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RESEARCH ARTICLE

# Intrinsic relationship between energy consumption, pressure, and leakage in water distribution systems

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## ABSTRACT

The basic implications of changes in delivery pressure on system energy use and cost, on leakage, excess pressure, and environmental impacts are explored. An analytical expression is first developed to characterize the primary relationships between energy use, leakage and pressure for a simple pipe segment. Then, two more realistic case studies, based on varying versions of the Anytown network, are considered. The results indicate that energy use responds more to changes in the delivery pressure in systems with higher leakage rates while reductions in pressures curtail energy use and leakage more dramatically in low resistance systems. Perhaps more surprisingly, systems with more effective water storage and thus uniform pressures tend to have higher leakage rates, greater energy usage, and higher GHG emissions relative to systems relying on direct pumping. The generalization that results from these studies is perhaps predictable but has profound implications: the higher the delivery pressure the greater will likely be the amount of water wasted and energy dissipated.

## ARTICLE HISTORY

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## 1. Introduction

Water distribution systems (WDSs) are historically designed to deliver safe and reliable drinking water with sufficient pressure. Yet, there are no universally accepted guidelines to specify the appropriate pressure standards for WDS designs. For example, most Canadian provinces and US states use a minimum pressure criterion (MPC) of 14 m, but Australia often requires 20 m and the UK only 10 m (Ghorbanian *et al.* 2015a). Maximum pressure standards are not established for many regions though a number like 70 m is sometimes suggested (ACWWA 2004). However, design standards do generally require that water mains be designed to be strong enough to withstand the maximum operating pressures in addition to transient pressures.

A lower value of the delivery pressure may reduce water consumption (e.g., consumptions from faucet, showers, and lawn watering) and also leads to efficient operation through reduced energy use, leakage, and frequency of pipe breaks. However, if the delivered pressure is too low, the system may be more susceptible to intrusion events resulting from hydraulic transients, and the system may also be incapable of supplying the required flows. Water utilities set a minimum pressure to ensure the delivery of adequate flows to fire hydrants and consumers at remote and high elevation areas. Most insurance companies are concerned with the risk of fires that often require a certain fire flow rate that meets a specific pressure standard. However, such a pressure standard is almost certainly temporally violated

during the transient event associated with the initial opening of the hydrant (Ghorbanian *et al.* 2015b). Moreover, the flow of a hydrant is governed by the orifice relationship and depends on the hydrant's outlet nozzle diameter, thus the required fire flows may be supplied under a pressure less than the MPC under steady state conditions (Ghorbanian *et al.* 2015a).

Colombo and Karney (2002, 2005) examined the impact of leaks on the energy consumption in water supply systems. Not surprisingly, they concluded that leaks increase both operating and energy costs, but that energy costs increase more than proportionately with leakage. They also found that leaky systems with storage may often have higher operating and energy costs as compared to systems with direct pumping systems. If a system is operating at high pressures, its delivery conditions and its energy use is suboptimal. Since this point is so critical, it seems logical to further explore these key pressure relations.

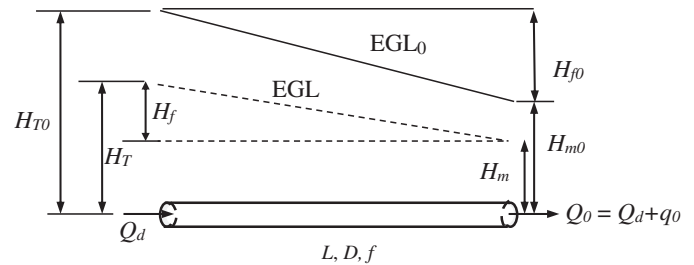
Traditionally, pressure management has been considered as an effective way of reducing the excess pressures and the amount of water lost in a system during off-peak hours (Gomes *et al.* 2011). To limit pressures, pressure reducing valves are installed with the number of valves, their location, and their set-points optimized (Liberatore and Sechi 2009). The pressure reducing valves setting can be adjusted automatically on the basis of the measurements of pressure at the control node and water discharge in the pipe if real time control is applied (Campisano *et al.* 2012, Creaco and Franchini 2013). In implementing a pressure management

strategy, the total energy supplied does not necessarily change and this energy may be still too high even though the system operating pressure is controlled. Additional benefits might be gained by reducing the energy supplied. A case study showed that significant energy savings can be achieved through reduced energy input (to decrease delivery pressure) for the service pressure using pumping at lower head (LeChevallier *et al.* 2014). However, only a few studies to date have considered the consequences of changes in the delivery pressure in terms of leakage, energy use, and environmental impact.

The pressure supplied by WDSs can be either above the requirement for service level or in a deficient condition (e.g. pipe outages, power failures at pump stations and fire flow conditions). For the former, the demand driven analysis (DDA) is often performed to determine performance of WDSs under normal condition. In demand driven models, the supplied demand is assumed to be independent of pressure and this approach is valid when the pressure is above the MPC considered according to design guidelines. In deficient condition however, the pressure driven models should be used to more accurately predict the system response (Wu *et al.* 2009). In pressure driven analysis (PDA), nodal demand is assumed to vary with the nodal pressure and when nodal pressure rises to a certain level, i.e., the MPC, the total demand is supplied. Several methods have been proposed to analyse water distribution system under insufficient conditions (Gupta and Bhawe 1996, Ang and Jowitt 2006, Siew and Tanyimboh 2011). The PDA can also be modeled by the emitter feature in EPANET2 which needs iterations at each node for computation of accurate head and demand (Assela 2010, Jun and Guoping 2013). The MPC is a key parameter to distinguish whether the total demand can be supplied, but this value varies around the world (Ghorbani *et al.* 2015a).

In this paper, the aim is to determine the potential for energy savings and benefits of leak reduction from reduced energy input for service pressure (i.e., reduction of delivery pressure). It is naturally assumed that such a reduced delivery pressure can still supply total demand (e.g., the delivery pressure is not lower than the assumed MPC). Thus, a demand driven analysis is still generally valid. Of course, in a leaky system, the leakage rate depends upon the pressure at the leak location and should be modeled based on PDA. Leakage is generally modelled here using the emitter feature of EPANET2 (Rossman 2000).

The context of this paper is slightly different from the study conducted by Colombo and Karney (2002, 2005). In these previous researches, leak size and location effects on water loss and energy use were examined as were leakage levels on energy costs in systems including storage tanks. In particular, in the work of Colombo and Karney (2002, 2005), the attempt was made to highlight the impact of leaks on the energy use and pumping costs of a system. No effort was made to determine the effectiveness of pressure reduction as a leak management strategy which is the main focus here. In particular, the current paper explores the effectiveness of changes in delivery pressure on system energy use, leakage, and environmental impact (the latter is explained in the supplementary material because of the Journal length constraints). A simple pipe is first considered to derive the analytical expression to characterize the relationship between energy use, leakage and pressure. The derived analytical equations offer a concise description of how pressure influences leakage rate and



**Figure 1.** Effects of reduction in pressure in a leaky pipe segment ( $L$  = Pipe length,  $D$  = Pipe diameter,  $f$  = Darcy-Weisbach friction factor,  $q_0$  = leakage rate).

energy requirements. Then, the Anytown network (Walski *et al.* 1987) is considered to highlight the impact of high delivery pressure on energy consumption, excess pressure, and leakage. To compare a typical network without storage with the Anytown system, the unrehabilitated Anytown without storage tanks, in which the tanks are removed from the Anytown network, is also considered.

## 2. Consequences of pressure reduction

To illustrate the essential response to a change in pressure, the simple system in Figure 1 is first considered. Although almost trivial, concise equations can be derived to describe how pressure influences both leakage and energy values. Although clearly idealized, the simplified approach helps focus attention on the key variables.

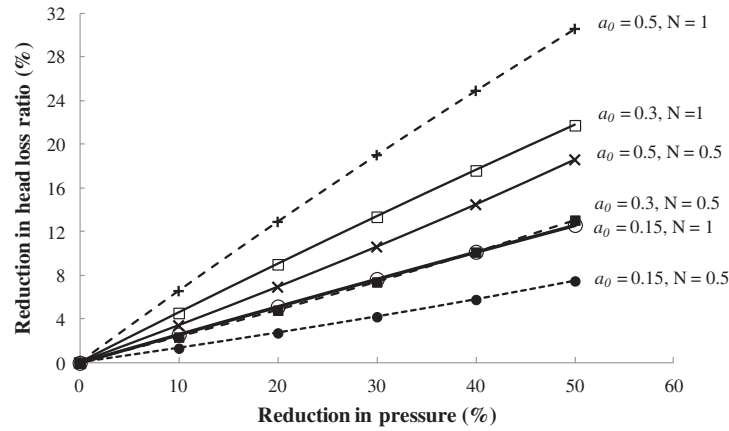
### 2.1. Pressure, leakage, and headloss

In Figure 1, it is assumed that the required flow  $Q_d$  is supplied at prescribed downstream heads, i.e.,  $H_{m0}$  and  $H_m$  denoted as delivery heads. Because of leakage, the flow in the pipe exceeds  $Q_d$  by  $q_0$ ; moreover, a steeper energy grade line ( $EGL_0$ ) occurs due to greater friction loss. The modified EGL reflects the effects of head loss and leakage if pressure at the demand end of the pipe decreases. The total leakage rate,  $q_0$ , can either be expressed as a proportion of demand,  $q_0 = a_0 Q_d$ , where  $a_0$  is the leakage fraction, or it can be modeled using the emitter function,  $q_0 = CH^N$ , where  $C$  is the discharge coefficient and  $N$  is an exponent. The emitter exponent  $N$  is thought to vary depending of type of leak. Lambert *et al.* (2013) pointed out that  $N$  could be mostly in the range from 0.5 (fixed area leaks) to 1.5 (variable area leaks). In 50 tests conducted by Lambert (1997, 2000), the exponent  $N$  ranged from 0.52 to 2.59. From the emitter expression, the relative leakage rate can be expressed as

$$\frac{q}{q_0} = \frac{a}{a_0} = R_p^N \quad (1)$$

where  $a$  and  $a_0$  are leakage fractions associated with delivery heads of  $H_m$  and  $H_{m0}$ , respectively, and  $R_p$  is relative delivery head,  $R_p = H_m/H_{m0}$ . The relative flow,  $R_Q$ , at the end of the pipe can be expressed as

$$R_Q = \frac{1+a}{1+a_0} = \frac{\frac{1}{a_0} + R_p^N}{\frac{1}{a_0} + 1} \quad (2)$$



**Figure 2.** Relative head loss as a function of reduction in pressure.

Equation (2) compactly indicates that if the delivery head is lowered, pressures at leak locations decrease and water loss is diminished. Because the leak is modeled as an increment to required demand, reduction in leakage causes total flow of the pipe to reduce. A sensitivity to reduction in pressure confirmed that the flow reduction as a result of reduced pressure is more noticeable for a higher leak fraction with the greater  $N$ . The head loss equation for fully developed turbulent pipe flow,  $H_f = KQ^E$ , where  $H_f$  is the head loss,  $K$  is pipe resistance coefficient, and  $E = 2$  considering the Darcy-Weisbach formula for head loss expression, relates the head loss in a pipe to the flow ( $Q_0 = Q_d + q_0$ ) it conducts. For a pipe with a single leak discharging  $a_0 Q_d$  at the demand node, the resulting expression for the head loss ratio,  $R_p$  becomes a quadratic function of  $a$  and  $a_0$

$$R_f = \frac{H_f}{H_{f0}} = \left( \frac{1+a}{1+a_0} \right)^2 = R_Q^2 \quad (3)$$

Figure 2 shows how the head loss ratio ( $1 - R_p$ ) varies with leak fraction and reduction in pressure. Clearly, as pressures decrease (for all leakage fractions and values of the exponent  $N$ ), the reduction in head loss ratio increases implying that lowering pressure in a pipe segment causes both pressure and leakage decrease. For higher leakage fractions and greater  $N$ , the reduction in head loss ratio is more noticeable, thus effects of reduction in pressure in systems with a high leakage rate is more than that of systems with low leakage rate in terms of reduction in head loss. Although Equation (3) indicates that the head loss ratio is nonlinearly related to leakage fraction, the results in Figure 2 show that the reduction in head loss ratio is linearly increasing with pressure reduction ranging from 0 to 50%. Of course, the nonlinear effect of reduced pressure on reduction in head loss ratio becomes evident for higher values of pressure reduction (not shown). A reduction higher than 50% in delivery pressure may not be practical and is not considered for the single pipe system. Despite each curve following the shape of a linear function, there is no simple “rule of thumb” for relating decrease in head loss ratio to reduction in pressure for WDSs. Clearly, however, leaks are expected to affect the head losses and the distribution of pressure.

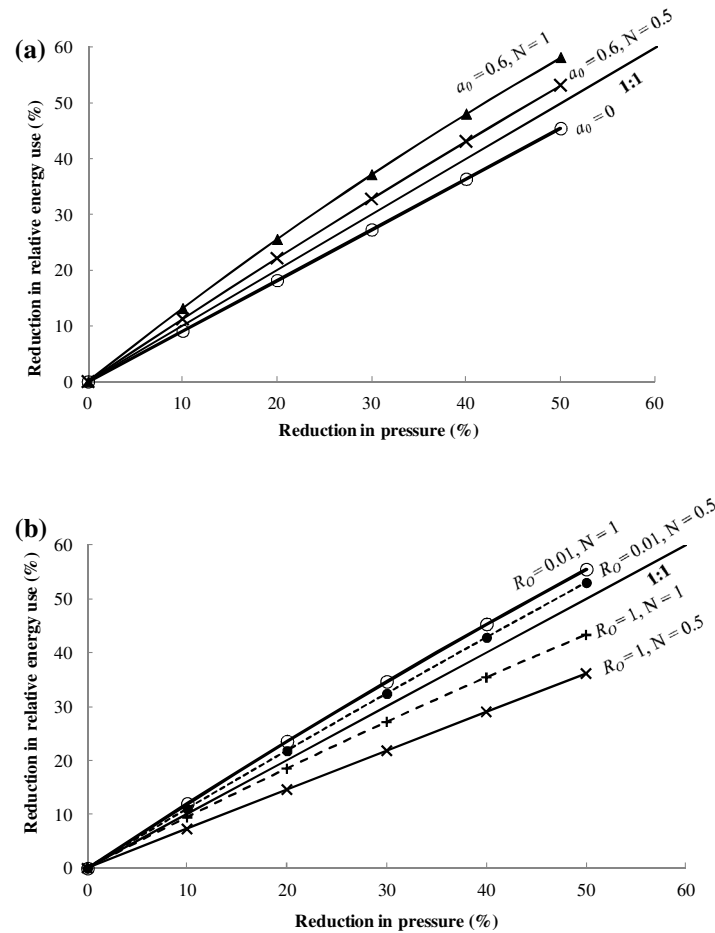
## 2.2. Pressure-energy relationship

If a system is leaking, reduction in pressure causes a decrease in both flow and pressure. The total head at the supply source decreases by  $\Delta H_T = \Delta H_m + H_{f0} - H_f$ , where  $\Delta H_m = H_{m0} - H_m$ , if  $H_{m0}$  is reduced by  $\Delta H_m$ . Thus, the amount of reduction in total supply head is greater than that of the pressure, i.e.,  $\Delta H_T > \Delta H_m$ . The leakage rate also reduces by  $\Delta q = a_0 Q_d (1 - R_p^N)$ . The amount of reduction in the energy at the source ( $\Delta E$ ) of the pipe segment shown in Figure 1 is proportionate to  $\Delta H_T \times \Delta q$ . To simply assess the energy effectiveness of changes in delivery pressure in a pipe segment, the energy use of the system, shown in Figure 1, can be expressed as a dimensionless term

$$\frac{E}{E_0} = \frac{\gamma Q H_T}{\gamma Q_0 H_{T0}} = R_Q R_p \left( \frac{1 + \frac{R_f}{R_p} R_Q}{1 + R_Q} \right) \quad (4)$$

where  $E_0$  and  $E$  are the energy supplied at the source for different scenarios in which delivery heads are  $H_{m0}$  and  $H_m$ , respectively,  $H_{T0}$  and  $H_T$  is the total head supplied upstream to meet pressure heads,  $H_{m0}$  and  $H_m$ , at the most downstream node, respectively, and  $R_Q = H_{f0} / H_{m0}$  indicating how the amount of friction loss is compared with the delivery head. In Equation (4), the supply efficiency associated with scenarios of  $H_{m0}$  and  $H_m$  is considered to be unchanged. From Equation (4), reduction in relative energy use depends upon  $R_Q$ ,  $R_p$ ,  $R_Q$ , and  $R_f / R_p$ . If in a specific system, the delivery pressure reduces, both  $R_p$  and  $R_Q$  are decreasing and  $R_Q$  is not influenced. Also, in a leaky system, if the pressure decreases  $a$  becomes less than  $a_0$ , then  $R_f / R_p > 1$  (this could be achieved by solving the inequality  $R_f > R_p$  considering Equations (1) and (3) and  $N = 0.5$ ). A sensitivity analysis of reduction in pressure indicated that the ratio of  $R_f / R_p$  is greater for a low leak system (e.g.,  $a_0 = 0.1$  and  $N = 0.5$ ) with respect to a reduction in pressure.

In a high leakage system, the response of the system is more noticeable in terms of energy use. The reason being that pressure reduction in a high leak system causes both  $R_Q$  and  $R_f / R_p$  to reduce more than that of a low leak counterpart. Thus, the reduction in energy use due to reduced pressures in systems with high leakage rate is more than that of low leak systems. The obvious point from



**Figure 3.** Reduction in relative energy use against changes in pressure: (a) Different leakage fraction ( $R_o = 0.01$ ,  $a_o = 0$  denotes no leakage rate), (b) Different friction regimes ( $a_o = 0.3$ ).

Equation (4) is that if the term  $(R_o (1 + (R_f/R_p)R_o)/(1 + R_o)) < 1$ , the percentage reduction in energy use is more than the percentage decrease in pressure. For this purpose,  $R_o$  and  $R_o$  should be relatively small, meaning the system should comprise a high leakage rate and low friction regime. This is confirmed in Figure 3 which depicts the response of a reduction in relative energy use ( $1 - E/E_o$ ) to changes in delivery pressure for different cases. Figure 3(a) indicates the effects of leakage. This figure represents a system with a low friction regime ( $R_o = 0.1$ ) and shows a reduction in pressure causes the relative energy use decreases and this reduction is more noticeable for a high leakage rate. As indicated in Figure 3(a), all curves associated with a leaky system ( $a_o > 0$ ) lie above the 1:1 line indicating that the percentage decrease in relative energy use is more than the percentage of the reduction in pressure. Indeed, leakage is a key parameter influencing the response of reduction in energy use to reduced delivery pressure. Pipe friction is also another key factor influencing reduction in the system energy use due to lowering the delivery head.

Figure 3(b) depicting a reduction in relative energy use against a reduction in pressure highlights this presumption. For a smaller reduction in pressure, the reduction in energy ratio changes only slightly with  $R_o$ ; however, as the reduction in pressure becomes greater, the dependence upon  $R_o$  is more noticeable. From Figure 3(b), it is clear that the energy saving, as a consequence of reduction in pressure, can be expected to be greater for low

friction pipes with a high leakage rate (the curves associated with  $R_o = 0.01$  and  $0.1$  with  $N = 0.5$  and  $1$  are above the 1:1 line). The main assumption to develop all curves as shown in Figure 3(a) and (b) is that the supply efficiency (e.g., pump efficiency) is considered to be equal for all scenarios involving changes in delivery pressure. However, if the supply efficiency changes, the relative reduction in energy use may become either more or less than what is indicated in Figures 3(a) and 3(b). Of course, increase in the supply efficiency strongly affects the energy saving in the system.

### 3. Case studies

Changes in energy use resulting from a reduction in pressure depend upon a wide variety of factors including system topology, pipe characteristics, pump arrangement, and operating policies. The priority here is to evaluate how changes in the delivery pressure affect the water loss, energy requirement, and maximum operating pressure in WDSs that is a key factor in pressure management strategies. To demonstrate the fundamental influence of changes in pressure, the Anytown network presented in Walski *et al.* (1987) is considered here as a representative network with storage. The Anytown system is considered as a realistic benchmark which has the topological complexity typical of many real-world systems. The layout of the system is depicted in Figure 4 and details can be found in Walski *et al.* (1987). The

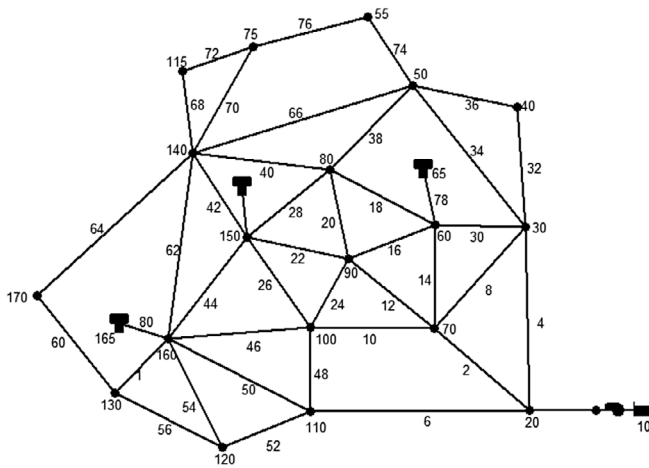


Figure 4. Layout of Anytown network—from Walski *et al.* (1987).

system topology for pipes and system configuration are set according to Gessler's optimization (Gessler 1985). The nodal demands and diurnal demand pattern for 2005, as explained in the original paper, are considered in this paper. Since the original data was in US customary units, all units were converted to SI equivalents. Tanks  $T_1$  and  $T_2$  are cylindrical with a diameter of 11.7 m and a height of 12.1 m and tank  $T_3$  is cylindrical with a diameter of 19 m and a height of 12.1 m. All tanks operate with the initial depth and maximum depth of 3 m and 10.6 m, respectively. Tanks' bottom elevations are all 92 m for the scenario in which the delivery pressure is 35 m at the highest demand node elevation. To determine energy costs, the base price of \$0.11/kWh is considered during the peak hours with price factors of 0.55, 0.85, and 1 for the hours 0–6 and 20–24, 6–12 and 18–20, and 12–18, respectively. To evaluate the effects of reduction in pressure on energy use of the storage scenario, the Anytown system without storage, represented as a network with a direct pumping strategy, is also tested.

For the Anytown, three identical pumps, defined by the curve  $H = 160 - 5 \times 10^{-4}Q^2$  ( $H$  is in meters and  $Q$  is in liters per second), in parallel are considered where the delivery pressure is set to be at least 35 m in the system. The system is considered to operate based on the tank water level, i.e., pumps are set to turn on when the tank level is at 3 m and to shut off when tanks are refilled to the level of 10.6 m. For the Anytown without storage tank, three identical pumps with the characteristic of  $H = 165 - 8 \times 10^{-4}Q^2$

( $H$  is in meters and  $Q$  is in liters per second) are used where the delivery pressure is 35 m. The on–off pump controls are specified for pumps operation. To consider the pump efficiency, the relationship between pump discharge ( $Q$ ) and pump efficiency ( $e_p$ ) can be estimated by (Walski *et al.* 2007)

$$e_p = a_1Q + a_2Q^2 \quad (5)$$

where  $a_1 = 2e_0/Q_0$ ,  $a_2 = -e_0/Q_0^2$ ,  $e_0$  is the efficiency at the best efficiency point (%), and  $Q_0$  is the flow at the best efficiency point. The best efficiency is set to 80% (that is assumed to be wire-to-water efficiencies, i.e., both motor and pump efficiencies) for all scenarios.

The reduced delivery pressure, for the Anytown system, is achieved by changing the tank elevations and pump curves. Extended period simulations of 72 h are also conducted to model daily demand and tank level fluctuations and to ensure a stationary pressure at the nodes. For the Anytown without storage, pumps are taken into account with a lower supplied head in order to achieve lower delivery pressure in the system. The performance of the two systems is tested for all scenarios with delivery pressures changing from 10 m to 35 m using EPANET2 simulations. Leakage rate is modeled as a percentage of demand although it has no revenue for municipalities and is not usable for customers (Colombo and Karney 2002). This is just a simplification to perform analysis considering the assumption that the demand node does not change and the leakage rate only depends on the pressure at leak locations. Leaks at nodes, in EPANET2, are modeled with the use of an emitter feature in which the flow rate is considered to be a function of pressure.

The emitter coefficient generally reflects the size and shape of a leak and is often adjusted when modeling leaks of different magnitudes. In the equation proposed by Germanopoulos (1985) and Tucciarelli *et al.* (1999), the emitter coefficient was considered to relate to pipe length, pipe diameter, and leaks surface per unit pipe surface of the pipe assuming that there is a constant leaking area per unit area of the pipes surface. Thus, the emitter coefficient depends on the system characteristic and can vary from one system to the other. However, the attempt here is to determine how the total leakage rate would alter if pressure in the system reduces and considering that the other factors contributing to the emitter coefficient remain unchanged. Of course, some pipes might have a higher leakage rate (depending on their lengths and diameters) than others but the total volume of leak for the

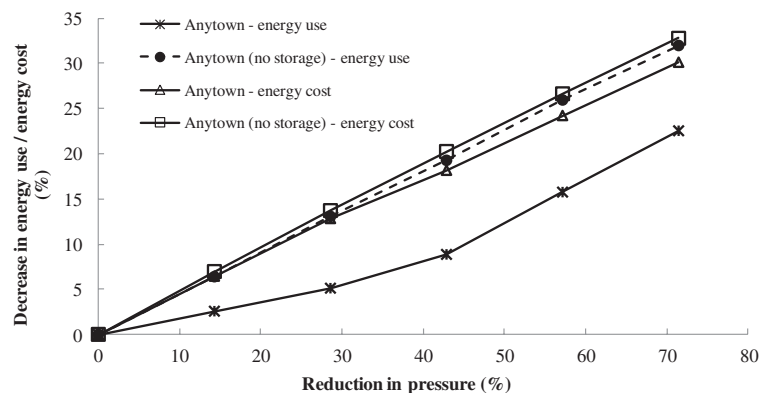


Figure 5. Energy use response to changes of MPC.

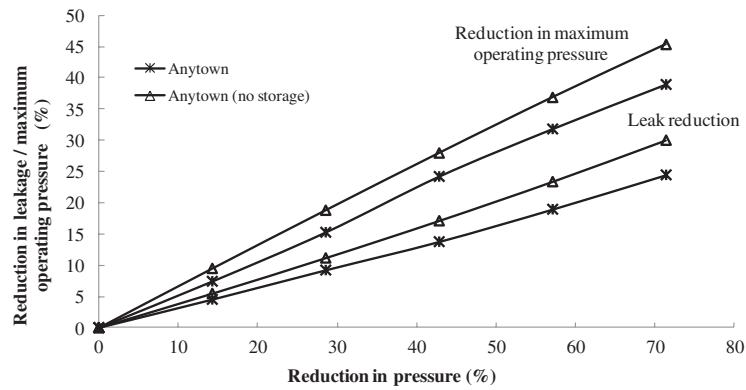


Figure 6. Leakage reduction and decrease in maximum operating pressure against reduction in pressure.

system should remain constant for the benchmark case (i.e., total leakage rate is assumed to be 30% of the total daily demand volume). In other words, the aim here is to examine how a system's leakage, if it leaks from a certain leakage orifice, would change due to changes pressure. A leak at a particular node is assumed to represent the existence of leaks in some or all of the incident pipes and indicates the equivalent leak concept (Colombo and Karney 2002). Considering this, the emitter coefficient is assumed to be the same for each leaky node, and the emitter exponent is set to be 0.5 throughout the analysis (Colombo and Karney 2002, 2005, Jun and Guoping 2013).

Leakage rate is controlled by the value of the emitter coefficient and in the first stage of analysis it is set to be 30% meaning that the total amount of water lost through the leak in a 24-hour cycle is 30% of the total daily demand volume (the emitter coefficient for the Anytown network is set to be  $1.18 \times 10^{-3} \text{ m}^{2.5}/\text{s}$ , and for the Anytown system without storage, the coefficient is  $1.27 \times 10^{-3} \text{ m}^{2.5}/\text{s}$ ). It is established as the reference leakage when the delivery pressure is maintained at 35 m in the system. Leaks are then computed for all pressure scenarios.

Changes in energy use and cost against reduction in the delivery pressure are shown in Figure 5. As expected, energy use and costs decrease for all scenarios as the delivery pressure is reduced and changes in energy use and costs are greater for the no storage configuration compared with storage counterpart as pressure changes. For a smaller percentage of reduction in pressure, the energy consumption changes only slightly for the two systems; however, as the reduction in pressure becomes greater, the dependence upon scenarios is more noticeable. The energy cost in storage configuration depends on the time of day that pumps operate and the price of energy during the hours that pumps operate. Thus, the trend of energy cost and energy use may not be consistent (as shown in Figure 5). According to Figure 5, a 30% decrease in pressure causes a reduction of about 5.5% and 13% in energy use for the Anytown network with and without storage, respectively.

Figure 6 depicts the leakage reduction curves for the two networks. For the no storage configurations, leak reduction response is more than its storage counterparts in terms of reduction in pressure. From the results shown in Figure 6, 30% decrease in pressure causes a reduction of about 12%, and 10% in leakage for, respectively, the unrehabilitated Anytown without storage, and the Anytown network. Comparison of results for reduction in

delivery head indicates that leakage decreases against reduction in pressure for the two systems under study and the leakage percentage for direct pumping is less than the storage configuration (not shown).

Not surprisingly, reduction in delivery pressure causes a decrease in the excess pressure of the system. Figure 6 also depicts the decrease in maximum operating pressure in the system with respect to reduction in the delivery pressure. The average maximum pressures in the system, defined as the maximum operating pressure, is estimated by taking the arithmetic mean of computed maximum pressures, during the simulation period, at all nodes of the system. Clearly, from Figure 6, reduction in average excess pressure is more noticeable for the no storage configuration against lowering the delivered pressure. From Figure 6, a 30% decrease in delivery pressure causes a reduction of about 16% and 19% in average excess pressure for, respectively, the Anytown with and without storage.

#### 4. Conclusion

Control and reduction of delivery pressure have the benefits of reduced energy expenses, leaks, and environmental impacts. The decrease in head loss due to reduction in pressure is more noticeable in systems with a high leakage rate. For systems including low friction pipes and a high leakage rate, the energy saving, as a consequence of reduction in pressure, can be expected to be greater. In other words, pressure reduction aimed at leakage reduction and energy saving is more effective in newer systems with smoother pipes. The inclusion of a storage tank causes the system's energy use to increase due to the boosting of the pressure in the system during off-peak time or when the tank level is at the minimum set point. For the two case studies considered in this paper, the difference in energy consumption is evident. A 30% reduction in delivery pressure would decrease leakage by 10% to 12%, energy consumption by about 5.5% to 13%, average excess pressure by about 16% to 19%, and GHG emissions by about 5.5% to 13% (the results for the latter are shown in the supplementary material) for the systems under study. Reduction in delivery pressure is shown to decrease leakage, however the inclusion of storage capacity decreases the leakage reduction response caused by the decrease in pressure.

The results of this study are patterned on an analytical expression developed for a single pipe segment and the Anytown network with and without storage tanks, to highlight the potential impact of high system operating pressures on energy use, leakage, and environmental impacts. The results clearly show that pressure should be limited not only for the purpose of the usual benefits of leakage reduction and possible decrease in pipe bursts, but for the key reason that energy must be paid, both financially and environmentally. Pressure management might be the ideal strategy for one system, but for another system, a better strategy might be to replace/refurbish the pumping system. The findings demonstrate how better control and management of pressures and a rethink about pressure standards can set a criterion for delivery pressure.

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