

An Energy Evaluation of Common Hydraulic Thresholds in Water Mains

Saeed Hashemi¹, Yves R. Fillion², Vanessa L. Speight³

¹ Water Design Specialist, CH2M Hill
Toronto, Ontario (Canada)

² Department of Civil Engineering, Queen's University
Kingston, Ontario, (Canada)

³ University of Sheffield, Sheffield, (UK)

¹ saeed.hashemi@ch2m.com, ² yves.fillion@civil.queensu.ca, ³ v.speight@sheffield.ac.uk

ABSTRACT

This study uses a regression-based modelling approach using an ensemble of 20,000 water mains compiled for 17 North American networks to understand the relationships between pipe factors (pipe flow rate, unit headloss, proximity to major components, average pressure, and diameter) and energy efficiency/energy loss performance metrics. The regression analysis aims to predict efficiency values in pipes based upon common-practice values of average pressure and unit headloss to better understand the energy performance associated with those thresholds.

The results of regression analysis show that commonly considered pressure ranges (30-50 m) correspond to good values of the energy needed by user (ENU) metric, with pressure deficient pipes by definition having lower, non-ideal ENU values. For unit headloss, common thresholds that would trigger pipe replacement (3 m/km in transmission mains, 10 m/km in distribution mains) correspond to net energy efficiency (NEE) of 74.9 and 74.6 percent, respectively, for the ensemble of water mains analyzed. These pipes represent the poorest performers and while there are not many such pipes within the ensemble, as NEE of 74.6 corresponds to the 7th percentile, there is a need for tools and analyses like these to help water utilities identify the pipes with the greatest energy impact from across their water distribution systems.

Keywords: Correlation and Regression Analyses; Pipe-level Energy Metrics; Unit Headloss.

1 INTRODUCTION

Water utilities often rely on thresholds of maximum unit headloss, leakage rate, and pipe breaks to trigger the rehabilitation or replacement of their linear assets. For instance, large-diameter pipes (16 in. or greater) having head losses greater than 3 m/km, or small-diameter pipes having head losses over 10 m/km are considered as potentially deficient [1]. In practice, minimum pressures should be between 30 and 50 m, although individual utilities and regulatory bodies can have different standards. Currently, the link between these hydraulic thresholds and the energy performance of pipes is not well characterised.

This research has novelty in linking pipe parameters to the energy dynamics of a distribution system. Furthermore, this study uses a large ensemble of pipes from several systems with different characteristics in order to attain a robust understanding of the relationship between pipe characteristics (pipe flow rate, unit headloss, proximity to major components, average pressure, and diameter) and the energy

performance of individual pipes. Most previous studies consider only network level energy inefficiencies [2, 3, 4].

This study applies correlation analysis to identify statistically significant relationships between pipe parameters and pipe-level energy metrics. The results of the correlation analysis are then use to select input parameters for a regression analysis that maps the relationship between energy performance of water mains and common pressure targets used in practice.

2 METHODS

2.1 Energy Metrics and Pipe Parameters

Four energy metrics developed by Hashemi et al. [5] are described briefly in this section. These metrics are used to describe the energy performance of pipes to explore relationships with pipe characteristics using statistical analyses. Mathematical definition of these metrics and pipe parameters is provided in Table 1.

Energy Metric	Definition
Gross Energy Efficiency (<i>GEE</i>)	$GEE = \frac{E_{\text{delivered}}}{E_{\text{supplied}}} \times 100\%$
Net Energy Efficiency (<i>NEE</i>)	$NEE = \frac{E_{\text{delivered}}}{E_{\text{supplied}} - E_{\text{ds}}} \times 100\%$
Energy Needed by User (<i>ENU</i>)	$ENU = \frac{E_{\text{delivered}}}{E_{\text{need}}} \times 100\%$
Energy Lost to Friction (<i>ELTF</i>)	$ELTF = \frac{E_{\text{friction}}}{E_{\text{supplied}} - E_{\text{ds}}} \times 100\%$

The gross energy efficiency (*GEE*) compares the energy delivered to the end-user (to satisfy demand for water) to the energy supplied to the pipe. The net energy efficiency (*NEE*) compares the energy delivered to end-users at the end of the pipe to 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 the pipe. The energy needed by the user (*ENU*) compares the energy delivered to the end-user against the minimum energy needed by the end-user. E_{need} is calculated based upon 30 m of required pressure, commonly imposed by North American water utilities [6, 7]. The energy lost to friction (*ELTF*) compares the energy loss components (e.g., friction due to flow, which includes demand and leakage) to the net energy in the pipe (excluding energy transferred to downstream pipes). This provides information on the relative magnitude of the energy losses in a pipe to the net energy supplied to the pipe. The hydraulic proximity indicator, presumes that hydraulic head or pipe flow (or both) tend to decrease as one moves away from major components to cul-de-sac zones in a system or a pressure zone.

2.2 Pipe Hydraulic Factors

Pipe hydraulic factors considered in conjunction with the energy metrics in this study include, average daily pressure of pipes (averaged for end nodes of a pipe), average daily flow of pipes, average unit headloss, diameter and Hazen-Williams roughness factor and hydraulic proximity of pipes to major components in a distribution system [5]. Hydraulic proximity is defined according to the following Equation:

$$\text{Hydraulic Proximity} = Q \cdot H_s \quad (\text{m}^4/\text{s}) \quad (1)$$

Where Q =pipe flow (m^3/s) and H_s =supplied head to a pipe at the upstream node.

2.3 Correlation Analysis

The Spearman rank correlation coefficient was used to identify statistically significant correlations between the pipe characteristics and energy metrics presented in Table 1. Spearman's rank correlation coefficient, r , for a sample of n measurements is defined as

$$r = 1 - \frac{\sum_{i=1}^n d_i^2}{n(n^2 - 1)} \quad (2)$$

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 and n is the sample size (number of pipes). The Spearman rank correlation coefficient in Equation (1) follows a Student 't' distribution so the Student 't' test statistic and its corresponding p-value at the 95% confidence level were used to determine statistical significance of correlations between pairs of input parameters [8].

2.4 Ranks of Pipe Parameters and Energy Metrics

Based on the correlation analysis, a regression model was used to establish the relationship between pipe characteristics that drive energy performance in water mains. The regression models were formulated in terms of ranks rather than the actual numerical values of the pipe characteristics and energy metrics to more easily examine the non-linear relationships between the parameters. As an example, Figure 1a depicts the scatterplot for the numerical values of average pressure against numerical values of *ENU* over the entire ensemble of 20,000 pipes. In this figure, there is no evident relationship between average pressure and *ENU*. However, Figure 1b reveals a monotonic relationship between the rank of average pressure and the rank of *ENU*.

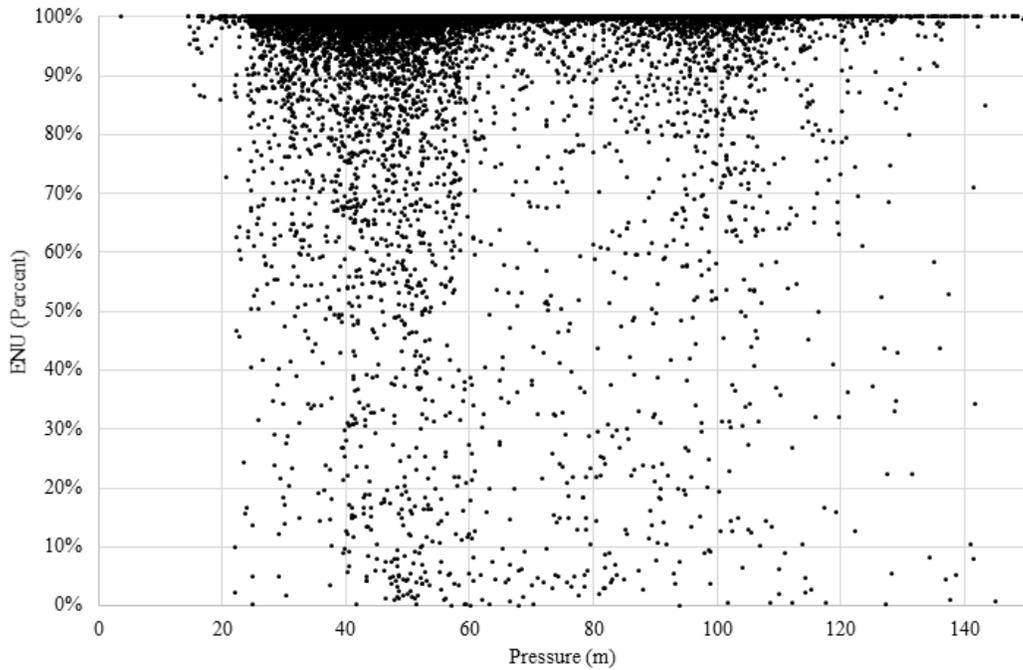


Figure 1a. Numerical values of average pressure against numerical values of ENU

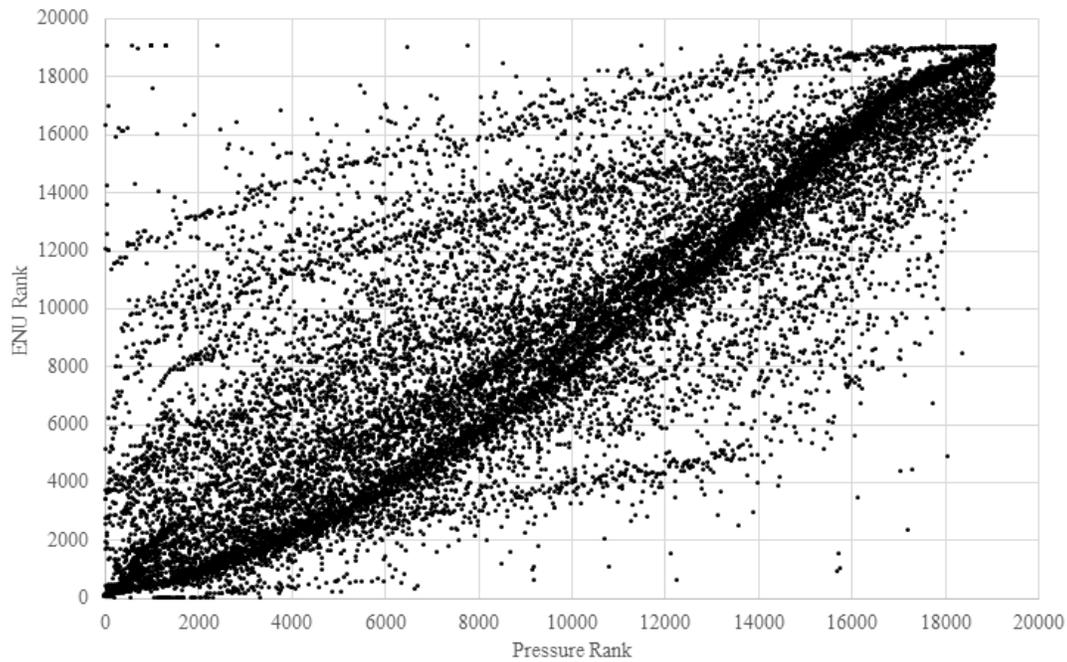


Figure 1b. Ranks of average pressure against ranks of ENU

3 Ensemble of Pipe Data from 17 Large Distribution Systems

Pipe and energy data were obtained from a large ensemble of 20,000 pipes across 17 distribution systems in Canada and the US to obtain statistically significant results. The 17 water distribution networks were selected from different North American regions including the States of Kentucky [9] and Ohio and the

Province of Ontario. The topographical and topological characteristics were typical of most systems in the US and Canada. These systems span a range of sizes from 56 km to 972 km of pipe, an average daily water demand that ranges from 3.5 MLD to 69.1 MLD, and a range of topographies with a ground elevation difference between 29 m to 248 m. The corresponding EPANET2 [10] hydraulic models of these systems range in size between 366 and 12,189 pipes, 271 to 11,177 nodes, 1 to 31 pumps, and 2 to 28 tanks and/or reservoirs.

4 RESULTS

The results in Table 2 suggest that *GEE* is for the most part influenced by flow rate ($r = -0.84$; $t' = 214$; p-value = 0.00), average unit headloss ($r = -0.63$; $t' = -114$; p-value = 0.00) and hydraulic proximity ($r = -0.80$; $t' = 184$; p-value = 0.00). This means that higher flows, higher headloss rates and close proximity to pump stations or elevated tanks tend to decrease the value of *GEE*. Similarly, *NEE* is also negatively correlated with flow rate ($r = -0.85$; $t' = 227$; p-value = 0.00), average unit headloss ($r = -0.88$; $t' = -260$; p-value = 0.00) and hydraulic proximity ($r = -0.82$; $t' = 200$; p-value = 0.00). Not surprisingly, *ENU* is highly and positively correlated with average pressure ($r = +0.85$; $t' = -221$; p-value = 0.00), as pressure is an important factor in satisfying energy requirements. *ELTF* is also highly and positively correlated with flow rate ($r = +0.80$; $t' = -181$; p-value = 0.00) average unit headloss ($r = +0.82$; $t' = 194$; p-value = 0.00), and hydraulic proximity ($r = +0.77$; $t' = -167$; p-value = 0.00). This is not surprising given that higher flow rates as a result of high demands or being close to major components generates higher headlosses and consequently tends to increase *ELTF* in pipes. Overall, flow rate has the greatest influence on *GEE*, while average pressure is the most influential parameter in driving *ENU*, and average unit headloss tends to affect both *NEE* and *ELTF*.

Table 2. Summary of strong correlation coefficients
(source: adapted from [11])

	GEE (percent)	NEE (percent)	ENU (percent)	ELTF (percent)
Avg. P (m) ³	0.06	0.10	0.85	-0.10
Avg. Q (MLD) ⁴	-0.84	-0.85	-0.09	0.80
Avg. Unit Headloss (m/km) ⁵	-0.63	-0.88	-0.14	0.82
Hydr. Proximity (m ⁴ /s) ⁶	-0.80	-0.82	-0.06	0.77

The regression model in Figure 2 depicts the relationship between average pressure and the energy metric *ENU*. Based on this figure, it can be seen that pressures below 30 m in the ensemble correspond to *ENU* < 1, which is considered deficient in terms of the users' expectations. Moreover, high pressures are associated with higher *ENU* values, some of which might be considered as excessive by users. High pressures produce surplus energy and may cause higher pipe breaks and increase water loss. In Figure 2, pressures of 20, 30, 50, 70 and 100 m correspond to *ENU* of 0.96, 1.0, 1.05, 1.08 and 1.13 respectively.

Desirable pressures based on standards (between 30 and 50 m) are associated with more desirable *ENU* values [11].

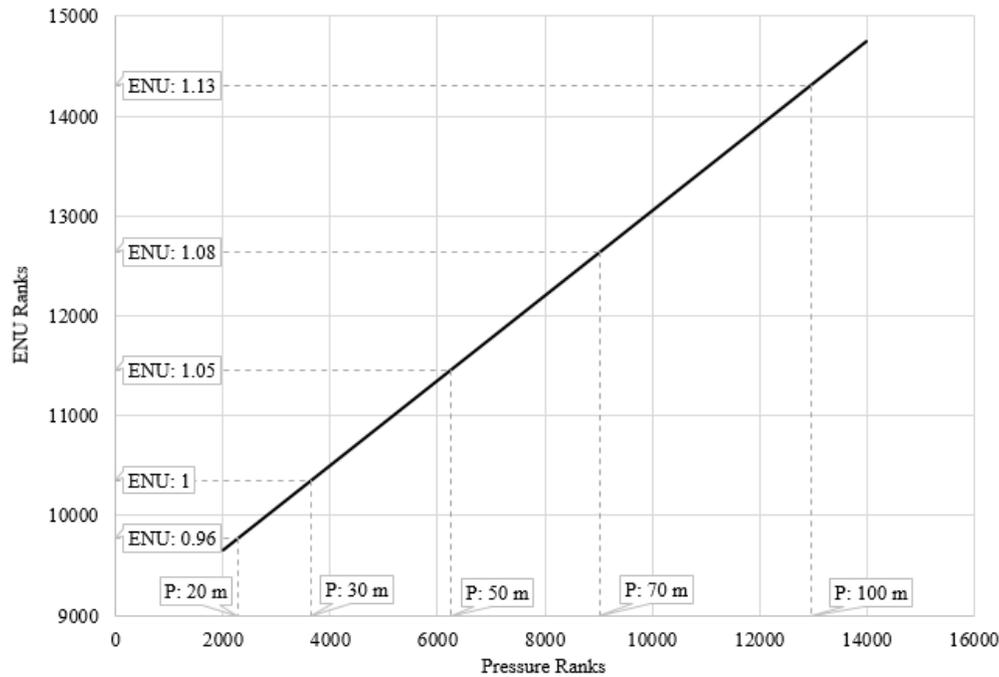


Figure 2. Regression model describing the relationship between average pressure (rank) and ENU

Unit headloss was also found to be strongly correlated with *NEE* and *ELTF* (Table 2). The typical unit headloss targets of 3 m/km for transmission mains and 10 m/km for distribution mains correspond to *NEE* values of 74.9 and 74.6 percent, respectively, and these represent the poorest performing pipes within the ensemble [11]. Similarly, the *ELTF* values that correspond to unit headloss of 3 and 10 m/km were found to be 4.2 and 6.4 percent, respectively [11]. Overall, 1.1% of pipes within the ensemble exceed the 3 m/km unit headloss threshold [11].

4 CONCLUSION

This paper summarized the relationships between pipe hydraulic factors and pipe-level energy efficiency metrics to examine the energy impact of common threshold values. While pipe replacement and rehabilitation decisions are often made by considering structural, water quality and other factors outside energy considerations, the results above suggest that there is merit in re-examining maximum average unit headloss and pressure thresholds used in practice in light of the possible savings in energy.

5 ACKNOWLEDGEMENTS

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