Impacts of Leaks on Energy Consumption in Pumped Systems with Storage

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Abstract: A conceptual examination of the energy impact of leaks in systems with storage is undertaken. Consideration of how leakage is experienced at the pump is followed by an analysis of how different leakage levels alter energy costs for a rudimentary system with three topological configurations: two with a storage tank located at different points, and one without storage. Additionally, two friction regimes are subsumed in the analysis. EPANET 2 simulations are used to determine system pressures, storage tank levels, energy costs, power consumption, and leakage volumes for all scenarios at five levels of leakage. Leaks increase operating costs in terms of lost water and extra energy consumption for all systems, and when a price pattern is implemented, the financial cost of energy can sometimes be traded off with actual energy consumption. Storage in a system does not guarantee lower energy use relative to direct pumping, and in some cases it may promote higher leakage due to elevated system pressures. The results, though system specific, suggest that the importance of leaks in a system with storage depends on a number of factors, especially the relative locations of system components and the pumping strategy. Thoughtful consideration of the latter can be instrumental in achieving operation that balances financial and energy conservation objectives. To further test key relationships, a representative network is briefly considered. In all cases, the percentage increase in energy cost is greater than percentage leakage when the same pressure requirements are met.

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Introduction

Concern over leaks finds its origin in a desire to limit the revenue loss utilities face due to lost water, and commensurate with this interest, leak-related research has traditionally focused on water loss quantification (Arreguín-Cortes and Ochoa-Alejo 1997; Lambert 2002; Buchberger and Nadimpalli 2004) and leak detection (Hunaidi et al. 2000; Brunone and Ferrante 2001; Kapelan et al. 2003). An awareness that leaks may compromise water quality has directed current research down new and interesting avenues, especially with regard to the transient intrusion phenomenon (Besner et al. 2002; Karim et al. 2003).

Although an implicitly acknowledged link between leaks and wasteful energy consumption has existed for some time, direct contemplation of the issue is apparently recent. Colombo and Karney (2002) developed simple analytical expressions relating energy efficiency to leak size and location for a leaky pipe segment, and in addition they examined the influence of leaks on energy costs for uncomplicated distribution systems. Not unexpectedly, it was found that leaks increase the energy costs associated with pumping, especially when equivalent service at demand points is maintained. The systems studied were assumed to have fixed customer demands and no storage, even though the majority of systems include both as major elements. The objective in this work is to relax several simplifying assumptions applied in these preliminary studies by introducing a diurnal demand pattern and storage to the systems so that a more comprehensive picture of the interaction between leaks and energy use may be obtained.

Leaks increase the energy consumption of a system in two ways: by comprising an extra demand and through greater dynamic losses that result from restoring equivalent service. The extra demand that a leak imposes means that the pump must bring water from the source to the leak: water that possesses pressure and velocity head. The "energized" water that escapes from a leak in an underground water main, for example, serves little useful purpose. Thus, an opportunity cost is paid in terms of energy that could be applied to a more useful purpose.

Pumping water is a major source of energy consumption. Brailey and Jacobs (1980) estimated that municipal water utilities were responsible for 7% of total electricity consumption in the United States and that power costs can amount to as high as 90% of operating costs. The American Water Works Association (AWWA) Water Loss Control Committee estimates that 5 to 10 billion kW·h of power generated in the United States is expended on nonrevenue water annually (AWWA 2003). Increased resource prices and/or scarcity coupled with escalating water and energy demand render the inefficiency of leaks especially acute. The possibility of climate change, superimposed on population growth and resource mismanagement, poses a particular challenge. Leak repair could become a valuable hedge against premature capacity expansion if a different climate regime is accompanied by higher water demand (Colombo and Karney

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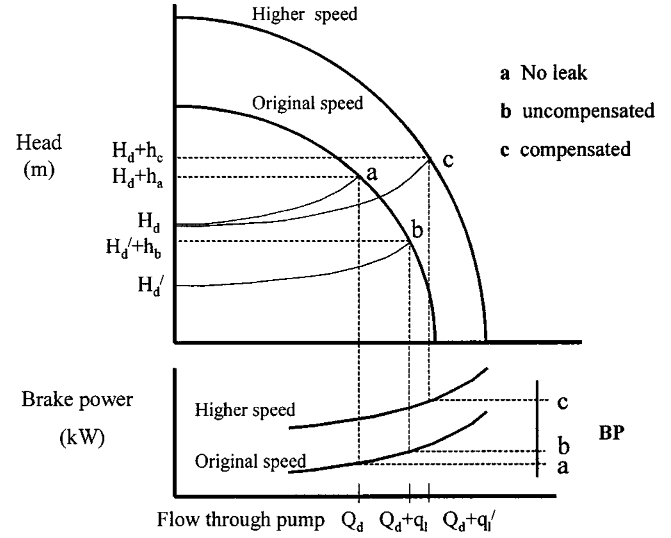

Fig. 1. Pump and power curves for typical centrifugal pump

2003b). Furthermore, the energy waste due to leaks has implications not only for resource depletion, but also for the externalities associated with energy consumption, such as greenhouse gas emissions, acid rain, and industrial hazards.

The advantages of improved leak characterization are many. A more thorough classification of the costs of leakage puts into perspective the urgency of leak repair and the value of leak detection research, technology, and services. Furthermore, a sophisticated appreciation of the myriad effects of leaks is a prerequisite to developing a useful decision framework that accurately considers the trade-offs between these effects. In general, a more comprehensive picture of leaks has implications for system design, operation, and rehabilitation. Because systems with storage are common, an appreciation of the role of leaks in these systems is necessary. Leaks have implications for tank capacity and may disrupt finely tuned operating policies in existing systems. For example, optimal pump operation is closely linked with an optimal tank trajectory (Ormsbee et al. 1989), and both are affected by leaks.

Although a vast number of systems could be analyzed in the quest for a better understanding of leaky systems with storage, exhaustive consideration of the many possibilities is not possible, and hopefully not necessary. The storage systems in this paper are hypothetical, but they have been selected for their simplicity and reproducibility and for the insights they provide in relation to the underlying impacts that leaks, in combination with storage, have on energy consumption. In particular, the goal is to examine what factors might distinguish leaky systems with storage from those without it and to obtain a preliminary understanding of the relative importance of these factors in terms of the energy consumption associated with system operation.

How Pumps Experience Leakage

In all but pure gravity-driven systems, at least some of the energy that drives the system must come from pumping. Since the pump introduces this energy to the system, consideration of what occurs there is both crucial and logical to understanding how the system responds to the flow and pressure changes caused by leaks. Fig. 1 depicts two characteristic (*H-Q*) curves typical of centrifugal pumps used for water transmission. Each characteristic denotes a different level of pumping capacity that could be achieved in a number of ways, such as by installing a larger pump, bringing a new pump into a revised configuration, or operating a variable-speed pump at a higher impeller speed.

Although Fig. 1 (Colombo and Karney 2003a) assumes this last possibility, the higher-speed curve could represent any of the three options. Three system curves representing a no-leak, an uncompensated leak, and a compensated leak scenario are plotted along with the pump characteristics. Compensation means that pump capacity is boosted to restore delivery pressure to its no-leak value (described in detail later). Juxtaposed with the pump/system curve plots are mechanical input power or brake power (BP) curves corresponding to each *H-Q* characteristic. Since the BP defines the power input to the system, and ultimately the amount of energy consumed and purchased, knowledge of where different operating points lie along these curves is important.

In the absence of a leak, the customer is assumed to receive the full demand Q_d at the specified pressure head H_d. This is denoted by operating point *a* on the pump curve, which is associated with the lower impeller speed. Point *a* corresponds to a pressure head of H_d+h_a since h_a represents the dynamic losses associated with the flow Q_d. If a leak is present somewhere in the system, it imposes an additional demand, thus causing the operating point for an unmodified pump to migrate along the pump curve to a point that corresponds to a flow of Q_d+q_l where q_l is the flow through the leak and the demand is still assumed to be met. The magnitude of q_l is generally a function of the pressure in the system at the leak location and is typically modeled with an orifice function (for which an exponent of 0.5 is assumed here).

Since the pump now passes a larger flow, the pressure head it supplies is reduced. Therefore, a new operating point at *b* is established, and the customer receives Q_d at the lower pressure head of H_d', involving a higher friction loss of h_b and a lower pump head. The system curve for this scenario is less steep than for the no-leak case since the total flow that passes through the pump is only transmitted through the portion of the system upstream of the leak (the exception being if the leak is at the extreme downstream end of the system). At point *b* the energy requirement of the pump is higher than for point *a* despite the reduction in head, since a typical BP curve for a centrifugal pump increases with flow.

To compensate for pressure loss from *a* to *b*, the pump must supply more pressure and energy to the flow, perhaps by operating at a higher impeller speed. At a higher speed, the pump curve shifts outward so that each value of flow has a correspondingly higher pressure head relative to the original speed curve. If the new pump speed is sufficient, it is possible to compensate fully for the pressure loss due to the leak. However, as this compensation occurs, the pressures in the system will increase, as will the flow through the leak q_l'. Ultimately, operating point *c* is established on the higher speed curve and represents the pressure compensated system that provides the customer with a near-equivalent level of service to the no-leak case. The frictional head loss associated with point *c* is h_c and the head developed by the pump is H_d+h_c.

The basic shape of the system curve is the same as that for the uncompensated case since it depends on the unchanging leak location and orifice size. Because a higher impeller speed involves more energy consumption, the restoration of H_d involves a shift to a new BP curve that sits above that representing the original impeller speed. Thus, for each value of flow passed through the pump, more power is required. Overall, the shift from the no-leak

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to the pressure-compensated case means an increase in BP from *a* to *c*, the extra energy consumption imposed by the leak. This energy waste translates into more atmospheric emissions, greater resource depletion, higher operating costs, and a proportional increase in other externalities associated with energy consumption.

In practice a pump may be operated at a flow just removed from its peak efficiency, and an increase in flow, such as is caused by a leak, may indeed place operation at, or closer to, peak efficiency (Walski 2004). Even if this should occur, the location along the BP curve determines the actual energy consumption (the equation for BP already incorporates pump efficiency). Therefore, in terms of energy consumption, operating is preferable at lower efficiency if that means operating at a reduced flow (that is, demand) and BP. The influence of water demand on energy consumption is readily apparent since increased demand is in some sense analogous to leakage.

Methodology

Pressure Compensation

How energy use changes with leakage depends on a wide variety of factors, including system topology and condition, pumping arrangement, selection, capacity, and operating policy. Changes in energy consumption are thus always specific to a system. Operational response to leakage covers a range of options from “do nothing” to the installation of pressure-reducing valves and pressure management. These realities guarantee that any numerical study of system performance with leakage is inevitably system specific. All real systems involve a complex set of interactions between variables involving the pump, the variation of demand, system and tank geometry, and related variables.

An uncompensated system as is used here is one whose downstream pressure and/or flow reduction occur in response to leakage without invoking any operational countermeasures. The only response considered is the natural shift in the pump’s operating point along its characteristic curve, a passive response akin to a “do nothing” alternative. Such an approach may be viable in practice if the system has sufficient excess capacity so that leakage effects do not violate any delivery constraints; it is probably typical when leakage is small or undetected.

Compensation is primarily intended to isolate the role of leakage from other interacting variables. There are two ways to think about this. The first approach is to examine initially all the logical options that could be applied to optimize pump operation, control pressures, deliver a minimum pressure, and anything else that might improve operation without reducing leakage. After all these initial steps, one could then ask, what if leakage is now reduced? The idea is to achieve a locally near-ideal state for the leaky system and to leave this state unchanged as leakage is addressed, thus isolating its role. Clearly this is an unlikely approach to adopt in practice since it is almost always more logical and efficient to combine several improvement steps.

A second way to isolate the role of leaks is to take the initial state as a given and then to find and fix the leak. Removing a leak would mean less water is required, and energy costs would thus decrease roughly proportionately to the reduction in leakage. But this is not all. Delivery pressures would also improve due to the reduced friction losses in the system, thus the system might now be operating in a better state than it was. How much better? It is difficult to provide an exact quantitative response to this question, but the supply pressure could be reduced until the same delivery conditions are achieved and a further reduction in energy use is realized. This outcome is exactly what pressure compensation seeks to achieve, and it anticipates that energy recovery from leakage is expected to be more than linear in many cases.

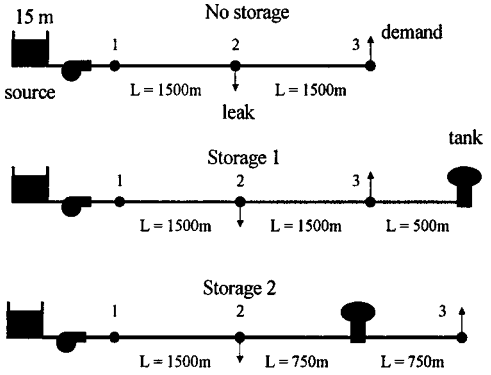

Fig. 2. Topology of simple system configurations

Rudimentary Systems

To expose the fundamental behavior of leaky systems with storage, a rudimentary system with three configurations is established. Essentially, this system is a single-reservoir, pump, demand, and leak system that must satisfy demand constraints with or without the use of a storage tank situated in one of two locations, either up or downstream of the demand point. Consideration of a direct pumping configuration (that is, no tank) is included so that the performance of the storage scenarios can be better evaluated and the role of leaks with regard to storage can be more effectively delineated. Its inclusion also serves to illustrate some of the motivation for implementing storage capacity for a leak-free system and in this way serves as a reference for the other scenarios. Although any basic system is not necessarily representative of typical, more-sophisticated networks, the goal is to identify key relationships that generally hold true for most or all systems.

System Topology and Scenario Characteristics

Fig. 2 shows the topology of this basic system for all three configurations. The top configuration is for pumping without storage (referred to as no storage), and beneath it are the two storage configurations indicated in the figure as Storage 1 and Storage 2. All configurations involve an upstream reservoir (15 m constant head), a pump, and a connecting pipe ($L=3$ km, $C=120$) that is defined by three nodes, all at the horizontal datum (0 m). Node 1 is the discharge node and marks the entry point of pumped water to the system, and Nodes 2 and 3 are the leaky and demand nodes, respectively. For all scenarios, the leak location was maintained so that it bisected the pipe between Nodes 1 and 3.

In the Storage 1 configuration, the tank is situated downstream of the demand node and linked by a 500-m pipe segment ($C=120$). In the Storage 2 configuration, the tank is situated equidistant between the leak and demand node. Tank properties are the same for both configurations: the tank has a cylindrical geometry with a diameter of 46 m, and the tank bottom is situated at a 33-m elevation above the datum. The height of the tank is set at 27 m to allow for easy fluctuation of water levels. The tank is arbitrarily large (total volume is just over twice the daily operating volume) in order to easily accommodate all scenarios. Obviously a tank belonging to an existing system would have a volume closer to the daily operating volume and a fixed geometry that imposes limits upon the maximum water level and degree of water level fluctuation.

To examine the nature of system trade-offs, two friction scenarios are considered. For simplicity, these scenarios are differentiated by the allocation of different pipe diameters to all pipe segments of each configuration. The low-loss scenario is established by assigning all pipe diameters a value of 0.5 m, and the higher-loss regime is governed by a pipe diameter of 0.4 m. Such a shift is roughly equivalent to a *C*-factor change from 130 to 72 for the 0.5-m diameter pipe.

A diurnal demand pattern is applied to Node 3, which has a base demand of 200 L/s (0.2 m^3/s). This base demand is multiplied throughout the 24-h cycle according to a coarsely discretized (4-h) pattern of multiples (the multiples are 0.5, 1.2, 1.7, 2 for the hours 0–4 and 20–24, 4–8 and 12–16, and 8–12 and 16–20, respectively). The demand pattern establishes the periodicity of the system, which in turn is reflected in tank levels, system pressures, and pumping intensity. All system configurations are driven by an identical pump defined by the characteristic curve $H=93.33-0.0004822Q^2$, where H is in meters and Q is in liters per second (the unrealistically high accuracy in the specifications is to facilitate accurate comparison by others). To limit the sources of variability, the pump is provisionally assumed to have 100% constant efficiency; energy costs can easily be scaled using the efficiency values. The base price of electricity is \$0.05/kW·h, but this is subject to a time-of-day pricing pattern. During the peak middle hours of the day (8–20 h) the full price of \$0.05/kW·h is realized. Outside of this period, the price is discounted by 75% (0–8 h) and 50% (20–24 h).

Pumping either follows closely or is influenced by the diurnal demand pattern. For the direct pumping configuration, an impeller speed multiplier pattern in 4-h increments is applied to the pump curve so that pumping intensity mimics demand throughout the 24-h cycle. In general, a uniform pumping approach is adopted for the storage scenarios, with pumping activity during the first 8 and last 4 hours of the day (referred to as the uniform 12, or U12, pumping strategy). In some cases a lower impeller speed is applied consistently throughout the day (uniform 24, or U24).

Pump Selection, Efficiency, and Operating Point Uniqueness

Although the modification of pumping capacity here is arbitrary, this discretion is justified since equivalent service implies a new but fixed pump operating point. The restoration of delivery conditions establishes the requisite discharge water power of the pump, and by simultaneously controlling pump efficiency, the point on the BP curve becomes unique. In such cases the choice of pump curve or the approach used to modify pump capacity (that is, pump speed, pumps in parallel, larger pump with flatter and/or steeper curve, etc.) becomes mostly irrelevant. Of course in practice the issues of pump availability and efficiency are only two of several important decision-making parameters.

The water power that achieves equivalent service defines an operating point that any pump or combination of pumps must be able to meet. These options can be represented by pump curves of different shapes that intersect at the operating point. Fig. 3 shows the pump curves for two generic pump characteristics along with their associated efficiency curves (determined from assigned BP curves). Pump 1 has a steeper characteristic ($H=68.7-0.00013Q^2$), while that for Pump 2 is flatter ($H=60-0.000066Q^2$). Both curves intersect at an operating point (in the example of Fig. 3, at 367 L/s and 53 m) that provides the adequate pump discharge, or supply, power required to ensure pressure compensation for an unspecified leaky system and to satisfy delivery constraints. The only difference here is that each pump has a different efficiency at the common operating point. For Curves 1 and 2 the efficiencies are 88 and 84%, respectively, an "efficiency gap" that leads to a difference in BP and energy cost.

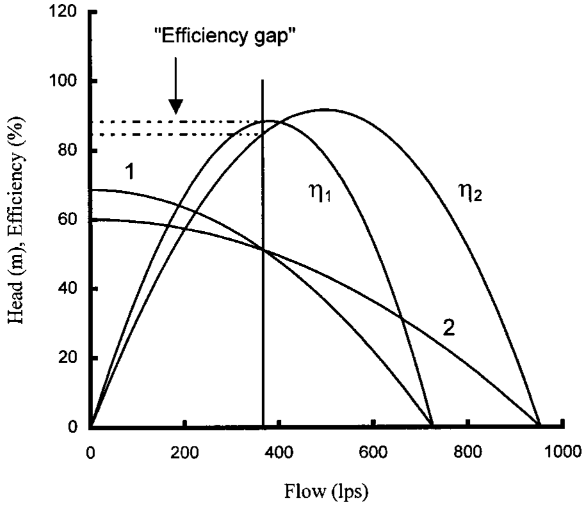

Fig. 3. Pump characteristic and efficiency curves at common operating point

Leakage and Pressure Compensation

The performance of this simple system is tested for all configurations as well as for both friction scenarios at five different leak sizes using EPANET 2 simulation. Leak size is controlled by incrementing the value of the emitter coefficient C_E across the range from 0 to 10 (0 to 35% leakage, depending on the configuration and loss scenario). Equivalent service among leak scenarios is maintained by adjusting pump impeller speed patterns so that pressures at Node 3 are restored to no-leak values. Following pressure compensation, leakage is calculated as a percentage of the total daily demand volume. Daily energy costs, hourly flows and pressures, and tank levels are determined by EPANET 2.

The concept of equivalent service, as depicted in Fig. 1, is the guiding assumption for the subsequent analysis. Equivalent service implies that a leak is compensated for by increasing pumping capacity such that the demand is met at the same pressure as for the no-leak case (30–31 m for no storage) or, in the case of storage configurations for which a range of pressures exist at all points in the system, that the minimum pressure head realized at the demand node during the 24-h cycle is equal to the specified minimum demand pressure (30 m for all analyses). Thus the term equivalent service is used interchangeably with pressure compensation. Without boosting the pump capacity to restore pressure, a reasonable basis of comparison would not exist for the two leakage scenarios. It is recognized that some systems can tolerate deteriorated performance without violating demand constraints by temporarily taking advantage of excess capacity. When new investment is contemplated, however, the trade-offs discussed here become particularly relevant and the recognition that leaks are wasteful is inescapable.

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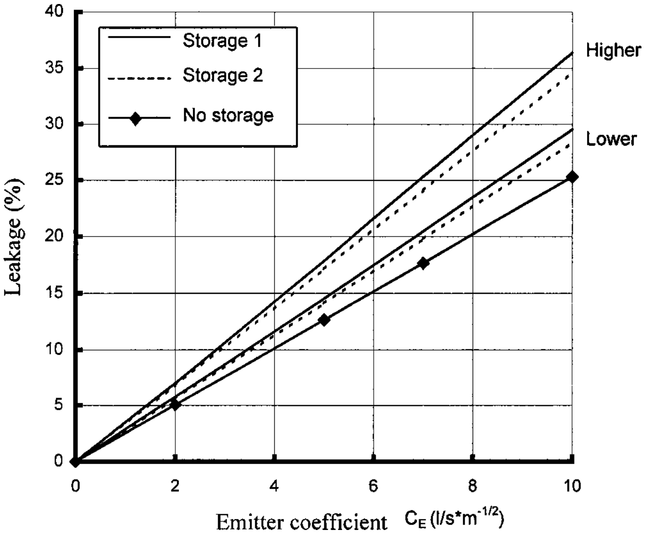

Fig. 4. Leakage as function of leak size, system configuration, and friction scenario

Analysis of Simple System

Water Loss and Energy Costs

Because the leak is modeled with the orifice equation, the amount of water passed through it is a function of system pressures, which in turn depend on both the demand at Node 3 and, in the storage configurations, the tank level. Therefore, when the system relies on direct pumping (that is, the no-storage configuration) to meet demand, the leakage rate changes every 4 h according to the discretization of the diurnal demand pattern. For the storage configurations, flow through the leak changes continuously as the tank levels fluctuate. The leakage value ascribed to a given scenario and value of C_E is thus determined as the total amount of water lost through the leak in a 24-h cycle expressed as a percentage of total daily demand volume (20.45 MLD). Not surprisingly, daily leakage depends on both the system configuration and the friction scenario.

Fig. 4 shows the leakage for all configurations and friction scenarios in the C_E range from 0 to 10. The curve for the no-storage configuration of the higher-friction scenario has been omitted to improve the visual clarity of the figure (it happens to lie between the curves of Storage 1 and 2 for the low-friction case). As expected, leakage increases for all scenarios as C_E increases. The range of leakage for the systems and leak sizes considered here is from 0 to a maximum of 35% of demand. Differences among the curves are easily explained by considering the daily evolution of pressures at Node 2 for the different configurations and friction regimes.

The most obvious categorization in Fig. 4 is between the pair of curves for the higher-friction case and the trio representing the configurations for the lower-friction case. Steeper hydraulic grade lines (HGLs) are maintained for the higher-friction configurations in order to meet the 30-m pressure requirement at Node 3. Therefore, higher pressures dominate at Node 2. For either friction regime, higher system pressures are experienced for Storage 1 than for Storage 2 since a greater distance of pipe (500 m) must be traveled during tank filling, and overcoming this extra resistance necessitates steeper HGLs. Consequently, leakage for Storage 1 is greater.

For each friction regime, the leakage curve for direct pumping lies below the corresponding storage curves. Higher pressures are experienced for the storage configurations because of the need to boost tank levels during the pumping hours (0–8, 20–24) so that Node 3 requirements are satisfied during pump shut-off. The daily distribution of pumping has an important effect on the degree of separation between the no storage and storage curves in Fig. 4. A more continuous but lower-intensity pumping approach (such as U24) would reduce leakage for a given storage configuration relative to a strategy that concentrates pumping activity into fewer hours.

Quantifying water loss has been the traditional concern regarding leaks because of the financial burden posed to the utility and broader society, a burden that varies according to how scarce supplies are and how expensive the water is to procure, treat, and distribute. However, an additional focus on the energy costs associated with leaks, while being more recent, has strong justification. The trade-off between the financial costs of lost water and wasted energy is a natural consideration of a more comprehensive decision and operational framework. Fig. 5, which plots daily total energy, extra energy and lost water costs against leak size, showcases such a trade-off for the three system configurations within the context of the lower friction regime. The intercepts of the total energy cost curves represent the daily expense for pumping in the best of conditions (no leak). Only a relatively small leak (13–15% leakage) is required for the daily lost water cost to become comparable with total energy cost under the resource price structure already outlined.

Because no variation is applied to the price of water, the curves for all three configurations in Fig. 5 maintain the relative placement they exhibit in Fig. 4. That is, daily lost water cost is directly proportional to leakage. The same is not true for total energy cost. Although pumping without storage is financially more expensive than its storage counterparts for this friction scenario, total energy costs for Storage 1 converge upon those for no storage as the leakage approaches 30%. The extra energy cost curves for both storage configurations are higher than for no storage. Thus, as the leakage at Node 2 increases, the financial benefit of implementing storage is eroded. The discrepancy between the two storage configurations in terms of both total and extra energy cost is explained by the greater distance (and thus losses) to the tank that must be overcome in Storage 1.

Costs for both water and energy are expected to be higher for

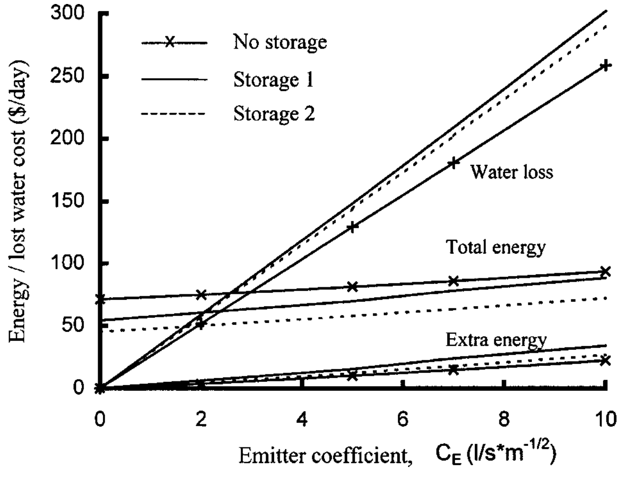

Fig. 5. Water loss and energy costs for low-friction scenario

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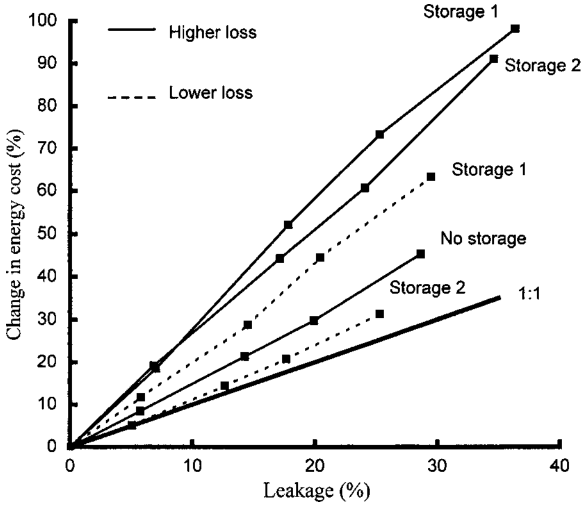

Fig. 6. Energy cost response to leakage

all configurations when friction is greater. Fig. 6 confirms this presumption. Operating in the higher-friction environment imposed by the 0.4-m diameter pipes entails a higher sensitivity to leakage in terms of financial cost. The storage configurations experience the greatest response to changing leak size, especially Storage 1, which sits above Storage 2 for most of the leak range (foreshadowed in Fig. 5 for the low-friction scenario). Thus, the financial advantage of storage for these systems disappears as leakage grows unless a shift in pump operation or scheduling can achieve some degree of compensation. Perhaps the most interesting observation is that all curves lie above the 1:1 datum, implying that the cost response to leakage is more than proportional and that storage does not obviate the energy cost impact of leaks.

Energy Consumption

Comparison of the mechanical flow energy supplied by the pump to that received by the customer can be a good indicator of the energy load the pump of each system and scenario faces. This difference represents the energy lost due to friction in the pipes and that which is surrendered by the system because "energized" water (that is, water that is under pressure and possesses velocity head) has escaped through the leak. The ratio of mechanical flow energy at the demand Node (Node 3) to that at the discharge node (Node 1) indicates the system's overall energy efficiency. It is determined by

$$E_d/E_s=\sum_{j=1}^{24}(Q_{3j}H_{3j}/Q_{1j}H_{1j}) \tag{1}$$

where E_d and E_s are the total daily mechanical flow energies at the demand node and supply node, respectively; Q and H are the flow and pressure heads at each node; and j is the hourly index. Values of the energy ratio E_d/E_s for each system configuration, both friction scenarios, and two leak sizes ($C_E=0$ and 5) are presented in Table 1. The obvious role of friction is evident by the higher corresponding values of E_d/E_s for each configuration and leak level for the lower-friction regime relative to the higher one. In the higher-friction scenario, dynamic losses are greater due to both the higher friction losses incurred throughout the systems and the larger exodus of energized water through the leak because of the higher pressure at the leak. The result is a lower transmission efficiency of flow energy.

The same mechanisms explain why the energy ratio is correspondingly lower for Storage 1 than for Storage 2. In this case the extra dynamic losses imply higher pressures upstream of the demand point. The no-storage configuration is most efficient relative to its storage counterparts because it avoids some of the friction peaks experienced during the 12 limited hours of pump activity in which the tank is filled. To further illustrate this effect, values for Storage 2 with a uniform 24-h pump schedule are included in the table. With this pump schedule, energy efficiency is sufficiently improved for both leak levels that it surpasses the efficiency for direct pumping without storage. These values support conventional wisdom that the implementation of storage can reduce energy consumption. However, this depends on the pump schedule and strategy adopted. For any configuration and friction level, a move from no leak to around 15% leakage has a significant and predictable effect on transmission efficiency when pressure compensation is undertaken.

The pattern of energy efficiency depicted in Table 1 is echoed in Fig. 7, which plots the daily energy consumption (kW·h/day) for all scenarios over the established C_E range. Power requirements are obviously greater for the higher-loss regime, and the relative situation of each curve is consistent for each friction regime: Storage 1 is more energy intensive than Storage 2, which in turn requires more energy than no storage. Without a leak, or at least for leakage less than 30%, the lower financial cost of Storage 1 (Fig. 5) obscures the fact that this is the most energy-intensive option. Even for the more ideal storage configuration, Storage 2, energy consumption is greater than for no storage despite the more agreeable financial cost.

This type of trade-off was encountered by Aptowicz et al. (1987) while using off-peak pumping to storage as part of a plan to cut operating costs for the Philadelphia Water Department. Thus, price patterns can be misleading if minimum financial cost is assumed equal to minimum resource use. Unlike the case for lost water as depicted in Fig. 5, where the cost of lost water parallels the volume of lost water, the financial cost of energy is not always a surrogate measure for energy resource consumption. Without the time-of-day electricity price pattern, the financial incentive for using storage disappears (even in the absence of a leak) unless a change in operational paradigm can bring energy consumption to a level below that for the configuration without storage.

Table 1. Energy Ratio for All System Configurations and Friction Scenarios at No Leak and for Approximately 15% Leakage

		Energy ratio (E_d/E_s)	
Friction scenario	System configuration	No leak ($C_E=0$)	≈15% leakage ($C_E=5$)
Higher ($D=0.4$ m)	No storage	0.42	0.35
	Storage 1	0.27	0.18
	Storage 2	0.33	0.22
	Storage 2 U24	0.54	0.43
Lower ($D=0.5$ m)	No storage	0.68	0.66
	Storage 1	0.48	0.40
	Storage 2	0.56	0.43

Note: A 12-h uniform pumping strategy is used except for Storage 2 U24, which is for all-day pumping at a constant and lower impeller speed.

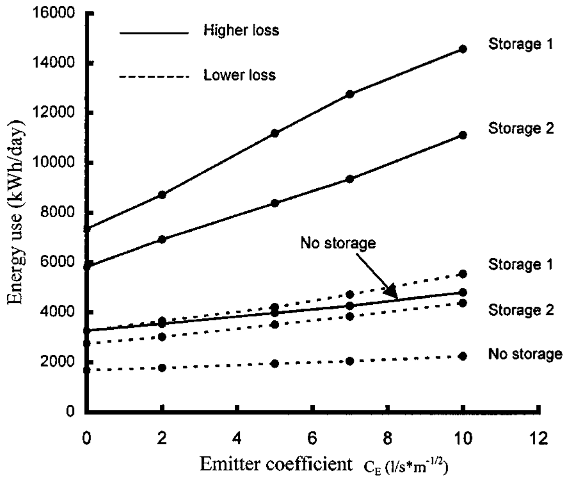

Fig. 7. Energy consumption as function of leak size

Compensation and Linearity of Pump Energy Use with Leakage

Although simulation results here and in Colombo and Karney (2002) suggest a nonlinear (that is, greater than 1:1) energy use response with leakage, it has been observed (Walski 2004) that the energy use of a variable-speed pump supplying a leaky system varies linearly (close to 1:1) with leakage. This can occur in practice when pump operation is controlled by a constant discharge pressure such that the change in operating point is determined solely by the flow. Fig. 8 shows a single leaky pipe and the conceptual pump characteristics for the three impeller speeds of the pump that feeds the system. When the pipe is leak free, the demand flow Q_1 is supplied with a delivery head of H_1 for a pump operating point (H,Q_1) on the innermost curve corresponding to the lowest impeller speed. To maintain a flow of Q_1 at the delivery end of the pipe and a discharge pressure of H when there is a leak of size $Q_2 - Q_1$, the pump must operate with a higher speed and at the operating point (H,Q_2). In such a case the water power γQH changes only linearly with flow since H is fixed; however, the delivery head is reduced to H_2 since the higher upstream flow of Q_2 involves a greater friction loss upstream of the leak.

If both the delivery head and flow from the no-leak situation are to be maintained, the discharge pressure must be higher than H. The HGL must be the same at the leak location for the no-leak and leak-compensated cases to ensure equivalent delivery conditions (H_1,Q_1). Because the larger upstream flow of Q_2 is supplied, the steeper upstream portion of the HGL associated with Q_2 establishes the requisite discharge pressure head of H_3. Therefore, the characteristic corresponding to the fastest impeller speed must contain the new operating point of (H_3,Q_2). The shift from the original operating point of (H,Q_1) to (H_3,Q_2) means that the water power, and thus the BP, are increasing nonlinearly with leakage. If the pipe has little friction and the reduction in delivery head is trivial, it may be acceptable to approximate the increase in BP linearly with leakage. Nonetheless, such a case would represent flow compensation only, and the delivery head would not be identical to the leak-free case, even if it happens to be close. Comparing the system operated in this way to its leak-free operation may conceal the full energy impact of the leak.

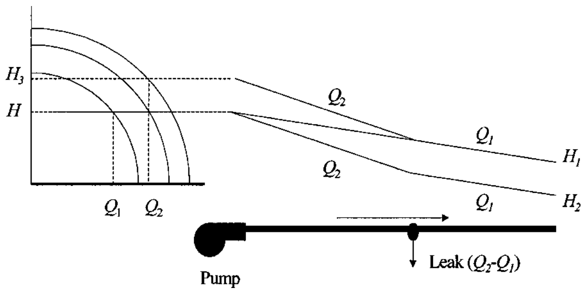

Fig. 8. Compensating for flow and/or pressure by operating at different impeller speeds

Pumping Strategy

It is clear that for some systems the use of storage is an effective way to reduce the financial burden of maintaining the system. For a given leak size and topology, Fig. 7 suggests that a choice of either higher financial cost or energy consumption must be made. This is true if the uniform 12-h pump schedule is adhered to. Fortunately, however, the adoption of storage makes available an expanded set of pumping strategies that, subject to some constraints, can be implemented in such a way as to mitigate the financial cost of operating the system, its energy burden, or possibly a combination of both.

These strategies may be limited by a variety of factors that can be broadly classified in terms of physical and operational constraints. Physical limits to the selection of pump strategy include such things as a fixed tank size and spatial position in an existing system. The elevation of an existing tank is effectively fixed and cannot be altered. Moreover, tank levels may be adjusted for a given strategy provided that the tank has sufficient room to accommodate the required levels. System pressure and pipe velocity boundaries can also pose other physical constraints that circumscribe the set of available strategies.

Operational concerns incorporate a wide range of constraints that may reduce strategy options. For example, tank operating trajectories reflect more than just one or two concerns, such as energy use or financial cost minimization. Other considerations include reliability for meeting emergency demands, water exchange and quality, and capital costs, some or all of which may compete with each other and against energy use and cost minimization (Walski 1993). This gives rise to a set of trade-offs and a multiobjective problem resolved in part by pump strategy and the prescribed range of tank levels.

Although the inherent nature of the problem is multiobjective, it is useful to assess individual trade-off pairs in order to complete the picture of the more complicated reality. Accordingly, discussion here focuses on the dual-objective problem of reducing both energy use and its financial cost. To this end, five rudimentary pump strategies are considered for the Storage 2 configuration (low-loss regime) subject to two leak sizes equivalent to approximately 15 and 30% of demand flow. These include the direct pumping (D) and uniform 12-h (U12) strategies already discussed. Additionally, a uniform 24-h (U24) and a polarized (P) strategy are considered.

As with the U12 approach, the polarized strategy calls for pumping during the first 8 and last 4 hours of the day, but with higher pumping intensity (larger pump speed multiple) during the first 8 h relative to the last 4 h of the day. The objective of this strategy is to pump only in off-peak hours and to emphasize the first 8 h when the electricity price is only 25% of its full price. Two nonuniform 24-h schedules (N1 and N2) are also added to

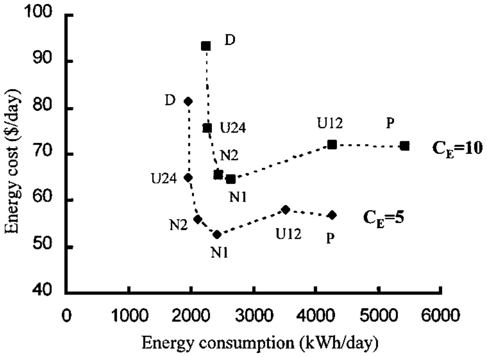

Fig. 9. Trade-off between financial cost of energy and actual energy consumption for selected pumping strategies of Storage 2, low-friction scenario

the analysis and are intended to represent a compromise between U24 and P. The nonuniform strategies entail pumping throughout the entire day, but with a shift of pumping activity from the peak period to off-peak times of day (0–8, 20–24 h). For simplicity, only two impeller speeds are contemplated, one for all hours of the peak period (8–20 h) and another for all off-peak hours.

Fig. 9 depicts the trade-off points for the five strategies at both leak sizes. Each point represents a strategy that satisfies hydraulic constraints and conforms to the equivalent service concept already described. The curves passing through the points are somewhat arbitrary and could be refined by enumerating more technically feasible and constraint-satisfying pump schedule options [Jowitt and Germanopoulos (1992) provide a relatively thorough treatment of pump schedule optimization]. Nonetheless, it is unlikely that they deviate greatly from the actual curves that derive from a more complete accounting of different strategies. Both curves, in fact, resemble production possibility curves that summarize the inherent trade-off of dual-objective optimization problems. The most striking feature of both curves is the clear inferiority of the uniform 12 h and polarized pump schedules.

Figs. 5–7 showcase the trade-off between energy consumption and monetary cost for the U12 and direct strategies, a relationship clearly evident in Fig. 9. The inclusion of the other strategies, however, illustrates that it is possible to use storage in a manner that avoids the high energy consumption of U12 and P, but at a significantly lower cost than for pumping without storage. Among the remaining three strategies, inferiority is less obvious. The steepness of the left portion of both curves suggests that either N1 or N2 achieves the best solution if a small amount of extra energy consumption is not deemed problematic when leakage is about 15%. For the larger leak, N2 may be marginally preferable to N1 since the cost difference is quite small.

The ultimate decision depends on how the relative importance of energy use and financial cost minimization is perceived. For both leak levels U24 achieves the lowest energy use, and the fact that other strategies with substantially higher energy use can save money underscores how a price pattern or economy of scale can discourage resource conservation. Of course, in a more comprehensive and realistic decision framework, other considerations such as water loss would weigh in on this decision because the problem is multiobjective. Interestingly, Wood and Reddy (1995) indicate that an optimized pump schedule can lead to reduced leakage as excess system pressures are curtailed. Such an optimized pump schedule could plot well in Fig. 9, especially if the pricing structure is conducive to minimizing resource consumption.

Representative Network with Storage

A study of single-pipe systems, while useful for exposing some key relationships among energy use, leaks, and storage operations in a framework of simplicity, is primarily intended to set the stage for analyzing more realistic networks. Extending the parallel with Colombo and Karney (2002), the writers have revisited the Anytown network presented in Walski et al. (1987). Fig. 10 depicts the layout of this system, and specific topological information can be found in Walski et al. (1987). For convenience, the numbering scheme for nodes and pipes found in the reference is reproduced here.

Alterations to the basic topology follow Gessler's optimization, specifically with regard to pipes 54 and 68–74, the addition of a tank connected to node 150, and several parallel pipes installed to rehabilitate the system. As outlined in the reference, the 2005 nodal demands and diurnal demand pattern are employed in this paper. Since the original formulation was in customary U.S. units, both these units and their SI equivalents are provided here. All three tanks are cylindrical, with elevation, initial level, diameter, and maximum operating level of 66, 3, 18, and 78 m, respectively (215, 10, 60, and 255 ft, respectively). To facilitate easy modification of pumping capacity, a single pump drives the system and is defined by the curve $H=97.5-1.194\times 10^{-5}Q^2$, where H is in meters and Q is in liters per minute (LPM) ($H=320-8.332\times 10^{-7}Q^2$, where H is in feet and Q is in gallons per minute GPM).

Leaks are introduced by defining emitters at selected nodes, and leakage amount is varied by incrementing their coefficient values in units of 10 from 0 to 60 gal./min/psi$^{0.5}$ (0 to 270 L/min/m$^{0.5}$). The emitter coefficient is the same for each leaky node, and the emitter exponent is 0.5 throughout the analysis. To test the influence of spatial parameters, two leak distributions are considered. The first is a centralized distribution where leaks are defined at nodes 60, 80, 90, 100, 150, and 160. A peripheral distribution with leaks defined at nodes 55, 90, 120,

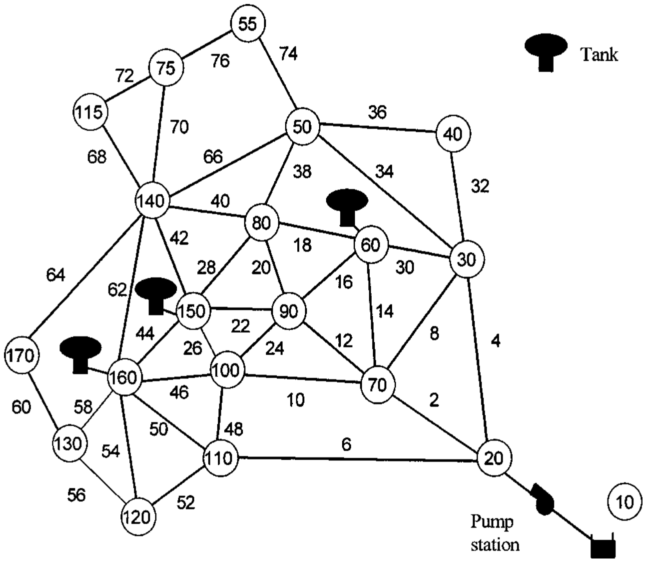

Fig. 10. Layout of Anytown network-from Walski et al. (1987)

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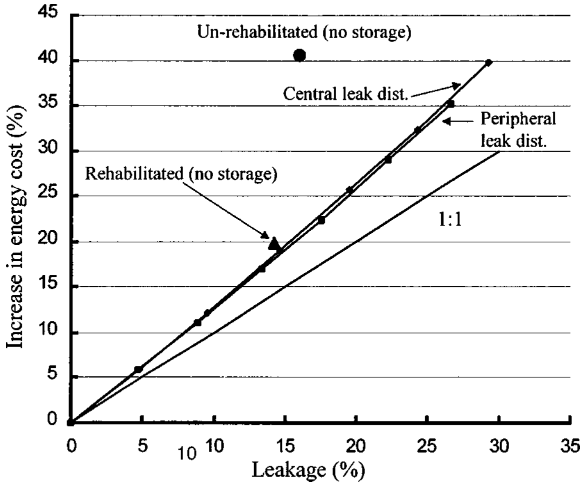

Fig. 11. Change in energy cost with leakage for Anytown network

140, 150, and 170 is also considered. Hydraulic constraints are determined to be satisfied when all nodes have a minimum pressure of at least 28 m (40 psi) over the diurnal cycle and pressure compensation is achieved by changing the impeller speed of the pump, which operates according to a U24 strategy. Extended period simulations of 96 h are conducted to ensure stationary pressure and tank-level time series.

The energy cost response to leakage is shown in Fig. 11. As in Fig. 6, the increase in energy cost is more than proportional to leakage. Interestingly, the difference between the two curves for the two different leak distributions is almost imperceptible (that for the peripheral distribution sits below). This indicates a departure from observation of the two leak distributions for the same system without storage (and some modifications such as fixed demands and lower pressure requirements) found in Colombo and Karney (2002). With several of the leaks relocated beyond the tanks, storage seems to mitigate the tendency for downstream leaks to aggravate energy consumption. The unrehabilitated Anytown system without storage is also tested for one value of leakage ($C_E = 30$) to assess its energy cost response relative to the no-leak case.

In this case, the tanks are removed and the system topology is that for the network as introduced in Walski et al. (1987), the only additions being Gessler's pipe selections for pipes 54 and 68–74. The demand pattern is not implemented, and only average nodal values are used. For leaks with $C_E = 30$, the dilapidated system exhibits a more dramatic energy cost response with 16% leakage corresponding to a 40% increase in energy cost. With the same leak characteristics, the rehabilitated system without storage plots essentially on the curves for storage with 14% leakage corresponding to 20% rise in energy cost. The importance of friction is clearly highlighted by the discrepancy between the deteriorated and rehabilitated incarnations of the network. The impact of leaks, or additional system demand, is exacerbated in a high-resistance network, the implications for system maintenance and demand management becoming readily apparent.

Conclusions

The inclusion of storage capacity does not circumvent the higher operating costs associated with leaks from a system, nor, as is often automatically assumed, does it guarantee lower energy consumption. In some cases, storage can encourage higher leakage if tank water levels and system pressures are high.

The impact of leaks on the energy use and pumping costs of a system depend on several factors. The spatial distribution of system components, specifically the relative locations of pump, tank, leak, and demand, affects both water loss and energy use. Perhaps the most important factor contributing to a system's energy response to leakage is friction, which is especially apparent when equivalent service is maintained through pressure compensation.

For the simple system considered in this paper, the difference in energy consumption between the two friction scenarios is evidence of friction's role. The comparative impact of leakage between the rehabilitated and deteriorated states of the representative network further underscores this result. When energy price varies, the discrepancy between the financial cost of pumping and actual energy use can obscure the true picture of resource consumption. Although the competition between financial cost and energy use is one of several trade-offs with which operators must contend, thoughtful attention to pumping strategy can help exploit this trade-off. Because leaks represent extra demands on a system, leak impact analysis has implications for demand management and conservation.

The results in this study are derived from hypothetical systems designed to isolate the potential impact of leakage on energy use. Fixing leaks saves water and energy, but the exact amounts saved are specific to a given system and its operation. Because utilities often do not practice pressure compensation for marginal or even moderate leakage, the relationship between energy saved and leakage reduction in those situations may appear modest relative to the examples provided here. Obviously leaks are only one source of diminished system performance, and it is ultimately desirable to incorporate all sources of inefficiency into a comprehensive planning model.

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Notation

The following symbols are used in this paper:

C = Hazen-Williams roughness coefficient;
C_E = emitter coefficient ($\mathrm{L/s \cdot m^{-1/2}}$ or $\mathrm{gal./min/psi^{1/2}}$);
D = pipe diameter (m);
E_d = mechanical flow energy received at demand node (kW·h);
E_d/E_s = energy ratio;
E_s = mechanical flow energy at discharge node (kW·h);
H = head (m or ft);
H_d = demand head (m);
H'_d = head at demand location due to uncompensated leak (m);
h_a = dynamic head loss associated with pump operating point *a*;
h_b = dynamic head loss associated with pump operating point *b*;
h_c = dynamic head loss associated with pump operating point *c*;

L = pipe length (m);
Q = flow (m^3/s, L/s, or gal./min);
Q_d = demand flow (m^3/s); and
q_l = flow through leak (m^3/s).

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