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Examining the Energy Performance Associated With Typical Pipe Unit Head Loss Thresholds

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The energy performance of water mains is rarely used as a criterion for pipe rehabilitation decisions, yet there is a need to identify the worst-performing pipes to target investment wisely. This study links pipe characteristics with energy performance to understand how traditional pipe replacement thresholds perform in terms of energy. A cross-correlation analysis between pipe characteristics and pipe energy performance metrics, using a benchmarking data set of more than 20,000 water mains from 17 distribution systems, showed that unit head loss is closely related to net energy efficiency and the energy lost to friction (ELTF) in pipes, along with flow. Under average flow conditions, 3.2% of the pipes exceeded 3 m/km (ft/1,000 ft) of unit head loss, with 1.1% exceeding the more stringent 10 m/km threshold. Over 90% of pipes have a unit head loss below 1 m/km, which corresponds to an ELTF of 1.9%.

Water utility managers are facing a large water infrastructure funding deficit, which poses a challenge to continued delivery of safe drinking water in North American water distribution systems (Roshani & Filion 2013, Mirza 2007). Given the backlog of aging and deteriorated pipes that require rehabilitation, the resulting loss of capacity and high leakage rates are partly responsible for high energy costs and drinking water quality issues (Prosser et al. 2013, Lambert et al. 1999, Kleiner et al. 1998, Sharp & Walski 1988). Under pressure to address the deficiencies in their water distribution networks as cost-effectively as possible, water utilities would benefit from understanding which water mains have a low energy performance (Scanlan & Filion 2017, Wong et al. 2017, Filion 2008). When managing the pipe infrastructure in their systems, water utilities often rely on thresholds for unit head loss, leakage rates, criticality, and pipe-break rates in their broader asset management evaluation of whether to rehabilitate or replace water main assets (AWWA 2017). For the case of unit head loss, large-diameter transmission mains (16 in./400 mm or greater) that have a head loss greater than 3 m/km (ft/1,000 ft), or small-diameter pipes (12 in./300 mm or smaller) that have a head loss of over 10 m/km (ft/1,000 ft), are typically earmarked as pipes of concern (AWWA 2017). The new insights into the energy performance of pipes for a range of unit head loss thresholds discussed in this article allow water utilities to include energy performance of pipes as an added consideration within their broader asset management strategies, alongside and complementary to capital costs of rehabilitation, water quality, pipe-break rates, criticality of the asset, and the probability and consequence of pipe failure. The inclusion of energy provides a more comprehensive set of considerations with which to rank the replacement and rehabilitation priority of water main assets (ISO 55000 2014, Kleiner & Rajani 2001, Mukherjee & Narasimhan 1996).

Previous energy audits of distribution systems have characterized energy relationships in a small number of case study systems (Cabrera et al. 2014a, 2014b, 2010; Dziedzic & Karney 2014); however, it is unclear whether the patterns observed are transferrable to other systems. A large ensemble of systems and pipe data is

needed to explore more general relationships between measures such as unit head loss and energy performance of water mains so that the results can be interpreted with statistical significance across a wide range of system sizes and configurations.

Most energy audits of distribution systems have been performed at the level of entire networks. Cabrera et al. (2010) developed a set of network-level energy metrics that consider a system's energy input and energy delivered to the demand nodes with respect to different types of energy losses. This comprehensive energy audit provided a useful analytical framework to help water utilities better understand how far their systems are from an ideal state of energy efficiency. Further, Cabrera et al. (2014a, 2014b) presented additional metrics to examine the energy efficiency of pressurized systems to prioritize energy improvement actions. Dziedzic and Karney (2014) adapted the metrics of Cabrera et al. (2014a, 2014b) to examine the energy dynamics of the Toronto distribution system with respect to water conservation and pressure management. While network-level analyses provide insights into the overall energy performance of systems, they do not provide information on the energy performance of individual or groups of water mains in their unimproved and rehabilitated states. To address this gap, Hashemi et al. (2017) developed a set of energy metrics that characterize energy interactions at the spatial resolution of individual water mains and applied them to a benchmark system and two large-scale distribution systems.

The intent of this article is to build upon energy audit approaches (Hashemi et al. 2017, Dziedzic & Karney 2014, Cabrera et al. 2010) using a large ensemble of pipes from multiple networks to develop a new understanding about the energy performance of pipes in the context of unit head loss thresholds used in practice to trigger pipe rehabilitation. With a large data set of pipe and network data, it is possible to achieve statistical significance in the results to ensure that the results are more broadly applicable than for a single case study. The specific objectives of the article are to

- identify cross correlations between pipe characteristics and the energy performance of pipes (as represented by energy metrics), examining their universality across different types of water distribution systems using a large data set of over 20,000 water mains selected from 17 systems covering a range of sizes, configurations, and topographies.
- further explore the relationship between pipe characteristics and energy performance of water mains using regression modeling.
- examine the energy performance of water mains that corresponds to maximum unit head loss thresholds used in practice to trigger the rehabilitation of these assets.

- explore the energy performance of water mains for a range of alternative, more stringent, maximum unit head loss thresholds and characterize the potential operational energy savings and additional pipe rehabilitation requirements associated with these alternative threshold levels.

METHODS

This analysis considered pipe characteristics of roughness (represented by the Hazen–Williams roughness coefficient, C_{HW}), pipe diameter (D), daily average pressure (Avg. P), daily average flow rate (Avg. Q), and average unit head loss. These pipe characteristics were then compared with pipe-level energy metrics, as described in this section.

Energy components in a pipe. The energy components that make up the balance of energy along a pipe are as follows (Hashemi et al. 2017):

$$E_{supplied} = E_{delivered} + E_{ds} + E_{leak} + E_{friction} + E_{local} \quad (1)$$

where $E_{supplied}$ is energy supplied to the upstream end of the pipe; $E_{delivered}$ is energy delivered to the user to satisfy demand Q_d at piezometric head (H_d); E_{ds} is energy that flows out of the pipe to meet downstream user demands; E_{leak} is energy directly lost to leakage; $E_{friction}$ is friction energy loss incurred along the pipe to satisfy demand located at the end of pipe, leakage along the pipe, and convey flow in the pipe to satisfy the water demand of users located further downstream of the pipe; and E_{local} is local energy corresponding to losses (H_{local}) through valves, appurtenances, and blockages. Table 1 provides the equations that relate the energy components in Eq 1 to the pipe flow and piezometric head measured in a pipe.

Metrics to evaluate energy performance of pipes. Four energy metrics, first reported in Hashemi et al. (2017),

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TABLE 1 Mathematical definition of energy terms in Eq 1

Energy Terms	Mathematical Equations
$E_{supplied}$	$\gamma \, Q \, H_s \, \Delta t$
$E_{delivered}$	$\gamma \, Q_d \, H_d \, \Delta t$
E_{ds}	$\gamma \, Q_{ds} \, H_d \, \Delta t$
E_{leak}	$\gamma \, Q_l \, H_d \, \Delta t$
$E_{friction}$	$\gamma \, [K \, (Q_d)^\alpha] \, (Q_d + Q_l + Q_{ds}) \, \Delta t$ where $Q_{ds} = Q - Q_d - Q_l$
E_{local}	$\gamma \, Q \, H_{local} \, \Delta t$

Source: Hashemi et al. 2017

α—2 in the Darcy–Weisbach formula, Δt—hydraulic time step, K—pipe resistance

are used to characterize the energy performance of pipes.

Gross and net efficiencies. The gross energy efficiency (GEE) in Eq 2 compares the energy delivered to the users (to satisfy demand for water) with the energy supplied to the pipe. GEE can range between 0 and 100%, where a value of 0% signifies that none of the mechanical energy is delivered to users along that pipe (pipe serves as transmission of energy only), and a value of 100% means that all the energy is delivered to users along that pipe (effectively a dead-end pipe with no further energy conveyed downstream). Given that demands are allocated only to the upstream and downstream nodes of a pipe, rather than continuously along its length, for the sake of practicality GEE is calculated at the downstream node of each pipe at each time step.

$$\text{GEE} = \frac{E_{\text{delivered}}}{E_{\text{supplied}}} \times 100\% \qquad (2)$$

The net energy efficiency (NEE) in Eq 3 compares the energy delivered to users along the pipe with the net energy in the pipe. Net energy is defined as the energy supplied to the pipe minus the energy supplied to users located downstream of the pipe and not directly served by that pipe. The maximum value of NEE is 100%, where all the energy supplied (exclusively to the pipe) is delivered to its users. The minimum value would theoretically be 0%, where none of the energy supplied to the pipe is delivered to its users, but in this case—i.e., the flow supplied to the pipe is passed entirely downstream, and the delivered energy is zero— NEE cannot be calculated, and in this case, those pipes were omitted.

$$\text{NEE} = \frac{E_{\text{delivered}}}{E_{\text{supplied}} - E_{\text{ds}}} \times 100\% \qquad (3)$$

Energy needed by user. The energy needed by the user (ENU) in Eq 4 compares the energy delivered to the pipe's users with the minimum energy needed by those users. E_{req} is calculated on the basis of 30 m of required minimum pressure, commonly imposed by North American water utilities (Region of Peel 2010, City of Toronto 2009). Numerical values of NEE above 100% indicate excess pressure delivered to the users, and values of NEE below 100% indicate a deficit in pressure.

$$\text{ENU} = \frac{E_{\text{delivered}}}{E_{\text{req}}} \times 100\% \qquad (4)$$

Energy lost to friction. The energy lost to friction (ELTF) in Eq 5 compares the energy loss from friction at a given flow, which includes demand and leakage, with the net energy in the pipe (excluding energy

transferred to downstream pipes). This metric provides information on the relative magnitude of the friction energy losses in a pipe to the net energy supplied to the pipe.

$$\text{ELTF} = \frac{E_{\text{friction}}}{E_{\text{supplied}} - E_{\text{ds}}} \times 100\% \qquad (5)$$

Evaluation of energy metrics with extended period simulation. The energy metrics in Eqs 2–5 were evaluated using extended period simulation (EPS), performed with the network model EPANET2 (Rossman 2000). An EPS was performed for each system over a 24 h diurnal period over a typical service day under average demand conditions to represent an average annual energy consumption. The hourly values of flow and piezometric head in each pipe were extracted to calculate hourly values of the energy metrics in Eqs 2–5. The hourly values of the energy metrics in Eqs 2–5 were then averaged throughout the 24 h diurnal period to calculate a time-averaged numerical value of the energy metrics.

Normalization of data. Certain parameters such as average pressure and average flow rate can vary by one or two orders of magnitude across systems of different sizes and attributes. To compare these parameters fairly across systems, the ensemble of data pertaining to these parameters was normalized using Eq 6, using average pressure as an example, which results in a scaled value between 0.0 and 1.0.

$$\text{Normalized pressure}_i = \frac{\text{Pressure}_i - \text{Min(Pressure)}}{\text{Max(Pressure)} - \text{Min(Pressure)}} \qquad (6)$$

where Pressure_i is the average pressure in a pipe throughout a day, and Max(Pressure) and Min(Pressure) are the highest and lowest average pressures in a system throughout a day, respectively. A pipe with a normalized pressure value near 1.0 indicates high pressure throughout a service day, and a pipe with a normalized pressure value near 0.0 indicates low average pressure throughout a day.

Cross-correlation analysis. Cross-correlation analysis was used to identify which pipe characteristics and pipe energy performance metrics to include in the regression equations to establish the link between the two sets of parameters. Specifically, the Spearman rank correlation coefficient was used to identify statistically significant cross correlations between pipe characteristics and pipe energy performance, as described by the four energy metrics presented in Eqs 2–5. Spearman's rank was chosen because it can capture the nonlinear relationships between hydraulic factors in water distribution systems. Spearman's rank correlation coefficient, r, for a sample of n measurements is defined as follows (Edwards 1984):

$$r = 1 - \frac{6 \sum\limits_{i=1}^{n} d_i^2}{n(n^2 - 1)} \qquad (7)$$

where $d_i = x_i - y_i$; x_i and y_i are the ranks of the variables X_i (pipe characteristics) and Y_i (energy metrics values) in ascending order, respectively; and n is the sample size (number of pipes). The Spearman rank correlation coefficient in Eq 7 follows a Student's t distribution, so the Student's t-test statistic and its corresponding p-value at the 95% confidence level were used to determine the statistical significance of correlations between pairs of input parameters (Weiss & Weiss 2012).

Regression modeling of pipe and energy parameters. The results of the correlation analysis were used to identify which pipe and energy performance parameters to include in the regression models. An initial analysis of the data revealed that many pipe characteristic–energy performance parameter pairs have a complex, nonlinear relationship that does not follow a monotonic pattern that would be amenable to regression analysis. As an example of this, there is no evident relationship between numerical values of average unit head loss and numerical values of NEE.

To overcome this difficulty, the plotting positions of the data on the pipe and energy performance parameters over the entire data set of 20,000 pipes were calculated to ascertain the monotonic relationship between these parameters while retaining the nonlinearities in the data. In this article, the plotting position is defined as the ordinal position of a data point in an ensemble of N data points organized in ascending order. Each numerical value of a parameter is assigned an ordinal position of w, with the smallest numerical value assigned $w = 1$ and the largest numerical value assigned $w = N$. The plotting position is calculated by dividing its ordinal position w by the number of data points, N, resulting in the plotting position = w/N expressed as a percentile. Considering the data on the pipe and energy performance parameters in terms of the plotting position makes it easier to depict monotonic trends and fit a regression model to the data. As an example, this is demonstrated in Figure 1, where the plotting positions of average unit head loss and NEE follow a monotonic trend.

With the parameters for pipe characteristics and energy performance represented in terms of the plotting position, regression models of the form shown in Eq 8 were constructed:

$$Y_{(\text{plot position})} = a_0 + a_1 X_{1(\text{plot position})} + a_2 X_{2(\text{plot position})} + \cdots + a_n X_{n\,(\text{plot position})} \qquad (8)$$

where $Y_{(\text{plot position})}$ is the plotting position of energy performance parameters (e.g., NEE, ELTF); $a_0, a_1,..., a_n$ are regression model coefficients; and $X_{1(\text{plot position})}, ..., X_{n(\text{plot position})}$ are the plotting positions of pipe parameters (e.g., unit head loss). Using the calculated plotting

FIGURE 1   Scatterplot of plotting positions of NEE (percentile) versus plotting positions of unit head loss (percentile)
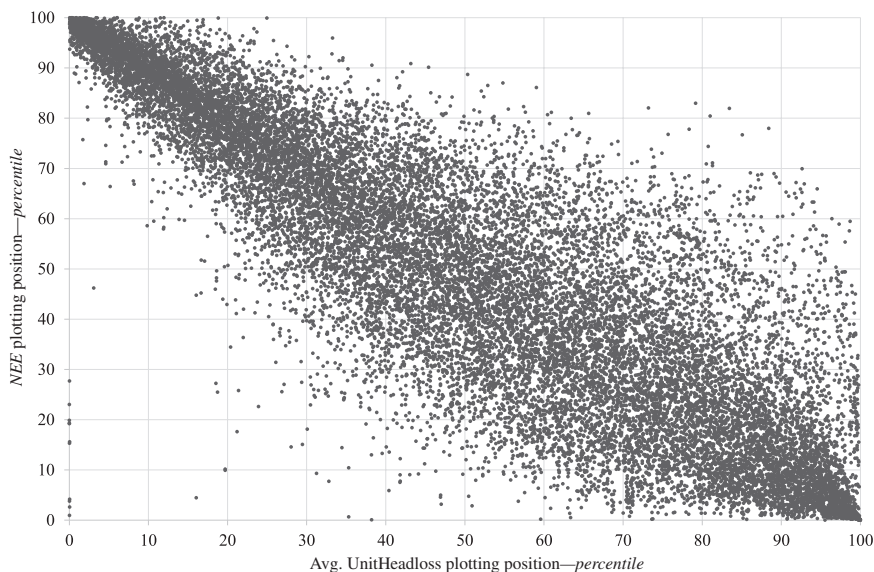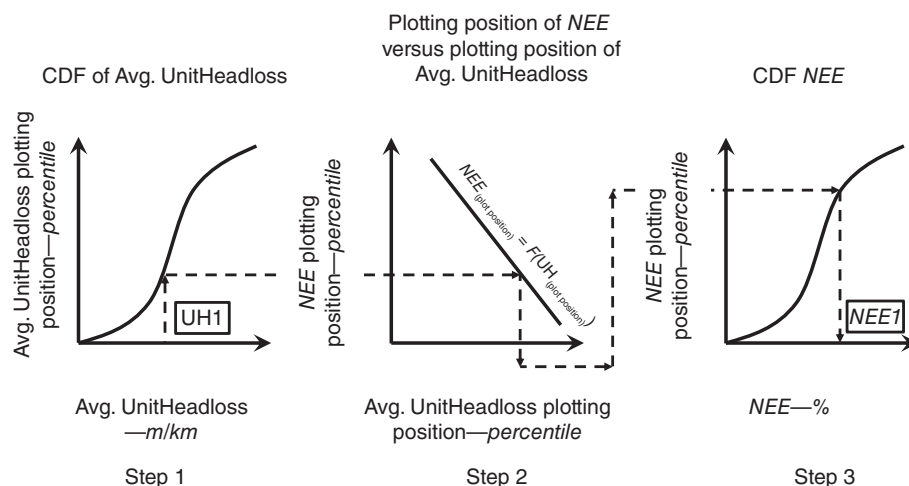
NEE—net energy efficiency

position data on the pipe and energy performance parameters for all $N = 20{,}000$ pipes, the model coefficients a_0–a_n were determined through regression analysis.

While the model in Eq 9 regresses the plotting position of an energy performance parameter against the plotting position of one or more pipe parameters, water utilities would be more interested in knowing the numerical value of energy performance metrics for given numerical values of pipe characteristics such as unit head loss. Given this need, a three-step procedure was applied to the regression model results to calculate the numerical value of the energy parameters corresponding to specific numerical values of pipe characteristics (e.g., unit head loss). As an example, the three-step procedure to calculate a numerical value of NEE from an input numerical value of average unit head loss (m/km) using Eq 8 is indicated in Figure 2. (Note that the parameters of unit head loss and NEE are used here as an example, but the procedure applies to all other model parameters.) In the first step, with a known numerical value of average unit head loss (denoted as UH1 in Figure 2, with units of m/km), the cumulative distribution function (CDF) of average unit head loss generated with the data set of 20,000 pipes is used to determine the plotting position (percentile) of average unit head loss, or UH(plot position). In the second step, the regression model of Eq 8 is used to calculate the corresponding plotting position of the NEE parameter, or NEE(plot position). In the third step, the CDF of NEE is used to transform the plotting position of NEE to the numerical value of NEE, denoted by NEE1 (as a percentage of energy supplied to the pipe) in Figure 2.

Ensemble of pipe data from 17 distribution systems. Pipe and energy data were compiled from a large ensemble of 20,000 pipes across 17 distribution systems in Canada and the United States to obtain statistically significant results. The data set includes systems that are fundamentally varied and different in terms of configuration, pipe age profile, and pipe condition. The diversity of the data set allows for robust statistical analysis that is more representative of the variability of distribution systems than could otherwise be achieved using a single case study. The 17 water distribution networks were selected from different North American regions, including the states of Kentucky (Jolly et al. 2013) and Ohio and the province of Ontario. In cases in which a zero value occurs in the denominator for the energy metrics (e.g., where $E_{supplied} = E_{ds}$ because there is no user demand), pipes are excluded from metrics evaluations (Hashemi et al. 2017) and also from the statistical analyses. The topographical and topological characteristics were typical of most systems in the United States and Canada (summarized in Table 2). These systems range from 56 km (35 mi) to 972 km (600 mi) of pipe, with average daily water demands between 3.5 ML/d (0.77 mgd) and 69.1 ML/d (18.2 mgd) and a variety of topographies, with a total ground elevation difference ranging from 29 m (95 ft) to 248 m (814 ft). Leakage is not included in the systems considered in this study. Descriptive statistics for the pipe characteristics and energy metrics from the data set of pipes are provided in Table 3. Overall, pipe diameters vary from 19 mm (0.75 in.) to 1,200 mm (48 in.), with most of the pipes in the data set having a diameter smaller than or equal to 200 mm (8 in.). Average operating pressures ranged from 4 m (13 ft or 5.6 psi) to 80 m (262 ft or 113 psi).

FIGURE 2 Three-step procedure to calculate a numerical value of NEE from an input numerical value of average unit head loss (in m/km) with Eq 8

CDF—cumulative distribution function, NEE—net energy efficiency

TABLE 2 Summary of 17 Canadian and US water distribution systems forming the data set of pipes for analysis

Network	State/ Province	Number of Pipes	Pipe Length *kft*[a]	Number of Model Nodes	Maximum Difference in Ground Elevation *ft*[a]	Number of Pumps	Number of Tanks	Average Daily Demand *mgd*[b]	Average Daily Pressure *psi*[c]
1	ON1	12,189	2,057 (627)	11,177	164 (50)	31	10	18.25 (69.07)	63.45 (44.86)
2	ON2	405	184 (56)	349	151 (46)	6	3	0.94 (3.54)	66.07 (46.71)
3	KY1	984	220 (67)	856	121 (37)	1	2	1.99 (7.52)	46.78 (33.07)
4	KY2	1,124	499 (152)	811	95 (29)	1	3	2.09 (7.92)	65.16 (46.07)
5	KY3	366	299 (91)	271	141 (43)	5	3	4.01 (15.19)	59.07 (41.76)
6	KY4	1,156	853 (260)	959	246 (75)	2	4	1.49 (5.65)	67.92 (48.02)
7	KY5	496	315 (96)	420	246 (75)	9	3	2.27 (8.58)	61.40 (43.41)
8	KY6	644	404 (123)	543	315 (96)	2	3	1.64 (6.19)	85.22 (60.25)
9	KY7	603	449 (137)	481	230 (70)	1	3	1.53 (5.8)	78.25 (55.32)
10	KY8	1,614	810 (247)	1,325	443 (135)	4	5	2.46 (9.32)	76.59 (54.15)
11	KY9	1,270	3,189 (972)	1,242	453 (138)	17	15	1.34 (5.07)	87.98 (62.2)
12	KY10	1,043	1,427 (435)	920	315 (96)	13	13	2.16 (8.18)	96.17 (67.99)
13	KY11	846	1,522 (464)	802	814 (248)	21	28	1.75 (6.61)	103.47 (73.15)
14	KY12	2,426	2,149 (655)	2,347	476 (145)	15	7	1.37 (5.18)	86.89 (61.43)
15	KY13	940	509 (155)	778	312 (95)	4	5	2.36 (8.92)	71.82 (50.78)
16	KY14	548	344 (105)	377	213 (65)	5	3	1.04 (3.94)	76.24 (53.9)
17	OH1	1,183	544 (166)	956	328 (100)	15	4	2.68 (10.13)	80.76 (57.1)

[a]Values for SI units are reported in parentheses (km for kft).
[b]Values for SI units are reported in parentheses (ML/d for mgd).
[c]Values for SI units are reported in parentheses (m of H2O for psi).

RESULTS

Identification of factors that drive energy performance in pipes by cross-correlation analysis. The cross-correlation analysis considered the six pipe characteristics, roughness (C_{HW}), diameter (D), daily average pressure (Avg. P), daily average flow rate (Avg. Q), and average unit head loss, alongside the four pipe-level energy metrics (GEE, NEE, ENU, and ELTF) across the data set of 20,000 pipes. Spearman's rank correlation coefficients for pipe characteristic–energy metric pairs are given in Table 4. In this article, positive or negative correlation coefficients are deemed important if they fall

TABLE 3 Minimum, maximum, mean, median, lower quartile (25th percentile), and upper quartile (75th percentile) of pipe characteristics and energy metrics across the data set of 20,000 pipes

Pipe Characteristics	Minimum	25th Percentile	Median	Mean	75th Percentile	Maximum
C_{HW}	55	90	120	114	150	150
D—*mm*	19	150	152	194	203	1,200
Avg. P—*m*	3.8	39.8	48.4	52.1	57.5	95
Avg. Q—*ML/d*	2.2×10^{-7}	0.022	0.11	0.53	0.36	339.9
Avg. unit head loss—*m/km*	4.0×10^{-14}	0.006	0.059	2.83	0.273	47
GEE—%	1.6×10^{-6}	1.1	4.8	23.3	26.9	100
NEE—%	3.4×10^{-4}	99.1	99.9	95.3	99.9	100
ENU—%	5.7×10^{-4}	105	110	111	116	281
ELTF—%	1.1×10^{-17}	7.7×10^{-4}	0.030	3.89	0.580	99.9

Avg. P—average daily pressure of a pipe, Avg. Q—average daily flow of a pipe, Avg. unit head loss—average daily unit head loss in a pipe, C_{HW}—Hazen–Williams pipe roughness "C" factor, D—pipe diameter, ELTF—energy lost to friction, ENU—energy needed by the user, GEE—gross energy efficiency, NEE—net energy efficiency

TABLE 4 Spearman's rank cross-correlation coefficients for all pipe characteristic–energy metric pairs calculated across the data set of 20,000 pipes

	C_{HW}	D mm	Avg. P m	Avg. Q L/s	Avg. UnitHeadloss m/km	GEE %	NEE %	ENU %	ELTF %
C_{HW}	1.00	–0.19	0.08	–0.04	–0.14	0.10	0.06	0.05	–0.10
D—mm	–0.19	1.00	0.00	0.59	0.09	–0.57	–0.30	–0.01	0.29
Avg. P—m	0.08	0.00	1.00	–0.08	–0.12	0.06	0.10	**0.85**	–0.10
Avg. Q—ML/d	–0.04	0.59	–0.08	1.00	0.77	**–0.84**	**–0.85**	–0.09	**0.80**
Avg. unit head loss—m/km	–0.14	0.09	–0.12	0.77	1.00	**–0.63**	**–0.88**	–0.14	**0.82**
GEE—%	0.10	–0.57	0.06	**–0.84**	**–0.63**	1.00	0.80	0.04	–0.76
NEE—%	0.06	–0.30	0.10	**–0.85**	**–0.88**	0.80	1.00	0.10	–0.92
ENU—%	0.05	–0.01	**0.85**	–0.09	–0.14	0.04	0.10	1.00	–0.07
ELTF—%	–0.10	0.29	–0.10	**0.80**	**0.82**	–0.76	–0.92	–0.07	1.00

Avg. P—average daily pressure of a pipe, Avg. Q—average daily flow of a pipe, Avg. UnitHeadloss—average daily unit head loss in a pipe, C_{HW}—Hazen–Williams pipe roughness "C" factor, D—pipe diameter, ELTF—energy lost to friction, ENU—energy needed by the user, GEE—gross energy efficiency, NEE—net energy efficiency

Values indicated in bold indicate important correlations if they fall within the range of +0.5 to +1.0 or –0.5 to –1.0.

in the range of +0.5 to +1.0 or –0.5 to –1.0 (indicated in bold in Table 4). The results suggest that GEE is mostly influenced by flow rate and average unit head loss, meaning that higher flows and higher head loss rates tend to decrease the value of GEE. Similarly, NEE is also negatively correlated with flow rate and average unit head loss. Not surprisingly, ENU is highly and positively correlated with average pressure, as pressure is an important factor in satisfying energy requirements. ELTF is also highly and positively correlated with flow rate and average unit head loss, as might be expected given that higher flow rates from high demands or proximity to major components can generate higher head losses and can consequently tend to increase ELTF in pipes. The cross-correlation coefficient, *p*-value, and Student's *t*-test statistic are reported in Table 5 for the significant cross-correlation pairs, all of which were found to be statistically significant at the 95% confidence level.

Energy performance of water mains for typical maximum unit head loss thresholds. CDFs of average unit head loss, NEE, and ELTF were determined (Figure 3) with the data from the ensemble of 20,000 pipes. The CDF of average unit head loss in Figure 3 shows that over 90% of pipes have a unit head loss below 1 m/km. Similarly, over 90% of pipes have an ELTF below 6%. The CDF of NEE in Figure 3 shows that only 20% of pipes have an NEE less than 98.3%.

The cross-correlation analysis suggests that both NEE and ELTF are strongly related to pipe flow and average unit head loss. However, water utilities often rely on unit head loss to make decisions about pipe rehabilitation; therefore, it would be informative to develop regression models to link the commonly applied maximum unit head loss thresholds that trigger the rehabilitation of water mains in practice (AWWA 2017), with the energy performance of water mains as described by NEE and ELTF. These regression models were used to

TABLE 5 Spearman's rank cross-correlation coefficient, *p*-value, and Student's *t*-test statistic for all pipe factor–energy metric pairs calculated across the data set of 20,000 pipes

Metric	Avg. Q			Avg. UnitHeadloss			Avg. P		
	R	*p*-Value	Student's *t*	R	*p*-Value	Student's *t*	R	*p*-Value	Student's *t*
GEE	–0.84	0.00	214	–0.63	0.00	–114	N/A	N/A	N/A
NEE	–0.85	0.00	227	–0.88	0.00	–260	N/A	N/A	N/A
ENU	N/A	N/A	N/A	N/A	N/A	N/A	0.85	0.00	–221
ELTF	0.80	0.00	–181	0.82	0.00	194	N/A	N/A	N/A

p-values are rounded to two decimal places.

Avg. P—average daily pressure of a pipe, Avg. Q—average daily flow of a pipe, Avg. UnitHeadloss—average daily unit head loss in a pipe, ELTF—energy lost to friction, ENU—energy needed by the user, GEE—gross energy efficiency, N/A—not analyzed for the case, NEE—net energy efficiency, *r*—Spearman's rank correlation coefficient

FIGURE 3 Cumulative distribution functions of NEE and ELTF and unit head loss of the data from the 20,000-pipe data set
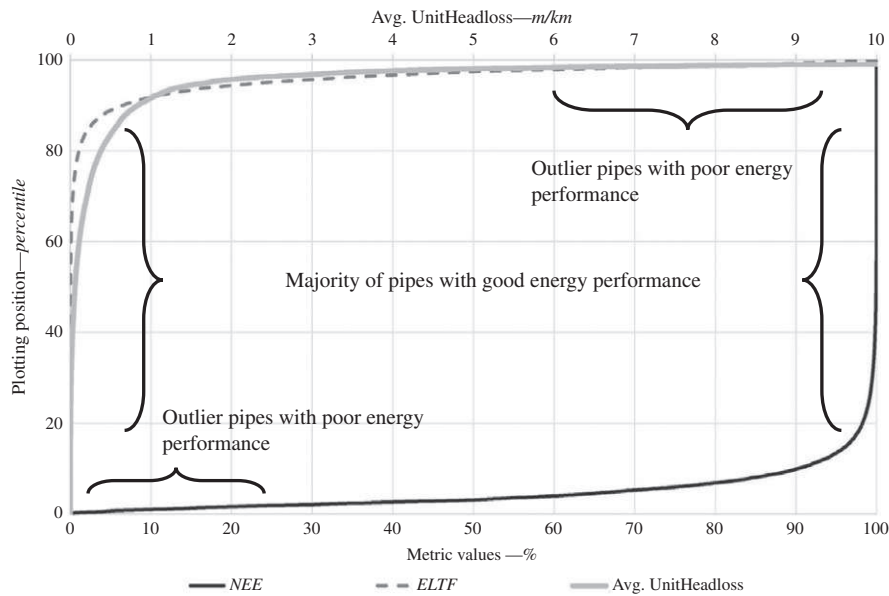
Avg. UnitHeadloss—average daily unit head loss in a pipe, ELTF—energy lost to friction, NEE—net energy efficiency

examine the energy performance of water mains that correspond directly to typical maximum unit head loss thresholds as well as to explore the impact of additional, more stringent, unit head loss thresholds.

The resulting regression model in Eq 9 explains the plotting position of NEE with respect to the plotting position of average unit head loss. Similarly, the regression model in Eq 10 explains the plotting position of ELTF with respect to the plotting position of average unit head loss.

$$\text{NEE}_{(\text{plot position})} = 17,946 - 0.88\,\text{UnitHeadloss}_{(\text{plot position})} \\ \times \left(R^2 = 0.78\right) \quad (9)$$

$$\text{ELTF}_{(\text{plot position})} = 1,762 + 0.82\,\text{UnitHeadloss}_{(\text{plot position})} \\ \times \left(R^2 = 0.66\right) \quad (10)$$

where $\text{NEE}_{(\text{plot position})}$ is the plotting position of the NEE expressed as a percentile of the 20,000 pipes in the data set, $\text{ELTF}_{(\text{plot position})}$ is the plotting position of the ELTF expressed as a percentile of the 20,000 pipes in the data set, and $\text{UnitHeadloss}_{(\text{plot position})}$ is the plotting position of the average unit head loss expressed as a percentile of the 20,000 pipes in the data set.

The regression models in Eqs 9 and 10 are shown in Figures 4 and 5 for NEE and ELTF, respectively, as solid lines, with dashed lines representing the 95% confidence limits. The numerical values of average unit head loss, NEE, and ELTF in Figures 4 and 5 are provided in callout boxes next to the x- and y-axes. For example, using the procedure from Figure 2, it can be determined that a value of average unit head loss of 10 m/km, which corresponds to the 99th percentile plotting position of average unit head loss, equates to the seventh percentile plotting position of the NEE in Figure 4. From Figure 3, the seventh percentile NEE is shown to be equivalent to a numerical value of 74.6% NEE.

The regression models were used to explore the energy performance of water mains in terms of NEE and ELTF for average unit head loss thresholds ranging from 10 to 1 m/km. Thresholds of 10 m/km (for distribution mains) and 3 m/km (for transmission mains) are typically used to trigger pipe rehabilitation in practice (AWWA 2017). The results in Figure 4 show that the values of unit head loss for the range bracketed by 10 and 1 m/km correspond to NEEs of 74.6 and 94.5%, respectively. Further, these values of NEE correspond to the seventh and 13th percentiles within the 20,000 pipe data set, respectively. For ELTF (Figure 5), unit head loss values of 10 or 1 m/km correspond to ELTFs of 6.4 and 1.9%, respectively. These levels of ELTF correspond to the 90th and 84th percentile of the 20,000 pipes in the data set.

The regression models of Eqs 9 and 10 were also used to explore additional maximum unit head loss thresholds for pipe rehabilitation and their corresponding levels of energy performance with respect to NEE and ELTF. Figure 4 indicates that the unit head loss

FIGURE 4 Regression model for NEE versus unit head loss

Regression line   — · — Lower limit   – – – Upper limit

NEE—net energy efficiency
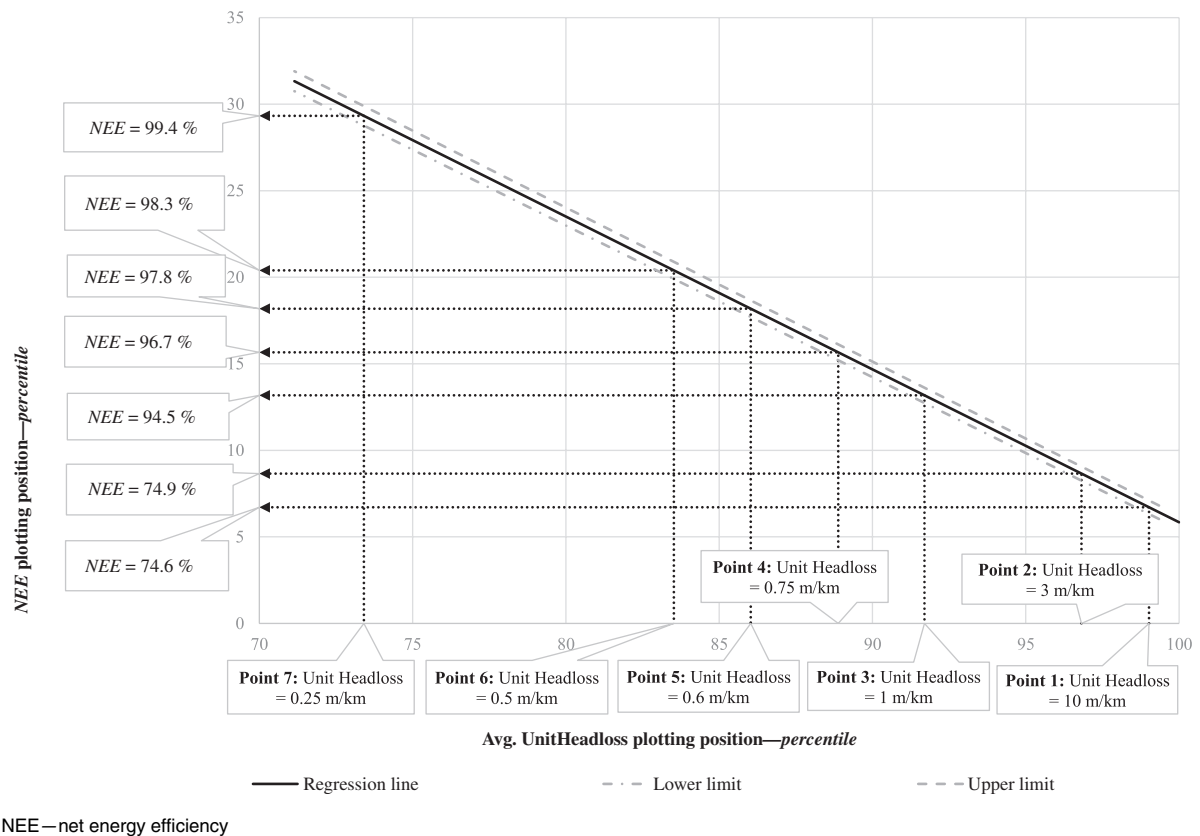
thresholds of 0.75 and 0.25 m/km correspond to NEE values of 96.7 and 99.4%, respectively. These NEE values are situated in the 16th and 29th percentiles of the pipe ensemble (Figure 4). The analysis was repeated to examine the levels of ELTF associated with these additional unit head loss threshold values. Figure 5 shows that unit head loss thresholds of 0.75 and 0.25 m/km correspond to ELTF values of 1.4 and 0.3%, respectively. These ELTF values are situated in the 82nd and 70th percentiles of the pipe ensemble.

The annual energy losses in the 20,000-pipe ensemble associated with the unit head loss thresholds used in practice were examined and are demonstrated in Figure 6. The x-axis in this figure indicates the unit head loss threshold levels examined in this article. The y-axis indicates (1) the annual energy loss in the targeted pipes (in megawatt-hours) for selected unit head loss thresholds, (2) the number of pipes that would be targeted for rehabilitation at the given head loss threshold (expressed as a percentage of the group of pipes that have a head loss greater or equal to the specified unit head loss threshold), and (3) the value of NEE and ELTF that relates to the specified unit head loss value

on the x-axis. The targeted annual energy losses in Figure 6 were based on an entire year of average distribution system operation and represent the energy lost for all pipes that have a head loss greater than or equal to the specified threshold. The targeted annual energy loss is used here as an indicator of potential energy savings achievable by rehabilitating pipes with a head loss greater than or equal to the average unit head loss thresholds reported in Figure 6. The results demonstrate that, for the unit head loss thresholds of 10 m/km, 1.1% of pipes exceed the threshold, and their rehabilitation would represent an energy savings of 61.9 MW·h. By contrast, if a threshold of 1 m/km was selected, 8.3% of pipes would be targeted for rehabilitation for an energy savings of 65.7 MW·h.

The results in Figure 6 indicate that the additional unit head loss thresholds of 0.75 and 0.25 m/km would trigger a larger number of candidate pipes for rehabilitation (11.0–26.1% of the 20,000-pipe data set), with targeted annual energy losses of 66.2–67.4 MW·h avoided. The implications of these results for energy savings and capital infrastructure expenditures are discussed in the following section.

FIGURE 5 Regression model for friction loss metric energy lost to friction (ELTF) versus unit head loss
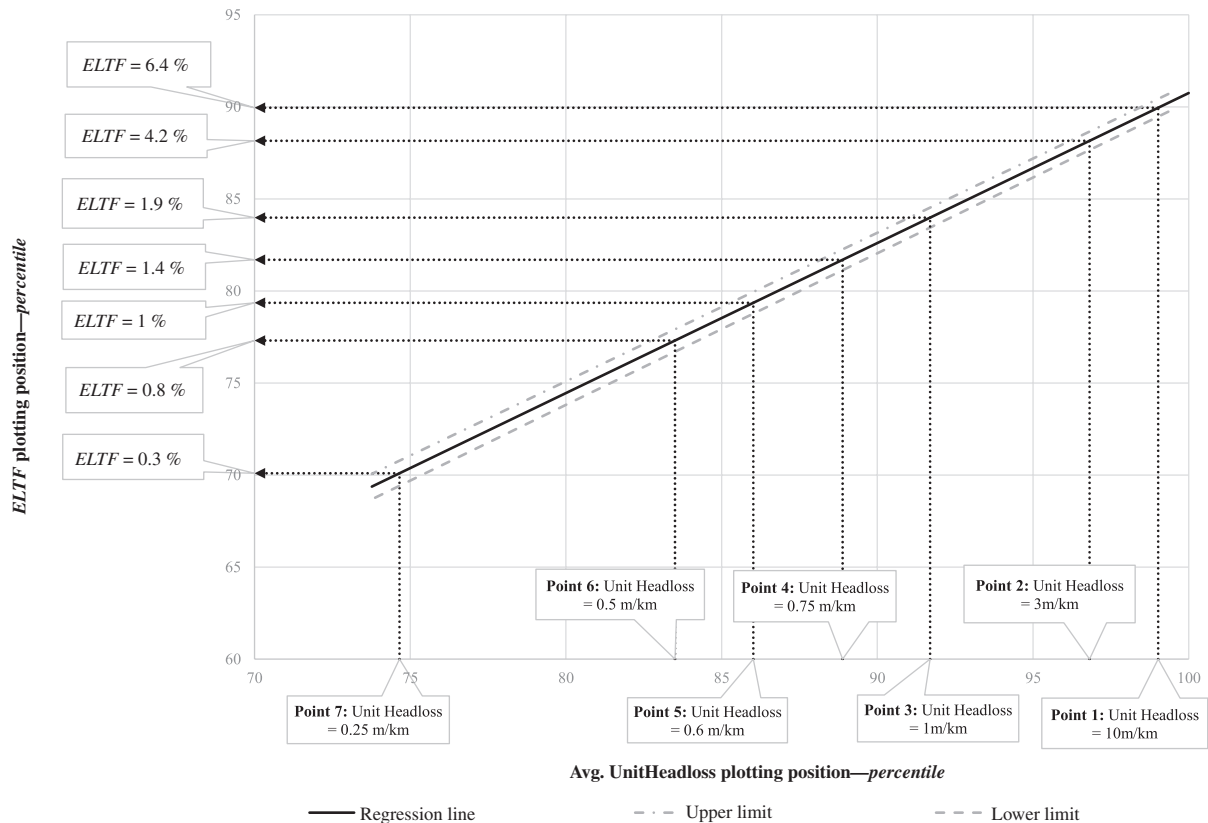
DISCUSSION

In a recent study, Dziedzic and Karney (2014) showed that water mains located in close proximity to treatment plants experience higher energy losses compared with those located farther away. The cross-correlation results of this article corroborated those previous findings by showing that both NEE and ELTF are strongly related to pipe flow (i.e., perceived to be higher in close proximity of major components of a system) and average unit head loss. While ELTF and unit head loss are closely related, their behavior is not exactly identical, as can be seen in the CDFs in Figure 3, particularly in the low (<1 m/km) and, to some extent, in the high (>9 m/km) ranges. Thus, there is a role for energy metrics, alongside traditional pipe characteristics and thresholds such as maximum unit head loss, in understanding the energy dynamics within water distribution systems at the individual pipe level. Even though unit head loss has been shown to be closely related to the energy metrics through statistical analyses, the advantage of these metrics is the combination of piezometric head and flow terms to explain energy performance in ways that cannot be fully explored by unit head loss alone (Hashemi et al. 2017).

The results (Figure 6) show that just over 8% of pipes in the 20,000-pipe ensemble have a unit head loss that exceeds a 1 m/km threshold, and only 3.2% of pipes exceed the 3 m/km threshold that is often used in practice to trigger pipe rehabilitation (AWWA 2017). This result is consistent with the fact that distribution systems are designed to minimize the number of pipes performing with unit head loss beyond that threshold. Replacing roughly 8% of pipes, assuming an average length of 1,000 m with an average replacement cost of $2,310/m, would result in a capital expenditure of $3.8 billion (Plotner 2015). This replacement would recoup energy losses on the order of 65.7 MW·h, with an energy cost savings of $6,570/year based on electricity prices for Ontario (MOE 2013). Reducing the unit head loss threshold to a more stringent threshold of 0.25 m/km would increase the percentage of pipes in need of replacement from 8.3 to 26.1%, on the basis of the results for this 20,000-pipe data set, with a corresponding estimated capital expenditure of $8.1 billion (Plotner 2015) and an annual energy savings of $6,740/year (MOE 2013). Clearly, the energy cost savings alone would not justify the expenditure for replacement, but as low-carbon trends continue, the potential savings

FIGURE 6 Annual energy losses in the 20,000-pipe ensemble associated with the unit head loss thresholds used in practice

ELTF—energy lost to friction, NEE—net energy efficiency
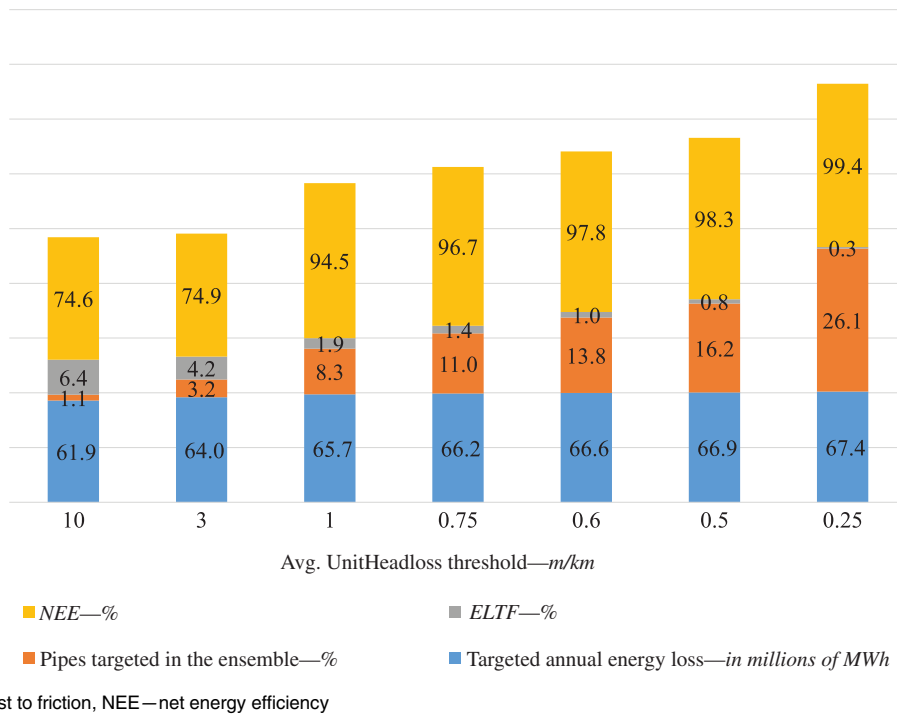
from greater efficiency in water distribution should not be completely ignored.

The use of energy metrics to explore distribution system performance and efficiency provides a new perspective, particularly when examining a sufficiently large data set of pipes, as was done in this study. Within this ensemble, it was confirmed that over 90% of pipes have a unit head loss below 1 m/km, and a similar quantity of pipes have an ELTF below 6%, which demonstrates good current efficiency for existing distribution systems with respect to friction losses. This efficiency likely is attributable more to oversizing for fire flow requirements in North America than to energy concerns. However, this result reinforces the need for water utilities to seek out the few pipes (3.2 or 1.1%, for the 3 and 10 m/km thresholds, respectively, in this case) that are contributing to higher energy losses in distribution systems. The result therefore provides strong motivation to develop metrics, techniques, and strategies for identifying losses. Given the high cost of pipe replacement and rehabilitation, the widest range of available information should be included in decisions to identify and prioritize distribution system interventions.

Furthermore, the spread in energy performance across the large data set of pipes used for this study can serve as a comparison benchmark for other water utilities. An

examination of the CDF for energy metrics provides a greater level of detail than system-wide metrics can deliver. Considering the pipes with unit head loss greater than 10 m/km, these pipes represent the 90th percentile with respect to ELTF and the seventh percentile with respect to NEE. While the values of NEE for the high unit head loss pipes are among the lowest in the data set, these pipes are not purely transmission pipes; they are also delivering flow to users (otherwise, NEE could not be calculated for them).

The absence of leakage data for several systems precluded the analysis of pipe energy performance linked to leakage rate for this study. While difficult in practice, future work should ideally include a sufficiently large data set of pipes with leakage data to derive new knowledge on the relationship between leakage level and energy performance.

CONCLUSIONS

This study examined the relationships between pipe characteristics and the energy performance of pipes. By performing a statistical analysis on a large ensemble of pipes from a variety of water distribution systems, the results can be considered more broadly representative than a case study for a single system and can serve as a benchmark for comparison by other utilities. The

application of this statistical approach showed that maximum average unit-head-loss threshold levels used in practice generally target pipes with low energy performance but that additional energy savings could be achieved, albeit at a high cost for pipe replacement, if head loss thresholds were stricter. Linking the energy performance of water mains to traditional head loss thresholds has the potential to widen the range of information available to water utility managers when making decisions about water main rehabilitation. It is believed that the proposed method could be integrated within a bigger asset management decision framework that considers risk assessment, criticality of asset, water quality, and pipe breaks to improve asset management decision-making.

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