Pressure Standards in Water Distribution Systems: Reflection on Current Practice with Consideration of Some Unresolved Issues

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Abstract: Pressure standards assist in the design of water distribution systems and the assessment of their performance. Although exact thresholds are sometimes rather vague, unusually high and low pressures are widely understood to increase costs and put systems at risk from events like pipe bursts at the high-pressure end and the risk of contaminant intrusion. Low pressures are more likely to disrupt firefighting conditions at the low-pressure end. Interestingly, the definition of what constitutes acceptable pressures differs around the world, and the means to evaluate them are not always clear. Specifically, what kinds of pressure transgressions are considered acceptable for system performance and economics varies. This paper aims to raise such a discussion that the pressure standards themselves. Still, revising (or clarifying) standards is never an easy task. Residential and industrial equipment has been installed, and infrastructure has been constructed based on existing standards and their interpretation. Thus, modifications to the service level, including pressure and pricing, are a multi-constraint decision that must consider wide stakeholder opinions and sufficient time for adaptation.

Introduction

The aim of a water distribution system (WDS) is to safely deliver adequate quantities of drinking water to end-users under sufficient pressure to permit or facilitate a wide range of human endeavors. In design, system pressure is generally expected to be maintained between minimum and maximum standards for safe, reliable, and economic operation. These standards were generally set to be both reasonable and economic, with the goal of specifying a moderate range that would generally prevent intrusion or ingress of contaminants, limit consumer complaints, and reduce damage due to inadequate fire protection, avoid problems in reservoir operation, and reduce problems with secondary pump operation (e.g., poor suction conditions). Pressure standards also aim to reduce excess demands, such as through reduced flow rates from faucets, showers, and lawn watering; frequency of pipe breaks; leakage rates; and excess energy use during high pressure.

However, the variation in standards among countries shows there is room for debate about the tensions that too high and too low pressure create and the benefits achieved through the pressure standards themselves. Still, revising (or clarifying) standards is never an easy task. Residential and industrial equipment has been installed, and infrastructure has been constructed based on existing standards and their interpretation. Thus, modifications to the service level, including pressure and pricing, are a multi-constraint decision that must consider wide stakeholder opinions and sufficient time for adaptation.

Though often neglected, transient pressures also influence both the performance of WDSs and the interpretation of what pressure standards might actually mean. Such pressure surges occur whenever flow conditions are altered in the network. Transient events are generally more severe when rapid and coordinated flow changes occur, such as those associated with the power failure of a pump or rapid valve and hydrant operations. Transient events are generally characterized by fluctuating pressures and velocities and can be severe enough to break or damage pipes or equipment, whereas transient low pressures can disrupt delivery conditions. Certainly, an effective practice to reduce the risk of contaminant intrusion is to always maintain distribution system pressures higher than external pressures, including transient events, but many utilities do not collect or submit pressure-monitoring data or records of low-pressure events for regulatory compliance (LeChevallier et al. 2011; Kirmeyer et al. 2001). LeChevallier et al. (2011) reported that no significant relationship was observed between pressure and the monitored water-quality parameters of free chlorine residual, conductivity, pH, and temperature at all monitoring locations of a system serving a hilly terrain [elevations range from 169 to 521 m (555 to 1,710 ft)]. However, the system had several areas of frequent pipe breaks. Other cross-section control and backflow prevention programs might efficiently reduce the risk of infection rather than increase pressure in the system (AWWA 2004).

In design, WDSs are also required to deliver large fire flows at adequate pressures. From a transient perspective, the designer must...
provide a system that can establish fire flows as quickly as practical. Yet a rapid hydrant opening can easily generate a transient low-pressure event in the system, particularly if fire crews receive little specific instruction on fire hydrant opening. Hence, one critical but too often forgotten issue that here is how to determine whether transient pressures violate pressure standards.

This paper highlights the ambiguity of pressure standards relating to WDS design and raises some key questions that currently are only incompletely addressed by the published criteria. It discusses how to better interpret the available pressure standards, where they succeed best, and where a revision might be helpful. Some useful metrics are used to evaluate the violation of minimum pressure criterion (MPC) in transient events. Also, the consequences of reducing a system’s minimum operational pressure are briefly explained. This paper addresses some issues associated with pressure criteria most applicable to developed countries in which water supply continuity is generally taken for granted. Certainly different design approaches must be adopted for use with intermittent supply systems.

Why Are Pressure Standards Required?

At first glance, several obvious but rather crucial questions might be raised. Why do we need pressure standards? In what ways do they help to deliver continuous and safe water to customers? How do pressure standards influence the methods for evaluating WDSs? One point is immediately obvious: WDS design is a challenging task. There are countless decisions to make—for example, pipes and their sizes, materials, pressure classes, pumps and their various capacities, size and location of reservoirs, types and location of valves, monitoring equipment, and pressure district boundaries. Thus, by setting pressure standards one rapidly establishes a benchmark for a reasonably cost-effective and efficient design. Walski (1985) pointed out that existing standards are performance standards (i.e., they evaluate the performance of a system) rather than design standards (they state how a system should be built). High and low pressures are both problematic and undesired in WDSs. High-pressure systems may cause more frequent pipe breaks and an increase in energy use and leakage (Lambert 2000). Low-pressure systems lead to consumer complaints and make systems more susceptible to negative pressures and possibly contaminant intrusions during transient events (Friedman et al. 2004). The overall goal of establishing a pressure criterion is to balance these opposing tendencies to ensure that reasonably safe, reliable, and economic WDS operation is almost always achieved.

Pressure standards are intended to help to monitor and assess system performance. Through a thoughtful and well-executed monitoring program, utility managers can determine how WDS performance compares with established standards and how the system is evolving over time. Overall WDS adequacy is clearly to be measured in terms of how well customers are served. Hydraulic performance measures relate to the delivery of an adequate supply of water and are usually measured in terms of pressure and flow parameters. The desired pressure is generally a “medium” pressure between the high and low limits set for the system. Industrial equipment and residential appliances are designed for specific pressure ranges. A minimum pressure is also required to supply adequate water from faucets and shower heads for customer satisfaction. The failure to meet these operational standards can cause customer dissatisfaction and complaints. Yet what equipment should be used to monitor the pressure, and how is the outcome of that monitoring to be interpreted? We return to these surprisingly vexing questions later. At the moment, it is perhaps enough to say that it is clearly not sufficient to glance at some convenient pressure gauge or even directly use the output from a supervisory control and data acquisition (SCADA) system. It is not uncommon to see pressures drop below MPC in WDSs, and this violation can only occasionally be captured through existing monitoring programs in most utilities (LeChevallier et al. 2014).

A key performance requirement that is part of the pressure standard is the maintenance of a minimum residual pressure during fire flows. A minimum pressure is required to overcome friction losses at the hydrant and in suction and delivery hoses so that adequate pressure is provided for supplying the required fire flow. In most U.S. states and Canadian provinces, governments are responsible for building codes and fire prevention regulations, and these regulations are generally enforced by local fire marshals or fire chiefs with the added weight of insurance provisions. In most European countries, however, water companies and fire authorities are jointly responsible for providing water for firefighting. It is historically accepted that a fire can be extinguished by spreading water on it, which can be achieved with the use of pressurized water. To provide the required fire flow, distribution system pipes should be sized to deliver the required flow rates at the desired pressure. However, in the absence of a fire, flow rates and velocities are often much smaller, leading to larger pipes that can substantially increase the residence time of water in the distribution system and lead to water quality degradation (Snyder et al. 2002). Fire flow requirements can induce powerful and not always well-understood stresses on system design and performance.

Current Pressure Standards

There are no universally acceptable or established rules or guidelines for the specification of pressure standards for WDS design. Table 1 lists some examples of pressure standards applied in WDS design around the world and clearly shows that there are inconsistencies and variations in acceptable standards in terms of required pressure and the conditions that the minimum standard is recommended to enforce in design. The MPC is technically defined as the required pressure above which there is no deficiency in system performance. The lack of globally accepted regulations has led water utilities to develop their own criteria for design and operation of distribution systems [e.g., the primary MPC in use in most U.S. states is 14 m (20 psi) during fire flow or emergency conditions (10 States Standards 2007)]. However, the tentative guidelines developed by local utilities tend to focus on specific system elements, such as enforcing a pressure criterion to meet a fire flow requirement, rather than on overall distribution system performance such as water quality, pipe breaks, leaks, and system operating pressures.

According to Table 1, the minimum pressure of 14 m (20 psi) is an acceptable MPC in several regions. The principal reason for enforcing it may be to provide a minimum flow and to overcome friction losses in the customer’s service branch, meter, and house piping at the a home’s second-story level (Walski 1985). But the standards do not specify whether this pressure criterion should be met at the elevation of the pipe, at the elevation of the ground, or at the customer’s first floor. The utilities appear unanimous in their belief that an evaluation of distribution system performance must reflect the level of service received by the customer. However, a modern question of some import is whether the fire standard must be met continuously in the system even when no fire is being fought. Is response to a fire in the time of emergency sufficient and equivalently reliable?

As is clear from Table 1, there is no universally agreed on value that specifies the maximum acceptable pressure in WDS design and operation. In practice, this value is usually constrained by pipe...
The design standard requires that water mains be designed to withstand total forces (i.e., static and transient pressures) acting on pipelines. The maximum allowable transient pressure cited in different national and international codes and standards is up to 1.5 times the design pressure (Pothof and Karney 2012). Design pressure is normally defined as system pressure during normal operation. Moreover, wide ranges of acceptable MPC imply that water delivered under the same pressure might be acceptable in some countries but unacceptable in others. Hence, water distribution costs (both capital and operating) to meet the same flow requirements inevitably vary from region to region even for the same or similar system topology and conditions.

Beyond regulatory requirements, Friedman et al. (2010) recommended five pressure performance goals (i.e., above 0 m during emergencies, such as main breaks and power outages; more than 14 m (20 psi) under maximum day demand and fire flow conditions; more than 25 m (35 psi) under normal conditions; less than 70 m (100 psi) under normal conditions; within ±7 m (±10 psi) of average pressure greater than 95% of the time) in order to optimize WDSs in terms of reducing unnecessary water losses, main breaks, and/or energy usage. The pressure criteria are invoked by designers and operators to help size distribution mains and services that are used for the final stage of delivering water to customers; however, these criteria are not always applied to the transmission mains that convey larger amounts of water over greater distances, typically between major facilities within the system (Walski et al. 2007).

In distribution systems, it is not uncommon for the pressure to be relatively low [less than 14 m (20 psi)] at locations close to ground tanks, whereas the discharge headers from pump stations often experience high pressure. However, such departures are usually tolerated because there are seldom service connections close to these two critical points.

For adequacy, pressure-related performance can be measured as how often operating pressures are above the MPC. In a risk-based optimization model to determine optimal WDS design, overall WDS robustness is defined as the probability of satisfying minimum pressure head constraints at all nodes in the network (Kapelan et al. 2006; Yannopoulos and Spiliotis 2013). Future required demands; pipe roughness coefficients; WDS operator behavior; estimation methods to determine needed fire flow; and demand patterns for residential, commercial, and industrial sectors are all subject to uncertainty. For this reason, the computed/measured minimum pressures, which are the real concern of insurance companies and WDS reliability, are not certain, either. Nor can any monitoring program under current conditions ensure that the required performance will be achieved when needed. Many utilities, even those with online monitoring, measure pressures only once every few minutes. Therefore, there is much of uncertainty about the specifics of pressure monitoring and management (LeChevallier et al. 2014). Pressures may well be below the MPC in some circumstances because of the upset of uncertain parameters in WDS design and operation. Therefore, the enforced/ensured pressure criteria cannot continuously guarantee the adequacy and availability of the required water and pressure to all consumers.

Required fire flows are described in fire codes published by insurance companies or other oversight jurisdictions. These typically specify the so-called needed fire flow (NFF), which is the rate of flow considered necessary for suppressing a major fire within a specific building. Based specifically on AWWA’s M31 manual (AWWA 2008), the required fire flow duration is 2 h if NFF is equal to or less than 158 L/s (2,500 gpm) and 3 h if NFF is equal to 189–221 L/s (3,000–3,500 gpm). Specific properties of a NFF in excess of 221 L/s (3,500 gpm) are evaluated separately and assigned an individual classification (ISO 2012). In North America, insurance companies often recommend the minimum pressure standard because they are concerned not so much with human comfort but with the risk of fires. They require that a certain fire flow rate (e.g., NFF) be met under a specific MPC, which is often 14 m (20 psi), which is measured as the residual pressure at the discharge point. However, they do not provide engineering advice on water

<table>
<thead>
<tr>
<th>Region</th>
<th>Minimum pressure</th>
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<tr>
<td></td>
<td>During fire flow</td>
</tr>
<tr>
<td>Canada</td>
<td></td>
</tr>
<tr>
<td>British Columbia</td>
<td>14 (20)</td>
</tr>
<tr>
<td>Alberta</td>
<td>15 (22)</td>
</tr>
<tr>
<td>Saskatchewan</td>
<td>14 (20)</td>
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<tr>
<td>Halifax</td>
<td>15 (22)</td>
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<tr>
<td>Manitoba</td>
<td>14 (20)</td>
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<tr>
<td>Other provinces</td>
<td>14 (20)</td>
</tr>
<tr>
<td>USA</td>
<td></td>
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<tr>
<td>Louisiana</td>
<td></td>
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<tr>
<td>Michigan</td>
<td></td>
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<tr>
<td>Connecticut, Oklahoma, Delaware</td>
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<tr>
<td>Other states</td>
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<tr>
<td>United Kingdom and Wales</td>
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</tr>
<tr>
<td>Brazil</td>
<td></td>
</tr>
<tr>
<td>Australia</td>
<td>20 (29)</td>
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<tr>
<td>New Zealand</td>
<td>10 (14)</td>
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<tr>
<td>South Africa</td>
<td></td>
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<tr>
<td>Netherlands</td>
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<td>Hong Kong</td>
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supply improvements, but rather provide guidelines on water demand for any new community development and the required pressure during fire flows for evaluating water supply systems in order to rate them (ISO 2012). If the pressure provided by the water supply is too low, customers have to pay higher home insurance premiums (ISO 2012). Even in the absence of a fire, the conventional design approach requires that the minimum standard be met assuming the possible occurrence of fires. This obligation to provide fire protection substantially affects WDS design and operation (Snyder et al. 2002).

Regardless of efforts that have been made to provide secured fire flow under the established MPC, this criterion is almost certainly temporally violated during a transient event associated with the initial opening of a hydrant and in power outage conditions (Ghorbanian et al. 2015b; LeChevallier et al. 2011). Moreover, the fire flow requirement may be supplied under a pressure less than the MPC even in steady-state conditions because the hydrant outflow is also controlled by the hydrant’s outlet nozzle diameter. That is, there is an important pressure-flow relationship that is established partly for convenience, partly by convention, and partly because of necessity. Pressure-flow relationships also show some variation around the world. Therefore, the specific reasoning for establishing a particular relationship is somewhat ambiguous globally. Different residual pressures with the same hydrant outlet size are assumed to provide the same flow rate, which is not acceptable in terms of hydraulic calculation.

Fire prevention is a philosophy of selecting the equipment, materials, and processes that will eliminate or lower the risk of fire. However, regulations vary in the requirements for operation or installation in Europe and North America. In Europe, a different set of fire code regulations exists that may determine that quick opening of a hydrant is not required. This contrasts with regulations in North America. For instance, in the United Kingdom many data centers use either a gaseous or a mist system for fire protection in data halls whereas in North America it is more common to use pipe water systems (Elliott 2006). North American codes tend to provide prescriptive solutions that favor active fire suppression, whereas European codes tend to provide performance requirements that favor passive fire protection. In North America, it is common to use automatic sprinkler systems to control a fire in nonresidential buildings and much less water is used to extinguish it (Hickey 2008; AWWA 2008). For a building protected by automatic sprinklers, the NFU needed for the sprinkler system, converted to 14 m (20 psi) residual pressure, with a minimum of 32 L/s (500 gpm) (AWWA 2008). But the installation of automatic sprinkler systems—from the installation of automatic sprinkler systems to their maintenance and periodic testing—transfers a significant cost to the private sector (Hickey 2008). There are economic incentives in the form of insurance premium reductions for commercial property owners having installed and properly maintained sprinkler systems (Hickey 2008). Even here, of course, an alternative exists. For example, with the use of foam to help extinguish fires, less water is needed, reducing the water demand associated with firefighting (Cote and Linville 1986). Hence, collecting and sharing data on processes for extinguishing fire would be extremely useful.

From the previous discussion, it is clear that pressure criteria and standards can be evaluated from a variety of overlapping but sometimes distinct points of view, representing the perspectives of regulatory agencies, health and environmental agencies, water utilities, fire departments, and customers. This number of stakeholders is perhaps a reflection of how universal water uses are and how many people have an interest in the water supply system. Such complexity is further intensified by the reality that systems, standards, and operation are constantly evolving in time.

Complying with a Pressure Standard

In conventional design approaches, all components should be sized to comply with regulations. Although a MPC is enforced in WDS design to ensure supplying adequate demands during periods of peak consumptions (e.g., the greater of the maximum hour demand and the maximum day demand plus fire flow), many systems experience higher pressures than necessary during offpeak demand periods. This is so much so that, in certain instances, residential customers might need to install pressure-reducing valves in their homes. Excessive pressure can also be controlled by regional pressure management, which is now recognized as one of the most efficient and cost-effective strategies for reducing pressure, burst, and leakage rates (Ulanicki et al. 2008; Gomes et al. 2011). Additional benefits might be gained by including specific strategies that decrease the energy supplied. Current regulations and guidelines indicate that pressure as a measure of performance should be based at least on MPC; however, consideration of both maximum pressures and variations in pressure is also necessary, though seldom stipulated, to reduce system costs and the risk of failure.

The unquestioned supposition is usually that, if certain design standards are adopted, the network provides pressures at or above the required minimum during peak demands, and therefore the probability of hydraulic failure is highly unlikely. Conceptually this is simple, but what does this mean in practice? If one installs a pressure gauge in the system, pressures are seen to vary; if the pressure gauge is more sensitive and read more often, pressures typically vary much more. It may be easy to dismiss certainly momentary transgressions of the pressure standard, but a judgment call is already needed to estimate the consequences/significance of the violation. This is seldom easy. Is a small violation allowed every hour, every day, or every week? How much of a violation is considered small? Do the duration, frequency, and magnitude of the violation matter? Are all parts of the system equally vulnerable to the same degree of transgression? Should this be prioritized based on the importance of the system component or its material (e.g., flexible versus rigid pipe wall), its age, or perhaps its failure history? One might turn pressure data into a kind of a pressure-duration-frequency curve with the goal of assessing how often and for how long low or high pressures actually occur, and how intense they may be. But what would one do with such a curve?

The continuous monitoring of water quality, hydraulics, and system pressure is normally undertaken with up-to-date SCADA systems. Data are centrally archived and used for infrastructure management and system evaluation. However, typical SCADA systems seldom have sufficient temporal resolution to resolve transient pressures, and the full analysis of the dynamic data is often inaccessible (LeChevallier et al. 2014). Currently many utilities collect data on pressures at key locations in a network (e.g., pumping stations and pressure zone boundaries) with low-resolution SCADA data. However, in light of all of these fluctuations, utilities may wish to reassess how the data collected by SCADA systems already in place will be used in the future. A variety of metrics might be considered for such a task.

If the pressure delivered to an area changes, perhaps because of a new standard or a new operational approach, new hydraulic grade lines are established. Therefore, before existing pressure zones are realigned by changing pumps or adjusting pump settings, thoughtful public notification and consultation are essential. Moreover, the feasibility of implementing pressure changes is system specific and requires a detailed engineering study (LeChevallier et al. 2014). In creating new pressure zones, topography and customer acceptance are often the limiting factors (Walski et al. 2007).
How to Evaluate MPC Violations in Transient Events

Rapid flow changes during transient events (e.g., valve closure or pump switching) cause pressure fluctuations in a WDS. Pressure fluctuations have many implications in light of pressure standards; in particular, some transient events certainly cause the MPC to be violated. Undesired transient pressures (i.e., too high, and negative) are controlled by surge control strategies (Boulos et al. 2005). But in planning and deploying transient mitigation, the aim is to avoid negative pressures rather than pressures below the MPC (LeChevallier et al. 2011). Technically, air release/vacuum breaker valves are placed at locally high elevations where the system is more susceptible to negative pressures in transient events. These valves admit air into the system to maintain local pressure near the atmospheric (0 m) pressure. However, valve vaults can be flooded, and contaminant intrusion is possible through valves during low-pressure transients if the valves are not well maintained (Ebacher et al. 2013). Indeed, the associated transient data obtained from actual system data often support the reality that pressure standards are not continually met. AWWA recommends installation of air valves at intervals along ascending, descending, and horizontal lines (AWWA 2001). This may be a conservative approach, however, and it is seldom specified how critical each location along a pipe profile is, nor the consequences of poor sizing (Ramezani et al. 2015). Proper sizing and positioning of air release/vacuum breaker valves can help reduce or limit contaminant intrusion.

Figs. 1 and 2 clearly indicate the MPC violation during a transient event. The centerline of the pipe is set at 0 m for simplicity, and the reservoir water level, \( H_r \), is set at 58 m. The transient condition can be introduced into this case by a sudden valve closure (in 1 s) at the most downstream end of the pipe (Fig. 1). Fig. 2 clearly shows that pressure fluctuations (a sequence of transient waves) during transient events often violate the minimum standard for water pressure (the MPC is considered to be 20 m in the system). The results in Fig. 2 raise, in more concrete terms, previously unanswered questions. What does it mean to achieve (or violate) the standards? How often is the standard transgressed, and by how much and for how long? Is a 1-s or 30-s violation serious? Do the frequency and severity of the violation matter? Should the standard be set for transient events? What does a pressure standard mean if transients are considered? In the background, there are other perhaps even more subtle questions. The kind of response shown here is typical of a numerical model using so-called quasi-steady friction approximations; in other words, it neglects unsteady friction effects that would typically cause the transient train to decay more rapidly. How good does a model need to be to assess system performance and by what measure? Field data would appear to be better but gathering them still has challenges, including the frequency of data collection and a host of measurement errors that can complicate the interpretation, not to mention the danger of experimenting on real systems with potentially severe events.

One immediate but vexing question any analyst faces is the choice of suitable metrics to evaluate the severity of transient events. Historically, little thought or reflection has been given to this important question. Of course, such metrics should evaluate the desired WDS performance. Table 2 summarizes some of the metrics used to quantify the severity of transient events. Clearly, all metrics are associated with maximum and minimum transient pressures occurring in the system; very few indices have been defined to quantify the severity of negative pressures; and almost none of them consider the transgression of MPC. These considerations highlight the ambiguity in using pressure standards and the key question of whether a certain pressure sequence is acceptable or unacceptable. For example, can pressures fall below the MPC for a mere second? It is obvious that many things are at stake, including intensity and frequency. For example, an extreme negative pressure (zero absolute pressure) for 1 s is much more dangerous than a zero gauge pressure for 10 s. For full negative pressures (–10 m), column separation is almost assured, which may give rise to sudden pressure spikes when the cavities collapse. To date, few efforts have been made to evaluate the pressure criterion in transient events.

In Fig. 3, which depicts several time steps of the transient response of the simple system shown in Fig. 1, several additional and useful metrics are shown. These metrics can be derived to determine the severity of MPC violation in a WDS [Eqs. (1)–(4)]. The negative pressure index, \( T_C \), can be determined as

\[ T_C = \sum_{i=0}^{T} t_{ci} \]  \hspace{1cm} (1)

where \( t_{ci} \) = time when pressure is negative; and \( T = \) transient event duration.

The duration of MPC violation, \( T_m \), is defined as

\[ T_m = \sum_{i=0}^{T} t_{mi} \]  \hspace{1cm} (2)

where \( t_{mi} \) = time when pressure is below MPC.

The period of MPC violation, \( T_p \), and the intensity of MPC violation, \( I_V \), can be determined as

\[ T_p = \frac{4L}{a} \]  \hspace{1cm} (3)

\[ I_V = \frac{\Delta H_f}{H_{cr}} \]  \hspace{1cm} (4)

where \( L = \) pipe length; \( a = \) wave speed in the pipe; \( H_{cr} = \) MPC; \( \Delta H_f = H_{cr} - H_{min} \); and \( H_{min} = \) minimum transient pressure.

In Fig. 3, it is clearly seen that the MPC is violated every 16 s (4L/a) in this case study. In the case of water networks, \( L \) is the characteristic length of the network, which is the sum of the pipe
 lengths from the source of the surge to the upstream reservoir or the system’s energy source. The duration and number of times of MPC violation during a transient event are greater when the MPC is considered to be higher. Fig. 4 confirms this presumption. As can be seen, both the number of times and duration of violation when the system experiences pressures less than a certain value are greater for higher MPCs. For instance, the number of times and duration at which the pressure is less than 10 m during the transient event are, respectively, 53 and 0.77 min, whereas for pressure less than 20 m, they are, respectively, 106 and 1.5 min.

Surge control, particularly control of high-pressure events, has typically been thought of in terms of preventing pipe bursts, and efforts have been made to reduce maximum pressures in particular. Concerns regarding negative transient pressures and their public health implications have received less attention (CPWSDS 2006). Minimum transient pressure standards should be set to prevent intrusion and structural problems. The consequences of low-pressure failure in transient events, including vacuum conditions, cavitation, and contamination risk, should be identified and deserve particular attention. Thus, evaluation of MPC should be part of the surge analysis. The minimum allowable pressure is rarely explicitly addressed in transient conditions. The commonly accepted minimum incidental pressure in WDSs is atmospheric pressure or the maximum groundwater pressure necessary to avoid intrusion at small leaks. But how comprehensively this transient-related MPC is achieved and scrutinized has yet to be specified. Certainly other actions might be taken sometimes. For example, negative pressures can be reduced by using plastic pipes (e.g., PVC and polyethylene) in WDSs, where the viscoelasticity of the pipe material significantly influences pressure wave dissipation and time propagation (Ramos and Covas 2006).

**WDS Response to Changes in Pressure Standards**

WDS performance is inevitably influenced by changes in pressure standards, with leakage being a case in point. Average leakage losses in water systems are reported to be approximately 16%, but of this up to 75% is likely be recoverable (Thornton et al. 2003). Water loss control strategies (e.g., pressure management programs) were explained in Thornton et al. (2003). Leakage rate has long been known to relate to the internal pressure of a pipe at leaky locations. Thus, lowering the pressure throughout the pipeline system causes leakage to decrease (Lambert 2012). The impact of leaks on the energy consumption of water supply systems was examined by Colombo and Karney (2002, 2005), who concluded

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**Table 2. Metrics Used to Quantify the Severity of Transient Pressures**

<table>
<thead>
<tr>
<th>Author</th>
<th>Index</th>
<th>Definitions of variables</th>
<th>Comments</th>
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<tbody>
<tr>
<td>Friedman et al. (2004)</td>
<td>Intrusion potential</td>
<td>Total number of nodes experiencing negative pressures and total time when those nodes experience negative pressures</td>
<td>To determine severity of surge and intrusion potential during transient events</td>
</tr>
<tr>
<td>Jung and Karney (2006)</td>
<td>$H_{\text{max}} - H_{\text{min}}$</td>
<td>$H_{\text{max}}$ and $H_{\text{min}}$ = maximum and minimum pressures, respectively</td>
<td>To minimize difference between maximum head and minimum head during transient events</td>
</tr>
<tr>
<td>Jung and Karney (2011)</td>
<td>SPDF = $\int_{t_c}^{N_{\text{risk}}} H_i dt$</td>
<td>$H_i$ = pressure at each node either $&gt; H_{\text{max}}$ (maximum allowable pressure) or $&lt; H_{\text{min}}$ (minimum allowable pressure)</td>
<td>Surge damage potential factor (SPDF) to determine likelihood of damaging transient event</td>
</tr>
<tr>
<td>Martin (1983)</td>
<td>$S = \frac{T_{SC}}{T_{TRI}}$</td>
<td>$S =$ severity of cavity index; $T_{SC} =$ duration when cavity occurs</td>
<td>To determine severity of cavitation during transient events</td>
</tr>
<tr>
<td>Radulj (2009)</td>
<td>$\text{TRI}^+ = \int_{t_2}^{t_1} P_{\text{max}}$; $\text{TRI}^- = \int_{t_{\text{min}}}^{t_{\text{max}}} P_{\text{min}}$</td>
<td>$\text{TRI}^+$ and $\text{TRI}^-$ = positive and negative transient risk index, respectively; $T_{\text{m}}$ and $T_{\text{c}}$ = maximum return period from data set–associated maximum and minimum pressures, respectively (days)</td>
<td>To quantify risk assessment associated with hydraulic transient</td>
</tr>
<tr>
<td>Shinozuka and Dong (2005)</td>
<td>$D = \frac{H_2 - H_1}{t_2 - t_1}$</td>
<td>$D =$ damage index; $H_2$ and $H_1$ = pressure heads at a node at time $t_1$ and $t_2$, respectively</td>
<td>To locate damaged pipe or malfunctioning equipment when water system exhibits acute transient behavior</td>
</tr>
</tbody>
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**Fig. 3.** Metrics to quantify the violation of the MPC

**Fig. 4.** Number of times of violation of the MPC and duration

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that, for systems with equivalent performance, leaks increase operating costs in all systems and energy costs increase more than proportionately with leakage. Several relationships between leakage rate and pressure have been developed indicating that leakage varies nonlinearly with pressure and can be reduced with a decrease in system pressure (Hiki 1981; Lambert 2000; Thornton 2003). A reduction in pressure may not only decrease the leakage rate but also may reduce the rate at which new leaks occur (Lambert 2000). LeChevallier et al. (2014) reported that a 24% reduction in average pressure [by 20 m (28 psi)] using flow-modulated pressure reduction caused a reduction of approximately 83% in background leakage.

In water supply systems, most of the energy is consumed by pumping to provide the necessary heads and flows. A pump must supply energy to lift water from a source to the point that satisfies a MPC and to overcome frictional head loss along the pipe to ensure that adequate demand reaches the downstream point. If a lower value of MPC is considered, less power is required. Overall, the change from a higher pressure to a lower one results in a decrease in break horsepower (BP). The net rate of pumping-energy savings is simply equal to the difference in power requirements between the two MPC scenarios. LeChevallier et al. (2014) reported that a reduced net-energy input via service pressure could be achieved through pumping adjustment and decreases in dissipated energy. A U.S. case study indicated that significant energy savings and improvement in distribution system energy efficiency were achieved via a reduction in excessive pressure at customer taps (LeChevallier et al. 2014).

WDSs operating under high pressure are susceptible to more frequent pipe breaks. Lambert (2012), using collected data on pressures associated with seven zones in an Australian utility reported that high WDS pressures may cause high pipe-break rates. Traditionally, pipe breaks can be prevented through active rehabilitation and replacement programs, which are utilities’ most common practices. The contribution of internal pressure to pipe breaks occurring simultaneously with one or more other sources of loads (e.g., thermal, soil cover, and traffic) has been addressed by many researchers (e.g., Kiefner and Vieth 1989; Rajani et al. 1996; Rajani and Makar 2000). Because MPC reduction influences the frequency of high pressures, the probability of pipe breaks can be reduced. A case study in the United States showed that, if the existing break frequency is high, small reductions in pressure can cause significant reductions in the frequencies of new breaks (LeChevallier et al. 2014). To better incorporate optimization of pressure management, relationships between pressure and other distribution system performance indicators, such as leakage, breaks, and energy usage, should be identified (LeChevallier et al. 2014).

A reduction in operational pressures may cause systems to become more susceptible to negative pressures and contaminant intrusions during transient events. Turning pumps on or off, opening and closing valves, and operating fire hydrants are all routine actions, but they cause sometimes important transient conditions associated with flow changes. To limit these pressures to an acceptable level, surge control strategies, including engineering, maintenance, and operational strategies must be performed. Even WDSs that are operated under low pressures have risk high-pressure transients, but both high and low transient pressures can be efficiently controlled using surge control strategies (Ghorbanian et al. 2015b).

End-users are the primary stakeholders influenced by low/excess water pressures. If water pressure is high at a building, it can cause both dangerous conditions (e.g., bursting heaters, boilers, and piping; lime-clogged relief valves) and costly building flooding. To reduce excessive pressure, pressure-reducing valves are often installed at building connections even if individual appliances are equipped with safety devices. Low-pressure conditions can cause customer dissatisfaction (e.g., unpleasant showering; malfunctioning dishwashers, clothes washers, and boilers). System energy is clearly wasted if water pressures are greater than required (Ghorbanian et al. 2015a). Yet a certain minimum pressure for appliance operations clearly should be supplied.

Conclusions

Pressure standards are the foundation of safe and reliable WDS operation and of the evaluation of WDS performance. Design guidelines require that a MPC be maintained across the network in order to supply required fire flow under emergency conditions. However, established pressure standards are different around the world, implying that water distribution costs (both capital and operating) to meet the same demand vary from region to region even for the same or similar system topology and conditions. Although WDSs are often designed to maintain a minimum pressure standard in the system during peak demand periods, the system may frequently experience high pressures (i.e., in a typical day during off-peak periods) that cause suboptimal system performance. Although a MPC is enforced in WDS design, it may be temporally violated during transient conditions. For this reason, although intuitively appealing, it is not in practice a simple matter to determine if, and by how much, pressure standards are violated. Several metrics exist to evaluate the severity of transient pressures, but almost none of them consider a precise definition of transient transgressions or the significance of such violations. In this paper, several new metrics are introduced to quantify MPC violations during transient events. They are appealing, but it is not yet clear how accurately any of them map into real system consequences for the range of conditions actually found in water delivery systems. Significantly, even the so-called fire flow requirement, often the main concern of insurance companies, may have somewhat fuzzy boundaries when the range of real conditions found in the field is considered.

Changing a pressure standard, whether by relaxation or tightening, is bound to have consequences for the design, operation, and performance assessment of WDSs. Reducing the pressure may improve performance through reduced water demands and leakage, and possibly significantly decrease energy use. The probability of pipe breaks can also be reduced by lowering the pressure. Reducing the MPC generally causes the system to be at lower pressures, and therefore makes the system more vulnerable to low pressures. However, the risk of low pressure can be curtailed by implementing surge control strategies and/or effective methods of backflow prevention. The required pressure for appliance operations may place a practical limit on pressure standards. Higher pressures are inevitably associated with greater energy needs.

Pressure standards are one of many concerns for utility managers that involve energy use, leakage, water quality through contaminant intrusion in transient events, pipe breaks, economic and insurance considerations, firefighting capabilities, and both public health agency and individual concerns about contamination. Still, all of these considerations are tied in one way or another to issues related to the adopted pressure standard, and there is almost certainly room for much more thought and debate regarding these critical and fascinating interactions.

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