Transient Modeling of a Full-Scale Distribution System: Comparison with Field Data

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Abstract: The usefulness of transient models depends on their predictive ability. Consequently, their results should ideally be validated with field data. Despite numerous theoretical developments in the area of surge analysis, comparisons between field and modeled data for large distribution systems (DSs) are scarce. Transient low-pressure events at a water treatment plant (WTP) resulted in negative pressures at numerous locations in the DS. Three distinct surge events were measured in a full-scale DS and modeled with transient analysis software. The simulated pressure profiles were compared with field data collected from 9–12 sites within the DS. The objective was to apply a commercial transient analysis algorithm to a large and detailed network model ($\approx$15,000 nodes/pipes) to estimate transient pressure variations within the network. Results showed similar trends for the three low-pressure events analyzed: the modeled pressures matched reasonably well with the measured pressures, as long as they remained positive. Whenever the pressures reached negative values, the simulated amplitude was larger than that of the recorded pressures. Modeling parameters and factors that might explain such results were tentatively investigated. The importance of field data in understanding and confirming the model outputs is highlighted. **DOI:** 10.1061/(ASCE)WR.1943-5452.0000109.

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Introduction

A growing interest in the occurrence of negative pressures in drinking water distribution systems (DSs) and their potentially adverse impact on tap water quality appears in the literature (Boulos et al. 2006; Fleming et al. 2006; Wood et al. 2005a; LeChevallier et al. 2004; Karim et al. 2003; LeChevallier et al. 2003; Kirmeyer et al. 2001; Funk et al. 1999). However, it is still unclear if intrusion represents a critical risk to public health. Because field sampling of intrusion volumes is practically unachievable, transient analysis represents a valuable tool for estimating potential intrusion volumes. To more accurately estimate the DSs' propensity for intrusion, confirmatory research requires the comparison of transient model output and field data. The fit between modeled and recorded pressure profiles needs to be assessed, because the calculations for intrusion volumes are performed with the low and negative pressure values and duration, not just with the transient amplitude or pressure range, which were the focus of many previous studies (Gullick et al. 2005; Friedman et al. 2004; LeChevallier et al. 2004). It is the first time that a wave characteristics method (WCM) transient analysis algorithm is used to model a large and complex network such as the one studied here, for which several transient negative and low pressure recordings are available to compare modeling with reality. Moreover, the simulated events are not artificial events generated only for the purpose of validating the transient modeling, but events that occurred during normal operation.

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Objectives

This article reviews published studies focusing on the comparison of simulated and measured transient pressure profiles and then documents such a comparison for three downsurge events recorded in a large and detailed DS. The objective is to determine how accurately a carefully calibrated commercial transient model can replicate, and thus predict, low and negative transient pressures. The rationale for this research is to apply a transient model for estimating intrusion volumes associated with downsurge events, with the ultimate goal of assessing the risk to public health.

Previous Studies Comparing Field and Modeled Transient Pressure Events

Comparisons of transient pressure data from field monitoring in a full-scale DS with model results have been reported in five previous studies. The primary characteristics of the DSs investigated and the models developed are summarized in Table 1. The level of skeletonization is expressed as the percentage of original pipe length used in the simplified model.

Table 1. Characteristics of DSs and Transient Models Used for Comparison of Field and Simulated Transient Pressures

Authors	McInnis and Karney 1995		Kirmeyer et al. 2001		LeChevallier et al. 2004; Gullick et al. 2005	Friedman et al. 2004		Fleming et al. 2006		
Software	*TRANSAM*		*SURGE 5.2*		*Surge2000*	*Surge2000*		*H2OSURGE*		
Numerical method	MOC		WCM		WCM	WCM		WCM		
Distribution system	Bearspaw Northwest		A	B	Davenport (Iowa)	5-Davenport (Iowa)	2	2	13	14
Characteristics of DS	1 pump station, 2 booster pump stations, 1 reservoir, 1 PRV		Pop. 550,000, 1 PZ, 2 pumps, 2 tanks, 2 cone valves, 11 connections to the balance of the DS	Pop. 100,000, 51 PZ, 11 pumps, 8 reservoirs, 27 tanks, 45 PRV	7 PZ, 12 supplies, 30 pumps	Pop. 130,000, 7 PZ, 7 pump stations, 1 reservoir, 5 tanks, 2 PRV	Pop. 300,000, 2 PZ, 2 WTP, 12 tanks	Pop. 1,305, 1 PZ, 1 pump, 1 tank	Pop. 30,900, 1 PZ, 9 pumps, 2 tanks, 1 standpipe	Pop. 83,000, 1 PZ, 18 pump stations, 7 tanks
Original pipe length (km)	90		443	886	871	—	—	10	149	660
Level of skeletonization	33%	—	11% and 100%	100%	100%	Min. d = 152 mm	—	100%	65%	82%
No. of pipes	132	47	156	666	1,703	—		109	624	2,570
No. of nodes	123	38	102	528	1,146			91	397	1,733
Wave speeds (m/s)	On the basis of Hazen-Williams C: 1,140, 1,150, 1,160, 1,200		—		915	Sensitivity analysis: 610, 760, 915, 1,065, 1,220	On the basis of diameter and material: 435–1,340	1,100	915	760

Note: The following abbreviations appear in Table 1—MOC is method of characteristics, Pop. is population served, PRV is pressure reducing valve, PZ is pressure zone, and WCM is wave characteristics method.

McInnis and Karney (1995) compared the pressures recorded after pump trips with modeled pressures to evaluate the impact of different demand models. They reported a good agreement between modeled and field pressures for the first downsurge, though a phase shift was observed for residual pressures. Energy dissipation was more significant in the real network than in the numerical model.

Friedman et al. (2004), LeChevallier et al. (2004), and Gullick et al. (2005) conducted field monitoring and transient modeling of the Davenport, Iowa, DS. Their monitoring showed that a low-pressure event caused by a 6 min power outage at a water treatment plant (WTP) resulted in a minimum pressure of 6.7 m. Calculations for the transient modeling of the Davenport system were performed with commercial software from KY Pipe, in Lexington, Kentucky, to simulate this power failure: eight scenarios with different numbers of operating pumps were created, because it was not known how many pumps were in service at the time of the outage. The modeled pressures roughly matched the recorded pressures at the six sites for which field data was available, although only the pressure range (i.e., minimum and maximum pressures) and pressure drop were considered. By using the same data, Gullick et al. (2005) observed that the slope of the pressure increase between the minimum pressure and the new steady-state pressure matched poorly. The maximum difference between field and calculated pressure drops was 33 m. This same power outage event was also presented in Friedman et al. (2004) who highlighted the uncertainty associated with the lack of knowledge of the system's operating conditions at the time of the surge event as a possible cause of the observed disagreement.

In addition, Friedman et al. (2004) conducted transient analyses for another DS, for which the surge model was calibrated by using both steady-state and transient field data, with recorded transient pressures as low as −7 m. After calibration, the pressure differences between model results and field data during transients ranged between 1 and 13 m (Average = 6 m). The calibrated transient model was evaluated by replicating, in the field, two modeled scenarios. The comparison of simulated pressures with pressure profiles from three monitoring sites showed that the magnitude of the predicted surge was smaller than that of the recorded transient. The recorded pressure drop was sharper than the modeled one, and the many small oscillations defining the return to the steady state in the field pressures were absent on the computed graphs. Friedman et al. speculated that these inadequacies could be attributable to the modeling of the pump as winding down to a stop at a constant rate, rather than closed with a valve or a combination thereof.

In subsequent studies, as in the Friedman et al. (2004) validation discussed in the preceding paragraph, researchers first conducted transient modeling of the network and then high-speed pressure transient data loggers were installed in vulnerable areas. The numerical modeling performed by Kirmeyer et al. (2001) indicated that a potential for the development of low and negative pressure transients under routine operations existed in two DSs, but the surge model was not calibrated with transient pressure recordings. Pressures were later recorded in these systems to verify this susceptibility. In one of the two monitored DSs, pressures were recorded at 10 different locations for a period of 2–43 d. In the other system, pressures were recorded at four sites only during specific activities, such as valve or hydrant operations. No negative pressures were recorded in either system; the lowest recorded pressure was 3 m. No attempt was made to reconcile surge modeling outputs and field pressure profiles.

Transient models of 16 U.S. DSs were developed by Fleming et al. (2006). Pressure transducers were installed in three water networks in areas identified, by transient simulations, as vulnerable to negative pressures attributable to pump shutdowns. Only one negative pressure (−0.2 m) was recorded. For two of these DSs, the researchers concluded from the comparison of the modeled and the field pressures for a pump shutdown event that numerical models tended to overestimate downsurges.

In all aforementioned studies, the recorded pressures remained above the theoretical vapor pressure (i.e., cavitation head) of water at 20°C (−10.1 m). However, the literature does not specify if the modeled pressures reached the cavitation head. Most writers (Fleming et al. 2006; Kirmeyer et al. 2001; McInnis and Karney 1995) ignored the effect of free or dissolved air. Some writers (Gullick et al. 2005; Friedman et al. 2004) employed smaller wave speeds to adjust for the possible presence of air, but none of the previous studies considered a two-phase flow.

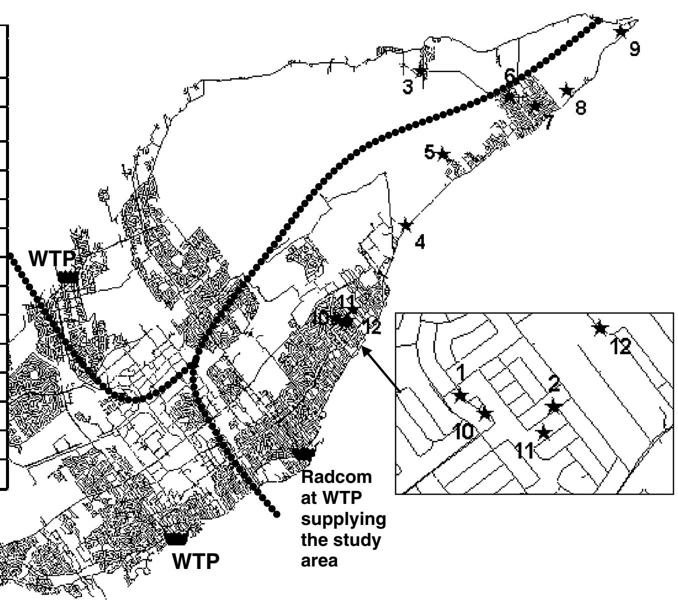
Previous studies aimed at comparing demand models (McInnis and Karney 1995), evaluating the maintenance of a positive pressure barrier to external contamination (LeChevallier et al. 2004), predicting the most conservative downsurges (Gullick et al. 2005), examining the impact of various surge protection devices and strategies (Gullick et al. 2005; Friedman et al. 2004; LeChevallier et al. 2004), and evaluating the usefulness of a worst-case uncalibrated surge model in providing information about vulnerable locations (Fleming et al. 2006; Kirmeyer et al. 2001) and intrusion potential (Kirmeyer et al. 2001). The goal for the current work is to evaluate how accurately a carefully calibrated commercial transient model can replicate low and negative transient pressures.

As shown in Table 1, the selected transient software employs either the method of characteristics (MOC) or the WCM to numerically solve the governing equations. These numerical algorithms are described in detail in Boulos et al. (2005) and Wood et al. (2005b). Both the MOC and the WCM are essentially wave propagation techniques; for each time step, both methods obtain a solution at all nodes. However, the MOC involves segmenting the pipes, to perform calculations at interior points on links. Such a procedure provides a more detailed support for vapor volume calculations along each pipe, and allows for a more complete distribution of friction and demand. With the WCM, the demand is allocated to nodes, and the friction is uniformly assigned to pipes as a whole, by using a single calculation per link. The longer the model pipes, the more error this simplification introduces. However, the WCM is computationally more efficient, and can thus be employed to solve larger systems. Studies comparing these numerical methods usually show an excellent agreement between the MOC and the WCM, with virtually identical pressure profiles for the two methods for most systems (Boulos et al. 2005; Wood et al. 2005b). However, these comparisons were conducted with relatively small networks (≤ 797 pipes), and for positive pressures only.

Methodology

Description of the Distribution System

The studied DS serves a population of about 380,000. The average daily demand is approximately 210,000 m^3/d and is supplied by three WTPs by using surface water as their raw water source. Though each WTP feeds the system at a different location, the entire network is hydraulically interconnected. In normal conditions, and as demonstrated by trace analyses, the DS area studied is supplied by a single WTP, as shown in Fig. 1. Apart from the clearwells at the WTPs, no storage tanks or pump stations are present in the interior of the network. Air-vacuum and combination air valves are the only types of surge protection devices installed in the DS. Each pump at the WTP is equipped with a pressure-reducing valve set at 60 m and a 50 mm air release valve, and a pressure relief valve with an opening pressure of 70 m is installed on the transmission main. The DS has a total length of 1,590 km, with pipe materials including cast iron (41% of the total pipe length), ductile iron (35%), prestressed concrete (10%), and PVC (8%).



Node	Elevation (m)
WTP	21.5
Telog	
1	43.7
2	49.9
3	18.9
4	12.2
5	20.9
6	19.1
7	16.3
8	15.2
9	11.0
10	45.6
11	49.7
12	48.9

Fig. 1. Location of pressure loggers in the DS for the period June–September 2006; dotted lines represent approximate boundaries of the WTPs' zones of influence; Radcom and Telog are the sensors used

Pressure Monitoring

Pressure monitoring of the study area and the supplying WTP was conducted for 17 months (June 2006–November 2007), by using high-speed pressure transient data loggers. The three events modeled took place during the summer of 2006. Sensors 1–9 (Fig. 1) were in place from June 20–September 8, 2006; Sensors 10–12 were installed on June 29.

Pressure monitoring was conducted by using two types of high-speed pressure transient data loggers. The RDL 1071L/3 model from Radcom Technologies in Woburn, Massachusetts, has a range of −11–158 m and was installed directly on a transmission main, downstream of all pumps, at the outlet of the WTP. Pressure values were read every second, and a tolerance of ±1 m was set for the recording of a new pressure reading. Before installation, the Radcom logger was zeroed to atmospheric pressure according to the manufacturer's instructions. The HPR31 model from Telog Instruments in Victor, New York, has a range of −11–141 m and was set to its maximum reading capacity of four pressure values per second, but only minimum and maximum pressure values over intervals of 15 s were recorded on the device's memory card. Telog sensors were installed on fire hydrants in the DS. Initially, loggers were positioned to examine DS areas with a history of low pressures, typically higher elevation locations, and to cover the area studied by Payment et al. (1997) in their seminal epidemiological studies. Some loggers were positioned in dead ends to tentatively observe wave reflections. Additionally, one node at the boundary of the WTP zone of influence was surveyed.

Transient Modeling

Three distinct downsurge events, initiated at the WTP and resulting in negative pressures in the DS, were modeled. These events were recorded on June 27, August 2, and August 22, 2006, and were caused by power failures (i.e., short power interruptions) causing pump shutdowns. Table 2 provides more details about these downsurges.

Surge modeling was conducted with the WCM-based *InfoSurge* software. For simulating cavitation, the discrete vapor cavity model (DVCM) was implemented within the WCM transient analysis framework (Jung et al. 2009b). The DVCM is the simplest and most widely used cavitation model. It is generally implemented in software intended for the analysis of large DSs because of its computational efficiency. Its use is acceptable in cases for which the potential cavities would form in isolated portions of the system, such as in elevated areas (Wylie and Streeter 1993). Some other models, such as the discrete gas cavity model (DGCM), are believed to be more accurate but are more complicated and time-consuming and require more input parameters (Bergant et al. 2006). The value of these additional input parameters can only be assumed for large and complex DSs.

The transient model was developed from the most up-to-date version (i.e., August 2007) of the extended period simulation (EPS) hydraulic model used by the water utility. The consumption data in the EPS model corresponded to average day demands. Because the studied network was not metered, the distribution of the demand at the time of the low-pressure events was unknown. Unmetered utilities are not unusual in the province of Quebec, in which only 20% of households are equipped with meters (Roy 2007). Hence, the only recorded information related to demand during the low-pressure events was the flow out of the three WTPs. For the simulations, the total flow recorded at the outlet of the WTPs was divided by the total model demand at the time of event, on the basis of the average day demand values and patterns, to obtain a global demand factor (GDF). Model average demands at the time of event were multiplied by the GDF, which was then held constant for the duration of the transient simulation (i.e., 300 s). This demand adjustment method was considered to be the best approach to account for the event-specific conditions.

Because the original model contained an unwieldy 29,213 nodes and 32,266 links, the skeletonization of the EPS model was conducted to reduce both the model complexity and the associated computational burden. The replacement of two or more pipes in parallel or in series by a single hydraulically equivalent pipe and the trimming of dead ends were not employed during the skeletonization process, as these traditional rules of steady-state model skeletonization ignore the complex interaction of transient pressure waves with different pipe properties and configurations (Jung et al. 2007). Instead, the interior nodes of series pipes with the same attributes (e.g., diameter and material) were eliminated, if the elevation difference between pipes end nodes was smaller than 2 m. The associated pipe segments were then combined into single, longer pipes. The nodal demands of the dissolved interior nodes were

Table 2. Description of the Low-Pressure Events Recorded at the WTP

Date and time of event	Operating pressure prior to event (m)	Minimum pressure recorded (m)	Time to reach back to normal pressure (min)
2006-06-27 17:19	43.2	7.0	3.3
2006-08-02 23:10	37.8	7.8	2.0
2006-08-22 08:21	44.2	3.6	3.0

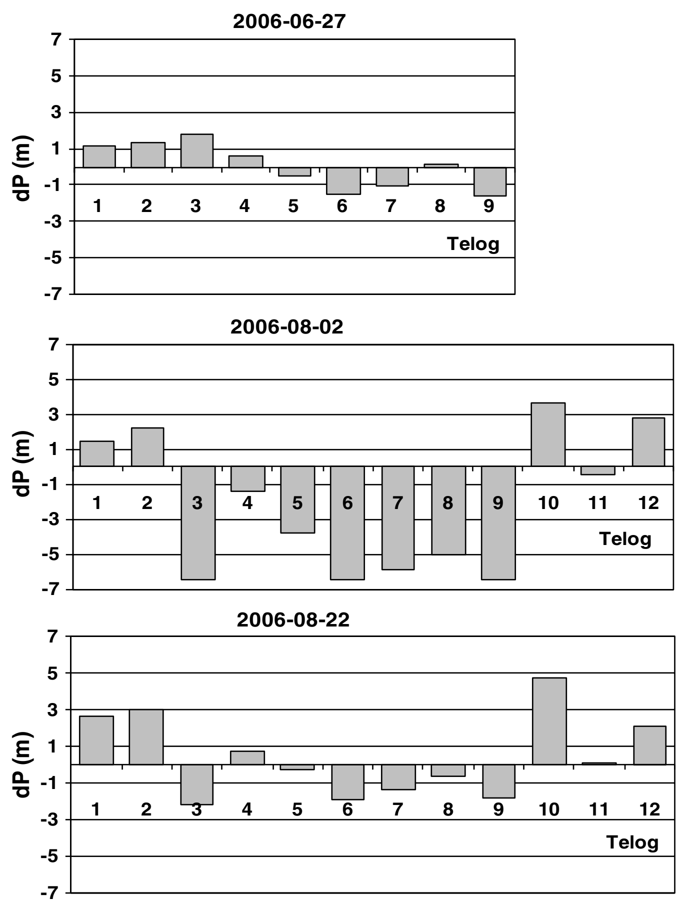


Fig. 2. Steady-state pressure differences (dP) between modeled and recorded pressures for the different monitoring locations and downsurge events; negative difference indicates recorded pressure > modeled pressure

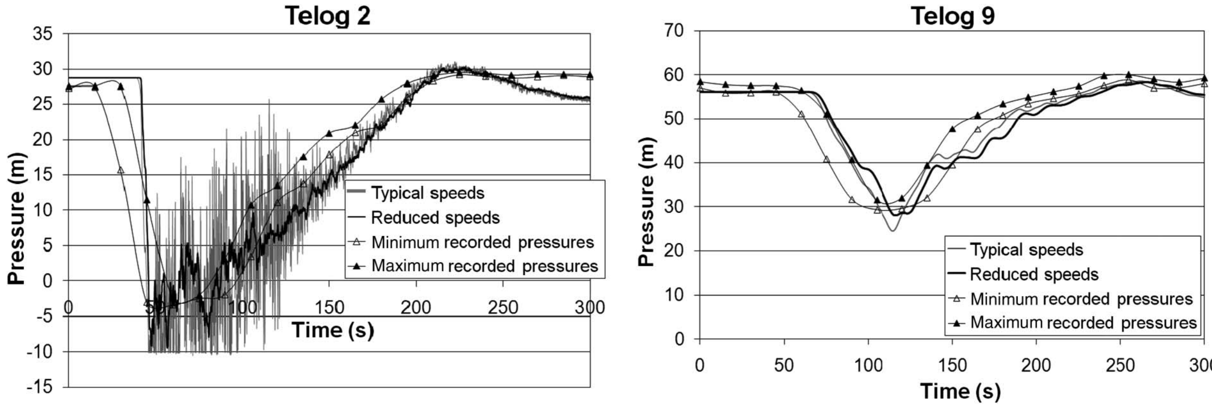


Fig. 3. Comparison of pressures recorded at two nodes and pressures modeled with typical wave speeds and with a reduced wave velocity in cast-iron pipes for the June 27, 2006, event; 4 pressure values were measured per second, but only the minimum and maximum pressures in each 15 s interval were saved

reallocated so that the skeletonization of the series pipes with the same attributes had only a minor effect on the surge analysis. The model size was thus decreased to 15,965 nodes and 19,044 pipes, preserving the original length of pipe and the total demand. Emphasis should be put on the facts that all DSs are skeletonized to some extent; for example, service and hydrant connections are rarely included in a utility's hydraulic model; and that the level of skeletonization of the model is minor, as it still includes more than 15,000 nodes and pipes. The key question is always an intensely pragmatic one: are the conclusions sensitive to the details omitted from the model? If the answer is clearly no, as would be the case here, the model representation is provisionally accepted as suitable and appropriate.

Typical wave speeds on the basis of pipe material were assigned to mains by using the chart provided in Boulos et al. (2006). Values of 1,060 m/s for cast iron, 1,200 m/s for ductile iron, 600 m/s for prestressed concrete, 300 m/s for PVC, and 1,200 m/s for steel were used. Minor adjustments in wave speed for pipe size and bedding conditions were not considered as part of this study.

For each low-pressure event, the boundary conditions of the surge model consisted in the recorded information about (1) pressure (1 value/s) and flow (1 value/10 min) out of the WTP supplying the studied area; and (2) pressure and flow out of the other two WTPs (1 value/10 min). Ten minute records were obtained from the water utility supervisory control and data acquisition (SCADA) system. At the WTP supplying the studied area, nine pumps were available to deliver water into the DS. Unfortunately, no record of which pumps were operating at a specific time in the past was available. From the flow and pressure recordings at the outlet of the WTP, it was estimated that three pumps were in operation before each power failure. Each sudden pump shutdown was simulated by using a pump trip, and the subsequent pressure changes were created with a pump speed change curve. The resulting pressure profile matched the measured pressure profile at the pumps discharge. The pump closure was set to start at $t = 30$ s after the start of the simulation.

The locations of 30 air-vacuum and combination air valves were known for the studied DS. Because design-specific characteristics of these valves were not available, single stage air-vacuum valves were assumed to be designed according to the American Water Works Association (AWWA) rule of thumb, [e.g., 25 mm inlet size per 300 mm of pipe diameter (AWWA 2004)].

In conventional water distribution models, it is presumed that the nodal demand is independent of the pressure (i.e., demand-driven analysis), and is satisfied under all operating conditions including zero and negative pressures. Under transient conditions, the pressure may drop to or below zero, so that the demand in the actual system will not be met. Therefore, a pressure-sensitive demand formulation was utilized for all surge analyses, as recommended in Jung et al. (2009a) and McInnis and Karney (1995).

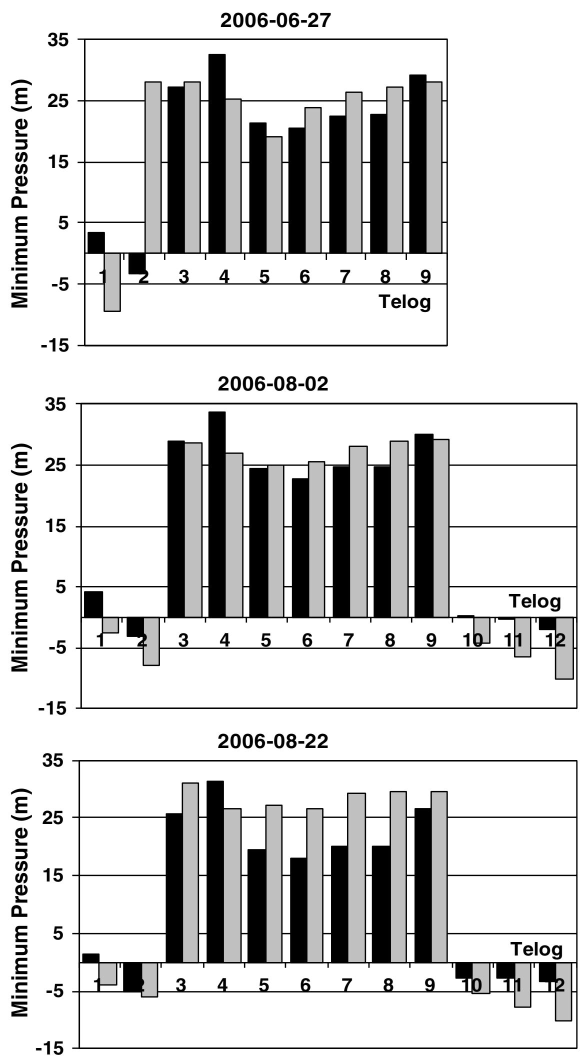


Fig. 4. Comparison of the computed (reduced wave speed) and the recorded minimum pressures for the different monitoring locations and downsurge events (black = Field; gray = Model)

Results

Steady-State Pressures

Differences between the modeled and the recorded steady-state pressures at each monitoring site prior to the occurrence of the low-pressure event ranged from 0–6.5 m (Fig. 2). Larger discrepancies were observed for the August 2 event.

Transient Pressures

The pressure profiles recorded at two DS locations were compared with the calculations for the pressures derived by using the typical wave velocities in Boulos et al. (2006) (Fig. 3). This figure clearly illustrates that the model simulates the downsurges fairly well as long as the pressure remains positive (i.e., Telog 9). Whenever the pressure is low or negative, the amplitude of the modeled pressure drop exceeds the actual drop; sometimes so much that the model run with typical wave speeds predicted water column separation at numerous monitoring nodes. However, recorded pressure profiles showed that the cavitation head (i.e., vapor pressure) was never reached at monitoring locations, with −5.1 m recorded as the lowest measured pressure. This overestimation of the downsurges amplitude is inconvenient, because the shape of the pressure profile is very different when cavitation develops.

Because many variables are either unknown or uncertain, adjustments were made to various parameters to improve the representation of the real network by the model. Considering the uncertainty of nodal demands at the time of the events, the magnitude and distribution of the demands were altered, but it was found that the model was quite insensitive to this parameter. The wave speeds initially chosen were typical values for a given pipe material, but they did not take into account the size, class,

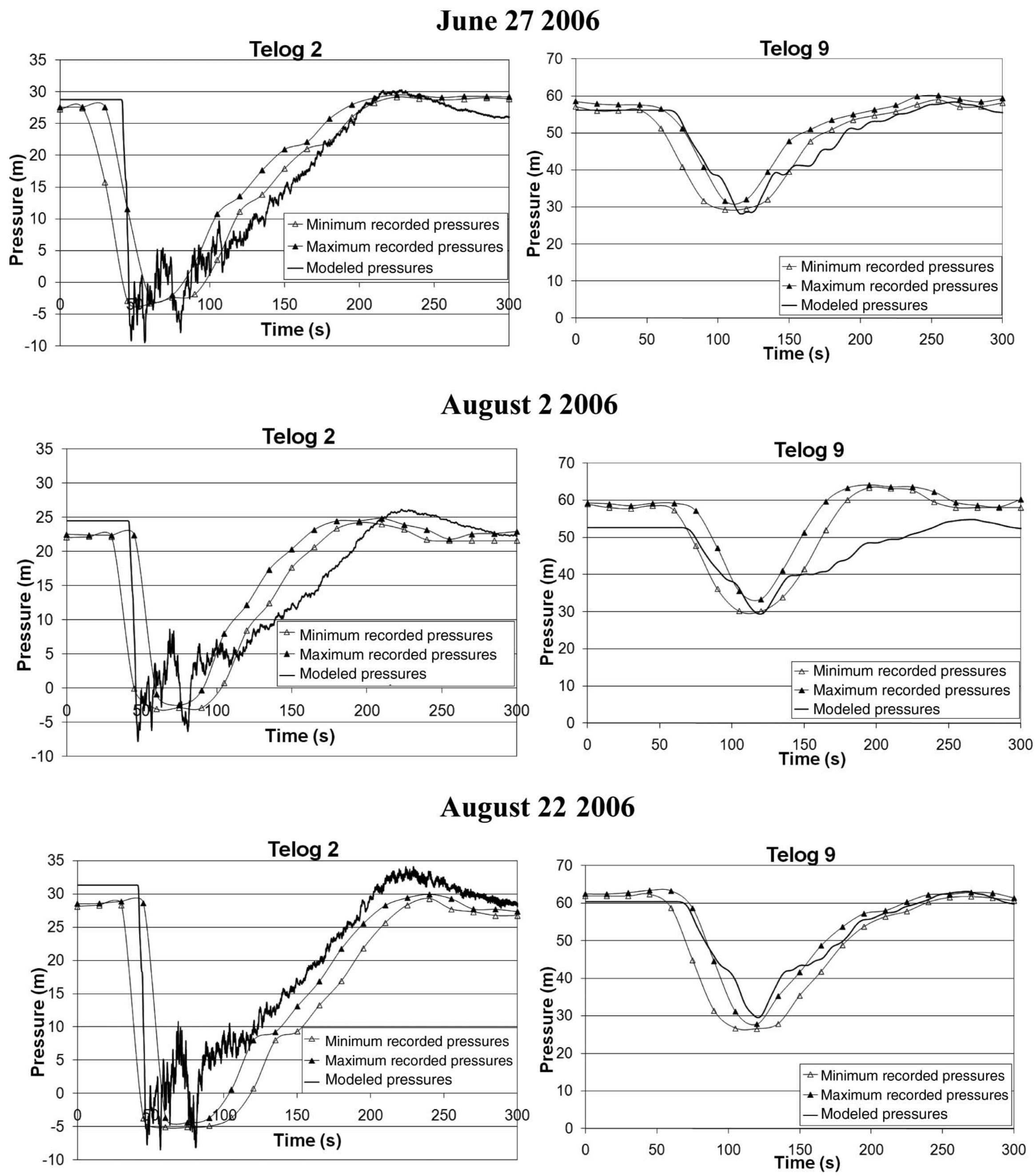


Fig. 5. Comparison of modeled (reduced wave speed) and recorded pressure profiles at two nodes for the three low-pressure events

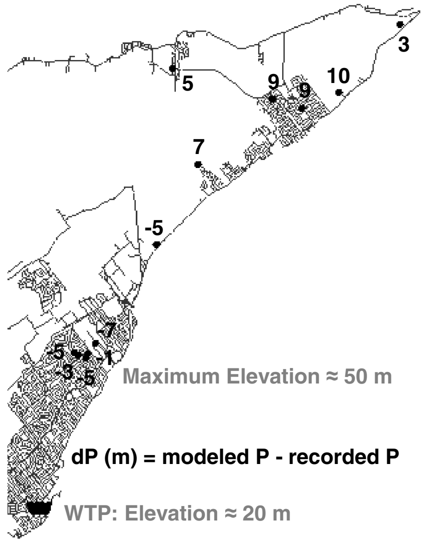


Fig. 6. Georeferenced pressure differences between modeled (reduced wave speed) and recorded values for the August 22, 2006, event; negative difference indicates recorded pressure > modeled pressure

or age of the individual pipes and the possibly variable air content of the water. The model response was tested for variations in the wave speed of all pipes and of pipes made of a certain material and was found to be sensitive to wave speed values. The effect on the simulated pressure profiles of a reduced wave speed in cast-iron pipes is illustrated in Fig. 3. With a lower wave speed, the minimum simulated pressure was higher, and, as expected, the event was slightly shifted forward in time. The percentage of wave speed decrease (i.e., 50%) was selected on the basis of the fit of modeled pressures with recorded pressures. For the June 27 event, when reducing the wave speed in cast-iron pipes from 1,060 m/s to 530 m/s, the portion of nodes experiencing negative pressures dropped from 8% to 4%.

All subsequent figures include only pressures computed by using a reduced wave speed in cast-iron pipes. For each low-pressure event, the computed and measured minimum pressures at all monitoring sites are displayed in Fig. 4. Sites 2, 10, 11, and 12 were vulnerable to negative pressures, whereas the pressure remained positive at all other sites, although sometimes below 14 m at Site 1. Modeled and recorded pressure profiles are compared in Fig. 5 for two DS locations (i.e., Telog 2 and Telog 9).

Pressure differences between model outputs and measurements were geographically positioned (Fig. 6). This figure clearly shows an area for which the predicted pressures are lower than the recorded pressures; the area for which the negative pressures were recorded. This affected zone has the highest elevation (i.e., 30 m above the WTP), which makes it more prone to low pressures and to air accumulation, although the extent of the latter parameter is unknown.

Discussion

In the 9–12 sites in the DS for which a comparison between field and modeled data was conducted, the computed steady-state pressures generally matched closely the pressures recorded prior to the transient events. As shown in Fig. 2, the maximum pressure difference between modeled and measured steady-state pressures was 6.5 m, which is smaller than the maximum variations reported by Gullick et al. (2005) and Friedman et al. (2004). These variations are likely attributable to the different hydraulic conditions in the field between the times of the EPS model calibration and the transient event occurrences. Because system demands were not recorded during the low-pressure events, it was difficult to refine the calibration with so little information. Moreover, even if another set of boundary conditions, such as a different distribution of demands, would improve the fit between modeled and recorded steady-state pressures, this set might not represent the actual DS conditions at the times of the transient events, and thus might cause different transient responses with the given low-pressure events.

The deviations among the transient minimum pressures (Fig. 4) do not appear to be correlated to the steady-state pressure differences (Fig. 2). The lack of correlation can be partly explained by the fact that the transient analysis requires a more detailed and representative model to estimate the transient pressure extremes accurately, because the transient response is fairly sensitive to system-specific characteristics (Jung et al. 2007). One of the many possible causes of the disagreement between modeled and recorded pressures may be the approach used for modeling pumps and the available information on pumps, which was outdated.

Diameter is closely related to the system dynamics through the link between the water velocity and the wave speed, so the deviations between the transient modeled outputs and the recordings could also be partly attributed to uncertain pipe diameters. The interior pipe diameter is different from the nominal diameter, which is often used in models, and tends to decrease over time because of the buildup of corrosion products, tuberculation, and scaling. The wave speed is also a function of the pipe material, wall thickness, and restraint and of the fluid density, elasticity, and air and solids content (Wylie and Streeter 1993). Unfortunately, many of these parameters were unknown, and most pipe properties change over time. When metal pipes have been rehabilitated with a lining, their diameter is slightly reduced, and the other pipe properties become more similar to those of plastic pipes (Escarameia 2005), in which pressure waves travel at a lower velocity. Moreover, the present analysis presupposes that the DS was constructed as per the plans provided, which would not be the case for real networks of this extent, and that the status of valves in the model was in agreement with field conditions.

The larger simulated pressure drops, especially with typical wave speeds, indicated that greater energy dissipation occurred in the real DS. Pipe junctions create reflections, which are an important mechanism of energy dissipation (Karney and Filion 2003). Pipe friction also attenuates the energy associated with the pressure wave. The skeletonization process reduces the numbers of nodes and pipes, thereby decreasing energy losses by reflections and friction. The selected friction model and the uncertainty surrounding friction coefficients both have an influence on the transient pressure outputs. The standard steady-state friction model (Wylie and Streeter 1993) was implemented in the selected software. The unsteady turbulent friction model (e.g., Vardy and Brown 2007) is generally thought to be more representative of the physical reality, but it is more computationally intensive and its use requires more data.

Demands also are important dissipative mechanisms (Colombo and Karney 2003; Karney and Filion 2003) and considerable uncertainty remained regarding the initial distribution of flows. Although the use of a GDF takes into account the total demand value at the time of the event, the geographic distribution of nodal demands was assumed to remain unchanged as compared to that of the average day. However, real demands fluctuate almost continuously, modifying the pressure wave. For example, the recorded downsurge amplitude would be smaller than the modeled one if the local demand at the time of event were greater than the modeled demand. Consider that leakage is modeled as a demand; the percentage of leakage is a coarse estimate and adds to the uncertainty. Additionally, the demand behavior under transient conditions, which was modeled as pressure-sensitive in this research, is another uncertainty.

The impact of air in the transported water could be crucial because even a tiny amount of air momentarily greatly decreases wave speeds, which become variable and highly pressure dependent (Jung and Karney 2008; Friedman et al. 2004; Wylie and Streeter 1993; Wylie 1992). Air is present in two forms in DS pipelines: discrete air pockets and continuously distributed dissolved air. The water leaving the studied WTP was slightly oversaturated with O_2 (i.e., 1–2 mg/L) because of the degassing system following the ozonation process. This air could be released in low-pressure or higher temperature conditions.

An extended distribution of air pockets of various sizes dampens pressure waves by absorbing their energy and creating multiple reflections that have a destructive interference effect (Escarameia 2005). Small air pockets may noticeably decrease the amplitude of the pressure transients generated by an abrupt interruption of flow following pump shutdowns (Burrows 2003; Burrows and Qiu 1995). Air pockets are likely to be trapped just before the high points and at large changes in gradient. It is currently impossible to precisely evaluate the volume, distribution, and pressure of air pockets in a DS, and these quantities are continuously changing. Pressure recordings were performed in the summer, during which season more air is released because of the warmer surface water source, so that the effect of air pockets was at its peak.

Degassing of the dissolved air is also likely to occur during the passage of the low-pressure wave. As the pressure decreases below the saturation pressure, the dissolved air comes out of solution, almost instantaneously reducing the wave's pressure amplitude (Wylie 1992). The dissolved air having come out of solution will take considerable time to redissolve (Edmunds 1979; Lescovitch 1972). This phenomenon is rarely included in models, but some researchers (Lee 1994) have used variable wave speeds in a preliminary attempt to represent the release and absorption of gas (i.e., air and water vapor) as the pressure changes. In addition to existing air pockets and dissolved air coming out of solution, air also enters the DS by all leakage orifices (i.e., those not submerged under the water table) under negative pressures.

The presence of free air in the supplied water modifies the fluid properties as compared to design assumptions. It decreases its density and increases its elasticity, so that the wave speed is greatly reduced when gas bubbles are uniformly distributed throughout the fluid (Wylie and Streeter 1978). The wall shear and flow field are also modified because of the vertical momentum introduced by the buoyancy of air bubbles (Escarameia 2005). Multiphase modeling becomes necessary when the gas fraction is significant, and when water and air pockets move independently. Numerous levels of two-phase modeling exist. However, few of these effects are modeled in commercial software. The modified MOC assumes a homogeneous flow with the same velocity in each phase (Escarameia 2005). In such case, reduced values of wave speed can be used. In the studied DS, the average water velocity was 0.06 m/s with a standard deviation of 0.08 m/s, which is quite small. For pocket volumes between 5 mL and 5 L, air pocket velocities typically vary from 0.02–0.6 m/s for downward sloping pipes (i.e., 0°–22.5°) (Escarameia 2005). On the basis of these numbers, air bubbles in the tested system were likely to move with the water flow. The use of reduced values for wave speed therefore appeared appropriate, though it was certainly an ad hoc and grossly simplified approach to an exceedingly complex phenomenon.

The equations solved by the employed software do not represent all physical phenomena. For example, the programmed mass equation does not account for the viscoelastic behavior of the pipe walls, potentially significant for plastic pipes. Other factors that may explain some of the energy dissipation in the DS and that were not taken into account include acoustic and mechanical vibrations, hysteresis effects in the elastic behavior of the pipe walls, confining soil, fluid-structure interactions (McInnis and Karney 1995), and pipe biofilm (Picologlou et al. 1980; Zelver 1979). Several of these dissipative mechanisms, normally unimportant, may become significant during the collapse of vapor pockets following cavitation, as the generated transients are very rapid (Wylie and Streeter 1993). Additionally, simulations were calculated by using a WCM-based model; the conclusions of our study are subjected to the assumptions behind this numerical method.

To mimic the effect of air and other energy dissipation mechanisms that were not included in the model, the wave speed was reduced for the entire simulation duration. If large amounts of air are present, the wave speed varies with the local pressure (Escarameia 2005), because the amount of degassing and the size of air pockets depend on the lowest pressure attained. Consequently, in smaller diameter mains in which the pressure is typically lower, more air is likely to be released. In the tested DS, smaller diameter pipes are made of cast iron or plastic. Intuitively, the older cast-iron pipes would contain more air than plastic pipes of the same diameter, because the corrosion turbercles are likely to restrain the movement of air pockets that accumulate to the pipe soffit (Wylie and Streeter 1993). Moreover, in the DS, the larger gradient changes happen in cast-iron pipes, so these pipes are likely to contain more air. For these reasons, the wave speed was decreased only in smaller lower pressure cast-iron pipes. The selected reduced wave velocity of 530 m/s for cast-iron pipes corresponds to an air content of about 0.13% for a static water pressure of 33 m in a pipe with a wave speed of 1,125 m/s without any air (Wylie and Streeter 1993).

The discrepancies between the recorded pressures and the pressures modeled with the typical wave speeds are a symptom of the model's inability to correctly simulate all important energy losses. The wave speed reduction is a commonly applied artifice (Gullick et al. 2005; Friedman et al. 2004; Boyd et al. 2004; Wylie 1992). Boyd et al. (2004) decreased the wave speed to 16–17% of standard velocities to reproduce the effects of air entrainment in a pilot-scale test rig used to simulate intrusion during transient events. Likewise, when comparing experimental pressure data with the corresponding transient pressure profiles simulated by using the MOC and the DGCM, Wylie (1992) observed that transient pressure results were highly sensitive to the amount and distribution of free gas. He greatly improved the fit between the modeled and the recorded pressures by introducing small air fractions (e.g., 0.09%, close to the 0.13% equivalent air content used in our model, corresponding to a wave speed of 480 m/s at the initial pressure level) in modeled pipes for which no air content was reported by experimenters. The use of larger air fractions in the model showed a more rapid decay of the many oscillations observed only in the numerical pressure profiles. Even though decreasing wave speeds slightly postpone the arrival of the low-pressure wave, it remains an attractive solution because of its simplicity and of the better pressure fit. Thus, it is more likely to yield realistic estimates of the minimum pressures and the number of nodes affected by negative pressures.

For all these reasons, one must be careful with the results obtained from transient simulations if no field data are available for verification. Many writers have noted an overestimation of the computed downsurges (Fleming et al. 2006; Friedman et al. 2004; McInnis and Karney 1995), which is also apparent from our results. Field data are needed to confirm the transient modeling output before it is subsequently used as input into a public health analysis or for the design of surge protection devices, which would otherwise probably be greatly oversized.

Transient analysis is more complex than EPS modeling and water utilities should be aware that even if their EPS model is well calibrated, the calibration of the derived transient model will not necessarily be as good. For example, EPS hydraulic calibration is generally simplified by adjusting only friction coefficients, instead of adjusting both friction coefficients and pipe diameters. However, Jung and Karney (2008) warned about such mathematical simplification for transient model calibration, because the physical system is less accurately represented, and the hydraulic interaction of the pipe diameter with the system dynamics through wave velocity is neglected.

Additional information, such as metered consumption and pump operation history, certainly increases the predictive ability of the transient model, which can, in itself, be quite useful in determining the DS areas susceptible to negative pressures, even if there is an overestimation of the downsurge. However, if such a model is used to evaluate intrusion volumes, the computed pressure results are likely to introduce errors leading to an inaccurate evaluation of the potential contamination. The cavitation head will likely be attained too early by simulated pressures, completely modifying the subsequent modeled pressures behavior. Because the evaluation of the public health risk posed by intrusion events is directly related to intrusion volumes, the impact of transient pressure modeling, in such a process, is significant.

Conclusions

The objective of this paper was to create a realistic transient model of a large DS. The simulated pressure profiles were compared with transient field data. For the three downsurges generated by power failures at the WTP, the computed and measured pressures matched quite closely as long as the pressure remained positive. However, the amplitude of the modeled pressure drops was larger than that of the recorded pressures whenever the pressure fell below zero. The larger simulated pressure drops suggest that more energy dissipation occurred in the real DS, which could be explained by the presence of air, transient friction, the level of network skeletonization, and the allocation of demand, among other things.

The hydraulic engineers attempting transient modeling should keep in mind that the system is underdetermined: friction coefficients, distribution and values of demands, and wave velocities are only estimates. As a consequence, it can be exceedingly difficult to calibrate the model with field data, because the many possible solutions can only mimic the system's response at certain nodes and during particular events. This attempt showed that transient modeling of large DSs remains a complex endeavor. The subsequent work of estimating intrusion volumes and risk for public health is directly affected by the pressure results obtained by using transient analysis. Field data are therefore important to evaluate the accuracy of such a process.

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