Pipe breaks and the role of leaks from an economic perspective

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Abstract A map depicting the major elements, interactions, and life cycle analysis issues of a typical water distribution system is presented as a network labyrinth. From this, focus is placed on the influence of leaks on energy and water consumption as well as the dissipation of hydraulic transients. Straightforward analytical expressions are derived in order to relate the energy efficiency of a leaky pipe to leak location and orifice properties. The ability of leaks to relieve pressure during hydraulic transients is briefly discussed with several challenges and issues surrounding the quantification of this attenuation effect being put forward. Considered from the broader perspective of the network labyrinth, a better understanding of leak related effects has implications for pipe rehabilitation models, system economics and environmental sustainability.

Keywords Energy costs; leaks; life cycle analysis; transient dissipation; waterhammer; water loss

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Introduction

In many respects, the map depicting the various issues and processes involved in water distribution system planning is a labyrinth. The term labyrinth is a particularly suitable one, not only because it reflects the reality of the physical system with its looped and interconnected topology, but also because it implies, like Theseus and the Minotaur, that successful navigation of the maze's complexity may allow an important goal to be achieved. In the case of water distribution systems, the labyrinth contains numerous processes, subprocesses, states of being with their associated causative factors, feedback loops and interrelationships. Most researchers and planners subconsciously appreciate this multiplicity when they model specific processes or limit their analyses to narrowly defined areas. Nonetheless, it is valuable on occasion to take a step back and view the bigger picture, particularly so that the efforts applied in analysing specific areas will not be wasted when model results are applied to the broader reality. The key processes and their interconnections that are relevant for water distribution system planning within the current context are shown in Figure 1.

The labyrinth in Figure 1 is supported by the three pillars of demand, capacity and performance.

- The **demand for water** is key, since it establishes the need for a distribution system in the first place and, just as importantly, it is the characterization and quantification of this demand that determines how much, and what kind, of capacity is required. Decisions about what investments to make in pipes, pumps, reservoirs and treatment plants are made on the basis of demand predictions. And this demand estimation is not a trivial issue, for projections must take into account both the average per capita level of demand, estimated and projected changes in population, and the variability of demand, particularly as it relates to peak usage.
- **Capacity** is achieved via the sizing, construction, installation and configuration of the distribution system with all its elements and includes installed, reserve, treatment and pumping capacities. Current capacity reflects the critical capital investments in the past,

and future capacity includes those capital decisions that are being made now to install, maintain, replace or upgrade key system components.

- The fit between demand and capacity, in addition to a variety of operational considerations, defines the overall **performance** of the system by its resulting **total cost**.

The cost of the system includes not only the financial cost of manufacturing and maintaining the infrastructure, but also such burdens as the health effects of poor water quality, the environmental impact of energy inefficiency and water loss due to leaks, disruptions due to breaks, and a variety of other burdens associated with the system and its operation. In this sense the total system cost reflects the broad definition of costs typically found in life cycle analysis (LCA) literature.

The crescent region circumscribed by the broken line in Figure 1 denotes the portion of the labyrinth that is introduced here. Hitherto, water loss has been the primary motivation for much of the research into leaks and has been discussed in significant detail in the literature. The connection between leaks and increased energy costs, while a logical parallel to water loss in pressure compensated systems, has typically been ignored. Colombo and Karney (2002) show that the extra energy costs due to leaks for both a single pipe and a representative network can be significant and on the order of lost water costs at current prices. Perhaps less obvious, and certainly less well understood, is the connection between leaks and pipe breaks.

Pipe breaks are an obvious source of system failure. Leaks can improve the transient robustness of a pipe by attenuating potentially destructive pressure spikes during certain waterhammer events. Thus, the possibility of a tradeoff between ongoing energy/water loss costs and those associated with pipe breaks and their repair may exist for some systems. The ability of leaks to protect against pipe breaks has barely been addressed in the literature; however, Wang *et al.* (2002) have implicitly exploited this attribute by considering the pressure wave attenuation associated with leaks of various sizes.

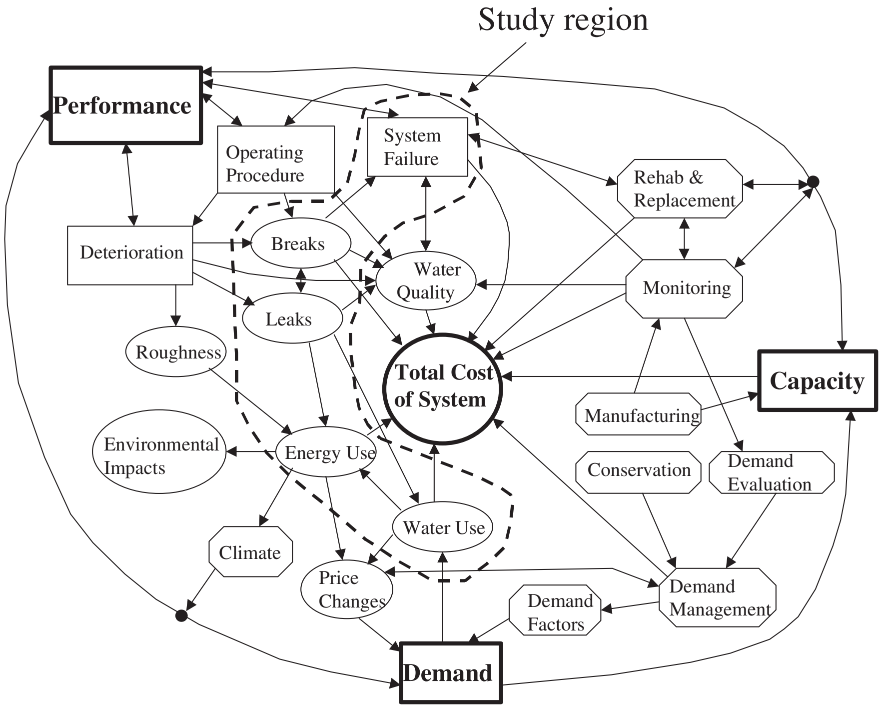

Figure 1 The water distribution system labyrinth

Evaluating a tradeoff between ongoing leakage associated costs (LAC), such as water loss and energy consumption, and pipe-break associated costs (BAC) such as water damage, penalties for service interruption and pipe repair/replacement is not an easy task. Hydraulic transients are stochastic in nature since both their severity and frequency are probabilistic. Therefore, any value of the BAC is an expected value based on one or more probability distributions. Such costs as water damage and interruption penalties are difficult to assess accurately and may inevitably rely on surrogate cost estimates. Moreover, transient response and robustness are often unique to an individual distribution system thus rendering straightforward analysis of transient induced BAC for systems considerably more difficult than analysis for LAC which depend chiefly on average operating conditions. Consequently, this paper is limited in scope to simple relationships for energy efficiency for a single leaky pipe segment and a brief qualitative and conceptual discussion of transient attenuation and its effect on pipe breaks.

The energy consumption and water loss of a leaky pipe segment

In a previous study, the authors derived several equations relating head loss and energy efficiency to leak size and location for a leaky pipe segment (Colombo and Karney, 2002). The following discussion of energy efficiency and water loss is extended from that study.For a pipe segment of length L, Darcy–Weisbach friction factor f, diameter D and a single leak located at xL, the leak's impact on energy consumption is clearly evident in the behaviour of the energy grade line (EGL) in Figure 2 (Colombo and Karney, 2002). The essential premise of Figure 2 is that an equivalent level of service is maintained between the leak and no-leak cases. That is, enough water must be supplied in order to meet the demand flow Q_d and to compensate for the flow through the leak $Q_l = aQ_d$ (where a is a fraction of demand) while maintaining sufficient head H_d at the downstream end. Therefore, a total flow of $(1 + a)Q_d$ must be supplied to the pipe. This causes the EGL to assume a discontinuity at xL since the upstream portion of the pipe carries a larger flow and thus experiences a steeper friction slope (dashed line in Figure 2).

Leakage is typically modelled using an orifice relationship of the form:

$$Q_l = C_d A\left[2g\left(H_l - H_{gw}\right)\right]^{\alpha} = C_E \Delta H^{\alpha} \tag{1}$$

where A is the leak area, ΔH is the head difference (m) across the leak, H_l and H_{gw} are the heads (m) in the pipe and in the surrounding groundwater, respectively, C_d is the discharge coefficient, and C_E is the emitter coefficient (in $m^{3-\alpha}/s$). The emitter exponent α is usually assigned a value of 0.5 (the default value used here) to reflect flow through a fixed-size

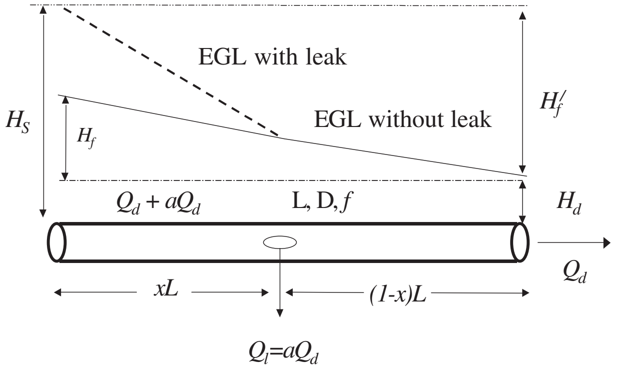

Figure 2 Energy grade line (EGL) of leaky pipe segment

orifice. Clearly this relation implies that as internal pressure in the pipe builds, Q_l increases, creating a feedback loop that can impose a burden on system capacity.

When H_{gw} is assumed to be zero (as for unsaturated soil conditions),the head at the leak H_l is determined from $H_l = H_d + (1 - x)H_f$ where H_f is the head loss in a leak free pipe. Consequently, the leakage fraction a is related to C_E through relationship (1) as:

$$a / a_0 = \left[1 + (1 - x)h_f\right]^{\alpha} \tag{2}$$

where $a_0 = C_E H_d^{\alpha} / Q_d$ is the minimum leakage fraction (which occurs when $H_l = H_d$) and $h_f = H_f / H_d$ is the relative head loss.

The Darcy–Weisbach equation $H_f = fLQ_d^2/2gDA^2$ relates the head loss in a leak-free pipe to the flow it conducts. For a pipe with a single leak discharging aQ_d at a point xL, the resulting expression for the friction head ratio h_F becomes a linear function of x and a quadratic function of a:

$$h_F = H'_f / H_f = x(1 + a)^2 + (1 - x) = 1 + ax(a + 2) \tag{3}$$

Therefore, as x decreases, the additional head loss imposed by the leak also decreases because a greater portion of the pipe segment carries only the design flow. However, if the orifice relation (2) is substituted into (3), the friction head ratio becomes a function of the dimensionless parameter x, h_f and the orifice/demand properties represented by a_o.

The ratio between the mechanical flow energy delivered to the downstream end of the pipe (E_d) and that supplied at the source (E_s) constitutes the energy ratio E_d/E_s and provides for a quick assessment of the energy efficiency of a leaky pipe.

$$\frac{E_d}{E_s} = \frac{\gamma Q_d H_d}{\gamma Q_d (1 + a)(H_d + H'_f)} = \frac{1}{(1 + a)(1 + \left[xa(a + 2) + 1\right]h_f)} \tag{4}$$

This expression is a function of the two dimensionless parameters a and x. If a is unknown, it can be reduced to a function of x only by combining (2) with (4). In this manner orifice properties can be directly related to E_d/E_s. Figure 3 depicts E_d/E_s as a function of x for a pipe of known demand conditions ($Q_d = 0.03$ m^3/s and $H_d = 40$ m), emitter exponent ($\alpha = 0.5$), relative head loss ($h_f = 0.25$) and emitter coefficient. C_E values of 0.001 m$^{5/2}$/s and 0.0015 m$^{5/2}$/s are used to represent different sized leaks, with leakages ranging from about 31–35% and 53–60%, respectively, depending on leak location. As the leak is moved

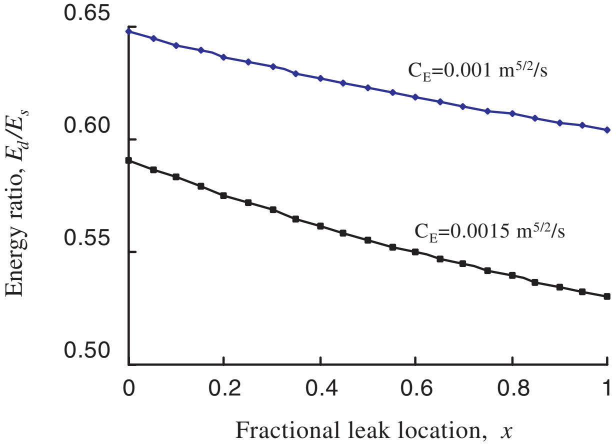

Figure 3 Energy efficiency of a leaky pipe as a function of leak size and location

downstream (x increasing) the leakage fraction a actually decreases because H_l follows the hydraulic grade line and is larger upstream. Although water loss is better for a downstream leak, energy efficiency is worse. As x increases E_d/E_s decreases for both leak sizes as a greater portion of the pipe carries the larger compensatory flow. The effect of leak size is clearly evident in the difference of the two curves. For each possible leak location, energy efficiency is lower for the larger leak. An obvious result of the fact that a larger flow must be passed upstream of the leak in order to compensate for the larger leak while still maintaining equivalent service.

The role of leaks in attenuating transients

An important issue raised in the context of pipeline system design is the connection between system function, the presence of leaks and the decay/attenuation of transient pressure waves. The essence of this idea was implicitly raised in a 2000 AWWARF call for proposals on the role of leaks pertaining to transient intrusion events. To quote an observation recorded in this context of this RFP: “Looping of pipes and the cumulative effect of thousands of open taps/orifices on the system tend to dampen out the effect of transients.” The contention in this paper is that leakage itself is an important mechanism for mitigating transient pressures in distribution systems, and it would be of value for operators and designers to better account for this dissipation process.

More precisely, there are at least six primary mechanisms for dissipating transient or surge energy in a distribution system, ranked approximately in their order of importance in a typical system.

1. The first and most obvious mechanism is conventional fluid friction. Although this subject has been studied for years, it still holds some challenge. In fact, fluid friction can be quite difficult to quantify, as in the case of determining friction factors for old pipes.
2. The second dissipation mechanism arises from the nature of network demand. For example, if flow increases for an increase in pressure, as it will for showers, sprinklers, dishwashers, etc., an effective outlet is provided for transient energy. Interestingly, if demand is assumed constant, as it commonly is in network models, this decay mechanism is poorly represented.
3. The third mechanism arises from the leaks themselves. This loss is essentially identical to that of demand, with one key difference being that leaks are generally unwanted, whereas the normal demands are what justifies the very existence of the system. The basic effect is displayed in Figure 4 which shows an incident transient pressure wave reaching a leak location and indicates that the transmitted and reflected waves have an attenuated magnitude. Leaks allow work to be done during the water discharge, they cause a more rapid convergence back to steady conditions, and they maintain a higher

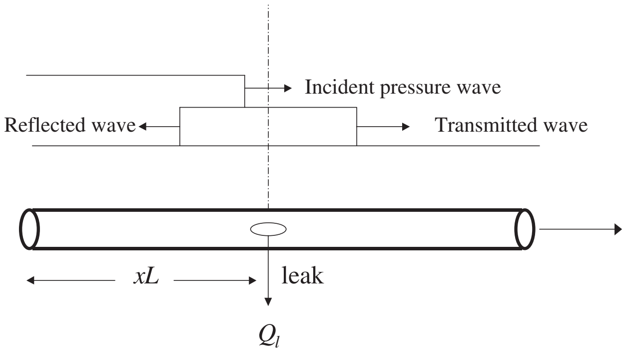

Figure 4 Conceptual wave reflection at a leak

base flow in the system; all of these effects directly reduce and decay the impact and magnitude of transient events in the system.

4. The fourth mechanism for dissipating transient pressure waves in a system arises from the distributed nature of most pipe networks. The complexity of the looped pipe system, the frequency of branch connections, the almost universal existence of service connections, the presence of many devices such as isolation valves and junctions – all these factors create the possibility of fragmenting a coherent pressure signal into a multitude of scattered pieces, and in this way of modifying the rate of energy dissipation. Although such network effects are potentially present, their significance is likely to be highly system dependent and they cannot be relied upon to play a dominate role.
5. The fifth decay mechanism arises under transient conditions due to unsteady friction (Brunone *et al.*, 2000). Although this mechanism also arises from the fundamental nature of fluid turbulence, its manifestation and role can be quite different from steady friction. Under transient conditions, the rapid acceleration or deceleration of the fluid can cause significant distortion of the velocity profile, and can cause much higher rates of frictional dissipation during a transient flow.
6. The first five of these mechanisms, in a sense, arise naturally in the system without any special design consideration. That is, they are intrinsically present in the general nature of a water distribution system, in its complexity and interconnections, and in the disturbances it experiences. The sixth dissipative mechanism is different; it is the dissipation designed into the system explicitly for the purposes of surge protection. This mechanism includes the possibility of surge relief valves, air-vacuum valves, accumulation devices and other specialized appurtenances in the system.

From a design point of view, the key question is this: how much dissipation exists naturally in the system and how much additional protection needs to be explicitly added? How much dissipation arises from leaks alone and will pipes be less well protected from some brakes if leaks are repaired or reduced? At the moment, no one is in a position to answer this question, for the data has to be systematically collected. Thus, it is all but impossible to efficiently design protection strategies in a way that gives any significant credit to the natural dissipation mechanisms. (And yet, interestingly, many designers who could not even articulate the mechanisms described here, do the opposite – they assume these mechanisms are completely efficacious, and that little or no surge protection is required in a distribution system!)

The broader context of leaks and the labryinth

In general, this paper aims to introduce and clarify some of the less well known, or at least less well discussed, costs and tradeoffs associated with operating a typical water distribution system by focusing on how leaks affect a pipe's performance. No water distribution system is perfect and, as a result, both water providers and broader society continually realize certain costs that result from inefficiency. As with all engineered systems and infrastructure, efficiency and waste reduction are important considerations and their attainment is almost always a prerequisite for achieving both financial and environmental sustainability. Current research into water distribution system performance, efficiency and rehabilitation is extensive and there has been a great deal published on these topics. Nonetheless, there is still much to uncover and comprehend. This is not surprising when one begins to appreciate the interconnectedness of the physical world within the context of LCA. Although current LCA methodology calls for such a broad scope of analysis that it can not fail to please the philosopher while troubling the practitioner, aspects of it can be employed to help identify, quantify and place in a relative context some of the costs and tradeoffs that result from the imperfect operation of imperfect distribution systems.

While conducting even a streamlined LCA is far beyond the scope of a paper, the spirit of LCA can assist in the discovery of less obvious costs/benefits and connections that are inherent in system design and operation. Elements of traditional LCA methodology such as Inventory Analysis can be applied in focusing on one or two selected aspects of water distribution system inefficiency such as leaks and their effects on energy consumption, water loss, and transient response. Specifically, the role of leaks on system performance, costs, design and rehabilitation should be assessed if sound decisions are to be made.

Leaks are interesting because of the myriad implications they entail for each of these aspects of a distribution system. The number of arrows which cross the broken line in Figure 1 clearly point to the multifaceted nature of leaks. Their presence is an obvious indication of system inefficiency. Not only do they represent a loss of treated water, but they also imply a waste of energy as additional water is pumped to feed them and still maintain service requirements. However, interestingly, leaks can attenuate transient pressure waves and, in some cases, protect a pipe from bursting. Unfortunately, quantitative analysis of this effect is far from straightforward as there are numerous variables and a variety of issues to consider. Further research into these complicated effects of leaks may lead to modifications of existing rehabilitation/repair models (which typically exclude the role of leaks), or the establishment of completely new ones.

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