Water Supply

Water Supply Vol 23 No 9, 3552 doi: 10.2166/ws.2023.227

How different regional approaches to the network design result in key differences in burst event severity and failure vulnerability

John H. Gibson [a,*] and Bryan Karney [b]

[a] Department of Chemical Engineering and Applied Chemistry, University of Toronto, 200 College St., Toronto, ON, Canada M5S 1A3
[b] Department of Civil and Mineral Engineering, University of Toronto, 35 St. George St., Toronto, ON, Canada M5S 1A4
*Corresponding author. E-mail: jh.gibson@utoronto.ca

JHG, 0000-0003-0915-8130

ABSTRACT

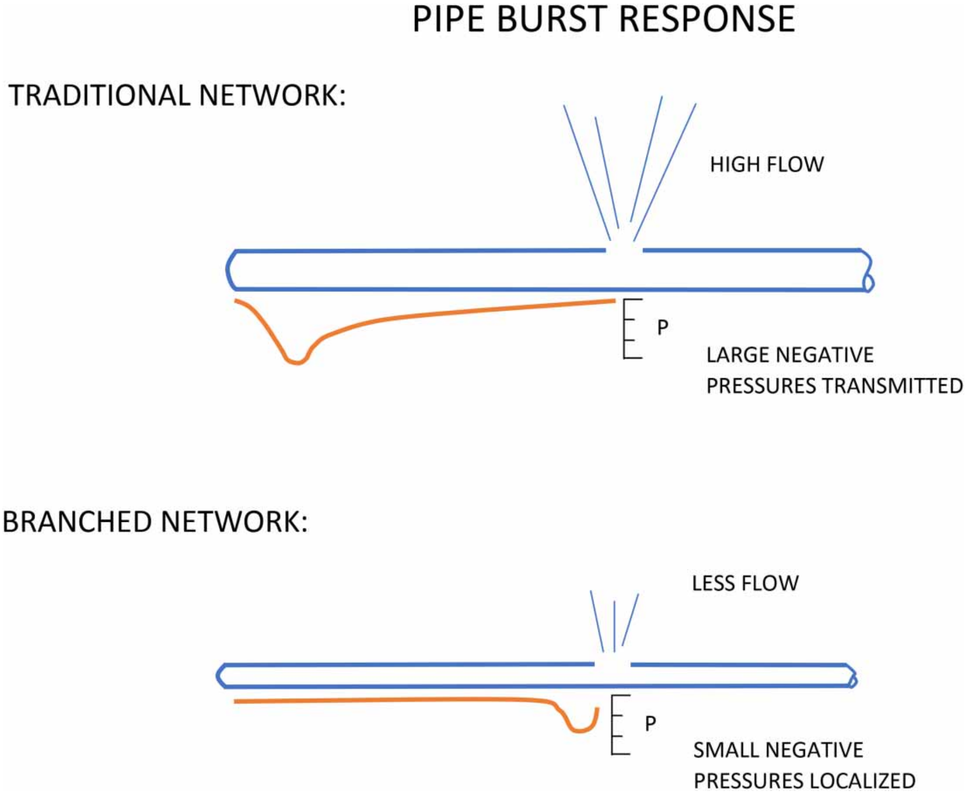
The pipe burst response of an innovative Dutch water distribution network is compared to a traditional looped North American network. Dutch networks focus on water quality and use smaller diameter pipes in branches. The branched network discharges much less water after a burst, which may reduce local flooding, traffic disruption, and product loss. In addition, high velocities and transient pressures are shown to be much localized in the branched Dutch network after a burst, reducing the risks associated with the intrusion of contaminants. However, despite improved water quality, less water loss, and more localized transients, the branched network cannot meet water demands downstream of the burst until the pipe is repaired, unlike a traditional looped network. For modern buildings that meet current design guidelines, the Dutch are content with much lower fire-flow requirements that provide the flexibility to improve water quality and reduce the consequences of pipe bursts, especially water loss.

Key words: fire flows, network design, pipe burst, transient pressures, water quality

HIGHLIGHTS

- Pipe bursts in two networks are considered: a traditional pipe layout and a design with smaller pipes with fewer loops.
- After a pipe bursts in a traditional network, considerable water is released, and negative pressures radiate some distance in all directions.
- After a burst in the Dutch network, less than one-tenth of the water is released, and negative pressures and other effects are highly localized.

GRAPHICAL ABSTRACT



INTRODUCTION

Though water distribution networks (WDNs) are critical to the functioning of urban centers, the public often takes them for granted. They provide water for drinking, business, and industrial applications and water for firefighting. The design of WDNs that often can involve thousands of pipes and uncertain demands presents a considerable challenge. A wide variety of techniques have sought to improve, or even to ‘optimize,’ design based on a range of assumptions. For example, maximizing flow entropy has been suggested to improve reliability (Liu *et al.* 2014), a Multiobjective Simulated Annealing Algorithm has been suggested for design optimization (Shokoohi *et al.* 2017), a Cost Gradient-Based Assessment has been suggested for design improvement under varying loads (Dziedzic & Karney 2016), and Agent Swarm Optimization has been suggested for design optimization (Montalvo *et al.* 2014). However, all these optimization approaches are subject to constraints, which can vary by the region. Common constraints in North America are that no pipes smaller than 150 mm in diameter are used and the flows needed for firefighting are large, often requiring a looped design to produce the required flow. This work examines two representative networks with different constraints based on regional preferences: a branched Dutch network with smaller pipes and lower needed fire flows is contrasted to a traditional North American style network.

The hydraulic design of WDNs is often constrained by the need to supply large fire flows. This constraint can dictate both pipe size and the topology of the network. In North America, in key urban areas, fire flows of 800 cubic meters per hour (CMH) or 3,500 gpm can be required (American Water Works Association 2008). In residential areas, flows of no less than 115 CMH (500 gpm) are required (Linder 1991; American Water Works Association 2008). In contrast, Dutch planners and engineers have worked with fire authorities to reduce the requirements in residential areas that meet modern building codes to just 30 CMH, or about a quarter of the American requirement (Vreeburg & Boxall 2007). In France and England, and many of its former colonies (except Canada), needed fire flows in residential areas are about half, which are approximately 60 CMH in residential areas (Benfer & Scheffey 2015). This reduced need for high fire flows provides more flexibility in pipe choice and network topology.

North American networks typically use large-diameter pipes ($\geq$150 mm diameter) arranged in a looped grid. The gird design ensures that many flow paths are available in case of fire, with each pipe contributing a portion. In contrast, the Dutch design emphasizes water quality and relaxes the need for a larger hydraulic capacity, thus permitting smaller pipes (63 or 40 mm) in a branched structure. Other factors being equal, smaller diameter pipes have higher velocities than larger ones, thus reducing transit time and water age and providing less time for the formation of disinfection by-products or disinfectant decay. Also, such pipes may be self-cleaning, where the higher velocities help to remove sediments, or possibly condition the pipes, so that red water events are less likely (Vreeburg & Boxall 2007; Vreeburg *et al.* 2009; Abraham *et al.* 2018).

There are at least 240,000 pipe bursts that waste over two trillion gallons of treated drinking water in the USA each year (Baird & Wagner 2020). Pipe bursts release pressurized water, thus leading to transient flows and pressures within the pipe system. Water hammer is the best-known example of a transient pressure and can damage pipes. For example, Wang *et al.* (2021) used a model of transient pressures to estimate the probability of failure of prestressed concrete cylinder pipe segments. Similarly, Kwon & Lee (2011) report that transient effects significantly increase the probability of pipe breakage. Low-pressure transients can occur downstream of a closing valve or a stopped pump or from a sudden water release. The role of low-pressure transients introducing contaminants into leaking pipes by suction has been widely studied (Lindley & Buchberger 2002; Betanzo *et al.* 2008; Besner *et al.* 2010). Other recent WDN transient research includes an active controller to reduce transients from changing demands (Martin *et al.* 2022), a computationally efficient adaptive model (Nault & Karney 2020), and new modeling approaches (Andrade *et al.* 2022).

Despite considerable progress, previous research has rarely attempted to link different regional constraints to pipe burst behavior. This work compares how an innovative Dutch network design performs after a pipe burst relative to a typical North American network design, with an emphasis on transient pressures.

METHODS

Estimating transient pressures

Arguably, the simplest way to estimate transient pressures is to use the Joukowsky equation which relates a sudden change in flow velocity (Δv) to the maximum pressure change possible (ΔP):

$$\Delta P = \mp \rho a \Delta v \tag{1}$$

in which ρ is the fluid density, and a is the wave speed (m/s). Wave speed is a function of the bulk modulus of water and the elastic modulus of the pipe material. For plastic pipe, the wave speed is often between 300 and 350 m/s, whereas, for cast iron pipe and many other more rigid materials, it is often between about 1,100 and 1,200 m/s. This work assumes plastic pipe with a wave speed of 350 m/s. The change in pressure (ΔP) can be either positive or negative. For example, when an inline valve is being closed, the upstream transient pressure change is positive, while the downstream pressure is reduced. A sudden outflow, say associated with a suddenly increased demand or a pipe burst, produces a low-pressure transient that propagates outward from its point of origin.

A more rigorous estimate of transient behavior is available in many widely cited texts (Wylie 1993; Chaudhry 2014), which derived a one-dimensional momentum and continuity balance shown below:

$$\text{Momentum equation:}\, \partial Q\,(x,\,t)\partial t + gA\,\partial H(x,\,t)\partial x + \mu Q(x,\,t)|Q(x,\,t)|\; = \;0 \tag{2}$$

$$\text{Continuity equation: } \partial H(x,\,t)\partial t + b^2 gA\,\partial Q(x,\,t)\partial x = 0 \tag{3}$$

where Q is the flow rate (m^3/s), H is the pressure head (m), x is the position along the pipe (m), t is the time coordinate (s), g is the gravity acceleration (m/s^2), A is the cross-section area (m^2), b is the pressure wave speed in the fluid (m/s), $\mu = f\,(Q)/2\phi A$, with ϕ the inner diameter (m) and f the friction factor. Here, $x \in [0,\,L]$ denotes the position along the pipe, and L is the equivalent straight length. These are nonlinear hyperbolic partial differential equations, and a general analytical solution to them is not available. However, the governing equations can be transformed by the method of characteristics (MOC) into two pairs of ordinary differential equations, and the transformed equations can be numerically integrated. Many commercial codes address the need for a more complete analysis of transient events.

Test networks

The design of the Dutch, branched test network simulated here is based on an example provided by Vreeburg & Boxall (2007). In this work, the network has a 150 mm main supported by branches of 110 mm that taper down 63 mm and then 40 mm as a dead end is approached. This contrasts with a typical North American network, which uses mainly 150 mm diameter pipes. In this work, the network was adapted to the North American style by replacing the previous pipes with a grid of 150 mm pipes serving the same demands, which is supported by a 250 mm main. All pipes are assumed to be PVC and to have a Hazen–Williams value of 100. The remainder of the both test networks was simulated with two constant head reservoirs with 35 m of pressure head. The layout and pipe diameters are shown in Figure 1.

Pipe bursts and calculations

A pipe burst was simulated by connecting a pipe with negligible resistance to the test node indicated. This pipe terminates in an emitter that allows the pipe to discharge freely into the atmosphere. The steady-state solutions were determined using EPANET 2.0 (U.S. Environmental Protection Agency), and the transient analyses were done using TransAM (Northwest Hydraulic Consultants Inc., Pasadena, CA). The transient analysis consisted of 12 s model run where a pipe burst occurs over 1 s. The model accounts for cavitation when negative pressures were reached. The vapor pressure of water was assumed to be 0.24 m.

SIMULATION RESULTS

Normal operation

Dutch networks are designed to maintain higher velocities during normal operation, which can reduce water age and stagnation. This goal is achieved as shown in Figure 2. The target velocities for ‘self-cleaning pipes’ are approximately 0.2 m/s (Vreeburg *et al.* 2009). From Figure 2, the median velocity in the Dutch network is 0.19 m/s, some four times larger than the North American network, and a value low enough to result in negligible head losses during normal operation.

However, higher velocities can result in higher transient pressures if the flow is suddenly changed. For the Dutch network, the median transient pressure expected during normal operation is 67 kPa (10 psi), as shown in Figure 3. In the Dutch test network, the maximum potential transient pressure is 120 kPa (17.4 psi). Since this is during normal operation, and flows will stop and start throughout the day, transient pressures approaching these values would be expected to occur frequently. In contrast, the transient pressure experienced in the North American network during normal hours is much lower, owing to their lower operational velocities.

Pipe burst: velocity map

This initial analysis using EPANET considers the steady performance of the network several seconds after the pipe burst has occurred and until the pipe is isolated. The transient analysis of the pipe burst on shorter time scales is considered below.

In the branched Dutch network, demands downstream of the burst will be unmet since no other flow path is available. The looped topology and large-diameter pipes of the North American network ensure that demands are met even after a pipe burst has occurred. However, this comes at a cost. In the North Americans network, approximately 930 CMH of water is discharged until the pipe is isolated. Owing to the looped topology, many pipes in this network experience high velocities after a pipe burst, as shown in red and yellow in Figure 4. In the North American network, three 150 mm diameter pipes feed water to the burst at velocities between 3 and 5 m/s. If this flow were suddenly arrested, these high velocities could produce transient pressures exceeding 1,000 kPa (145 psi). This illustrates why it is important to close isolation valves slowly after a burst even if flooding is occurring.

In contrast, the potential for transient pressures and product loss after a burst is much lower in the Dutch network. Here, a 63 mm diameter pipe restricts velocities exceeding 3 m/s to a single short pipe (Figure 5). Much of the network is unaffected by the burst, as shown in Figure 5. Since there are not multiple large-diameter pipes feeding the burst, the rate of water loss is restricted to just 50 CMH, some 16 times lower than for the traditional North American network used in this study. Overall, the Dutch network has a much lower potential for water loss and transient pressures following a burst.

Pipe burst: transient analysis

Negative pressures are the focus of this discussion since they are the primary outcome of a burst event. Even relatively small negative pressures can introduce contaminants into the pipe through existing leaks, which can pose a health risk. When a

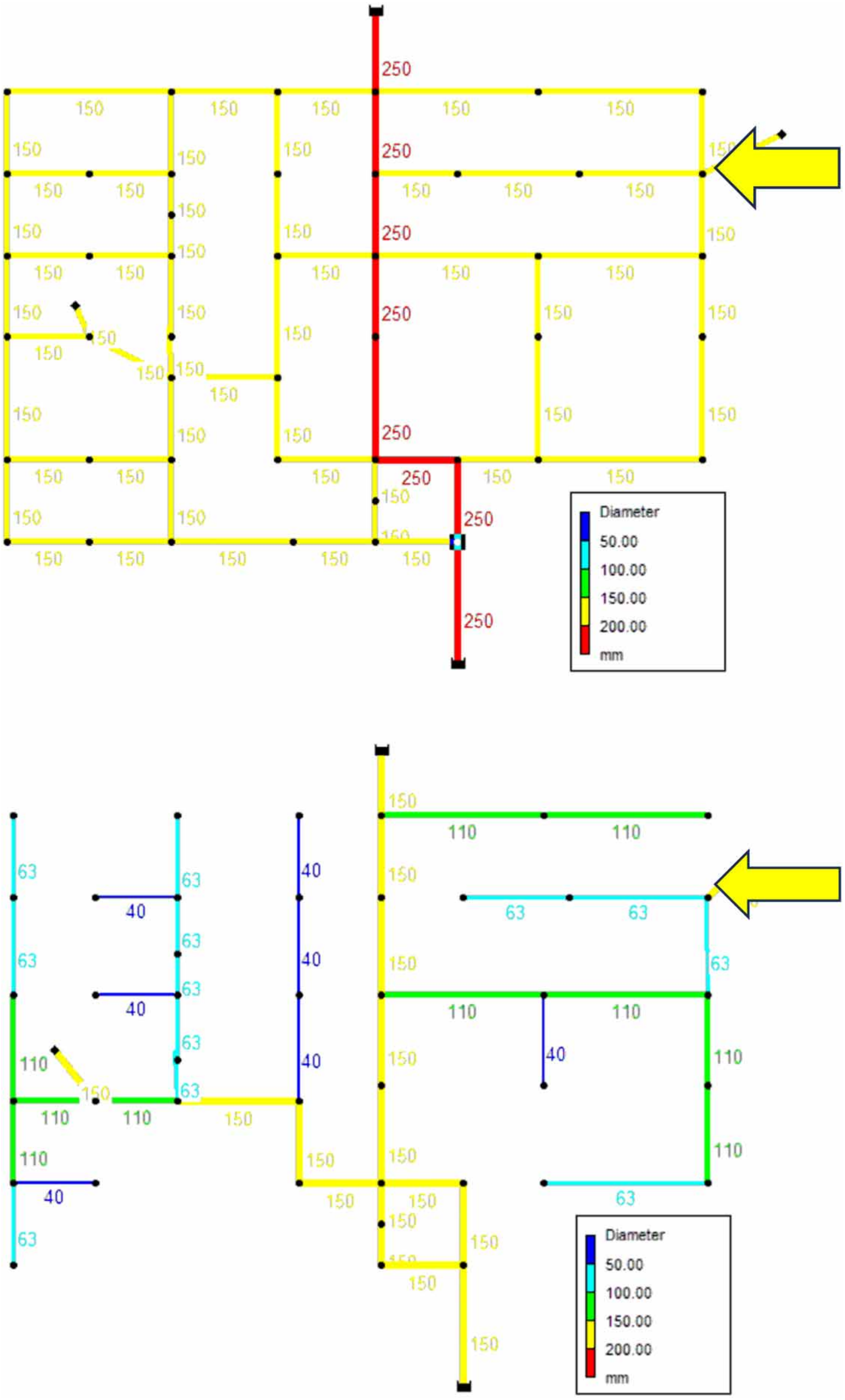


Figure 1 | Pipe layout and diameter in millimeters for a North American looped (top) and Dutch branched (bottom) test network. The test node where the pipe burst occurs is indicated by the arrow.

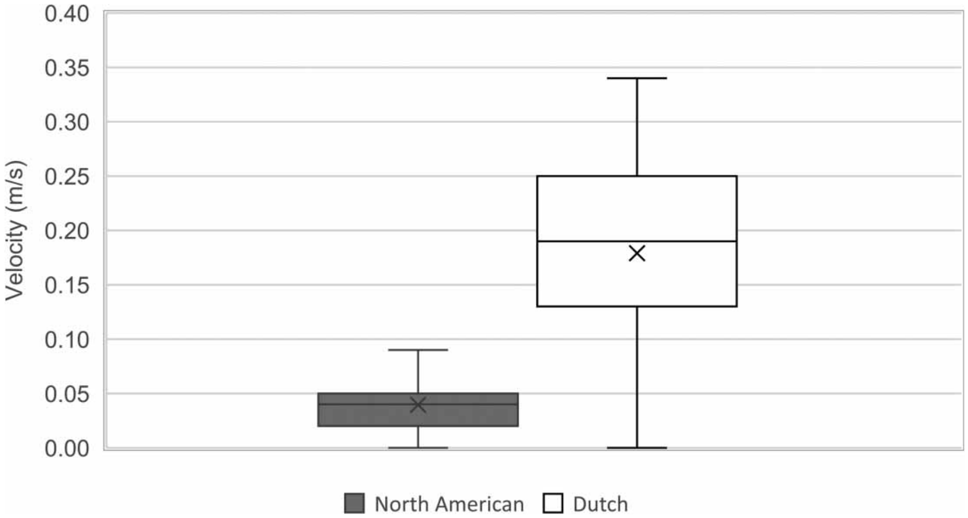


Figure 2 | Distribution of flow velocities in the pipes of two networks during normal operation.

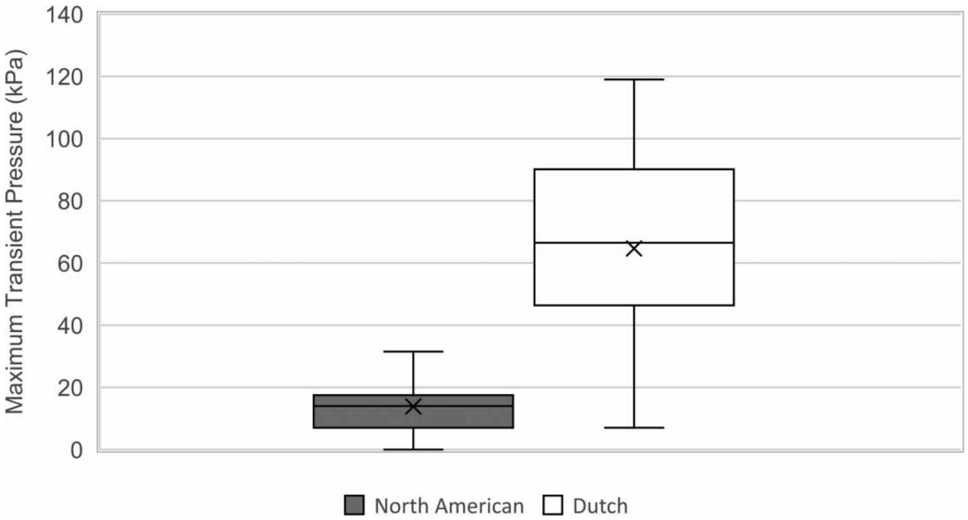


Figure 3 | Expected transient pressures in the pipe of two networks during normal operation.

pipe burst occurs in the North American network, full vacuum pressures are transmitted approximately 50 m upstream of the burst (Node I), as shown in Figure 6. The light blue dotted line shows the minimum pressure experienced at each location. This model restricts negative pressures to approximately −10 m where the vapor pressure of water is reached, inducing cavitation. Just one of the three high-velocity flow paths feeding this burst experiences negative pressures. The other two paths approach zero pressure but do not become negative (not shown). At point E, the 150 mm diameter pipe meets the larger 250 mm diameter main and the negative pressure effects are diminished. Transient pressure waves are modeled based on the conservation of momentum and when they reach a larger diameter pipe at point E, they are reflected and attenuated.

Because the Dutch network is branched, there is just a single flow path and its transient pressure profile is shown in Figure 7. Downstream of the pipe burst at Node I, depending on the nature of the demand model, there might be considerable negative pressures as the model tries to meet the demands that are being interrupted by the burst. This is likely an artifact of the model since water demands are pressure-dependent. Nonetheless, this downstream length of pipe will require decontamination after the burst. However, upstream of the burst, there was effectively no negative pressures, unlike the North

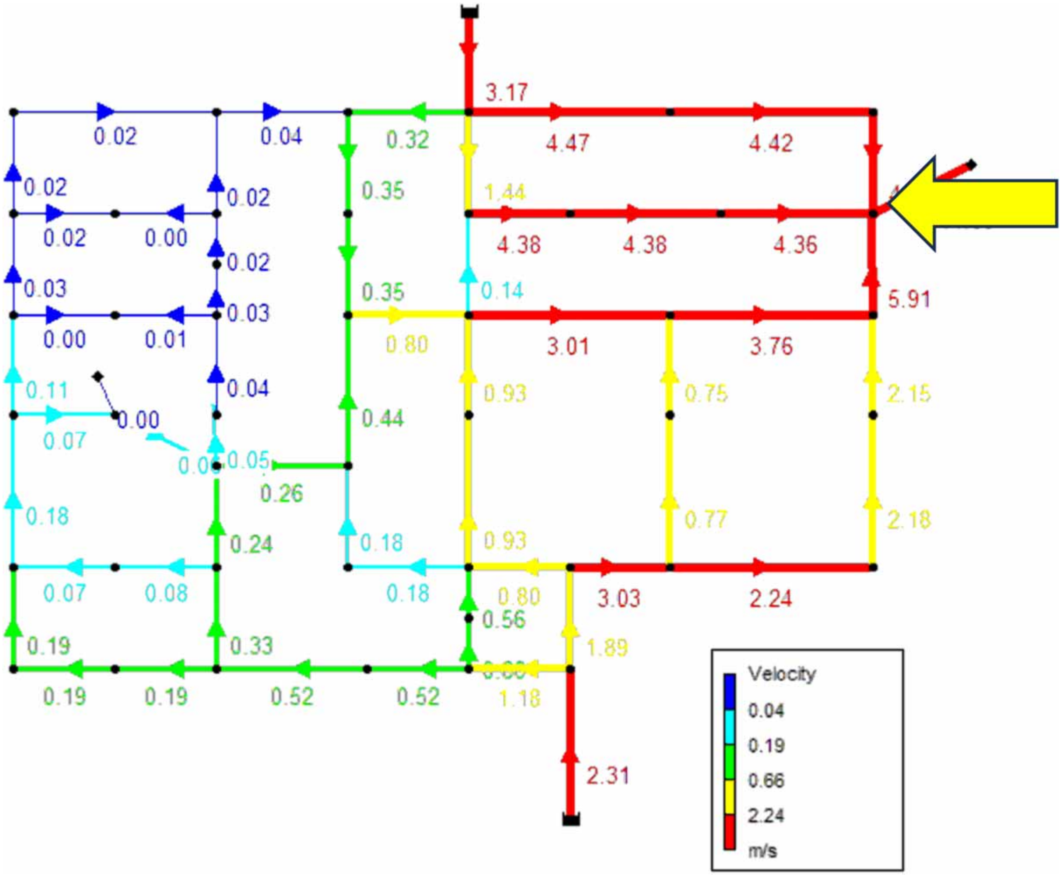


Figure 4 | Pipe velocities after a pipe burst in the North American network. The node where the burst occurs is indicated by the arrow. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/ws.2023.227.

American test network. In general, the high velocities in the Dutch network are more localized. Also, in the Dutch network, pipe diameter tends to increase when moving upstream. This increase in diameter tends to attenuate the effects of negative pressures due to wave reflections. Figure 7 presents the light blue 'staircase' of stepwise decreasing negative pressures when moving upstream of the burst.

DISCUSSION

All design and modeling choices require analysts to make assumptions and simplifications. Since the objective here is to compare different network design approaches, no surge protection or air valves were included. In actual networks, these devices have the potential, if well chosen and maintained, to dampen transient effects. Because both networks were assumed to have only plastic pipes, transients associated with sudden events were relatively mild; more severe transients would be expected for bursts associated with cast iron or other rigid pipe materials. For simplicity, the soil surrounding the pipe burst is assumed to be quickly washed away, and unrestricted discharge after the burst is the result. Overall, other than the choice of plastic pipes, the approach is conservative.

Design inevitably involves trade-offs depending on what aspects are prioritized. Thus, it is unsurprising that the two design approaches considered here have their advantages and disadvantages. The North American test network acts as an effective and robust fire extinguisher. When a burst occurs, the pipe contents are rapidly mobilized and negative transient pressures are expected. In this example, 50 m of the pipe upstream of the burst experiences pressures of −10 m. Also like a good fire extinguisher, the potential flow available is considerable. In this example, 930 CMH of water can be released after a burst. These high flows can result in water damage, product loss, local flooding, street damage and traffic interruption, pipe contamination, and disruption of other services like electricity (Gaewski *et al.* 2007; Pietrucha-Urbanik 2015; Karney & Gibson 2021). Much higher direct and indirect costs are expected after a pipe burst in the North American network.

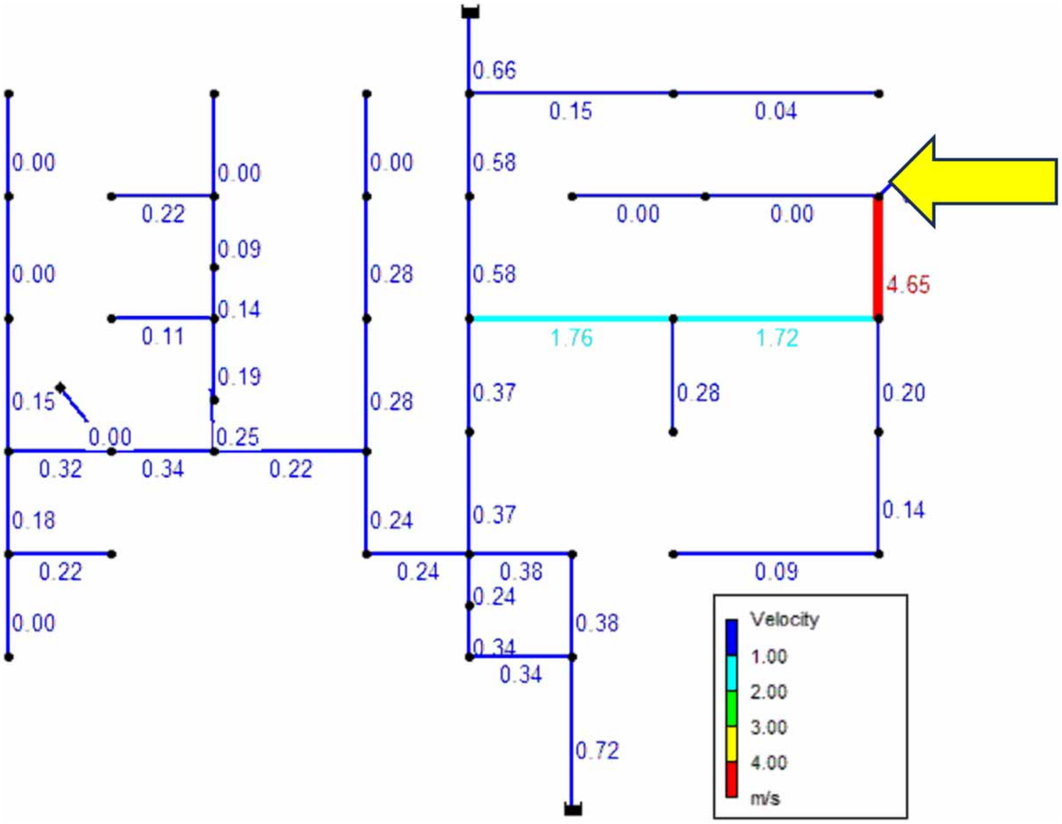


Figure 5 | Pipe velocities after a pipe burst in the Dutch network. The node where the burst occurs is indicated by the arrow.

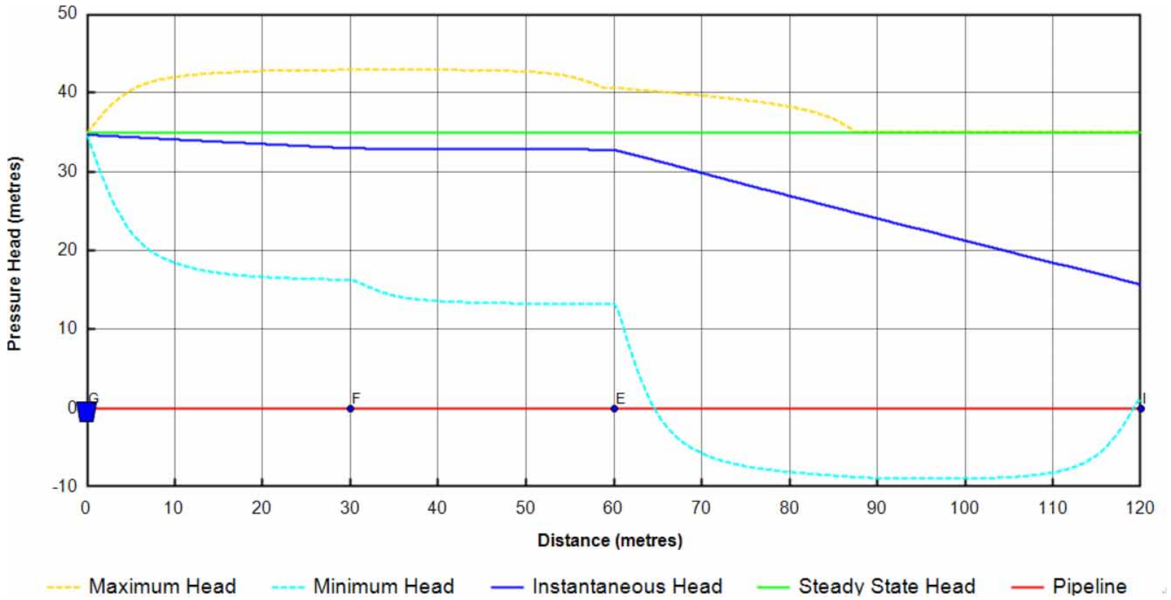


Figure 6 | Transient pressures experienced on the flow path to a pipe burst at Node I in the North American test network.

In the Dutch design, the small diameter pipes act essentially as a limiter or governor, localizing the effects and restricting the flow that can be produced after a burst to just 50 CMH. In this case, there is a lower expected cost associated with a pipe burst since much less product loss and flooding are expected.

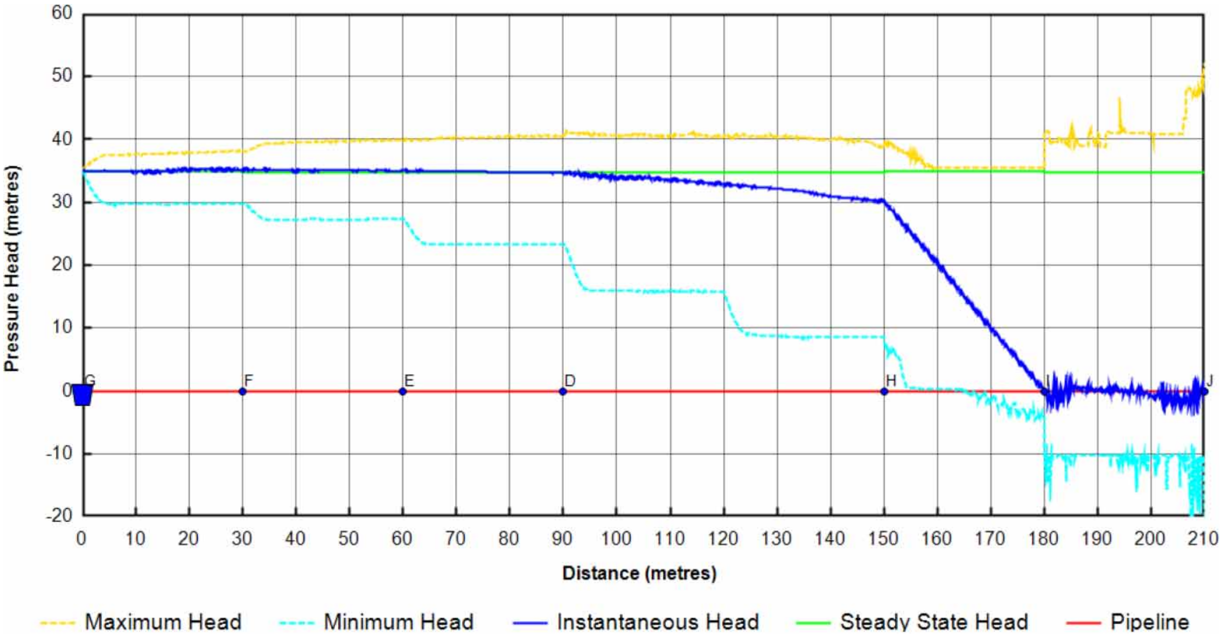


Figure 7 | Transient pressures experienced on the flow path to a pipe burst at node I in the Dutch test network.

When not being used to fight fires, the contents of a fire extinguisher are at rest, a situation that is nearly true for the North American test network. The median flow velocity is a mere 0.04 m/s. Such a small velocity can lead to stagnation and degraded water quality, something the Dutch have sought to remedy in their design.

A potential disadvantage of the Dutch network, highlighted here for the first time, is that the Joukowsky equation predicts higher transient pressures during normal operation. In the top 10% of pipes of the test network, transient pressures of at least ±107 kPa (16 psi) would be experienced during the sudden switching of demands, even in normal operation. This is not severe enough to result in negative pressures and intrusion under most conditions. However, such routine transient events may affect the network in unexpected ways, finding and damaging weakened pipes for example. But these transients pressures also likely help to mobilize sediments and keep the pipes clean (Weston *et al.* 2021). The overall effect of these relatively low, but frequent, transients remains unclear.

Negative pressures can result in the ingress or intrusion of contaminants. Before the pipes are put back into service, they should be decontaminated where negative pressures are suspected. In the North American test network, there are three pipes that experience high velocities (>3 m/s) as they feed water to the burst pipe. Negative pressures can occur in any one of these three pipes. In addition, high velocities occur throughout the network due to its looped topology and high flows are produced. As such, all pipes adjacent to the burst should be decontaminated for approximately 50 m, which is a challenge in a grid network. The problem is simpler for the Dutch network. The pipe downstream of the burst should be decontaminated, which is easier to execute.

SUMMARY AND CONCLUSIONS

The WDNs studied here represent two different design philosophies. The key question is this: is it better to design networks so that their performance is excellent during normal conditions but merely adequate during emergencies, or is it better to design the network for best performance during emergencies and slightly compromised during normal conditions? Although there are difficult choices, it is worth noting that fires may represent just a few hours of operation in the 30-year service life of many pipes. Based on the results presented here, each of these designs has several advantages and disadvantages. For North American Networks:

- High fire flows are readily and reliably achieved due to large pipes (≥150 mm) and grid topology.
- Water is discharged to the environment at a very high rate after a burst, which can result in product loss and local flooding.

- All pipes near the burst should be decontaminated for approximately 50 m. Many parallel flow paths feeding the burst means negative pressures can occur in any one of them.
- Network demands can likely still be met during a pipe burst.
- Flow is nearly stagnant during normal operation.

For Dutch networks:

- Water demands cannot be met downstream of a burst pipe until repair is completed.
- The smaller pipes and branched structure act as flow limiters. Less water damage and flooding are expected after a burst, but also less fire flow is available.
- Lower water age and better water quality are expected. The median pipe velocity during normal operation was approximately 0.2 m/s, which was four times higher than the North American example.
- Only the pipe downstream of the pipe burst needs to be decontaminated.
- Transient pressures of approximately 100 kPa (16 psi) are expected in the top 10% of pipes during normal operation, likely mobilizing or conditioning sediments.

There are many advantages associated with the Dutch design, including better water quality, and lower costs and less damage expected after a pipe burst. However, it is not currently possible to implement this design, as shown here, in North America due to fire-flow requirements. Fundamentally, the controversial background question is how much water is really needed to provide fire protection in modern neighborhoods. The Dutch approach implies this need is much less than that currently provided in North America. This may suggest that it may be time to re-examine fire-flow requirements in North America that have remained largely unchanged for many decades.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the contribution of David Axworthy and Northwest Hydraulic Consultants Inc.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Abraham, E., Blokker, M. & Stoianov, I. 2018 Decreasing the discoloration risk of drinking water distribution systems through optimized topological changes and optimal flow velocity control. *J. Water Resour. Plan. Manage.* **144**, 04017093. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000878.

American Water Works Association (ed). 2008 *Distribution System Requirements for Fire Protection*, 4th edn. American Water Works Association, Denver, CO.

Andrade, D. M., de Freitas Rachid, F. B. & Tijsseling, A. S. 2022 A new model for fluid transients in piping systems taking into account the fluid–structure interaction. *J. Fluids Struct.* **114**, 103720. https://doi.org/10.1016/j.jfluidstructs.2022.103720.

Baird, G. M. & Wagner, T. B. 2020 The high cost of using AWWA's buried no longer pipe service life table for capital budgeting. In *Pipelines 2020*. American Society of Civil Engineers, San Antonio, TX (Conference Held Virtually), pp. 34–44

Benfer, M. E. & Scheffey, J. L. 2015 *Evaluation of Fire Flow Methodologies*. Springer, New York, NY.

Besner, M. C., Ebacher, G., Jung, B. S., Karney, B., Lavoie, J., Payment, P. & Prévost, M. 2010 Negative pressures in full-scale distribution system: field investigation, modelling, estimation of intrusion volumes and risk for public health. *Drink Water Eng. Sci.* **3**, 101–106. https://doi.org/10.5194/dwes-3-101-2010.

Betanzo, E. W., Hofmann, R., Hu, Z., Baribeau, H. & Alam, Z. 2008 Modeling the impact of microbial intrusion on secondary disinfection in a drinking water distribution system. *J. Environ. Eng.* **134**, 231–237.

Chaudhry, M. H. 2014 Transients in hydroelectric power plants. In: *Applied Hydraulic Transients*. Springer, New York, NY, pp. 155–220.

Dziedzic, R. & Karney, B. W. 2016 Cost gradient-based assessment and design improvement technique for water distribution networks with varying loads. *J. Water Resour. Plan. Manage.* **142**, 04015043. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000573.

Gaewski, P., Tata and Howard Inc. & Blaha,, F. 2007 *Analysis of the Total Cost of Large Diameter Pipe Failures*.

Karney, B., Gibson, J., 2021 Misbehaving drinking water systems: risk and the complex nature of failure. In: *Water Risk and Its Impact on the Financial Markets and Society: New Developments in Risk Assessment and Management* (Walker, T., Gramlich, D., Vico, K. & Dumont-Bergeron, A., eds.). Springer International Publishing, Cham, pp. 283–301.

Kwon, H. J. & Lee, C.-E. 2011 Probability of pipe breakage regarding transient flow in a small pipe network. *Ann. Nucl. Energy* **38**, 558–563. https://doi.org/10.1016/j.anucene.2010.09.026.

Linder, K. 1991 *Fire Protection Handbook*, 17th edn. National Fire Protection Association, Quincey, MA.

Lindley, T. & Buchberger, S. 2002 Assessing intrusion susceptibility in distribution systems. *Am. Water Works Assoc. J.* **94**, 66–79.

Liu, H., Savić, D., Kapelan, Z., Ming, Z., Yixing, Y. & Hongbin, Z. 2014 A diameter-sensitive flow entropy method for reliability consideration in water distribution system design. *Water Resour. Res.* **50**, 5597–5610. https://doi.org/10.1002/2013WR014882

Martin, A., Delgado-Aguiñaga, J. A. & Puig, V. 2022 Control of transients in drinking water networks. *Control. Eng. Pract.* **119**, 104986. https://doi.org/10.1016/j.conengprac.2021.104986.

Montalvo, I., Izquierdo, J., Pérez-García, R. & Herrera, M. 2014 Water distribution system computer-aided design by agent swarm optimization. *Comput.-Aided Civ. Infrastruct. Eng.* **29**, 433–448. https://doi.org/10.1111/mice.12062.

Nault, J. D. & Karney, B. W. 2020 Comprehensive adaptive modelling of 1-D unsteady pipe network hydraulics. *J. Hydraul. Res.* 1–17. https://doi.org/10.1080/00221686.2020.1770878.

Pietrucha-Urbanik, K. 2015 Failure analysis and assessment on the exemplary water supply network. *Eng. Fail. Anal.* **57**, 137–142. https://doi.org/10.1016/j.engfailanal.2015.07.036.

Shokoohi, M., Tabesh, M., Nazif, S. & Dini, M. 2017 Water quality based multi-objective optimal design of water distribution systems. *Water Resour. Manage.* **31**, 93–108. https://doi.org/10.1007/s11269-016-1512-6.

Vreeburg, I. J. H. G. & Boxall, J. B. 2007 Discolouration in potable water distribution systems: a review. *Water Res.* **41**, 519–529. https://doi.org/10.1016/j.watres.2006.09.028.

Vreeburg, J. H. G., Blokker, E. J. M., Horst, P. & van Dijk, J. C. 2009 Velocity-based self-cleaning residential drinking water distribution systems. *Water Sci. Technol. Water Supply* **9**, 635. https://doi.org/10.2166/ws.2009.689.

Wang, W., Bahrami, O., Norton, J., Wang, W., Bahrami, O., Norton, J., Jin, S., Wolf, C. & Lynch, J. P. 2021 *Use of Transient Pressure Data in a Drinking Water Transmission System to Assess Pipe Reliability*. SPIE, pp. 1159107–11.

Weston, S. L., Collins, R. P. & Boxall, J. B. 2021 An experimental study of how hydraulic transients cause mobilisation of material within drinking water distribution systems. *Water Res.* **194**, 116890. https://doi.org/10.1016/j.watres.2021.116890.

Wylie, E. B. 1993 *Fluid Transients in Systems*. Prentice Hall, Englewood Cliffs, NJ.

First received 14 February 2023; accepted in revised form 18 August 2023. Available online 31 August 2023