as controls since low pressures were predicted to occur in these areas.

Data collected from the pressure monitors show low pressures in locations 4, 5 and 6. Transient low pressures were not observed at locations 1, 2 or 3 on either Telog or Radcom monitors. Figure 5-1 and Figure 5-2 show the pressure profile for monitoring locations 4 and 5, respectively. The source of the transient event that produced a pressure drop of approximately 49.4 psi at location 4 (1.1 psi lowest pressure) has not been determined.

Table 5-2
Summary of maximum and minimum gage pressures measured in System #1

Site #	Monitoring Duration (days)	Monitor Type	Data Points	Mean pressure - psi (kPa)	Maximum pressure - psi (kPa)	Minimum pressure - psi (kPa)	Low pressure difference from mean - psi (kPa)
1	21	RADCOM	62.9×10^6	49.4 (341)	56.5 (390)	39.7 (274)	9.5 (67)
	21	TELOG	1004	50.0 (345)	53.8 (371)	38.8 (268)	10.2 (70)
2	21	RADCOM	65.2×10^6	51.1 (352)	74.7 (515)	34.0 (234)	17.1 (118)
	NA	TELOG	1004	50.0 (345)	53.4 (368)	32.9 (227)	17.1 (118)
3	11	RADCOM	34.1×10^6	51.2 (353)	68.1 (470)	25.0 (172)	26.2 (181)
	NA	TELOG	NA	NA	NA	NA	NA
4	5	RADCOM	15.0×10^6	50.5 (348)	85.2 (587)	1.1 (8)	49.4 (340)
	21	TELOG	1004	46.1 (318)	53.6 (370)	7.9 (54)	38.2 (264)
5	11	RADCOM	27.2×10^6	40.6 (280)	74.4 (513)	11.5 (79)	29.1 (201)
	NA	TELOG	NA	NA	NA	NA	NA
6	NA	RADCOM	NA	NA	NA	NA	NA
	21	TELOG	1004	40.7 (281)	47.9 (330)	7.3 (50)	33.4 (231)

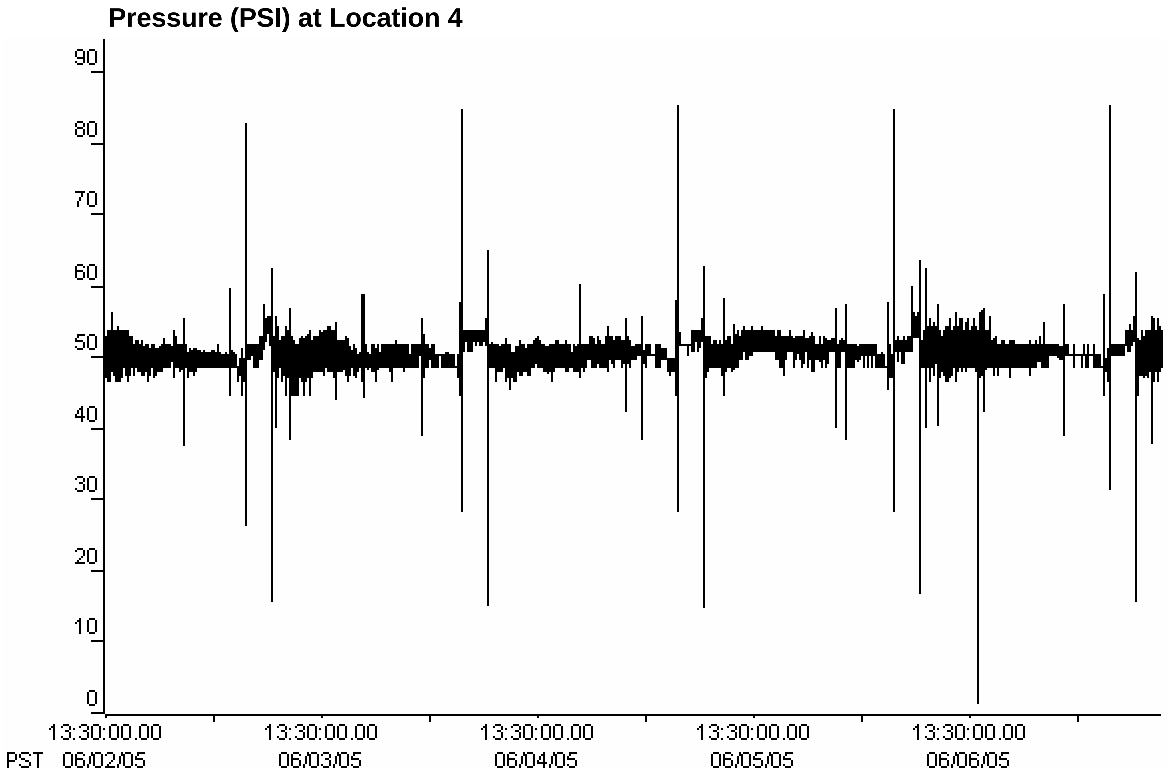


Figure 5-1 System #1, Location 4. Pressure transients measured at a fire hydrant (elevation = 25 ft) using a RADCOM data logger. The hydrant was fed by a 16-inch main. Pressure was measured at a rate of one sample per second for 5 days. A new pressure value was only recorded if a pressure change greater than 1 psi was detected. Lowest pressure detected over monitoring period was 1.1 psi.

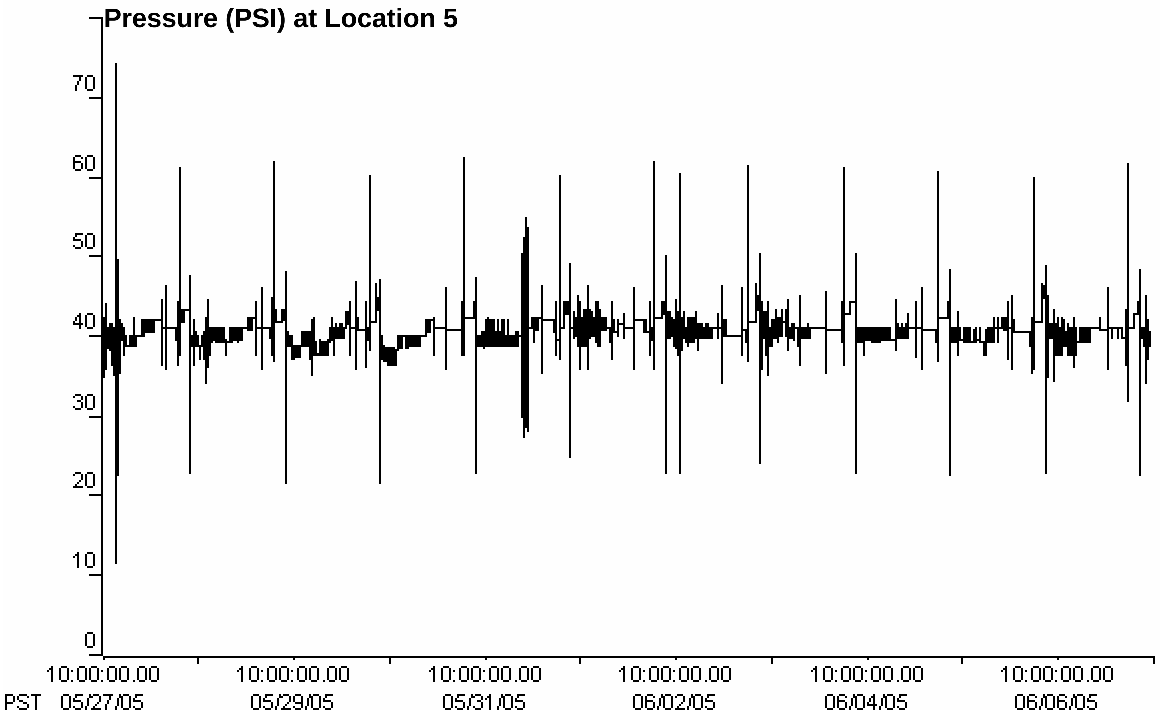


Figure 5-2 System #1, Location 5. Pressure transients measured at a fire hydrant (elevation = 31 ft) using a RADCOM data logger. The hydrant was fed by an 8-inch main. Pressure was measured at a rate of one sample per second for 5 days. A new pressure value was only recorded if a pressure change greater than 1 psi was detected. Lowest pressure detected over monitoring period was 11.5 psi.

System 2

Pressure monitors were placed in System 2 to capture the low pressure transients that were predicted to occur as various pumps shut off. Five RADCOM and four Telog pressure monitors (Table 5-3) were available for the field study. RADCOM and Telog monitors were placed at hydrants near Locations 1, 3 and 5 (Figure 3-2). An additional Telog monitor was placed at Location 6 and only RADCOM monitors were placed at Locations 2 and 4. The only low pressure spike detected for this system (17.2 psi) occurred at Location 6 as highlighted in Figure 5-3. As seen in System 1, the pressures measured by the RADCOM and Telog monitors show very good agreement. Because the Telog monitors, sampled at a rate of 1 per second, but only stored the lowest pressure reading over 15 second intervals, the average pressures recorded by the Telog monitors were 1 to 2 psi lower than the average pressures recorded by the RADCOM monitors.

Table 5-3
Summary of maximum and minimum gage pressures measured in System #15

Site #	Monitoring Duration (days)	Monitor Type	Data Points	Mean pressure - psi (kPa)	Maximum pressure - psi (kPa)	Minimum pressure - psi (kPa)	Low pressure difference from mean - psi (kPa)
1	14	RADCOM	36.3×10^6	43.1 (297.2)	56.3 (388.2)	27.4 (188.9)	15.7 (108.2)
	14	TELOG	660	40.1 (276.5)	47.6 (328.2)	27.1 (186.8)	13.0 (89.6)
2	3	RADCOM	9.4×10^6	50.3 (346.8)	64.0 (441.3)	30.4 (209.6)	19.9 (137.2)
	NA	TELOG	NA	NA	NA	NA	NA
3	14	RADCOM	37.1×10^6	44.1 (304.1)	58.7 (404.7)	26.6 (183.4)	17.5 (120.7)
	14	TELOG	660	41.9 (288.9)	48.5 (334.4)	23.9 (164.8)	18.0 (124.1)
4	3	RADCOM	11.3×10^6	52.4 (361.3)	70.2 (484.0)	33.1 (228.2)	19.3 (133.1)
	NA	TELOG	NA	NA	NA	NA	NA
5	3	RADCOM	13.1×10^6	63.4 (437.1)	74.5 (513.7)	55.3 (381.3)	8.1 (55.8)
	14	TELOG	660	59.4 (409.5)	65.7 (453.0)	52.8 (364.0)	6.5 (44.8)
6	NA	RADCOM	NA	NA	NA	NA	NA
	14	TELOG	660	39.5 (272.3)	45.9 (316.5)	17.2 (118.6)	22.3 (153.8)

NA = not applicable

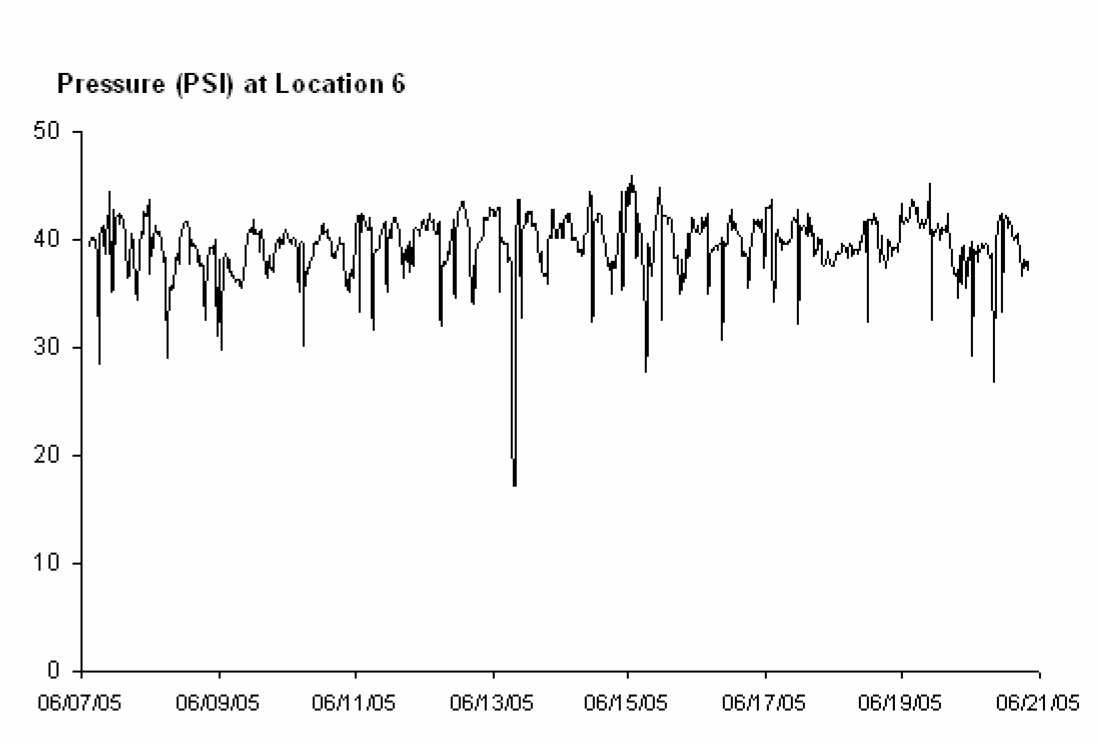


Figure 5-3 System #2, Location 6. Lowest pressure transient detected at any location in the system (17. 2 psi) using a TELOG monitor. Pressure was measured at a hydrant with elevation of 45 ft and connected to 16-inch main. Pressure data was sampled at a rate of one per second, but only the lowest pressure measured in a 15 second interval was stored.

COMPARISON OF SURGE MODELING AND FIELD MONITORING DATA

The surge models used to assess the vulnerability of each distribution system to low and negative pressures were developed using calibrated EPS models without additional adjustment. In addition, a wave speed of 3,600 ft/s was approximated for all systems. To verify that this approach gave reasonable low and negative pressure predictions, pressure monitoring data from two locations were compared to modeling predictions for the same locations. The pressure monitoring data obtained at locations 4 and 2 in System 1 and location 2 in System 2 were selected for comparison with the model output from the respective systems (Figure 3-1 and Figure 3-2).

In System 1, the lowest pressures observed corresponded to pump station #9 shutting off. Pump station #9 shuts off at approximately 8 am in the morning. A surge simulation was performed at hour 8.0 where the pump was shut down in one second, two seconds after the simulation began. Figure 5-4 shows comparable transient behavior between field and model data. In the field data, the lowest pressure is 36 psi lower than the initial steady state condition. The model output shows a similar drop in pressure (42 psi). In both cases, the low pressure surge lasts for approximately 24 seconds. When the wave speed was adjusted to 3,000 ft/s, the lowest pressure predicted by the model is approximately 37 psi lower than the initial steady state pressure, and the timing of the minimum pressure more closely corresponds to the timing of the minimum pressure recorded in the field (Figure 5-5).

The pressure data collected at monitoring location #2, when pump #9 shuts off, does not show the sharp wave front predicted by surge modeling(Figure 5-6), but the trend in the model and field responses are similar. In the field data, the lowest pressure is 15 psi lower than the initial steady state pressure while, the lowest pressure predicted via modeling for the same location is 41 psi lower than the initial steady state pressure.

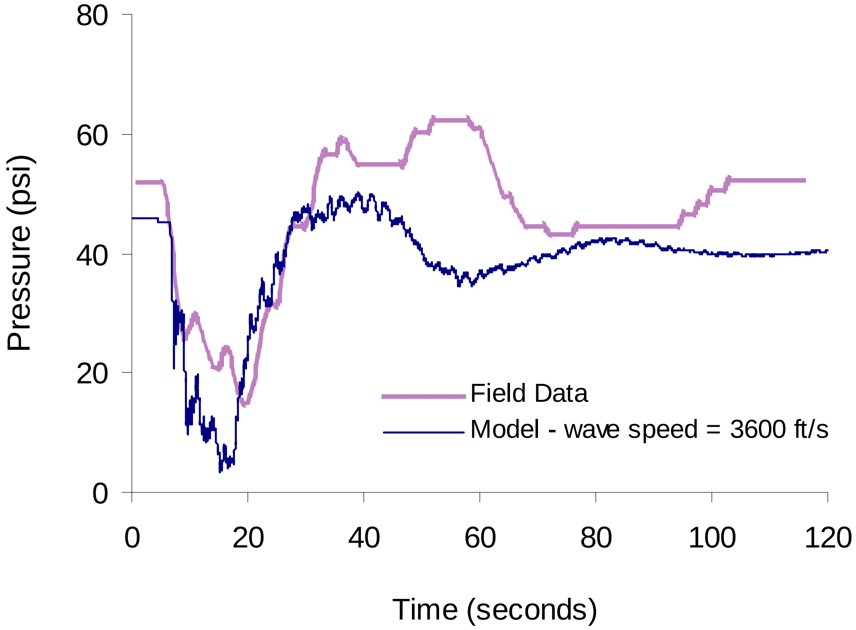


Figure 5-4 Model and field results - System 1, monitoring location #4, pump #9 shuts down in 1 second

Figure 5-5 Model and field results - System 1, monitoring location #4, pump #9 shut down in 1 second and wave speed reduced from 3600 ft/s to 3000 ft/s

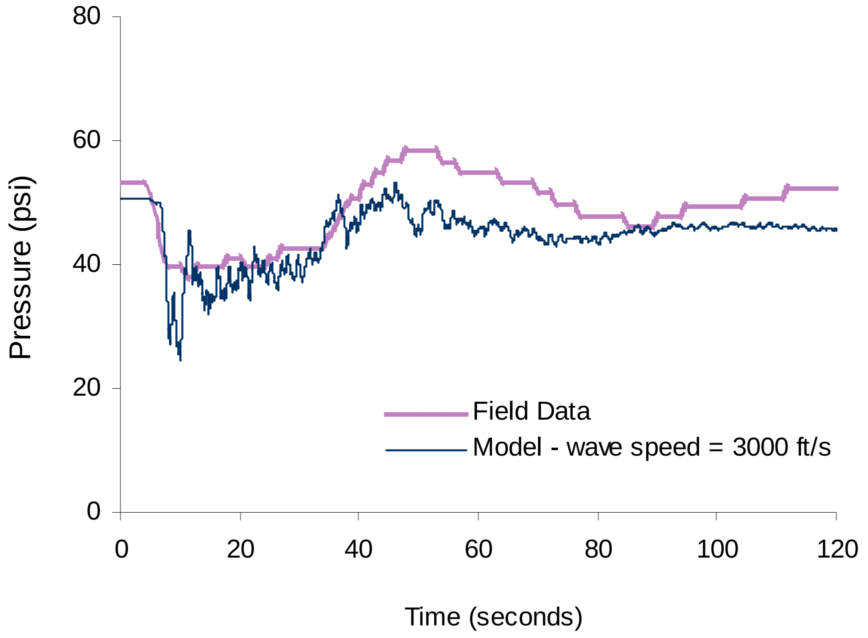


Figure 5-6 Model and field results - System 1, monitoring location #2, pump # 9 shut down in 1 second and wave speed = 3000 ft/s

In System 2, the lowest pressures measured using the RADCOM monitors corresponded to a pump at pump station #1 shutting off at approximately 10:30pm. A surge simulation was performed at hour 22:30 where the pump was shut down in one second, two seconds after the simulation began. The wave speed was adjusted to 2,500 ft/s. Figure 5-7 shows field versus model data. The wave front predicted using a pump shut down time of 1s is significantly sharper than is measured in the field. In the field data, the lowest pressure is approximately 20 psi lower than the initial steady state condition. The model output shows more than twice (47 psi) the pressure drop if the simulation uses a pump shut down time of 1s. Figure 5-8 and Figure 5-9 show increasingly better correlations of model and field data as the pump shut down time is increased to 3s and 6s respectively. With a 6s shut down time, the lowest pressure predicted is 37 psi lower than the initial steady state condition - nearly twice the pressures measured in the field. However, the timing of the minimum pressures correspond more closely. In addition, the low pressure surge lasts approximately 7 seconds in both cases.

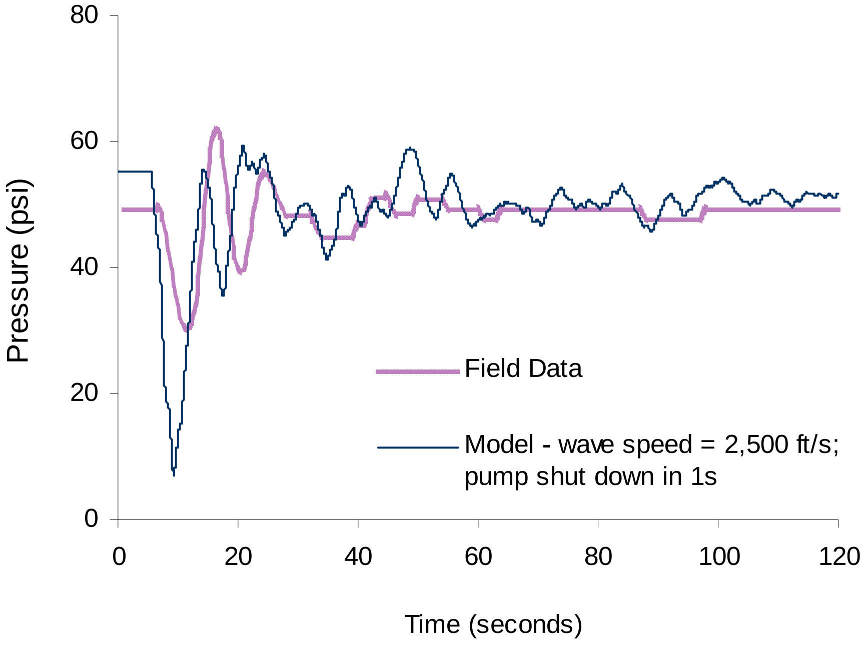


Figure 5-7 Model and field results - System 2, monitoring location #2, pump shut down in 1 second

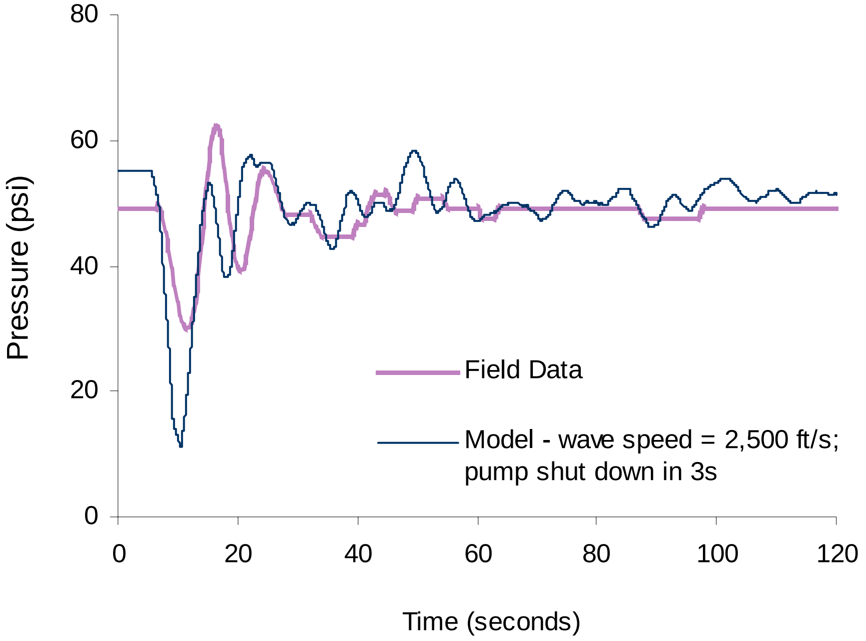


Figure 5-8 Model and field results - System 2, monitoring location #2, pump shut down in 3 seconds

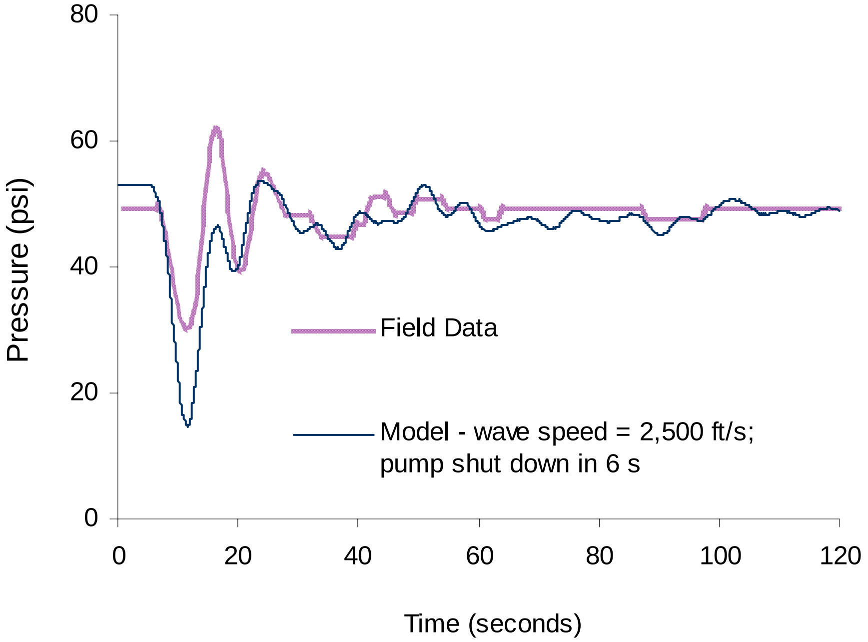


Figure 5-9 Model and field results - System 2, monitoring location #2, pump shut down in 6 seconds

SUMMARY OF SIGNIFICANT FINDINGS

- All systems were predicted to experience low or negative pressure transients when a complete loss of pumping power was simulated.

- Areas of local elevation greater than 30 to 40 ft above immediate surroundings, areas within 1 mile of an elevated tank and areas that were not well gridded were more susceptible to low or negative pressures

- In general, distribution system locations in close proximity to pump stations with average downstream velocities greater than 3 fps were most susceptible to low and negative pressures. Areas near pump stations that power on and off several times a day will be more susceptible to low and negative pressures than areas near pump stations that operate continuously.

- Negative pressures were not detected in the two distribution systems monitored. However low pressures (pressure < 20 psi) were measured in three locations in System 1 and in one location in System 2. The lowest pressure measured in either system was 1.1 psi.

- Calibrated EPS models produce surge models that can adequately assess distribution susceptibility to low and negative pressures. However, the predicted pressures may be lower than observed in the field.

- With wave speed reduced to 3,000ft/s in System 1, the magnitude of the surge predicted by the model was consistent with the magnitude of the surge measured in the field. The trend in the model and field responses were also very similar. In System 2 (wave speed = 2,500 ft/s), the magnitude of the surge predicted by the model was greater than the magnitude of the surge measured in the field, but the trend in model and field responses were similar.

- The surge models used in this project predicted lower pressures than were measured in the field, because the initial and boundary conditions used during field monitoring corresponded to initial and boundary conditions for lower flow conditions than were used during surge modeling. Additionally, the timing of transient producing events (pump shutdown for example) and the wave propagation speed were only estimates. The presence of entrapped air pockets and leaks help to dampen transients. With the near worst case scenarios used for all systems, the discrepancy is inevitable. Models will have to be further developed on a system by system basis if more detailed information (more than locations susceptible to low and negative pressures) is required.

- The Telog monitors used in this project are adequate for detecting low pressures in the distribution system. However, the monitors may not be suitable if more detailed information on the transient pattern is required.

- Increasing the time in which transient producing events occur, can help reduce the impact of the event. Increasing the pump shut down time in System 2 reduced the magnitude of the transient produced by approximately 3 psi.

CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

Surge models were developed for five distribution systems and used to identify the locations within the distribution systems where low or negative pressures were most likely to occur. Ultimately, the purpose of investigating pressure transients is to improve the operator's understanding of how the system may behave in response to a variety of events such as power outages, pump shut downs, valve operations, flushing firefighting, main breaks and other events that can create significant rapid drops in system pressure and/or low pressure waves.

A holistic review of system conditions and utility procedures is recommended to effectively minimize a system's susceptibility to pressure transients. To accomplish this, several key elements should be considered: 1) determination of the occurrence of low pressure surges (including magnitude and duration, as well as locations of lowest pressures); (2) the causes of surges; 3) system response to surges (or system robustness); 4) susceptibility to contamination when surges occur; and (5) means of controlling surges.

Characteristics that increase distribution system susceptibility to low and negative pressures

The frequency and magnitude of surge events varies from system to system and are functions of several variables. Surge modeling results indicate that areas with the following characteristics have increased susceptibility to low and negative pressures:

- Locations close to a pump station with downstream velocity greater than 3 ft/s and no surge protection (hydropneumatic tank for example). Close proximity to pump station that turns on and off several times a day increases susceptibility.

- Locations greater than one mile away from elevated storage

- Areas of local elevation greater than 30 to 40 ft above surroundings

- Areas near dead ends

- Areas located near a hydrant on a major main

- Areas with low static pressures

Mitigation strategies for minimizing the occurrence and impact from negative pressure transients

A surge model developed from a calibrated EPS model (maximum day scenario) can be used to identify vulnerable distribution system locations, but will likely overestimate the severity of transient pressures. This can occur since the initial and boundary conditions (pump flow, tank levels etc.) used in the developing the EPS model may differ from the conditions at the time pressure monitoring occurs. In addition, the wave propagation speed and speed of the transient producing events are only estimates. Based on the results of this research, using wave speeds ranging from 3,000 ft/s to 3,600 ft/s will likely provide a good initial estimate of the transient wave propagation speed. If more detailed information is required, then the surge model should be developed from an EPS model calibrated using the boundary conditions for the day pressure monitoring occurred.

As utilities throughout the state develop surge models for their respective systems, pressure monitoring should be performed for a few of the locations to verify the susceptibility of the locations that have been predicted to be vulnerable to low and negative pressures. The vulnerable areas identified via modeling should be prioritized for maintenance of a disinfectant residual, mitigation via surge control, leak detection and control, and cross connection control.

The strategies by which surge control is achieved may be classified as either direct action or diversionary tactics (Thorley, 1991). Direct action strategies attempt to influence the behavior of the primary causes of the flow changes, such as valve action or pump operations. As demonstrated in Chapter 5 (field studies), increasing the pump shut down time by a few seconds can decrease the magnitude of the transient generated. Other similar actions that can be used to slow the rate at which a transient action occurs include, slowing the opening and closing of fire hydrants, prolonging valve opening and valve closing times, and avoiding complete pumping failure by putting a major pump on a universal power supply. For distribution systems still in the planning stages, rerouting pipelines, using larger diameter pipes (or otherwise lowering the flow velocity), changing pipe material, or applying changes in system topology are all other direct actions that can be applied (Boulos et al., 2005). Diversionary tactics, such as the installation of hydropneumatic tanks, attempt to control the magnitude of the transient once it has been created. The final choice for surge protection should be based on the initial cause and location of the transient disturbance(s), the system itself, the consequences if remedial action is not taken, and the cost of protection measure(s).

Recommendations and Application and use by NJDEP

As the NJDEP considers distribution system transients, it is important to realize that significant low pressure surges can occur as routinely as high pressure surges. As such, full consideration should be given to the transient low pressures that occur in distribution systems. Surge models can be used to identify those locations within a distribution system where low or negative pressures are most likely to occur, thus guiding utilities to the most appropriate monitoring locations, and also enabling analysis of alternative mitigation techniques. Modeling can help save utilities time and money spent on less fruitful monitoring efforts or less effective corrective actions.

Recommendations For Future Research

This project highlighted the factors that may increase the susceptibility of distribution systems to low and negative surge pressures. However, further investigation is required to determine how water quality is impacted once these low and negative pressure surges occur. If a cross-connection exists and the pressure in the distribution system is lower than pressure exerted by liquid outside of the system, then backflow, the undesirable reversal of flow into the distribution system, may occur. Although many utilities may have cross-connection control programs in place, few include monitoring and detection for backflow incidents. American Water is currently leading a 3-year project (from Spring 2005) funded by AwwaRF that will evaluate the monitoring technologies available to detect backflow incidents. Methods will also be developed for the optimal placement of the monitoring technologies.

To better define the public health impact associated with contamination due to pressure transients, additional research is also recommended to determine the efficacy of different levels of chlorine and chloramine for microbial inactivation under different backflow scenarios.

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ABBREVIATIONS

AWWA	American Water Works Association
AwwARF	Awwa Research Foundation
c	wave speed or acoustic velocity in liquid filled pipe
D	pipe diameter
g	acceleration due to gravity
E_c	Elastic modulus of the pipe
E_f	Bulk modulus water; describes how the density of water changes when pressure is applied. The bulk modulus of water is 2.15 X 10^9 N/m^2.
H	pressure head
K_R	coefficient of restraint for longitudinal pipe movement
L	distance between a flow control operation and some other terminal point in the system
Ma	Mach number; the ratio of speed to the speed of sound in the medium
N	rotational speed
Pa	Pascal; 1 pascal = 0.000145 psi
PRV	pressure reducing valve
psi	pounds per square inch
rpm	also r/min; represents revolutions per minute and is a measure of the rotational speed
T_c	time taken to bring water flow to a stop
t_l	pipeline thickness
V	fluid velocity
Δ	delta – used to indicate change in a parameter
μ_p	Poisson’s ratio; elastic constant that is a measure of the compressibility of material perpendicular to applied stress.
ρ	represents fluid density. The density of water is approximately 62 lb/ft^3 or 1000 kg/m^3.

APPENDIX A
SENSITIVITY ANALYSIS

Table A1
Summary of flows brought to a stop when complete loss of pumping power occurred in each system.

System #	Total main length (mi)	*Floating storage		Total # nodes	† Negative Pressure Nodes					
					under steady state start conditions		EPS @ time of max flow ***from*** storage		EPS @ time of max flow ***to*** storage	
		#	1 facility per X miles of main		#	Percent negative	#	Percent negative	#	Percent negative
1	60	3	20	415	284	68%	0	0	282	68%
					total flow - 9.9 mgd		1.9 mgd @ 5:00 hrs		9.9 mgd @ 0:00 hrs	
2	410	7	59	1,765	241	14%	242	14%	327	19%
					total flow - 15.5 mgd		15.8 mgd @ 5:42 hrs		16.8 mgd @ 22.48	
3	747	17	44	2,777	488	18%	453	16%	424	15%
					total flow - 114.3 mgd		110.6 mgd @ 9:00 hrs		107.2 mgd @3:00 hrs	
4	509	18	28	1,679	116	7%	135	10%	172	8%
					total flow - 69.8 mgd		80.7 mgd @ 9:00		69.0 mgd @ 1:00 hr	
5	†† 409	0	NA	2,182	2134	98%	2,133	98%	2,110	97%
					total flow - 23.9 mgd		68.3 mgd @ 4:00 hrs		31.8 mgd @ 23:42 hrs	

* Includes standpipes and elevated tanks that are active when maximum flow is being supplied to the system.

† Negative pressures occurred within the first two minutes of simulation for all systems examined.

†† System 5 has no floating storage, but 3 pumped storage tanks. Analysis was performed when the most flow was being delivered to and from the pumped storage facilities.

APPENDIX B

SUMMARY OF SURGE ANALYSES

System 1

In System 1, maximum flow from storage occurred at time 5:00 hrs and maximum flow to storage occurred at time 0:00 hrs (12 pm mid-night). Flow supplied to the system from pumps at 5:00 hrs and 1:00 hr were 2 mgd and 9.9 mgd respectively. Table B1 summarizes the pump operating conditions at 0:00 hrs and Table B2 summarizes the low and negative pressures that occur in the system under several transient producing simulations. The distribution system model used for this system had a total of 415 nodes.

Table B1
Pump operating conditions in System 1

Pump Station #	Elevation (ft)	# Operating pumps	Flow @ 18.9 hr		Max velocity just downstream of station (ft/s)
			gpm	mgd	
1	9	1	679	1.0	4.1
2	5	1	671	1.0	1.8
3	5	1	643	0.9	3.8
4	7	2	1,600	2.3	0.18
5	5	off	off	off	off
6	5	1	706	1.0	4.2
7	5	1	794	1.1	1.7
8	5	1	521	0.8	5.9
9	31	1	1357	2.0	2.1

Table B2
Summary of surge analyses performed for System 1
(t = 5:00 hr & wave speed = 3,600 ft/s)

Run #	Transient Event	Tanks within 1 mile?	# nodes with pressures < 0 psi	# nodes with pressure 0 to 20 psi	Comments
1	Complete loss of pumping power	in some areas	282	114	See Figure B1
2	15-in break on 24-in main	No	67	35	Negative pressures observed up to 5 miles away from break
3	ramping up to fire flow in 5s	No	0	45	Low pressures in region around pump #9
4	24-in butterfly val. + 1-s linear open/closure	No	17	54	Negative pressures occur downstream resulted from valve closure
5	24-in butterfly val. + 5-s linear open/close	No	15	37	Negative pressures occur downstream resulted from valve closure.
6	24-in gate valve + 5-s linear closure	No	15	37	Negative pressures downstream resulted from valve closure. see Figure B3
7	pump station # 9 off	No	25	48	see Figure B2

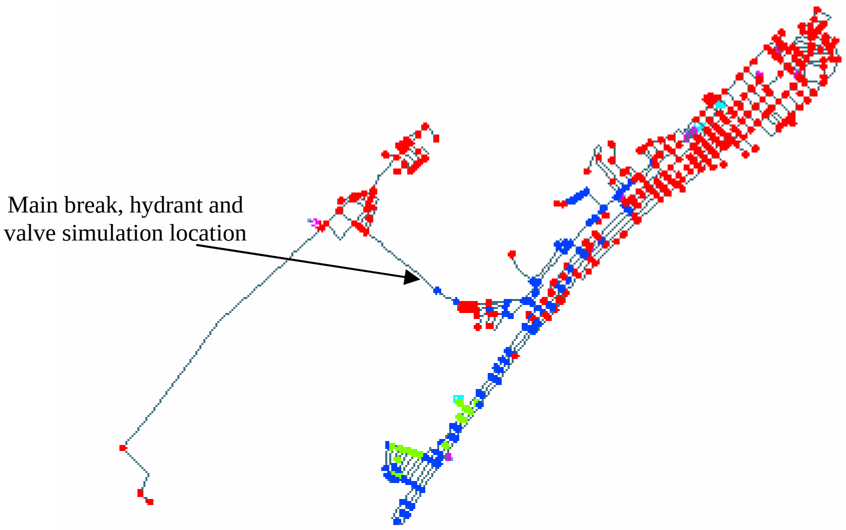

Figure B1 Negative and low pressure nodes resulting from a complete loss of pumping power in System 1.

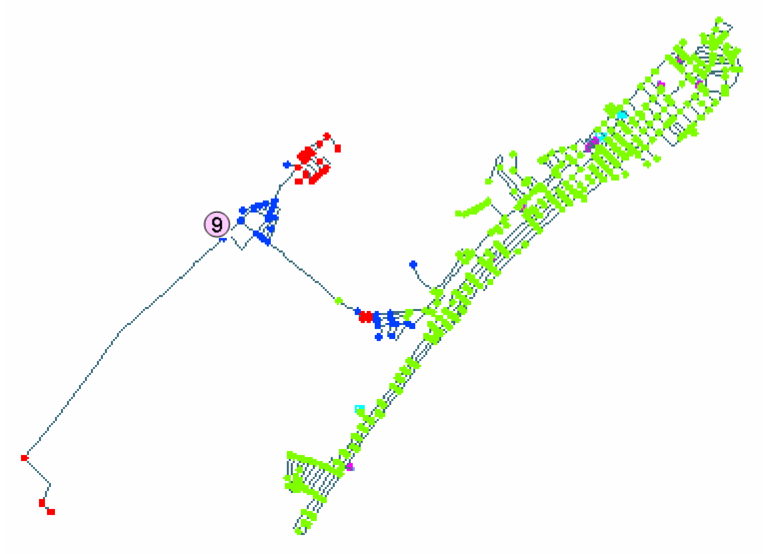

Figure B2 Low and negative pressure nodes resulting when pump #9 shuts off

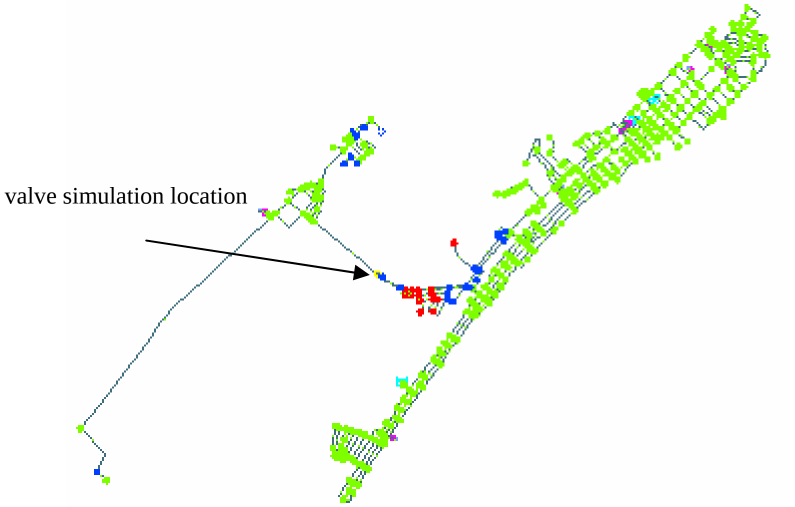

Figure B3 Low and negative pressure nodes resulting when valve on 24-in main is closed in 5 seconds then open in 5 seconds ~ 60 seconds later.

System 2

Table B3summarizes the pump operating conditions at t = 11:15 hours and Table B4 summarizes the low and negative pressures that occur in the system under several transient producing simulations. The model used for this distribution system had a total of 1,765 nodes.

Table B3
Pump operating conditions in System 2 @ t= 11:15 hour

Pump Station #	Elevation (ft)	# of Operating pumps	Flow @ 11.30 hr		Max Velocity just downstream (ft/s)	Max velocity 200 ft downstream (ft/s)
			gpm	mgd		
1	33	3	2,459	3.5	10.3	5.4
2	44	1	714	1.0	4.6	2.0
3	61	1	751	1.1	4.8	2.1
4	47	1	932	1.3	3.8	2.6
5	19	1	642	0.9	1.8	1.8
6	54	0	0	0	0	0
7	54	1	663	1.0	4.2	1.1
8	43	1	580	0.8	1.7	1.7
9	65	1	1,059	1.5	6.8	1.1
10	62	1	321	0.5	2.1	3.0
11	27	2	2,148	3.1	4.2	3.5
12	21	1	593	0.9	2.4	1.1
13	19	1	798	1.1	5.1	1.7
14	26	1	1,248	1.8	7.8	2.8
15	20	1	797	1.1	5.1	1.7
16	14	1	240	0.3	2.7	1.7
17	5	1	1410	2.0	2.3	1.8
18	18	1	499	0.7	3.3	3.3

Table B4
Summary of surge analyses performed for System 2

Run #	Transient Event	Tanks within 1 mile?	# nodes with pressures < 0 psi	# nodes with pressure 0 to 20 psi	Comments
1	pump station #1 & 3 pumps off	NO	50	123	most LP within 1 mi SE of pump, especially near dead ends.
2	#1 & 2 pumps off	NO	17	83	
3	#1 & 1 pump off	NO	0	20	2 other pumps at station as far as 500 ft away from pump that was shut down.
4	pump station #2 off	NO	2	12	LP clustered within 0.01 mi radius of pump & clustered 0.3 mi NE of pump; NP located within 0.2 mi W of pump
5	pump station #3 off	NO	0	72	LP up to 4.0 mi N of pump
6	pump station #4 off	NO	7	164	LP up to 5.0 mi NW of pump
7	pump station #5 off	NO	0	3	LP up to 1.0 mi SE of pump
8	pump station #7 off	NO	2	8	LP N of pump, up to ~0.2 mi; NP within .04 mi of pump
9	pump station #8 off	NO	2	7	Five LP junctions within a 0.01 mi radius of pump; NP ~0.5 mi NE and 0.02 mi away
10	pump station #9 off	NO	4	30	LP within 1.1 mi radius of pump; NP clustered ~ 1.0 mi NE of pump
11	pump station #10 off	YES	0	0	Elevated storage located 150 ft away with 96 ft of head above pump station
12	pump station #11 off	NO	34	119	LP clustered 2 mi N & 0.6 mi S of pump; NP ~ 1.5 mi NW of pump (Figure B4)
13	pump station #11 off with two 100-gal HP tanks installed	NO	0	31	Low pressures occurred in locations with elevation 25 to 35 ft above pump station's elevation
14	pump station #11 off with two 500-gal HP tanks installed	NO	0	0	--
15	Fire hydrant ramped up to 2,000 gpm in 5s	NO	0	31	LPs occurred in same locations as seen with Run #14.
16	1-inch main break along 16-in line leading from pump station # 11	NO	0	0	Pumps remain on during break
17	8-inch main break along 16-in line leading from pump station # 11	NO	26	118	Pumps remain on during break
18	pump station #12 off	NO	1	1	LP & NP within 0.01 mi of pump
19	pump station #13 off	NO	0	12	LP within 1.5 mi NW of pump
20	pump station #14 off	NO	1	74	LP within 1.0 mi SW of pump; elevations at LP locations 0 to 5-ft less than pump station

21	pump station #15 off	YES	0	16	LP ~ 0.4 mi NE of pump
22	pump station #16 off	YES	0	1	within 0.01 mi of pump
23	pump station #17 off	NO	0	0	
24	pump station #18 off	YES	0	3	LP within 0.06 mi of pump
25	16-in butterfly val. + 5-s linear open/close	NO	0	23	Initial water velocity = 0.9 ft/s
26	16-in GATE valve. + 5-s linear open/close	NO	0	17	Initial water velocity = 0.9 ft/s

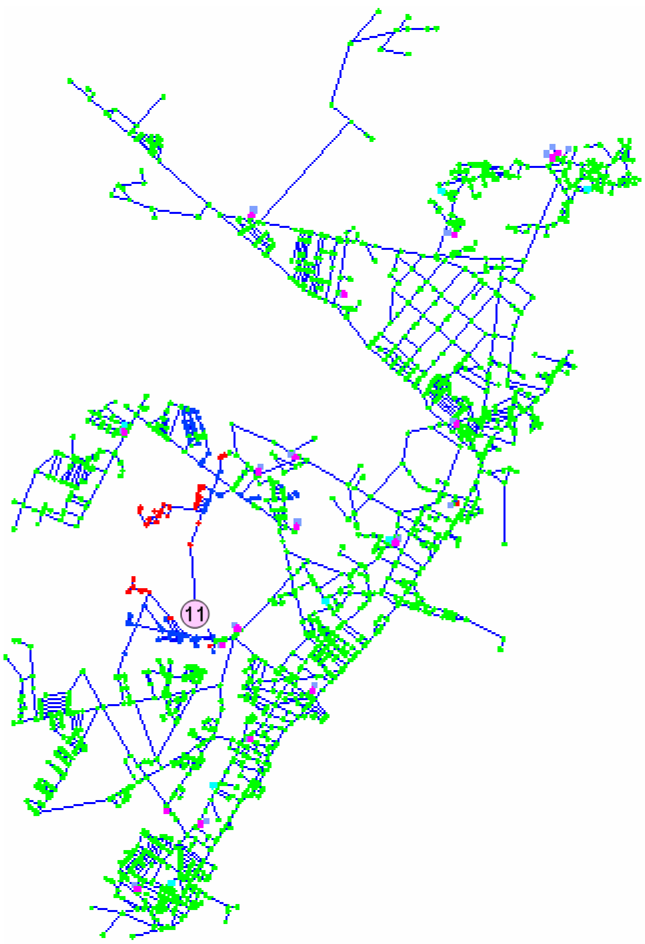

Figure B4 Low and negative pressure nodes when pump #11 shuts off.

System 3

In System 3, maximum flow from storage occurred at time 9:00 hrs and maximum flow to storage occurred at time 3:00 hrs (3 am). Flow supplied to the system from pumps at 9:00 hrs and 3:00 hr were 112 mgd and 110 mgd respectively. Table B5 summarizes the pump operating conditions at 9:00 hrs and Table B6 summarizes the low and negative pressures that occur in the system under several transient producing simulations at this time. The distribution system model used for this system had a total of 2,777 nodes.

Table B5
Pump operating conditions in System 3 @ t= 9:00 hours

Pump Station #	Elevation (ft)	# Operating pumps	Flow @ 20.42 hr		Max Downstream Velocity (ft/s)
			gpm	mgd	
1	12	1	980	1.4	4.6
2	45	1	646	0.9	1.4
3	64	3	21,567	31.0	5.0
4	44	2	1,398	2.0	2.2
5	74	2	1,497	2.2	4.2
6	74	2	1,238	1.8	1.3
7	47	1	1,082	1.6	1.7
8	72	2	3,348	4.8	3.4
9	151	2	3,499	5.0	3.1
10	83	3	3,344	4.8	5.3
11	130	1	985	1.4	6.3
12	128	1	1,255	1.8	3.6
13	74	2	3,361	4.8	5.8
14	79	1	1,362	2.0	2.8
15	90	1	618	0.9	3.9
16	79	1	1,405	2.0	2.2
17	58	4	2,952	4.3	4.7
18	52	1	2,108	3.0	1.5
19	132	1	98	0.1	0.3
20	70	1	665	1.0	4.2
21	62	1	2,461	3.5	3.9
22	62	1	198	0.3	0.4

Table B6
Summary of surge analyses performed for System 3

Run #	Transient Event	Tank within 0.8 mile?	# nodes with pressures < 0 psi	# nodes with pressure 0 to 20 psi	Comments
1	complete loss of pumping power	at certain locations	389	908	See Figure B5.
2	pump station #1 off	No	5	46	Negative pressures at or near dead ends several miles away from pump; low pressures in NE region near pump
3	pump station #2 off	No	3	0	Negative pressures near dead end 0.8 mi away from pump
4	pump station #3 off	No	87	342	Most negative pressures located along branching 16-inch and 54-inch mains (Figure B6)
5	pump station #4 off	No	15	48	Pump station #4 has a close connection to pump station #6 via 16-inch, 1.6 mile pipe. Most low & negative pressures occurred near pump station #6, which is ~40 ft above pump station #4
6	pump station #5 off	Yes	0	2	Elevated storage ~400 ft from pumps with 63 ft of head above pump station. LPs occur just downstream of pump discharge
7	pump station #6 off	Yes	0	0	Elevated storage ~300 ft from pumps with 121 ft of head above pump station
8	pump station #7 off	No	0	23	Elevated storage ~ 1.4 mi away with 148 ft of head above pump station
9	pump station #8 off	No	16	107	Negative pressures occurred near pump station
10	pump station #9 off	No	5	25	Negative pressures occur within 0.4 mi of pumps
11	pump station #10 off	No	7	47	Elevated storage ~ 1 mi away with 114 ft of head above pump station
12	pump station #11 off	Yes	2	22	Elevated storage ~ 500 ft away with 51 ft of head above pump station
13	pump station #12 off	No	0	47	-
15	pump station #13 off	No	35	88	Negative pressures extend several miles from pump station
16	pump station #14 off	No	3	67	Elevated storage ~ 1 mi away with 97.5 ft of head above pump station
17	pump station #17 off	No	30	135	Negative pressures occurred near pump station and at/near a dead end location ~27 miles away (~20 ft above pump station)
18	pump station # 17 off + 100-gal HP tank	No	2	90	--

19	pump station # 17 off + 500-gal HP tank	No	1	39	--
20	pump station # 17 off + 1000-gal HP tank	No	0	22	--
21	pump station #18 off	No	3	93	Negative pressures occur at locations 15 to 20 feet above the pump station
22	pump station #21 off	No	3	49	--
23	pump station #22 off	Yes	0	0	Elevated storage located 0.5 mi away with 139 ft of head above pump station
24	1-inch main break on 54-in main 1.3 miles downstream of pump station #3	No	74	293	Most negative pressures located along branching 16-in and 54-in mains

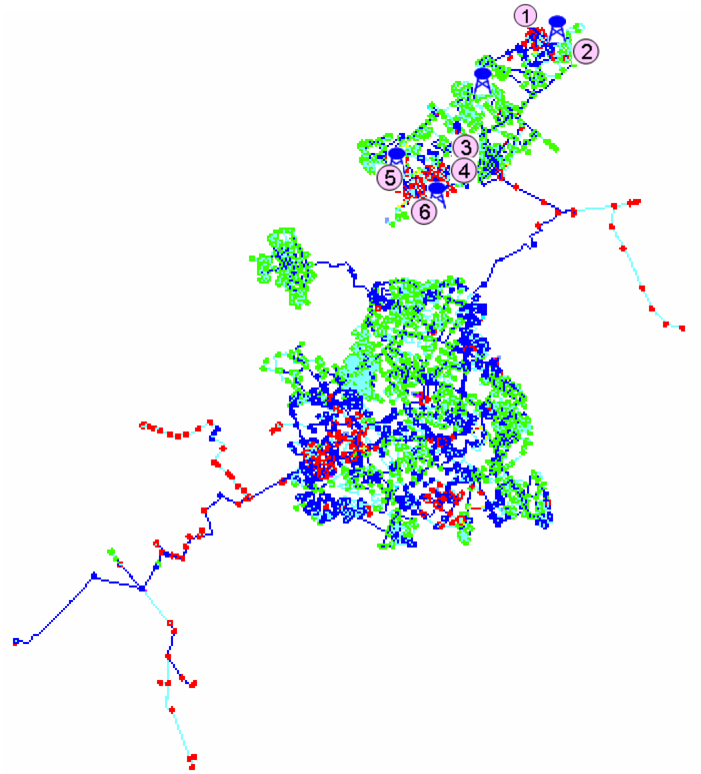

Figure B5. Low and negative pressure nodes resulting from a complete loss of pumping power

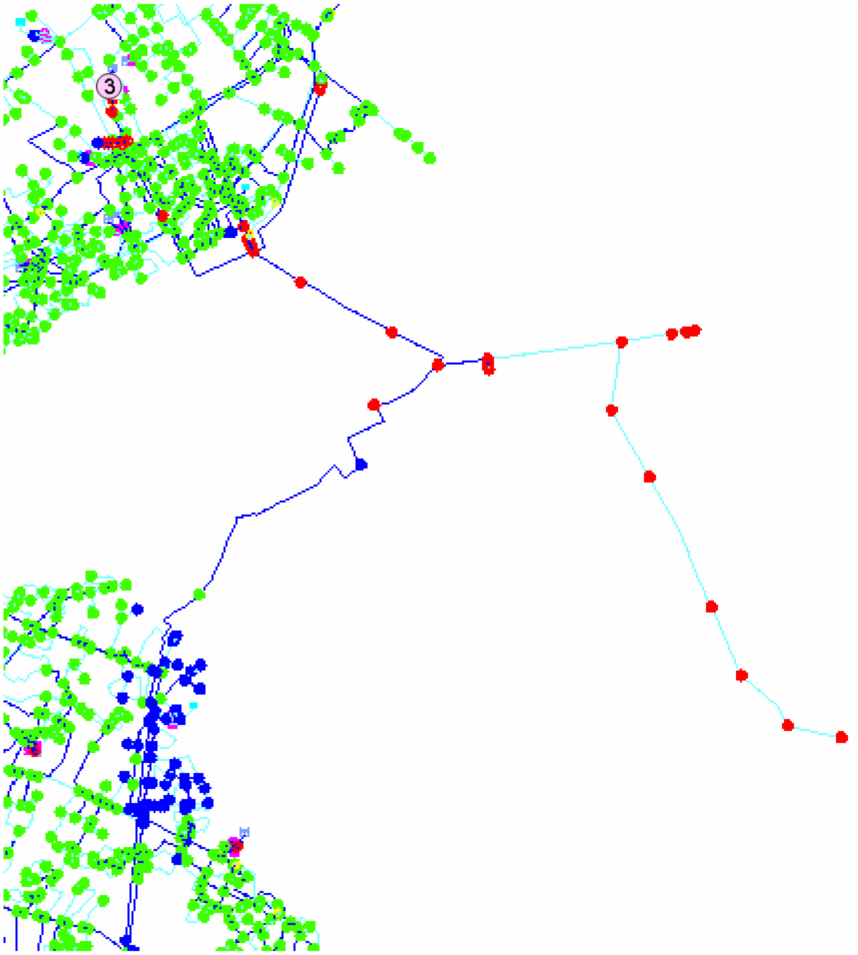

Figure B6 Low and negative pressure nodes when pump station # 3 shuts off

System 4

In System 4, maximum flow from storage occurred at time 9:00 hrs and maximum flow to storage occurred at time 1:00 hrs. Flow supplied to the system from pumps at 9:00 hrs and 1:00 hr were 81 mgd and 69 mgd respectively. Table B7 summarizes the pump operating conditions at 9:00 hrs and Table B8 summarizes the low and negative pressures that occur in the system under several transient producing simulations at this time. The distribution system model used for this system had a total of 1,679 nodes.

Table B7
Pump operating conditions in System 4 @ t= 9:00 hours

Pump Station #	Elevation (ft)	# Operating pumps	Flow @ 12.90 hr		Max Downstream Velocity (ft/s)
			gpm	mgd	
1	402	2	5,288	7.6	3.8
2	555	1	30	0.04	0.2
3	172	1	1,424	2.1	1.0
4	133	1	3,564	5.1	3.6
5	265	1	3,255	4.7	5.3
6	175	3	13,945	20.1	4.4
7	160	2	1,398	2.1	1.4
8	292	2	7,095	10.2	5.0
9	460	1	1,206	1.7	3.4
10	280	2	1,438	2.1	4.1
11	483	2	1,095	1.6	2.1
12	198	3	6,835	9.8	1.1
13	215	1	1,612	2.3	1.6
14	370	2	2,198	3.2	6.2
15	180	2	2,596	3.7	4.2
16	250	2	1,673	2.4	4.7
17	563	2	583	0.8	1.8
18	524	2	423	0.6	0.6

Table B8
Summary of surge analyses performed for System 4 @ t = 9:00 hrs

Run #	Transient Event	Tank within 1 mile?	# nodes with pressures < 0 psi	# nodes with pressure 0 to 20 psi	Comments
1	complete loss of pumping power with all open pipes	in some locations	197	328	See Figure B7
2	pump station #8 off	No	0	12	--
3	ramping up to 1,500 gpm in 5s on 24-in, 2.3 mile main	No	126	174	most negative pressures were at local elevations > 60 ft above surroundings and near closed pipes/valves. Initial water velocity = 5.0 ft/s
4	15-in main break along 24-in, 2.3 mile main	No	45	79	--
5	24-in butterfly val. + 5-s linear open/close	No	0	12	--
6	24-in gate val. + 5-s linear open/close	No	0	13	--

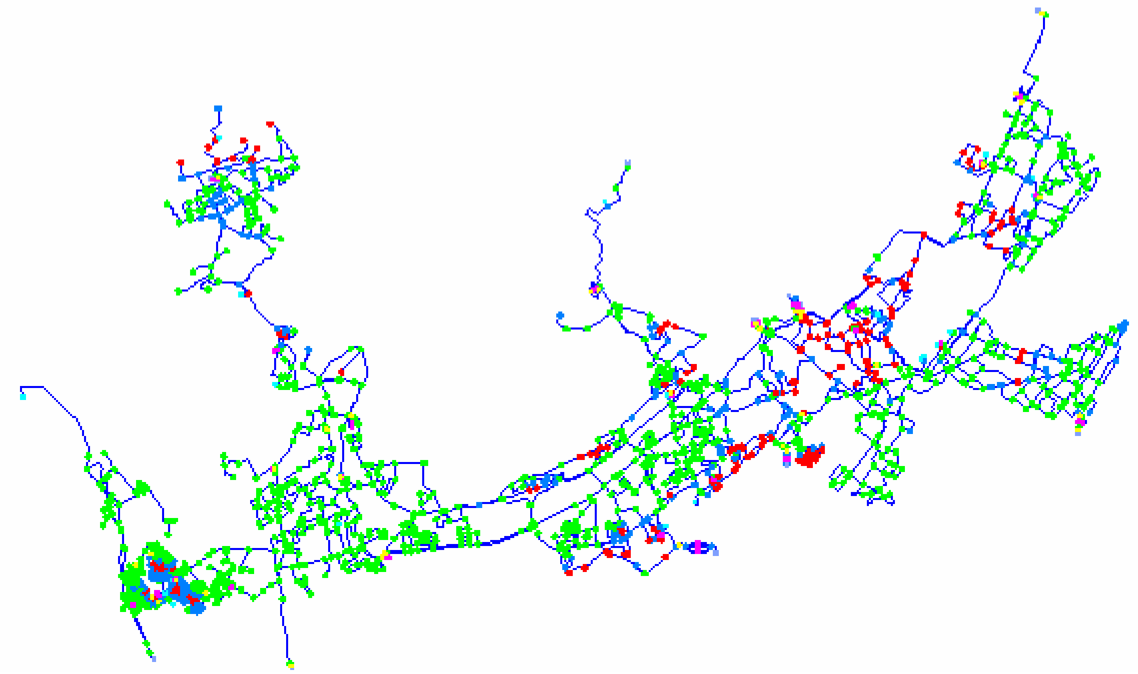

Figure B7 Low and negative pressure nodes resulting from a complete loss of pumping power.

APPENDIX C

LIST OF PUBLICATIONS AND PRESENTATIONS RESULTING FROM THIS PROJECT

Publications

Fleming K.K., R.W. Gullick, J. P. Dugandzic and M.W. LeChevallier. 2006. *Susceptibility of Distribution Systems to Negative Pressure Transients*. AWWA Research Foundation. Denver, CO.

Fleming K.K., R.W. Gullick, J. P. Dugandzic and M.W. LeChevallier. 2005. *Susceptibility of Potable Water Distribution Systems to Negative Pressure Transients.* Report prepared for the New Jersey Department of Environmental Protection, Trenton, NJ.

Presentations

Fleming K.K., R.W. Gullick, J. P. Dugandzic and M.W. LeChevallier. 2006. Using Modeling to Determine Distribution System Vulnerability to Backflow. To be presented at the NJAWWA Spring Conference in March 2006.

Fleming K.K., R.W. Gullick, J. P. Dugandzic and M.W. LeChevallier. 2005. Using Distribution System Modeling to Identify the Potential for Low Pressure Transient Events. Presented at the MWH International Geo-engineering Conference on August 8th 2005.

Fleming K.K., R.W. Gullick, J. P. Dugandzic and M.W. LeChevallier. 2005. Identifying the Potential for Low Pressure Surge Events Using System Modeling. Presented at the NJAWWA Spring Conference on March 31st 2005.