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# The Effects of Pipe Size and Location on Water Main Headloss in Water Distribution Systems

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## Abstract

This study discusses practical implications of considering unit headloss in different pipe sizes and in different locations of the water distribution systems (WDSs) with regard to operation and maintenance. By visualizing unit headloss (using the Hazen-Williams relationship) in pipes obtained from eighteen WDSs in North America, changes in unit headloss are put into perspective in different pipe sizes and different locations of WDSs. The results suggest that importance of diameter is higher than Hazen-Williams roughness factor, that flow rate plays a more important role than diameter in determination of headloss in pipes closer to water sources, while diameter seems to be more important than flow rate in pipes at the periphery. Moreover, aging, tuberculation and subsequently reduction in effective diameter can have a more critical effect on headloss in smaller pipes at the periphery of a system. Finally, effects of water conservation and pump scheduling in different locations of the network, as far as headloss is considered, can potentially be more evident on larger pipes closer to water source and in some cases on smaller pipes at the periphery. Therefore, it is suggested that network-level energy management decisions can have different effects on different pipe sizes in different locations.

**Keywords**: Energy Efficiency, Water Mains, Water Distribution Systems, Roughness, Pipe Class

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## Introduction

Energy in WDSs has been examined in many ways, including operation of pump stations, leakage, and friction losses in pipes. Wong et al. (2017) compared pumping energy costs in different urban forms (e.g. grid-iron, cul-de-sac), accounting for different population densities. The results showed that urban forms with higher population densities had lower energy use per capita. Scanlan and Filion (2017) studied the proportion of energy lost to friction, leakage, and excess pressure in four WDSs in Canada. Even though leaky WDSs seemed to lose energy mainly to leakage and friction, no statistically significant relationship was found between energy use and variables of interest such as nodal elevations and peak demands. Therefore, Hashemi (2018a) used similar statistical methods and explored relationships between pipe hydraulic parameters and energy efficiency.

Energy assessments in previous studies have mostly focused on the system-wide energy performance of WDSs (Alegre et al., 2006). Cabrera et al. (2010) presented a set of metrics to characterize the system-wide energy performance that included losses to friction, leakage, and excess pressure. These energy metrics provide a useful set of tools to help water utilities compare the current state of their WDSs to an ideal energy-efficient state. However, Cabrera et al. (2010) did not develop a way to identify individual pipes that were problematic. Building on their earlier work, Cabrera et al. (2014) presented additional metrics to assess the energy efficiency of a pressurized system and procedures to prioritize interventions on a system-wide basis. Moreover, Dziedzic and Karney (2015) developed energy metrics to examine energy efficiency of the Toronto WDS, regarding time and location. To conclude, these previous studies did not consider energy dynamics and performance at the pipe level. Moreover, transferability of the results to a wide range of WDSs was not an objective in these studies.

This study is influenced by Hashemi et al., (2017; 2018 a & b), to monitor energy dynamics at the pipe-level in large WDSs for pipe size and roughness groups and regarding proximity to major components (e.g. storage and pumping facilities). This study is however, a simplified statistical analysis that may be used by water system operators. In the search for pipe-level energy assessment tools for WDSs, this study aims to 1) understand the practical implications of energy behaviour of pipe sizes in different locations, 2) examine the influence of pump scheduling and water conservation on energy dynamics of different pipe sizes, and 3) characterize the effect of aging and reduction of effective diameter on different pipes and locations in the system. For this purpose, unit headloss is examined in a large ensemble of pipes from eighteen WDSs from North America regarding their location in a system. In this study, pipe size and roughness are used as the best available representatives of age, material, and year of installation.

## Methods

### Hydraulic Proximity Indicator

Proximity of a pipe to a water source is considered as a factor that can influence the energy performance of a pipe. The hydraulic proximity indicator is based on the observation that flow and pressure (head) generally decrease with increasing distance from a water source. It is important to note that hydraulic proximity does not represent the linear distance between a pipe and water source, but rather an indirect indicator of the influence of a water source on a pipe. The hydraulic proximity indicator is represented by the following equation (Hashemi et al., 2017):

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

where Q is the pipe flow ($m^3/s$) and $H_s$ is the hydraulic head provided at the upstream node of a pipe (m) calculated with the EPANET2.0 hydraulic model. High values of the hydraulic proximity suggest that the water main is located near a water source, and low values suggest farther.

### Unit Headloss

Unit headloss due to friction is examined to better understand the effects of pipe size and roughness (without the effects of pipe length). The unit headloss using the Hazen-Williams relationship is shown in Equation (2):

$$\text{Unit Headloss} = \frac{10.68}{D^{4.87}}\left(\frac{Q}{C}\right)^{1.85} \text{ (m/m)} \qquad (2)$$

where Q is the pipe flow, C is the roughness coefficient of the pipe and D is the internal diameter of the pipe.

### Data Normalization and Data Ranks

Hydraulic Proximity (used in Equation 1) can vary by one or two orders of magnitude across systems of different sizes. To compare these parameters fairly across different systems, the data was normalized. As a result, a scaled normalized proximity value between 0.0 and 1.0 is used for completion of the analysis. A pipe with a normalized proximity near 1.0 indicates the highest proximity to major components, and vice versa. Moreover, based on statistical analysis performed by Hashemi et al. (2018a), Spearman's ranks of proximity and unit headloss were chosen, to capture the non-linear relationships between Hydraulic Proximity and Unit Headloss. Spearman's rank method uses the rank of each value, instead of the actual value. For instance, in an ensemble of "n" pipes, highest value of a parameter is ranked one, while the lowest value is ranked "n". The hydraulic parameters such as unit headloss and hydraulic proximity are calculated on an hourly basis, using extended-period simulation, and then averaged throughout the day.

### Application of the Method in a Large Ensemble of Pipes

The approach was applied to a comprehensive dataset representative of the wide variety of WDS characteristics such as pipe configuration, physical condition, and age profile, found in different systems. Eighteen WDSs were selected from different areas in North America (Kentucky, USA (Jolly et al., 2013), Ohio, USA (Prosser et al., 2013; Wong et al., 2017), and Ontario, CA), totalling over 55,000 pipes. The system characteristics of the eighteen locations are summarized in Table 1. In terms of hydraulic model calibration, the models for the Ohio systems are calibrated, while the models for the Kentucky and Ontario systems are not. Pipe physical data from the models (retrieved from the indicated studies) such as diameter, length, and roughness are all a part of the study modelling inputs. Model pipe diameters and lengths are often based on GIS databases, which have some inaccuracy associated with them. Roughness values are assumed based on textbook values for non-calibrated models, and calibration results for calibrated models. However, it is noted that Hashemi et al. (2018 b) found that the results for calibrated and un-calibrated systems exhibit the same patterns. Since the calibrated values are ranked based on relative value, the effect of calibration is dwarfed by the effect of the ranking method used for Spearman's method.

### Results

Further investigation in the present study, based on the extensive statistical analysis by Hashemi et al. (2018a), revealed that ranking of the data exhibits a non-linear correlation between hydraulic proximity (x-axis) and unit headloss (y-axis) for different pipe sizes, shown in Figure 1. Smaller ranks on hydraulic proximity axis represent higher values of hydraulic proximity and pipes closer to a water source such as a booster station, elevated storage or a treatment plant, while, larger ranks represent pipes at the periphery of the network that experience smaller flows and pressure. On the unit headloss axis, smaller ranks represent larger unit headloss, while larger ranks represent smaller headloss. Each pipe in the dataset is a point on the graph, and marked for a specific diameter group. Curves at the bottom left (indicated by circles) correspond to the smallest pipe diameter group (less than 150 mm, composed of 8,800 pipes). Curves at the top right (indicated by black diamonds) correspond to the largest pipe diameter group (greater than 300 mm, composed of 8,500 pipes). The curves in the middle of the graph (shown in different shades of grey by triangles and squares), correspond to medium-sized pipe groups (150-200 mm, composed of 12,800 pipes and 250-300 mm, composed of 12,900 pipes, respectively).

Similar to diameter, roughness (as another pipe input in the hydraulic model), based on Equation (2), also has a noticeable effect on the formation of curves in Figure 1. Pipes with higher C-factors within each diameter range form on the top of the curve (similar to >300 mm pipe group), and those with lower C-factors on the bottom (similar to <150 mm pipe group). Therefore, it is evident that both C-factor and diameter can differentiate headloss in pipes in Figure 1. However, diameter forms more distinguished curves because it merits from a higher power in Equation (2).

It is noted that the group of smaller diameters (smaller than 150 mm) is less distinguished which may be due to the wider range of diameters, when compared to other groups such as 150-200 mm and 200-300 mm.

## Discussion

Interpretation of the results in Figure 1, suggests that headloss in larger diameters (which is highest near a water source), drops significantly moving towards transitional sections (neither close to water source or peripheries of the system). This is also seen by inspection of the Hazen-Williams headloss relationship. In areas closer to a water source, flow is more dominant compared to roughness and diameter. Since flow drops significantly in pipes after a few flow splits (Wong et al., 2017), the unit headloss decreases accordingly. However, the same pipe size located at the periphery of the WDS displays a more gradual decrease in unit headloss (closer to the top left of the graph), due to a gradual decrease in flow at each flow split. Based on Boulos et al. (2006) and C-factor tests in calibration studies such as CH2M Hill (2018), for a certain pipe material, because of higher hydraulic conductivity, generally larger diameter pipes are found to have higher C-factor values, and subsequently less influence from flow in the headloss relationship, especially at the periphery of the WDS (Walski, 1983). In conjunction with related studies on this topic by Hashemi et al, (2017) as well as Colombo and Karney, (2005 and 2002), the unit headloss patterns shown can imply that conservation strategies in consumption, even though welcome from a system-wide point of view, can be more effective in lowering unit headloss in pipes closer to water sources than those at the periphery. Therefore, if water conservation is combined with pump scheduling, headloss throughout the system would be optimized (Hashemi et al., 2017).

In contrast, smaller diameter pipes maintain higher rates of headloss moving from water sources to the transitional sections of the system. This may be the result of diminished importance of flow in the headloss relationship, due to higher hydraulic resistance against flow (lower roughness factors) in smaller pipes, close to the water source. This allows less flow into the pipes (smaller Q in Equation 1), compared to larger diameters in these areas and therefore, smaller flow splits compared to larger pipes that go through larger flow splits, which can in turn retain the high headloss in these pipes. In these small pipes, however, unit headloss diminishes quickly approaching the network periphery. In transitional areas and the periphery, WDS is mostly composed of smaller diameter pipes, and therefore the flow is distributed in a network of smaller pipes. The headloss is still high in transitional areas in smaller pipes, however as the flow is split between pipes, the unit headloss declines as well. Therefore, this implies that ageing pipes (reduced effective diameter as a result of tuberculation) may cause more serious problems to pipes with smaller diameters at the network periphery, as the slope of the corresponding curves for smaller diameters is more critical (see Figure 1).

Also, pump scheduling, used by itself, can perhaps reduce leakage losses throughout the system, as a result of reducing excessive pressure. Considering the negative effect of leakage on friction (Colombo and Karney; 2002), if the leaky pipes are located closer to the water source, pump scheduling would have a more evident effect in larger diameters (based on Figure 1), because small reductions in flow in these pipes can reduce the headlosses. However, if the leaky pipes are closer to the network periphery, the effect of pump scheduling can be two-fold. First, smaller changes in pipe flows at the network periphery would improve headloss rates in smaller pipes (according to the curves specified using circles and triangles in lighter shades of grey). Second, the cumulative reduction of flow in larger pipes closer to a water source as a result of smaller reduction of flow in downstream smaller pipes can highly improve headloss in large pipes, according to the black curve.

Finally, by comparing the effects of C-factor and pipe size on the formation of curves, it can be concluded that in energy classification of water mains, pipe diameter seems to have more importance compared to roughness, based on separation of diameter clusters in Figure 1. This is also corroborated by the power of C-factor, 1.85 to that of diameter, 4.87 in Equation (2). Even though calibration studies show that the two factors seem to have a relationship, it would be a useful knowledge to decision makers how to prioritize the importance of these available deciding factors.

## Conclusions

This study provided a visual transition of Hazen-Williams headloss with regard to proximity of pipes to major components in a WDS, for different pipe size and roughness groups, as the most influential parameters. The discussions included the implications of results for pump scheduling and water conservation based on the findings of previous related studies regarding water conservation, leakage and pump scheduling in WDSs. The novelty of this study is guaranteed by analyzing over 55,000 pipes gleaned from eighteen real-world North American WDSs with different characteristics. As expected by Hazen-Williams relationship, the results showed that different pipe sizes would form distinct clusters. As a result, the following conclusions in characterization of unit headloss were made, 1) diameter is more important than roughness factors in all pipes when forming clusters, 2) flow rate is more important than diameter in close proximity of a water source while diameter is more important than flow rate at the network periphery, 3) pipe aging and tuberculation have more severe impact on smaller pipes at the network periphery, and 4) pump scheduling in leaky systems can potentially improve headloss in different locations of a system. Also, these positive effects are expected to be maximized when combined with water conservation.

Although some of the conclusions such as implications of roughness and size regarding headloss relationship may seem obvious, putting location of the pipe in perspective is worthwhile for distinguished pipe size and roughness groups (i.e., pipe class). As well, this study could only introduce a new perspective to decision makers shedding light on the effects of network-level decisions such as water conservation and pump scheduling on pipe-level energy assessment. Reader of this technical note may consider Hashemi et al., (2018a and 2017), to develop a better understanding of pipe-level energy auditing as a new school of thinking in energy assessment of WDSs.

## Data Availability

All data and models used during the study are available from the corresponding author by request.

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