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Drinking Water Engineering and Science Discussions

Interactive comment on "Negative pressures in full-scale distribution system: field investigation, modelling, estimation of intrusion volumes and risk for public health" *by* M. C. Besner et al.

M. C. Besner et al.

mcbesner@polymtl.ca

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The authors would like to thank the reviewer for his interest and comments. Here are our responses to the specific comments:

Comment #1: This point was also raised by the other reviewer (comment #3) and our response is copied here. We believe that the frequency of measurements used in this study is adequate for the type of investigation conducted. The resolution of pressure data used in this study (1 to 4 readings per second) is typical of what has been used in all other studies characterizing the occurrence of low or negative pressure events in full-scale distribution systems. See the following references:

- Kirmeyer et al., 2001. Pathogen intrusion into the distribution system. AwwaRF Report, Denver, Colorado.

- Friedman et al., 2004. Verification and control of pressure transients and intrusion in distribution systems. AwwaRF Report, Denver, Colorado

- Gullick et al., 2004. Occurrence of transient low and negative pressures in distribution systems. Journal of the American Water Works Association 96 (11), 52-66.

- Fleming et al., 2006. Susceptibility of distribution systems to negative pressure transients. AwwaRF Report, Denver, Colorado

- Hooper et al., 2006. Assessment of microbiological water quality after low pressure events in a distribution system. 8th Annual Water Distribution Systems Analysis Symposium, Cincinnati, Ohio.

o Such resolution is considered adequate to the application presented here, where we are primarily interested in the occurrence of negative pressure. We agree that such resolution would be inadequate for other types of application such as inverse transient analysis, used for leak detection and system parameter calibration. In such case, high frequency pressure information is needed (kHz resolution) as "fast transients" (opening or closing of appurtenances in the range of milliseconds) are created to obtain clear pressure wave reflections from the investigated features.

o The very high number of pressure data collected in the distribution system during this study led to pressure profiles that were quite similar at all sites (smooth pressure variations), especially for those events related to sudden pump shutdowns at the plant. If the pressure would have been highly variable (peak low and high pressures not captured through our 4 readings per second), we could at least expect that such variations would have been captured once and a while at some sites, which was not the case.

o In the context of intrusion into a full-scale distribution system, it is hypothesized that shorter duration (<25 ms) transient events, that would not have been captured here, would have a low impact in terms of potential volume coming in.

The measurement frequency will be justified in the revised paper.

Comment #2: The 2m elevation difference was selected as it is the minimum elevation difference we could apply that would result in a skeletonized model with less than 20,000 pipes. The commercial transient analysis software used has a limitation regarding the model size (max. 20,000 links).

Comment #3: The simulation time was set at 300 seconds (5 minutes) considering that: (i) the duration of the modeled pump shutdown event was approximately 2-3 minutes (time to reach back normal pressure) and, (ii) the distance between the water treatment plant (location of pump) and the end of the distribution system is approximately 20 km. Assuming an average wave speed value of 1000 m/sec, it would take approximately 20 sec for the pressure wave to reach the end of the distribution system. Comparison of modeled pressure profiles to field pressure data obtained at the end of the distribution system showed good agreement. The pump closure was set to start at t = 30 s after the start of the simulation.

Comment #4: The stagnant water found in the air-valve vaults could originate from two potential sources: infiltrated groundwater due to the vault (and water main) being located below the water table or street runoff following wet weather events. However, the relative contribution from these sources cannot easily be established. It is unlikely that some of the flooded vaults located at high elevation were located below the water table. The Bacteroidales fecal indicator results showed that the source of the microbial contamination in the vaults was mostly from animals (e.g. cats, dogs, mice, rats, birds, and other wildlife), which would indicate that street runoff could be a major source of contamination in those vaults.

The lower frequency of detection of indicators of fecal contamination in the soil and trench water samples could be explained by the distance between the sewer lines and the drinking water mains. Although this distance is not known, the sewer mains were

not visible at any excavation site except one.

Comment #5: The transient analysis work is the topic of a paper written by Ebacher et al that has been peer-reviewed and accepted for publication in the ASCE Journal of Water Resources Planning and Management in April 2010. The authors provide a detailed discussion of the uncertain parameters of the model, the potential causes of greater energy dissipation observed in the field, and expose the reasons behind the use of reduced wave speed in cast-iron mains to improve the model response. We can briefly summarize these here:

Uncertain parameters of the model:

- The interior pipe diameter is different from the nominal diameter, which is often used in models, and tends to decrease over time due to the build up of corrosion products, tuberculation and scaling.

- The wave speed is 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 are unknown, and most pipe properties will change over time.

- Metal pipes may have been rehabilitated using a lining, their diameter slightly reduced, with other pipe properties becoming more similar to those of plastic pipes (Escarameia 2005), in which pressure waves travel at a lower velocity.

- Status of valves in distribution system (opened/closed) may be different than in model

Factors explaining lower energy dissipation in model than in reality:

- The skeletonization process reduces the numbers of nodes and pipes, thereby decreasing energy losses by reflections and friction.

- The standard steady-state friction model (Wylie and Streeter 1993) is 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 are important dissipative mechanisms (Colombo and Karney 2003; Karney and Filion 2003) and considerable uncertainty remains regarding the initial distribution of flows in the distribution system at the time of the event.

- The impact of air in the transported water could be crucial as 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).

o Degassing of the dissolved air is also likely to occur during the passage of the low pressure wave, almost instantaneously reducing the wave's pressure amplitude (Wylie 1992).

o The presence of free air in the supplied water decreases the density of fluid, while increasing its elasticity, so that the wave speed is greatly reduced when gas bubbles are uniformly distributed throughout the fluid (Wylie and Streeter 1978).

There are reasons to believe that the studied distribution system contains a considerable amount of air: (i) water leaving the studied WTP is oversaturated with O2 (1-2 mg/L); (ii) air could be released under low pressure or higher temperature conditions. Pressure recordings were performed over the summer; and (iii) air may enter the distribution system through leakage orifices under negative pressures.

The large discrepancies between modeled and recorded pressure profiles are a symptom of the model's inability to correctly simulate all energy losses. The wave speed reduction is used to mimic energy dissipation mechanisms that are not included in the model. This artifice is commonly applied (Gullick et al. 2005; Friedman et al. 2004; Boyd et al. 2004; Wylie 1992), and is referred to as the modified MOC in Escarameia et al. (2005). We agree that this artifice has serious limitations:

- It is unable to precisely describe the recorded downsurge.

- Slowing the wave speed introduces a phase shift, which means that the modeled downsurge is moved forward in time. However, this phase shift has very little impact on the computation of intrusion volumes.

- It brings up confusion, because one might think that the typical values of wave speed are wrong, while this is not the case. The wave speed does vary depending on air content, which changes over time during a transient event. However, the wave speed reduction is used to simulate energy dissipation mechanisms that were omitted in the actual model (ex. unsteady friction).

Despite these limitations, this approach has the advantage of being simple, while still providing the user with reasonable modeled pressures that can be used in the estimation of intrusion volumes.

This calibration approach involving the reduction of wave speeds may be crude, but it still provides an effective mechanism for dissipating the excess model energy. Instead of reducing wave speeds for the entire duration of the event, McInnis and Karney (1995) decreased the Hazen-Williams C-factor after the first wave cycle, in order to improve the fit of the residual pressure waves, and gradually restored the original C values to allow the normal steady state to recover. Both methods are simple, but they overcome the difficulties in implementing the numerous possible dissipation mechanisms in commercial transient models. The mathematical formulations are complex, and so would the numerical methods required to solve these complicated equations. The governing equations and numerical methods could be improved just to realize that the "Uncertainty about initial conditions alone may overshadow the effects of less important energy-dissipation mechanisms." (McInnis & Karney 1995). It was observed that transient modeling is very sensitive to some initial conditions, such as air content, which are virtually impossible to evaluate precisely in the field and change over time (Wylie 1992).

Comment #6: Section 3.4 will be removed. The sentence has been integrated to the revised Conclusions section.

Marie-Claude Besner, on behalf of the authors

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