Life-Cycle Energy Analysis of a Water Distribution System

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Abstract: The paper presents a life-cycle energy analysis (LCEA) to quantify energy expenditures in the fabrication, use, and end-of-life stages of the pipes of a water distribution system. The methodology incorporates the capabilities of environmental input-output life-cycle analysis to quantify the energy required to fabricate pipes. The EPANET2 hydraulic model is applied in conjunction with a pipe-aging model to calculate the theoretical energy recovery in the use stage. An exponential pipe-break model is applied to quantify the energy required to repair pipe breaks during the use stage of a system. Simple formulations are developed to estimate the energy required to dispose of and recycle pipes once their service period has expired. The LCEA methodology is then applied to the New York City (NYC) water supply tunnels example to quantify energy expenditures in four planning scenarios with 10-, 20-, 50-, and 100-year pipe replacement frequencies. The results of the NYC example highlight the tension between the energy costs incurred in the fabrication and end-of-life stages of a system and those incurred in the use stage. A pipe-replacement period roughly equal to 50 years yielded the lowest overall energy expenditure in the three life stages. A sensitivity analysis was carried out to assess the influence of uncertain system parameters on energy expenditure estimates.

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Introduction

Physical infrastructure such as water, wastewater, solid-waste disposal, and transportation systems have served, and continue to serve, a vital role in sustaining human activities and supporting the development of civil institutions and cultures. Specifically, water supply and distribution infrastructure is often seen as the stalwart component of a larger urban infrastructure system that fosters public health and public safety and that underpins most economic activities in the urban setting. Urban populations typically rely on water-distribution networks to provide clean, potable water to perform basic domestic activities such as washing, cooking, cleaning, and waste disposal. The occasional compromise of water safety in such systems, and the loss of life sometimes associated with such failures, serve as reminders of the fundamental role they play in daily life. Water distribution networks also serve an important role during civil emergencies, such as when a fire erupts in a city, and to support the city's commercial and industrial activities.

The need to replace and rehabilitate deteriorating water infrastructure coupled with concerns about environmental degradation and resource scarcity will, it is hoped, spur governments to conduct such activities on a more sustainable footing. Ideally, future efforts to develop sustainable infrastructure should embody the sweeping objective to ‘‘meet the needs of the present [generation] without compromising the ability of future generations to meet their own needs’’ first articulated by the World Commission on the Environment and Development (WCED 1987). More pragmatically, the sustainable development of infrastructure is likely to be guided by specific criteria such as resource efficiency, minimization of waste residuals, and so on. Governmental agencies should incorporate some of these criteria and objectives in future infrastructure planning efforts.

In addition to technical goals and objectives, the sustainable development of water supply and distribution infrastructure must increasingly be guided by planning approaches that ‘‘push back’’ the analytical boundaries to include the economic, environmental, and even social dimensions. Arguably, the tightly linked nature of social institutions and infrastructure systems within industrialized societies (material production and manufacturing, transportation, energy and food production, water supply, rural and urban communities, and so on) mandates the development and use of holistic planning approaches to trace the interactions between these factors. For example, systems planning and integrated approaches such as life-cycle costing (LCC) and life-cycle assessment (LCA) can be used to track life-cycle stage impacts of water supply infrastructure on biospheric and social networks (ISO 1998).

The academic literature provides notable examples of studies that have explored the life-cycle cost and life-cycle environmental impacts of key civil infrastructure systems. For example, Salem et al. (2003) presented a general risk-based framework to predict the range of possible life-cycle costs associated with the construction and rehabilitation of infrastructure systems, while others have focused on bridge infrastructure (Mohammadi et al. 1995; Freyermuth 2001). Tsagarakis et al. (2003) have estimated and compared the life-cycle cost of different wastewater projects in Greece to determine the most cost-effective alternative. Life-cycle inventory assessment studies have also investigated the environmental impacts of transportation infrastructure components such

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as bridges and road construction (Horvath and Hendrickson 1998). Ries and Mahdavi (2001) have quantified the life-cycle impacts of building infrastructure. In similar studies, Dennison et al. (1998, 1999) and Lundin et al. (2000) have determined the environmental impacts of wastewater and water infrastructure.

Researchers have also begun to focus on the broader economic and environmental dimensions of water supply and distribution system management. Savic and Walters (1997) discussed how conventional optimization approaches could be combined with a sustainability framework to find management alternatives that minimize resource consumption. Skipworth et al. (2002) have comprehensively investigated the whole life costing of water distribution systems, specifically in the United Kingdom. Kleiner et al. (1998) developed an optimization approach to investigating the long-term economic sustainability of operating, maintaining, rehabilitating, and renewing pipe networks. Colombo and Karney (2002) considered the relationships between pipe leakage and energy expenditure in the broader context of water distribution system operation and management.

The recent studies cited above are a first effort to venture beyond the narrowly established objectives of least-cost design and optimization in solving the water supply and distribution problem. This paper extends this recent activity by grappling with the broader issues of sustainable design, operation, and management of water distribution systems and their environmental input. This investigation is carried out under the rubric of a life-cycle energy analysis (LCEA), which seeks to quantify energy expenditures incurred in the fabrication, use, and end-of-life stages of a water-distribution system. It is the first study of its kind that deals with energy expenditures incurred in all life-cycle stages of a water-distribution system.

The selection of energy as a key environmental measure is crucial and is based on three important considerations. First, given the pervasive use of energy in all spheres of water supply and distribution, one can argue that *energy expenditure* can be employed as a natural, albeit crude, indicator of the amount of resources (energy and material) being consumed and of the air, water, and solid-waste streams being generated (Hocking 1999). Second, tracking energy expenditures in all life-cycle stages of a water distribution system can be completed with a reasonable amount of data available to many regional municipalities. As such, the LCEA proposed here can be thought of as a ‘‘streamlining’’ process that reduces the onerous and sometimes arresting data requirements often associated with its more comprehensive cousin, LCA. Third, energy expenditures form a nice, integrating assessment of capital and operating expenses. This approach avoids the obvious pitfall of assuming that large pipes are necessarily more efficient because they have lower friction losses during the use phase [for example, Lovins (1989)].

While the LCEA has indisputable merits, it also comes with some disadvantages. For example, such an analysis is mute on the sources of primary energy (fossil fuels, nuclear, wind, etc.) and what proportions come from renewable and nonrenewable origins. Furthermore, if nothing is known about the provenance of energy, then it is impossible to determine the nature of the waste streams (air, water, and solid) from these resources. This also means that it is not possible to determine the composition of these waste streams biochemical oxygen demand, heavy metals, suspended solids, etc.), much less their relative toxicity to environmental and ecological systems (Hocking 1999). Moreover, focusing on a single indicator can shift the environmental problem from one area to the next. For example, a system with low life-cycle energy requirements may conceivably produce a large amount of air pollution and solid waste. Notwithstanding these clear shortcomings, the writers believe that while the LCEA falls short of a full LCA, it can help decision makers identify and trade off system efficiencies as well as opportunities to save energy and can serve as a screening model for later and more detailed assessment studies.

Following an outline of the conceptual framework of the LCEA, the well-known New York City water-supply tunnels are used to quantify the energy expenditures associated with four disparate pipe-replacement scenarios (10, 20, 50, and 100 year). These four discrete scenarios have been chosen to be representative of the full spectrum of possible pipe-replacement schedules. A sensitivity analysis assesses how uncertainty in select parameters affects the total energy calculated in the solution. The paper concludes by discussing the broader implications of the New York City water supply tunnels example and energy expenditures in water supply and distribution activities.

Life-Cycle Energy Analysis Methodology

Planning Period and System Boundaries

The planning period T of the LCEA is assumed to coincide with the theoretical service life of pipes in a water distribution system. This assumption is motivated by two important facts. First, pipes often constitute the largest component of embodied energy in a system (energy required to fabricate pipes); and second, pipes often have longer service lives than almost all other components in a system.

The system boundaries of the LCEA are shown in Fig. 1. The activities included involve energy expenditures directly associated with (1) *fabrication stage*: material extraction, material production, and pipe manufacturing (pipe transportation and installation excluded); (2) *use stage*: pumping energy, energy recovered through thermodynamic shaft work (turbines), and energy required to repair pipe breaks (rehabilitation, maintenance, and cleaning excluded); and (3) *end-of-life stage*: pipe disposal (landfilling) and pipe recycling (pipe replacement activities such as surface restoration and repaving excluded). The energy requirements to fabricate and dispose of system components such as valves, reservoirs, pumps, and so on, are not considered in the analysis.

Environmental Indicators

The gross energy requirement (GER) indicator is used in the LCEA as a proxy that roughly characterizes the environmental impacts associated with the fabrication, use, and end-of-life stages of a water distribution system. The assumption is that the level of energy expended is proportional to the level of energy and material resources consumed, the level of wastes generated, and, perhaps less directly, the level of harm done to the environment through water distribution activities. In other words, it is assumed that a lower GER results in lower environmental impacts, even though this is an oversimplification.

Functional Units and Comparison of Scenarios

The functional unit is defined as the volume of water delivered to consumers throughout the planning period, usually expressed in megaliters (ML) of water delivered. The energy expenditures in different planning scenarios can be normalized with the functional unit.

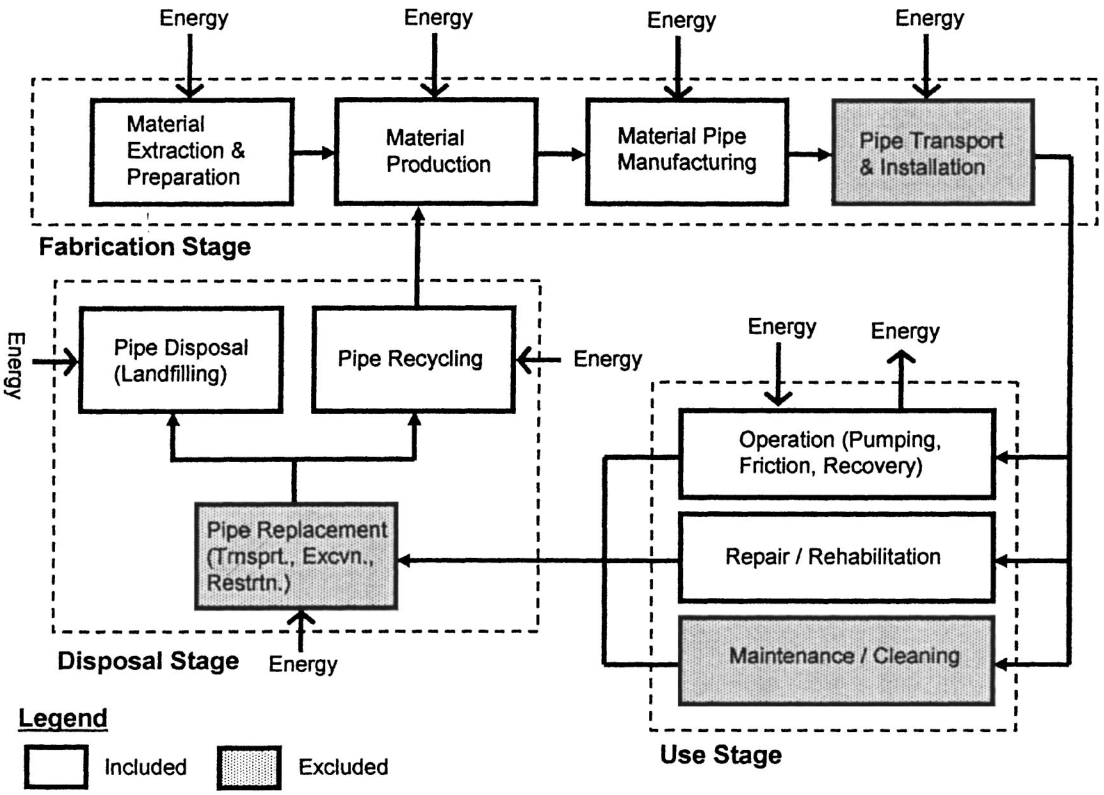

Fig. 1. Life-cycle energy analysis boundaries and life stages

A simple criterion is established to compare the performance of a system in different planning scenarios. A water distribution system is deemed to perform in a satisfactory manner if it is capable of delivering water to consumers at a residual pressure above some minimum threshold, such that $h \geqslant h_{\min}$. Using this criterion, different planning scenarios can be evaluated by counting and comparing the number of pressure violations over the lifetime of a system. Additional water quality criteria such as minimum acceptable residence time or minimum acceptable residual chlorine concentration could be used to evaluate more comprehensively the performance of systems.

Energy Expenditures in Life-Cycle Stages

Fabrication Stage

The fabrication stage of a pipeline includes the activities of raw material extraction, material processing and production, and the manufacturing of pipe. An environmental input-output life-cycle assessment (EIO-LCA) model is used to determine this energy requirement since it can trace all monetary and resource flows between the many sectors that directly or indirectly participate in the fabrication of a pipe segment. The EIO-LCA used in this paper is based on the U.S. Department of Commerce's commodity-by-commodity input-output table of the U.S. economy (Carnegie 2003). This model can calculate the total energy used by the chain of direct and indirect suppliers (n-tiers) throughout a national economy to produce the inputs needed to fabricate a segment of steel pipe.

Once the unit energy requirement to fabricate a unit length of pipe of a certain diameter and thickness is known, the total energy required to fabricate new pipe to replace old pipe in the system is calculated with

$$E_F=(1-\alpha)\sum_{j=1}^{M}\sum_{i=1}^{P} L_i e_f \qquad (1)$$

where L_i=length of pipe segment i (m); e_f=unit energy required to fabricate pipe i (GJ/m); M=number of pipe-replacement cycles in planning period (e.g., there are five 20-year replacement cycles in a 100-year planning period); P=number of pipes in the system; and α=closed-loop recycling rate, which simply denotes the fraction of material that can be recovered from old pipe and recycled into new pipe.

Use Stage

In the use stage of a water distribution system, energy is required to carry out key operation and maintenance activities such as pumping water and repairing breaks. In some systems, there is also an opportunity to recover energy through shaft work (turbine work). Energy expenditures in the use stage are estimated by first dividing the planning period T into discrete time steps. Projected future water demands and the increasing frictional resistance of pipes are then updated at each discrete time step as consumer needs change and the system ages. With inputs of demand and pipe resistance at every step, pipe flows and residual pressures in the system are computed with a pipe network model. The estimates are then used to calculate pumping, incremental turbine recovery, and repair energy rates, which are tallied over the planning period.

Pipe Aging. The roughness-growth model proposed by Sharp and Walski (1988) is used to simulate the aging of pipes throughout a system's planning period. Their model is chosen here simply because no comparable models exist in the hydraulics literature. This model predicts the temporal increase in hydraulic resistance

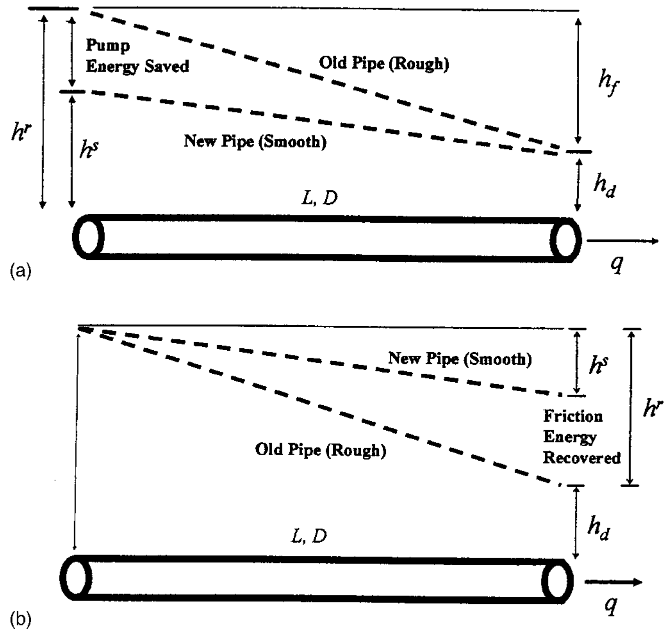

Fig. 2. (a) Theoretical pumping energy savings in single-pipe system; and (b) theoretical energy recovery through shaft work in a single-pipe system

of a pipe resulting from processes such as internal corrosion, biofilm formation, and tuberculation. It combines the common formulations such as Hazen-Williams, Darcy-Weisbach, and Colebrook-White, which determine energy loss in a pipe into a single expression that relates the Hazen-Williams's *C* friction coefficient to the time-varying relative roughness of a pipe. The model is as follows:

$$C=18.0-37.2\log X \quad \text{where} \quad X=(e_0+at)/D \tag{2}$$

where e_0=initial height of wall roughness at time $t=0$ (mm); a=growth rate in roughness height (mm/year); t=number of years after pipe replacement; D=pipe inner diameter (mm); and X=time-varying relative roughness (roughness divided by pipe diameter).

Pumping Energy. Most systems require some form of pumping to lift water from a source, such as a lake or river, to a higher elevation in the system in order to provide an adequate residual pressure. Pumps are also called upon to overcome pipe frictional losses driven by demand in a system. The lift requirement is usually called the static head, and both the lift and friction requirements taken together are called the dynamic or total head supplied by a pump. The dynamic head is simply the thermodynamic work done by a pump or total mechanical energy added to the fluid.

The basic notions of static and dynamic head are elucidated with the single-pipe system outlined in Fig. 2(a). Here, an arbitrary datum of zero is chosen to coincide with the pipe centerline. A pump located at the upstream section of the pipe [left-hand side in Fig. 2(a)] lifts water from a source that is at the datum elevation to some point that satisfies a prescribed pressure head of h_d (the static head) downstream of the system. In addition to the lift requirement, the pump must also supply the mechanical energy h_f to overcome the frictional head loss along the pipe and to ensure that water reaches the downstream point to satisfy the demand *q*. The total rate of mechanical energy or total dynamic head supplied by the pump to lift water and overcome friction in the system is the sum of the static head h_d and frictional losses h_f along the pipe [Fig. 2(a)].

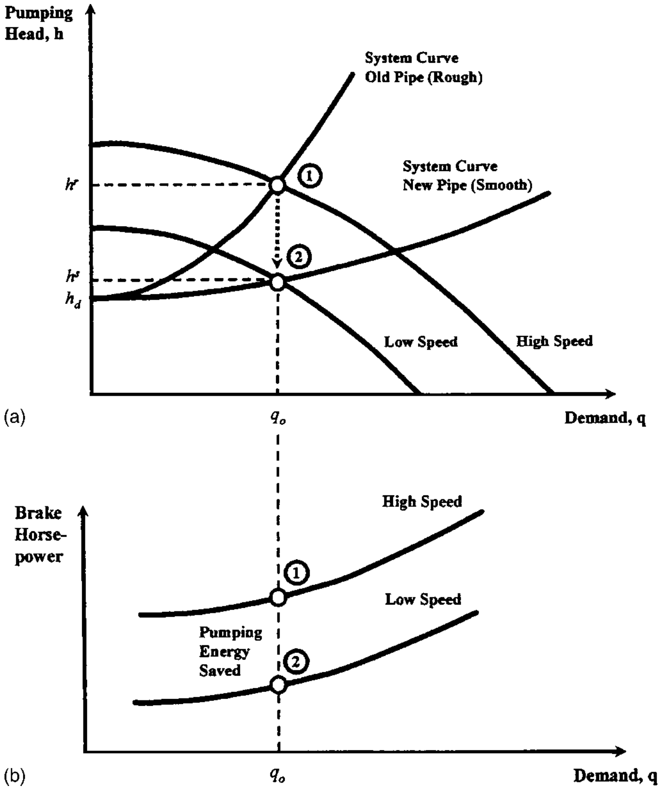

Fig. 3. (a) Pump and system curves that correspond to rough-pipe and smooth-pipe replacement scenarios; and (b) brake horsepower curves for low- and high-speed pump settings

The physical interplay between the pump and the single-pipe system is indicated in Fig. 3(a). The downward paraboliclike lines in Fig. 3(a) represent the pump's characteristic curves for different impeller speeds. A pump characteristic curve maps the dynamic head as a function of flow rate. Typically, the larger the flow rate, the smaller the dynamic head the pump can provide. The upward paraboliclike lines in Fig. 3(a) represent the system curves, a plot of the dynamic head required by the system to overcome both static lift and friction losses. The point at which the system curve intersects the pump curve denotes an equilibrium position whereby the energy required by the system is equal to the energy supplied by the pump.

The amount of pumping energy saved by replacing a pipe is nicely represented through the notion of a net energy benefit (NEB). The idea of a NEB is akin to that of opportunity benefit in economics; in the context of pumping it is defined as the savings in potential friction energy losses gained by replacing a pipe before it has reached the end of its prescribed service life. The idea is best described with a simple example. In the first instance, suppose a pipe is replaced every 75 years, a period that coincides with the end of its service life. After 50 years of service, the pipe is expected to be tuberculated and of a reduced hydraulic capacity; this is the rough-pipe case. To meet a demand *q*, the pump must supply a dynamic head to overcome the static lift and frictional losses, such that $h^r=h_d+h_f$, as indicated in Figs. 2(a) and 3(a) at operating point 1. The pump also requires a power input—the rate at which energy must be supplied to the pump—that corresponds to point 1 in Fig. 3(b).

Now suppose that the pipe is replaced more frequently, say, every 20 years. This means that after 50 years, the pipe will have been in service for only 10 years and will likely be in a relatively pristine state, with little or no tuberculation; this is the smooth-pipe case. Under these conditions, the pump has to supply a dynamic head h^s to satisfy demand q at a residual pressure h_d and to overcome a reduced frictional loss across the pipe, as indicated in Fig. 2(a). This pumping requirement corresponds to operating point 2 in Fig. 3(a). To meet demand q at the lower dynamic head h^s, the pump curve can be revised downward. It is assumed that the pump has variable-speed capacity and can meet the lower dynamic head h^s condition by switching to a lower speed, as indicated in Fig. 3(a). However, the same result would be achieved by shutting off pumps or simply substituting a smaller pump. By lowering the requirements, the power is also reduced from point 1 to point 2 on a lower power curve in Fig. 3(b). Thus, the net rate of pumping energy savings is simply equal to the difference in power requirements between the rough-pipe and smooth-pipe scenarios and schematically represented by the difference between points 1 and 2 in Fig. 3(b). In mathematical terms, this energy difference is expressed as

$$\dot{W}_t=\sum_{j=1}^{n_1}\sum_{i=1}^{n_2}\frac{\rho g}{75}\left[\frac{q_{ij}^r h_{ij}^r}{e_{ij}^r}-\frac{q_{ij}^s h_{ij}^s}{e_{ij}^s}\right]_t \tag{3}$$

where ρ=density of water (1,000 kg/m^3); g=gravitational constant (9.81 m/s^2); n_1=number of pumping stations in system; n_2=number of pumps in pumping station j; q_{ij}^r=flow at time t delivered by pump i in pumping station j to a system in which pipes are replaced only at the end of their theoretical service life (rough-pipe case) (megaliters per day, or MLD); h_{ij}^r=total dynamic head delivered at time t by pump i in pumping station j to a system in which pipes are replaced only at the end of their theoretical service life (rough-pipe case) (m); and e_{ij}^r=mechanical efficiency of pump i in pumping station j, which delivers a flow q_{ij}^r to the system at time t (%). The variables q_{ij}^s, h_{ij}^s, and e_{ij}^s are similarly defined for the smooth-pipe case.

Energy Recovery. In some systems, turbines might be used to recover energy that would otherwise be lost to frictional dissipation. As in the case of pumps, the notion of net energy benefit is germane to the understanding of energy recovery and can be defined as the savings in potential friction energy losses gained by replacing a pipe before it has reached the end of its prescribed service life. The assumption is that these energy loss savings can be converted into useable forms of energy (i.e., electricity) through thermodynamic shaft work performed by in-line turbines.

The basic recovery mechanism that leads to the notion of NEB is outlined in Fig. 2(b) and again illustrated by example. Suppose that a pipe is replaced only at the end of its service life, which is again assumed to be 75 years. Now further suppose that at time $t=50$ years, the frictional head loss through this pipe is as indicated by the steep energy grade line in Fig. 2(b). The downstream hydraulic head (elevation+pressure head) assumes the value h_d, which corresponds to an acceptable service level to the water consumer, such that $h_d \geqslant h_{\min}$ (rough-pipe case). In an alternative scenario, assume again that the pipe is replaced prematurely, say, every 20 years. Thus, at time $t=50$ years, the pipe will be only 10 years old (relatively new) and will incur only slight frictional losses, as indicated by the shallow energy grade line in Fig. 2(b). This is again the smooth-pipe case. Therefore, in the smooth-pipe case at time $t=50$ years, it is possible to recover mechanical energy from the system with a turbine at a rate that corresponds to the difference between the frictional dissipation rates in the rough-pipe and smooth-pipe cases (schematically shown as the difference between energy grade lines corresponding to both cases). This implies that in the smooth-pipe case, the downstream hydraulic head is maintained at the acceptable level h_d encountered in the rough-pipe case, and the level of service to the consumer is therefore equivalent in both cases. The energy recovery process is summarized as

$$\dot{W}_t=\sum_{i=1}^{P}\eta_i\rho g(q_i^r h_i^r-q_i^s h_i^s)_t \tag{4}$$

where q_i^r=flow at time t in rough pipe i replaced at the end of its theoretical service life (MLD); h_i^r=head loss at time t in rough pipe i replaced at the end of its theoretical service life (m); q_i^s=flow at time t in smooth pipe i replaced before the end of its theoretical service life (MLD); h_i^s=head loss at time t in smooth pipe i replaced before the end of its theoretical service life (m); and η_i=average turbine efficiency (%). The turbine efficiency parameter η_i in Eq. (4) describes the portion of shaft work done on the turbine that can be converted into a useable form of energy such as electricity (remaining portion is transformed into heat).

The total pumping energy saved E_P (TJ) and/or mechanical energy recovered with a turbine E_T (TJ) for a particular scenario can be determined by carrying out a numerical integration with calculated values of $\dot{W}_t$ over the planning period

$$E_P \text{ or } E_T=\sum_T(\dot{W}_t+\dot{W}_{t+\Delta t})\frac{\Delta t}{2} \tag{5}$$

where $\dot{W}_t$=rate of pumping energy saved and/or energy recovered at time t (TJ/year); $\dot{W}_{t+\Delta t}$=rate of pumping energy saved and/or energy recovered at time $t+\Delta t$ (TJ/year); Δt=simulation time step; and T=planning period.

Energy to Repair Pipe Breaks. Many studies have established the link between pipe aging, structural deterioration, the onset of leakage, and the increase in pipe breaks that typically follows. The panoply of factors that contribute to pipe deterioration and pipe breaks (aging of material, corrosivity of soil, frost heaving and settlement, poor installation, service pressures, surface loading, etc.), the scarcity of data on such factors, and the difficulty in developing models that account for these factors have led researchers to resort to statistical methods to simulate histories of pipe breaks in systems (Shamir and Howard 1979; Walski and Pelliccia 1982; Kleiner et al. 1998; Kleiner and Rajani 1999). Moreover, Shamir and Howard (1979) found that pipe breaks often conform to a monotonic, exponential trend. Since the first study by Shamir and Howard (1979), other researchers have confirmed the monotonic, exponential behavior of pipe breaks (Walski and Pelliccia 1982; Kleiner et al. 1998; Kleiner and Rajani 1999).

One such model is Shamir and Howard (1979), which is used in the LCEA to predict the number of pipe breaks per year per length of pipe, such that

$$N(t)_i=N(t_0)_i e^{\psi_i(t-t_0)} \tag{6}$$

where $N(t)_i$=number of breaks in pipe i at time t after replacement (breaks/year/km); $N(t_0)_i$=number of breaks in pipe i in year of replacement t_o (breaks/year/km); ψ_i=breakage growth rate (year^{-1}); t=current year; and t_0=year of replacement of pipe i.

Integrating the exponential formula in Eq. (6) over a single replacement cycle of length T^C (years) gives the total number of breaks in pipe i as

$$\text{Br}(T^C)_i = \int_0^{T^C} L_i N(t_0)_i e^{\psi_i(t-t_0)} dx \tag{7}$$

where $\text{Br}(T^C)_i$=number of breaks in pipe i per replacement cycle; L_i=length of pipe i (m); and x=dummy variable of integration.

The energy required to repair a single break in pipe i is calculated by multiplying a typical break length with the unit energy required to fabricate the segment of broken pipe of a certain diameter and thickness, such that

$$e_{bi} = 2L_b e_f \tag{8}$$

where L_b=typical break length (m); and e_f=unit energy of pipe fabrication (GJ/m). It is assumed that damaged pipe segments are replaced with new segments fabricated with virgin material. The calculation in Eq. (8) only considers the energy required to fabricate replacement pipe segments and excludes the energy required to operate equipment and provide materials for excavation, backfilling, and surface restoration and to transport materials—incidentally, activities that are part and parcel of any pipe-repair operation. Unfortunately, these repair activities cannot be explicitly considered in this study for lack of energy data in the literature. However, to roughly account for these activities, the energy of fabrication e_f was multiplied by a factor of 2.

Combining Eqs. (6), (7), and (8) and adding the pipe-break energy requirements of the P pipes in the system that are replaced every M cycle in the simulation, we get

$$E_B = \sum_{j=1}^{M} \sum_{i=1}^{P} e_{bi} \frac{L_i N(t_0)_i}{\psi_i} (e^{\psi_i T^C} - 1) \tag{9}$$

where E_B=total energy required to repair pipes in the system (TJ); and M=number of replacement cycles in the planning period.

End-of-Life Stage

The end-of-life stage of a water distribution system includes the disposal and recycling of pipes. The total energy to dispose of old pipe material is calculated with

$$E_D = (1-\alpha) \sum_{j=1}^{M} \sum_{i=1}^{P} L_i e_d \tag{10}$$

where E_D=total energy required to dispose of old pipes (TJ); and e_d=unit energy required to dispose of old pipes (GJ/m).

Similarly, pipes replaced after a number of years of service can be recycled in a closed-loop fashion. In the case of steel pipes, this means that the recycling process would include the melting down of steel for use in the steel production stage, as indicated in Fig. 1. The total energy required to recycle a portion of old pipe material is calculated with

$$E_R = \alpha \sum_{j=1}^{M} \sum_{i=1}^{P} L_i e_r \tag{11}$$

where e_r=unit energy required to recycle old pipe material (GJ/m).

The recycling rate α is assumed to remain constant up to some threshold age. For example, if a pipe is replaced before the threshold age of t_a, then a portion α of its material can be recycled in a closed-loop fashion. However, if the pipe is replaced after the threshold time t_a, no portion of its material will be salvaged (α=0), and all the pipe material will have to be disposed of. These pipe-recycling constraints are summarized as

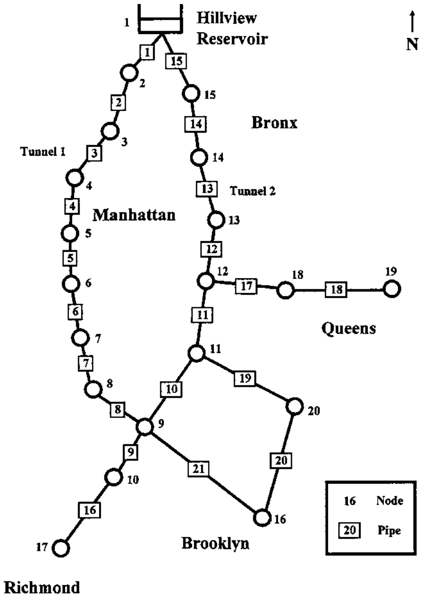

Fig. 4. Topology of New York City primary water supply tunnels

$$\alpha(t) = \begin{cases} \alpha & \text{if } t < t_a \\ 0 & \text{otherwise} \end{cases} \tag{12}$$

where t=number of years after pipe replacement; and t_a=threshold pipe age after which the recycling rate is equal to 0. Determining a threshold age t_a is difficult since the aging of pipe material is influenced by a host of local factors. Moreover, the binomial logic in Eq. (12) is likely a simplification of the complex physical, biological, and chemical processes that lower the recycling rate of pipe material as it ages. Thus far, little research has been conducted to link the presence of such factors to the recycling potential of worn pipe. It should also be noted that Eqs. (10) and (11) do not account for the fact that pipes may simply be abandoned instead of being disposed of or recycled.

The total energy requirement E_{TOT} (TJ) associated with a particular planning scenario is calculated by adding the energy requirements in all life-cycle stages of a system:

$$E_{\text{TOT}} = E_F + E_P + E_T + E_B + E_D + E_R \tag{13}$$

Example: New York City Primary Water Supply System

System Description

The New York City (NYC) primary water supply system comprises two large-diameter rock tunnels (ranging from 1.52 to 5.18 m) that carry water by gravity from the Hillview reservoir to the five boroughs. Tunnels 1 and 2 shown in Fig. 4 were built in the 1920s and 1940s, respectively, and constitute the backbone of the system. Secondary and tertiary distribution networks are connected to the primary system and directly convey water to consumers (Dandy et al. 1996). This system is selected for study because it has received continuous and close scrutiny in the optimization literature for over 20 years. None of these previous studies have considered anything beyond steady-state pressure considerations, nor have they considered overall energy use as an objective.

Projected Demands

The system demand was forecast over an assumed planning period of 100 years (2000–2100), with historical population and demand data taken from the literature. Historical data on NYC's population between 1850 and 2000 (U.S. Bureau of the Census 2000) was used to predict the average population growth rate over the assumed planning period of 100 years. The data showed an average annual growth rate of 11.3% between 1850 and 1950, and a stagnant and sometimes declining average annual growth rate of 1.9% between 1950 and 2000. The plummeting growth rate was assumed to stabilize at a nominal value of 0.2% per annum in the year 2000 and remain fixed for a 100-year planning period. This small annual growth rate corresponds to a 22% population increase over the assumed lifetime of the system.

The per capita demand was assumed to remain constant over the 100-year planning period and the systemwide demand was assumed to increase in step with NYC's population. A per capita average-day demand (ADD) of 650 Lpcd (liters per capita day) was calculated by dividing the systemwide average-day demand of 4,933 MLD (megaliters per day) reported in the literature (assumed to correspond to year 2000) by the NYC population of 7,494,000 in the year 2000 (U.S. Bureau of the Census 2000). This per capita average-day demand was assumed constant and unaffected by changes in household income, climate, cultural patterns, technology, and so on, throughout the 100-year planning period. Next, the systemwide average-day demand of 4,933 MLD at year 2000 was increased, in decadal increments (2% per decade or 0.2% per annum), over the entire 100-year planning period (22% demand increase over 100-year planning period).

System Topology

The system's topology, as reported in the literature by Dandy et al. (1996) and others, was altered slightly for analytical convenience. Since node elevation was unavailable in the literature, all system nodes were arbitrarily set to approximately 30 m (100 ft). The diameters of pipes 16 through 21 were increased to yield values of hydraulic head above the minimum of 77.2 m stipulated in the literature at nodes 16 through 21 under ultimate-demand loading conditions of 6,022 MLD (22% increase over baseline of 4,933 MLD) and ultimate pipe hydraulic roughness of $C=69$ (heavily tuberculated) at the end of the planning period. Also, the old rock tunnel lining reported in the literature was replaced with steel pipe of equivalent diameter. Correspondingly, the Hazen-Williams roughness coefficient of 100 cited in the literature was increased to 140 for new steel pipe.

System Parameters

The planning period was set at 100 years to roughly coincide with the practical service life of steel pipe. Each simulation was discretized into 10-year time increments to calculate energy expenditures in all life-cycle stages of the NYC system. This time-step selection necessarily implies that water demand remains constant over a decadal increment. A coarse time discretization can be defended on two grounds: (1) average conditions (ADD) tend to dominate in pumping and/or turbine recovery energy estimates; and (2) the improvements in accuracy in energy estimates achievable with a shorter time step are likely to be negated by uncertainties in other simulation parameters, and indeed in the precise nature of the demand variation.

Table 1. Pipe Diameters, Thicknesses, and Values of Unit Energy for Pipe Fabrication, Pipe Recycling, and Pipe Disposal

Internal diameter (m)	Pipe thickness (mm)	Unit energy of fabrication (GJ/m)	Unit energy of recycling (GJ/m)	Unit energy of disposal (GJ/m)
1.52	14.5	9.8	5.9	0.7
1.83	17.3	14.0	8.6	1.0
3.35	31.8	47.2	28.7	3.5
4.57	43.4	87.8	53.4	6.4
5.18	49.1	112.8	68.6	8.3

The unit energy of pipe fabrication was approximated for pipe diameters encountered in the NYC system. Table 1 indicates a schedule of pipe diameters, pipe thicknesses, and corresponding values of unit energy of fabrication. For each diameter considered, the required pipe thickness was calculated with the hoop stress formula, assuming a maximum internal pressure of 200 m (steady and unsteady pressures) and an operating hoop stress at half the yield strength of 206.8 MPa (30,000 psi) for low-carbon steel used in waterworks applications. With values of pipe thickness and pipe unit mass (metric tons/m) as well as a producer price (in 1997 dollars) of steel of \$656/ton (USGS 2003), the unit pipe cost (\$/m) was approximated in 1997 dollars to correspond to the year of the most recent EIO-LCA model. Note that the producer price of steel underestimates the total cost of pipe production because it excludes the cost of pipe manufacturing and other related activities.

Following this, the 1997 DOC Industry Benchmark I-O (input-output) table in the EIO-LCA model maintained by the Carnegie Mellon University Green Design Institute (Carnegie 2003) was used to determine the amount of energy required to fabricate a unit length of pipe (GJ/m). This last calculation involved a number of substeps. First, the industry sector #331210 entitled "Iron, Steel Pipe and Tube from Purchased Steel" was selected to represent the activities inherent to the pipe fabrication process. With this selection made, the EIO-LCA model was run to compute the total energy required throughout the U.S. national economy to fabricate the amount of steel pipe that is worth an arbitrary value of \$1 million (1997). This energy value was determined to be 24.0 TJ. Finally, the energy required to fabricate a unit length of pipe (GJ/m) was calculated by dividing the total energy of 24.0 TJ by the pipe length corresponding to the arbitrary value of \$1 million (1997) entered into the EIO-LCA model. These steps were repeated for each pipe diameter-thickness combination indicated in Table 1.

The literature on pipeline hydraulics was reviewed to find appropriate values of initial roughness height e_0 and roughness growth rate a. Sharp and Walski (1988) have reported an initial roughness height e_0 of 0.18 mm for new metal pipe in common sizes (150–600 mm). This translates to a relative roughness (roughness height divided by diameter) of 0.03% for 600-mm diameter pipe. An initial roughness height e_0 of 2.2 mm was chosen for all large-diameter pipes encountered in the NYC system (3.35–5.18 m) to roughly match the relative roughness value reported in Sharp and Walski (1988) and to obtain a C factor of 140 for new steel pipe. Researchers have found the roughness growth rate a to vary significantly, sometimes by as much as 2 orders of magnitude. For example, the California Section of the AWWA (1962) found roughness growth rate a to range between

0.34 and 0.61 mm/year in steel pipe. Studies conducted by Hudson (1966a,b) reported growth rate values ranging between 0.015 and 0.61 mm/year for metal pipe, while Lamont (1981) reported values of a between 0.025 and 0.76 mm/year. In this example, the average value of roughness growth rate a was set to 0.4 mm/year for all pipes in the NYC system.

A suitable average value was needed for the turbine efficiency parameter in Eq. (4). While the efficiency of a turbine usually varies according to the flow and driving head across it, in this study an average value of efficiency (for all flow conditions) was assumed in order to calculate theoretical recovery rates across all pipes of the NYC system. Thake (2000) reports typical yield efficiencies ranging between 0.50 and 0.60 for small, well-designed turbines; large systems may have values in the range of 0.8 to 0.9, or even higher.

The EPANET2 model (Rossman 2000) was used in conjunction with Eq. (4) to quantify the total energy recovered through thermodynamic shaft work (NEB). EPANET2 is a public domain software that tracks flow in pipes, pressure at nodes, and variations in reservoir level to meet changing water demands in a water distribution network (Rossman 2000). At the start of each 10-year step, pipe roughness C values calculated with Eq. (2) were entered into the EPANET2 model to track the flow and head loss in the P' pipes of the system in the next time step. The pipe flows and head losses calculated with EPANET2 were entered into Eq. (4) to determine the rate of energy recovered through shaft work $\dot{W}_t$ at the start of each time step. These energy recoveries were then numerically integrated with Eq. (5) to determine the total energy recovered in the system (NEB).

Values of breakage growth rate ψ_i and break rate $N(t_0)_i$ were also taken from the literature. Shamir and Howard (1979) reported values of ψ_i ranging between 0.01 and 0.15 year^{-1} for metal pipe; Clark et al. (1982) reported a typical value of $\psi_i = 0.086\ \text{year}^{-1}$ for cast iron pipe; and Kleiner and Rajani (1999) found values of ψ_i ranging between 0.003 and 0.134 year^{-1} for pit and spun cast-iron pipes. In the absence of published data for steel pipe, a typical breakage growth rate of 0.07 year^{-1} was assumed for all steel pipes encountered in the NYC system. The initial break rate $N(t_0)_i$ was also estimated from values taken from the literature. In their study, Walski and Pelliccia (1982) reported values for $N(t_0)_i$ of 0.0160 breaks/km/year for new pit cast-iron pipe and 0.0390 breaks/km/year for new sandspun cast-iron pipe. In a more recent study, Kleiner and Rajani (1999) found values of $N(t_0)_i$ to range between 0.0090 and 0.1340 breaks/km/year for spun cast-iron pipes ranging between 0 and 16 years of age. In the absence of published data, a typical initial break rate of 0.04 breaks/km/year was applied to all steel pipes in the NYC system.

The energy required to repair a single break in pipe i was based on a number of assumptions. First, a typical length of pipe damaged in a single-break event L_b was estimated with detailed data on repair and replacement costs for ductile iron pipe (150–600 mm) reported in Walski and Pelliccia (1982). Pipe repair costs were constituted from crew, equipment, pipe sleeve, repaving, and overhead costs obtained from the city of Binghamton, N.Y. Pipe replacement costs were derived for pipe diameters ranging between 150 and 600 mm and a typical cover depth of 1.5 m.

In assuming that repairing a pipe break involves roughly the same activities as replacing a pipe (i.e., excavation, backfilling, restoration), a typical break length L_b (m/break) was calculated by dividing pipe repair costs ($/break) by pipe replacement costs ($/m) as cited in Walski and Pelliccia (1982). This simple calculation yielded typical pipe-break lengths ranging between 9 m for 150-mm pipe and 5 m for 600-mm pipe. A typical break length of $L_b = 5$ m/break was selected in this study for large-diameter pipe (>600 mm). The energy required to repair a pipe break (GJ/break) was calculated by multiplying the typical break length L_b 5 m by the unit energy of fabrication e_f (GJ/m), corresponding to a particular pipe diameter as indicated in Eq. (8). In the present example, actual pipe repair costs are likely to exceed those predicted by Eq. (8) due to large soil cover of the primary supply system and the fact that many areas of NYC are densely developed and have high-traffic streets.

Due to a lack of published end-of-life data on pipelines, recycling and disposal parameters for steel pipe were taken from the material production literature. The unit energy for recycling and disposal indicated in Table 1 was estimated for each diameter-thickness combination by multiplying the unit pipe mass (metric tons/m) by values of unit energy of recycling and disposal (in GJ/ton) for structural steel sections (Geyer et al. 2002). To simplify the analysis, the recycling threshold age t_a was assumed to be 50 years (exactly half the 100-year planning period), and the recycling rate was assumed to be 0.5.

Results of Planning Scenarios

The energy expenditures in all life stages of the NYC system are shown in Fig. 5 for the four planning scenarios considered. Here it is evident that energy expenditures for pipe fabrication and pipe repair are, in some cases, an order of magnitude larger than the net energy benefit and energy expenditures for pipe recycling and disposal. Moreover, the total energy expenditure in Fig. 5 (indicated by the dotted line) is largely influenced by fabrication and repair activities. The results suggest that the least energy-intensive pipe replacement period is around 50 years. It should be noted that the net energy benefit is a negative quantity in the 10-, 20-, and 50-year scenarios in Fig. 5 because it is computed relative to the 100-year (baseline) scenario and considered to be an energy ‘‘gain’’ in these scenarios. Also, since the recycling rate is assumed to be zero after the threshold year t_a of 50 years, the energy expended to recycle old pipe material is exactly zero in the 50- and 100-year scenarios.

The average energy expenditure for each scenario is indicated in Fig. 6. Here the average energy expenditure is calculated by dividing the total energy expenditure of a particular scenario by the volume of water delivered to the consumer in that scenario (in GJ/ML). Since all pipe replacement scenarios were found to yield residual pressures above the 47.2 m minimum threshold value stipulated by Dandy et al. (1996) at nodes 1–20, they were deemed to be functionally equivalent.

Sensitivity Analysis

A sensitivity analysis is carried out to assess the influence of parameter uncertainty on the energy expenditure solution indicated in Fig. 5. In this analysis, the values of the parameters selected are increased and decreased by 50%, in graduated 10% increments. For each incremental change in value, the corresponding energy expenditure (measured in GJ/ML) is calculated. In the discussion that follows, the calculated energy expenditure is referred to as the solution.

The solution has been found to be moderately sensitive to changes in unit energy of steel pipe fabrication (e_f), which is not surprising given the disproportionately large sum of energy expended on pipe fabrication in each of the four scenarios in Fig. 5.

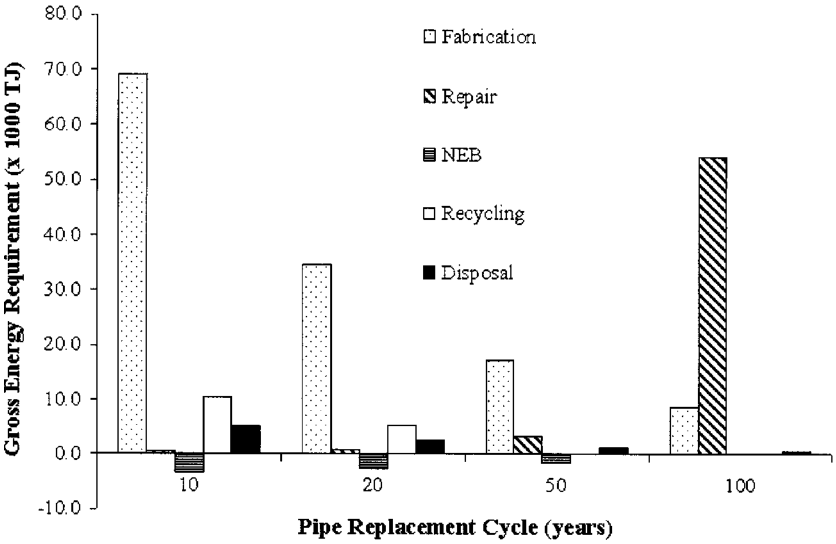

Fig. 5. Gross energy requirement corresponding to 10-, 20-, 50-, and 100-year planning scenarios

Also, the solution is found to be sensitive to a change in the breakage growth rate ψ_i, especially in the 50- and 100-year scenarios when a great deal of energy is expended to repair pipes that break frequently. This sensitivity is elucidated more clearly in Eq. (9), which establishes the nonlinear relationship between energy expenditures associated with pipe repairs E_B and the break growth rate ψ_i.

The analysis also suggests that the solution is insensitive to a change in a surprising number of parameters. More specifically, a variation in energy of disposal (e_d), energy of recycling (e_r), recycling rate (α), typical break length (L_b), initial break rate $[N(t_0)]$, and turbine efficiency (η) produced only small changes in the solution. The relative insensitivity of the solution to a change in these parameters is due mostly to the fact that the activities of pipe recycling, pipe disposal, and thermodynamic recovery constitute a small portion of the total energy expended in all scenarios, as is made clear in Fig. 5. The typical break length and initial break rate were found to have only a small influence on the solution in the 20-year scenario investigated. The influence of these parameters on the solution is expected to be greater in the 50- and 100-year scenarios as more energy is expended to repair pipes.

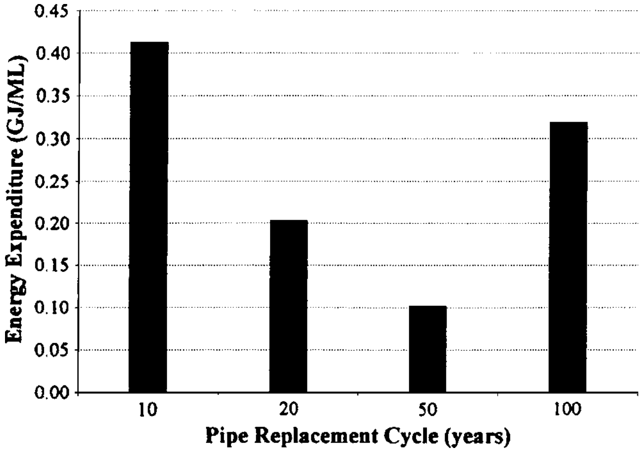

Fig. 6. Gross energy requirement normalized against total volume of water supplied to consumers for 10-, 20-, 50-, and 100-year planning scenarios

Parameters such as the year-by-year population growth, the initial pipe roughness (e_0), and the pipe roughness growth rate (a) were not subjected to sensitivity analysis. Since the NYC example does not have any pumping capacity, the parameters mentioned are not expected to have a large influence on the solution.

Broader Implications

While the net energy benefit (NEB) constitutes a minor energy component in the present study, the mechanical energy saved by replacing pipes before they reach the end of their service life in the use stage is expected to be greater in systems with pumping capacity. The reason for this is twofold. First, pipes often develop leaks as they age and tend to increase water demand and pumping energy requirements in a system. Moreover, since leaks constitute a large component of water demand in a system (ranges between 20 and 50% in North America), replacing leaky pipes can be expected to produce larger savings in pumping energy (Colombo and Karney 2002). Second, unlike turbines, which recover energy at a thermodynamic cost, often expressed in terms of some theoretical efficiency $(\eta<1)$, the savings in pumping energy achieved by replacing a pipe (either by eliminating leaks and/or by increasing the pipe's hydraulic capacity through rehabilitation) before it reaches the end of its service life can be fully recovered $(\eta=1.0)$. Therefore, in a typical system with pumping capacity, one might expect the calculated NEB to constitute a larger portion of energy expended in the use stage than that indicated in Fig. 5.

The results indicated in Fig. 5 also highlight the tension that exists between energy expenditures incurred in the fabrication and end-of-life stages (namely pipe fabrication), on the one hand, and the energy costs incurred in the use stage (namely pipe repair), on the other. This tension or dialectic relationship between pipe replacement expenditures and pipe repair expenditures often complicates the planning efforts of utilities. The question is often posed in the slightly different context of cost-effectiveness where the desire is to balance replacement costs with repair and pumping costs. This raises the concern that even if a pipe replacement strategy is deemed optimal on the basis of cost-effectiveness—as in the studies above—it may not necessarily yield the lowest environmental impacts.

In fact, two factors can widen the gap between the cost-effective solution and the "green" solution (one with the smallest environmental impact). The first is the dissipative nature of discounting calculations that tend to weight monetary costs incurred in the short term more heavily than costs incurred in the long term. If monetary costs are assumed to be roughly proportional to energy costs in Fig. 5, discounting calculations would inflate net present costs in the 10- and 20-year scenarios and deflate net present costs in the 50- and 100-year scenarios. This would shift the cost-effective solution beyond the "green" 50-year solution. Second, the exclusion of externalities (environmental and social costs) can distort the market price and lead to suboptimal environmental designs. For example, government subsidies to the steel-producing sector would lower the price of steel and hence lower pipe fabrication costs. Lower pipe fabrication costs would reduce overall costs more dramatically in the 10-year scenario than in the 100-year scenario, thus shortening the optimal replacement cycle in Fig. 5. Replacing pipes before or after the 50-year environmental optimum may entail needless energy expenditures, needless depletion of resources, and needless creation of environmental pollutants.

Beyond the competing objectives of cost and energy efficiency, other factors such as water quality risks, time disruptions, and user/nonuser costs actually complicate and confound the functional comparison of different scenarios. Scenarios in which pipes are replaced frequently are likely to result in costly service disruptions to domestic, commercial, industrial, and institutional users, as well as frequent road closures, increased incidences of traffic congestion, and costly disruptions to normal commercial and industrial activities in a city. However, in these scenarios, service disruptions are likely to be partly offset by improvements in water quality and a decreased risk to human health. Conversely, replacing pipes infrequently is likely to entail fewer service disruptions but more pipe breaks and unplanned repairs, an increased risk of water quality impairment, and a corresponding increase in human health risks.

Summary

A methodology was presented to conduct a life-cycle energy analysis (LCEA) of a water distribution system. The scope of the proposed methodology includes energy expenditures incurred in the fabrication, use, and end-of-life stages of a water distribution system. By way of example, the methodology was applied to the NYC primary water supply system to determine energy expenditures associated with four different pipe-replacement strategies (10-, 25-, 50-, and 100-year). The results indicated a "natural" tension between energy expenditures in the three life stages of the NYC system. This tension was found to be greatest around a 50-year pipe replacement frequency, where total energy expenditures are minimized and a balance between energy expenditures in all life stages is achieved. A sensitivity analysis indicated that the energy expenditure solution was sensitive to a change in system parameters such as pipe fabrication energy and pipe break growth rate. The analysis also showed that total energy expenditure was relatively insensitive to changes in energy of disposal and recycling, recycling rate, typical break length, initial break rate, and turbine efficiency.

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References

American Water Works Association (AWWA) California Section. (1962). "Loss of carrying capacity in water mains." *J. Am. Water Works Assoc.*, 54(10), 1293–1312.

Carnegie Mellon University. (2003). "Economic input-output life cycle assessment (EIO-LCA) model." Green Design Institute, ⟨http://www.eiolca.net/⟩ (November 7, 2003).

Clark, R. M., Stafford, C. L., and Goodrich, J. A. (1982). "Water distribution systems: A spatial and cost evaluation." *J. Water Resour. Plan. Manage.*, 108(3), 243–256.

Colombo, A. F., and Karney, B. W. (2002). "Energy and costs of leaky pipes: Toward comprehensive picture." *J. Water Resour. Plan. Manage.*, 128(6), 441–450.

Dandy, G. C., Simpson, A. R., and Murphy, L. J. (1996). "An improved genetic algorithm for pipe network optimization." *Water Resour. Res.*, 32(2), 449–458.

Dennison, F. J., Azapagic, A., Clift, R., and Colbourne, J. S. (1998). "Assessing management options for wastewater treatment works in the context of life cycle assessment." *Water Sci. Technol.*, 38(11), 23–30.

Dennison, F. J., Azapagic, A., Clift, R., and Colbourne, J. S. (1999). "Life cycle assessment: Comparing strategic options for the mains infrastructure—Part I." *Water Sci. Technol.*, 39(10–11), 315–319.

Freyermuth, C. (2001). "Life-cycle cost analysis for large segmental bridges." *Concr. Int.*, 23(2), 89–95.

Geyer, R., Jackson, T., and Clift, R. (2002). "Economic and environmental comparison between recycling and reuse of structural steel sections." *Int. Iron and Steel Institute World Conf.*, 13–18.

Hocking, M. B. (1999). "Net energy expenditure: A method for assessing the environmental impact of technologies." *Measures of environmental performance and ecosystem condition*, National Academy Press, Washington, D.C.

Horvath, A., and Hendrickson, C. (1998). "Steel versus steel-reinforced concrete bridges: Environmental assessment." *J. Infrastruct. Syst.*, 4(3), 111–117.

Hudson, W. D. (1966a). "Loss of water main capacity." *J. Southeastern AWWA Sec.*, 30(1), 44–54.

Hudson, W. D. (1966b). "Studies of distribution system capacity in seven cities." *J. Am. Water Works Assoc.*, 58(2), 157–164.

International Organization for Standardization (ISO). (1998). *ISO 14000 environmental management*, 58(2), Geneva.

Kleiner, Y., Adams, B. J., and Rogers, J. S. (1998). "Long-term planning methodology for water distribution system rehabilitation." *Water Resour. Res.*, 34(8), 2039–2051.

Kleiner, Y., and Rajani, B. (1999). "Using limited data to assess future needs." *J. Am. Water Works Assoc.*, 91(7), 47–61.

Lamont, P. A. (1981). "Common pipe flow formulas compared with theory of roughness." *J. Am. Water Works Assoc.*, 73(5), 274–280.

Lovins, A. B. (1989). "The negawatt revolution: Solving the CO_2 problem." *Green Energy Conf.*, Canadian Council for Nuclear Responsibility, Montréal.

Lundin, M., Bengtsson, M., and Molander, S. (2000). "Life cycle assessment of wastewater systems: Influence of system boundaries and scale on calculated environmental loads." *Environ. Sci. Technol.*, 34(1), 180–186.

Mohammadi, J., Guralnick, S. A., and Yan, L. (1995). "Incorporating life-cycle in highway-bridge planning and design." *J. Transp. Eng.*, 121(5), 417–424.

Ries, R., and Mahdavi, A. (2001). "Integrated computational life-cycle assessment of buildings." *J. Comput. Civ. Eng.*, 15(1), 59–66.

Rossman, L. A. (2000). *EPANET 2: User's manual*, National Risk Management Research Laboratory, Cincinnati.

Salem, O., AbouRizk, S., and Ariaratnam, S. (2003). ‘‘Risk-based life-cycle costing of infrastructure rehabilitation and construction alternatives.’’ *J. Infrastruct. Syst.*, 9(1), 6–15.

Savic, D. A., and Walters, G. A. (1997). ‘‘Evolving sustainable water networks.’’ *Hydrol. Sci. J.*, 42(4), 549–564.

Shamir, U., and Howard, C. D. D. (1979). ‘‘An analytic approach to scheduling pipe replacement.’’ *J. Am. Water Works Assoc.*, 71(5), 248–258.

Sharp, W. W., and Walski, T. M. (1988). ‘‘Predicting internal roughness in water mains.’’ *J. Am. Water Works Assoc.*, 80(11), 34–40.

Skipworth, P., Engelhardt, M., Cashman, A., Savic, D., Saul, A., and Walters, G. (2002). *Whole life costing for water distribution network management*, Thomas Telford, London.

Thake, J. (2000). *Micro-hydro Pelton turbine manual*, ITDG Publishing, London.

Tsagarakis, K. P., Mara, D. D., and Angelakis, A. (2003). ‘‘Application of cost criteria for selection of municipal wastewater treatment systems.’’ *Water, Air, Soil Pollut.*, 142(1–4), 187–210.

U. S. Bureau of the Census. (2000). *Statistical abstract of the United States (1921–2000)*, Washington, D.C.

U. S. Geological Survey (USGS). (2003). *Historical statistics for mineral commodities in the United States* (computer file), Reston, Va.

Walski, T. M., and Pelliccia, A. (1982). ‘‘Economic analysis of water main breaks.’’ *J. Am. Water Works Assoc.*, 74(3), 140–147.

World Commission on Environment and Development (WCED). (1987). *Our common future*, Oxford University Press, Oxford, England.