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EVIDENCE-BASED WATER LOSS MANAGEMENT: DEVELOPMENT AND DEPLOYMENT OF A MOBILE DMA TESTING UNIT

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Abstract: There is a strong connection between water supply and energy consumption which, considering trends towards reducing system stresses, provides an opportunity to take advantage of the synergies associated with leakage reduction and energy conservation. In recognition of these synergies, a multi-year project has been initiated in Ontario through funding from the province's Independent Electricity System Operator to promote water loss reduction practices. The project involves the development and deployment of a mobile testing unit designed as an affordable method to accurately and reliably measure minimum night flow (MNF), an indicator of leakage, into discrete sectors of water distribution systems commonly referred to as district metered areas (DMAs). In addition to flow monitoring, the mobile unit is equipped with a pressure reducing valve (PRV) to directly test the effectiveness of pressure moderation on leakage reduction. More broadly, the project involves the collection of data across 22 DMA sites in Ontario with results informing the development and application of evidence-based benchmarking metrics used to assess the performance of DMAs in similar municipalities elsewhere. Moreover, analyses of the project's testing results, previous DMA work and advanced metering infrastructure (AMI) data are presented to support the establishment of MNF benchmarks (representing healthy systems). While this project is still ongoing, initial successes have proven the mobile testing unit concept and substantial value has already been realized. Accordingly, a case study is featured where exceptional savings were demonstrated and quantified as a result of intervention efforts informed by the project.

1 PROJECT INTRODUCTION

Leakage in water distribution systems (WDSs) has significant impacts on both energy utilization and water supply depletion. In appreciation of the needless energy consumption associated with leakage, the Independent Electricity System Operator (IESO) is supporting a multi-year (2019 to 2021) water loss management project through its Grid Innovation Fund. This cross-sectoral project is being led by HydraTek & Associates (HydraTek) in collaboration with the National Research Council, the Ontario Water Works Association (OWWA), the University of Toronto, and several participating municipalities. The principal objectives of the project are listed below:

1. Develop a diagnostic tool to accurately and reliably measure minimum night flows (MNFs) on a temporary basis into district metered areas (DMAs);
2. Derive meaningful evidence-based benchmarking metrics to evaluate DMA performance; and
3. Directly measure and analyze the effectiveness of pressure reduction on leakage reduction.

This paper first outlines the inherent linkage between WDS leakage and energy consumption which motivate the application of the mobile testing unit and associated evidence-based benchmarking metrics. Interim project results are then presented, alongside an assessment of advanced metering infrastructure (AMI) data to support the project's methodologies.

2 SYNERGY BETWEEN LEAKAGE AND ENERGY

Apart from the relatively few WDSs that utilize gravity supply, pumping energy generally represents the largest form of energy consumption in water system operation. In addition to treatment processes, pumping energy plays three roles: (i) to overcome elevation differences between the supply and point-of-use; (ii) to compensate for mechanical energy losses arising from friction; and (iii) to provide an adequate service pressure to consumers.

Furthermore, pumps are fraught with inefficiencies where an average wire-to-water energy loss of 30% is common in Ontario WDSs (HydraTek 2013). Accordingly, significant investments in terms of both financial and natural resources are continually required for the provision of potable water to service the growing population. In an increasingly resource-constrained environment, it is therefore important to confront the waste of such fundamental natural resources as water and energy. Efforts that reduce system flow, such as through leakage control, are directly proportional to the reduction of required power consumption, yielding both financial and environmental benefits. These benefits arrive naturally from the pump power equation:

[1] $$\text{Required Pumping Power} = \frac{\gamma Q H}{\eta}$$

where Q = flow, H = total dynamic head, γ = unit weight of water, and η = wire-to-water pump efficiency. Note that reducing the flow rate (Q) has the additional benefit of reducing a portion of the head losses due to friction.

2.1 Estimate of Energy Consumption from Leakage in Ontario Water Systems

To provide a high-level estimate of the energy consumed from lost water in WDSs throughout Ontario, the following assumptions are made: of Ontario's population of approximately 13.5 million, approximately 85% are serviced by municipal water systems; average consumption is 250 litres per capita per day (Lpcd); a typical WDS has an average total dynamic lift of 110 m; 10% of water produced and pumped is lost through leakage (noting that the median value in the AWWA validated water audit data initiative of water utilities in the US and Canada in recent years was found to be about 15%); and an average pump energy consumption rate of 4,000 kWh/Mm^3/(m lift), as derived in an earlier IESO (formerly OPA) Conservation Fund project conducted by HydraTek (2013). The result? About 50 GWh per year is wasted, which is equivalent to the annual electricity consumption of nearly 6,000 homes.

Furthermore, the resulting excess energy expenditure has adverse impacts to earth's diminishing natural energy resources and contributes to the rise of global greenhouse gas emissions. Using an emissions intensity factor representative of Ontario of 40 g CO_2/kWh (National Energy Board 2017), the estimate of energy consumption from leakage in Ontario WDSs contributes to approximately 1,940 tonnes of CO_2/year.

3 LEAKAGE MANAGEMENT METHODOLOGY

Leakage management has historically been split between two concepts: leakage assessment and leakage detection. Leakage assessment deals with evaluating the quantity of leakage in a system, whereas leakage detection attempts to identify where leaks are localized (Puust et al. 2010). Localized leak detection is often uneconomical unless segments of the system containing considerable leakage can first be identified.

One of the most prevalent leakage assessment methods is the top-down IWA/AWWA Water Balance. This system-scale method is performed through component analysis of various inputs and outputs of the WDS, in which real losses can be crudely estimated through a simple mass balance (Puust et al. 2010). While the water balance may be a useful start to inventory system components, it lacks spatial resolution (i.e., leak location) and may be fraught with uncertainty. To complement this process and help address such concerns, a bottom-up analysis may be used. A bottom-up approach uses detailed (pipe-level) flow data to generate performance metrics, one of which is the analysis of minimum night flow (MNF). MNF can be a valuable indicator of leakage as it represents an instance in the system (typically between 2 to 4 am) where leakage constitutes the highest fraction of total system flow as legitimate consumption is at its lowest (Liemberger and Farley 2004).

3.1 Minimum Night Flow Assessment

MNF data is obtained by delineating a WDS into discrete sectors, commonly referred to as district metered areas (DMAs). DMAs are created by closing several isolation valves and providing an inlet (or multiple inlets/outlets) where the supply and consumption can be individually monitored. Although DMAs have been widely successful in Europe since the 1980s (Savic and Ferrari 2014), practices in Canada have been rather inconsistent, consisting mostly of pilot studies with little in the way of long-term programming, although notable exceptions include the Cities of Halifax and Ottawa. Figure 1 (left) displays a typical night flow profile, where a centralized 60-minute moving averaging is applied during post-processing of minutely data to capture the overall flow profile (i.e., MNF_{60}).

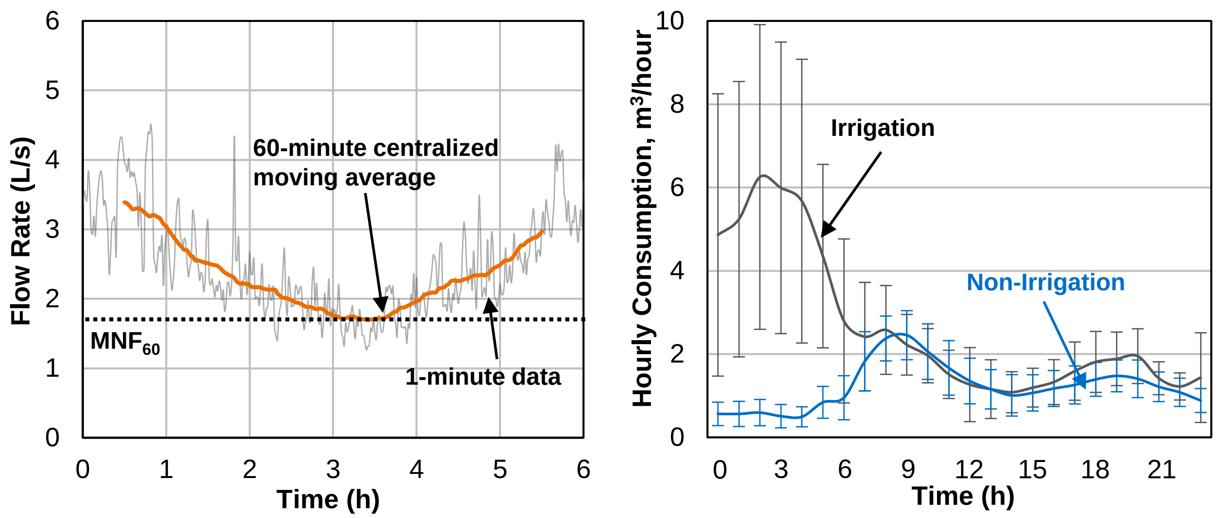

Figure 1: Typical nightly flow profile (left); sample average diurnal demand profiles – Credit: Steve Genser, Infrastructure Initiatives (right)

The assumption that system demand is at its minimum between 2 and 4 am can be attributed to the highly consistent consumption pattern of residential consumers. Section 5 of this paper details an investigation using AMI as well as a review of HydraTek's in-house DMA testing data which supports the repeatability of residential demand. To ensure such demand repeatability, this work focuses on testing only in residential areas (e.g., greater than 90% residential). Furthermore, MNF testing in this project is restricted to non-irrigation months (generally from October to May) given that the impact of automated irrigation systems on demand patterns can be significant; in some cases, as displayed in Figure 1 (right), irrigation use dwarfs what would otherwise be a typical diurnal demand pattern.

3.2 Barriers to DMA Implementation

DMAs, and more particularly the flow metering technology as a component thereof, can be implemented on a temporary or permanent basis. Temporary measures typically consist of insertion or clamp-on flow meters that are relatively inexpensive to install but may sometimes be unable to reliably measure MNF as a result of very low flow velocities that are below the technology detection limit. This is an outcome of the sizing of pipes in North American WDSs being predominantly determined by fire-fighting requirements, rather than the delivery of much smaller domestic demands; the difference between these flow regimes is often two orders of magnitude. Accordingly, as DMAs become smaller in size, reliable data becomes increasingly difficult to obtain. The secondary y-axis of Figure 2 shows the detection limits of temporary metering solutions (in green) compared to those of in-line flow metering technologies associated with permanent DMA implementation (in orange). The black plots (primary y-axis) represent a cumulative distribution of MNFs for a sample distribution of DMA sizes and, at some points in the graph, MNF estimates are unable to be captured by the temporary metering technology's detection limit.

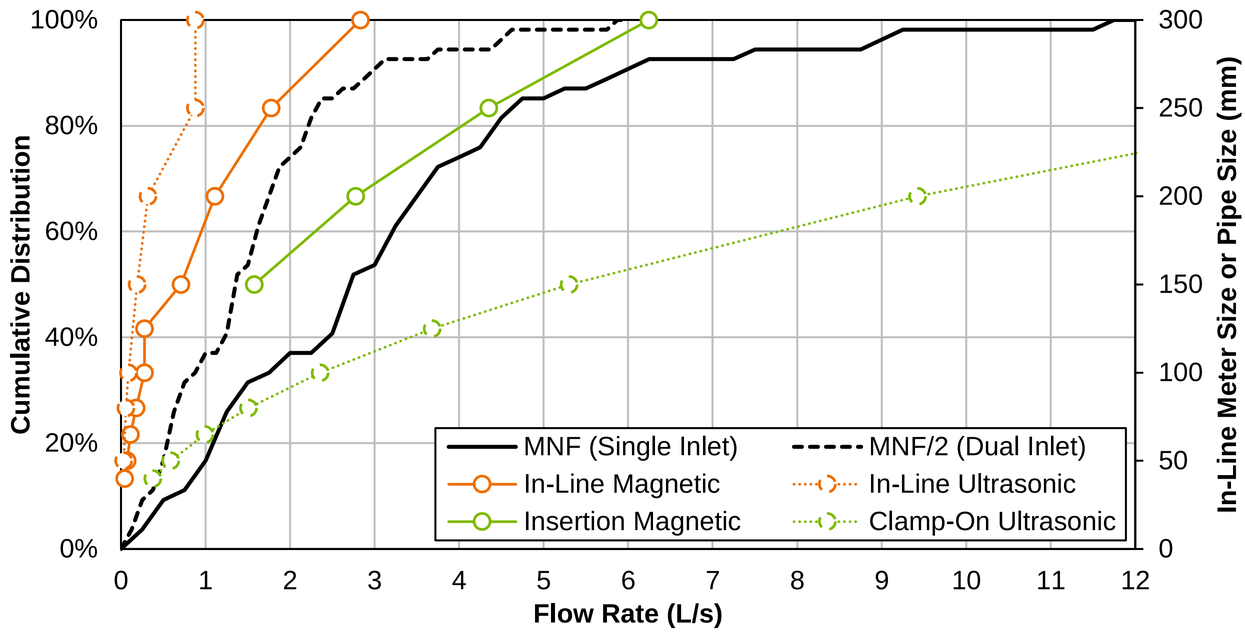

Figure 2: Distribution of DMA sizes in representative city relative to flow metering technology capabilities

Where temporary flow measurement is unable to accurately measure potential low MNFs, permanent installations with higher-resolution metering technologies (e.g., in-line electromagnetic or ultrasonic meters) may be implemented. Permanent installations, however, involve the construction of underground chambers and preparatory measures involving valve and related fittings required to ensure operability and maintainability. These installations are moderately expensive, ranging between $150k-$400k per DMA based on the authors' prior project experiences. Table 1 summarizes the approximate costs associated with both temporary and permanent DMA installations.

Table 1: DMA implementation costs

DMA Type	Data Collection	Cost/DMA
Temporary Measurement	Periodic	< $20k
Permanent: Excluding Pressure Management	Continuous	~ $150k to $200k
Permanent: Including Pressure Management	Continuous	~ $250k to $400k

In summary, a barrier exists in current practice emanating from the trade-off between reliability and cost associated with data collection.

3.3 Mobile Testing Unit

To help overcome the identified barriers, the current project introduces the development and deployment of a mobile testing unit to measure MNFs into temporarily configured DMAs. The diagnostic tool is affordable by virtue of its mobility, and it is accurate by virtue of the metering technology it is equipped with.

The concept of the mobile unit builds on earlier work conducted in the City of Ottawa in conjunction with the National Research Council of Canada in the mid-2000s (Hunaidi and Brothers 2007; Hunaidi 2010). Although the nature of that work may aptly be characterized as applied experimental research, it provided a valuable reference in the design of the tool constructed for this project.

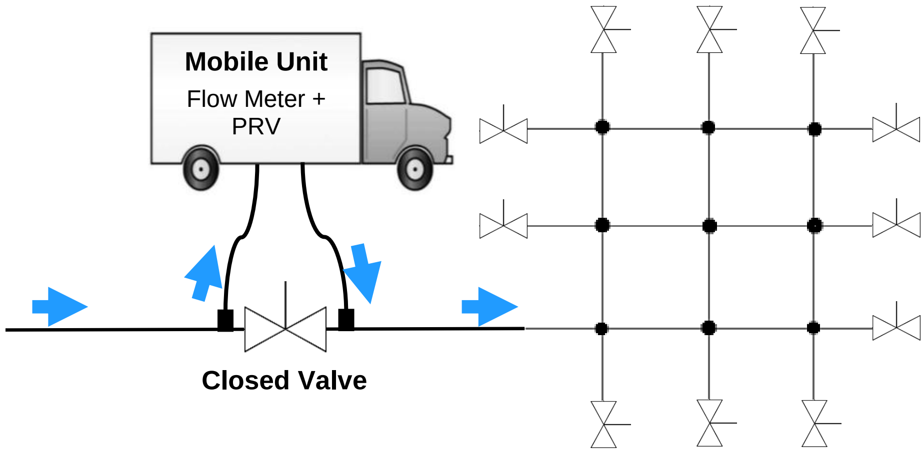

Figure 3: Mobile testing unit concept

As illustrated in Figure 3, flow is rerouted on the upstream side of a closed valve and through the mobile unit which houses an in-line flow meter and pressure reducing valve (PRV) in series before connecting into the isolated DMA. The flow meter technology and size were carefully selected to ensure that potential very low flows were within the meter detection limits. Overall, the objective of deploying the mobile unit is to cost-effectively collect reliable MNF data to compare against benchmarks representing well-performing (or "healthy") systems, thereby informing the prioritization of further leak detection investments. In fact, the development of evidence-based benchmarking metrics has been explored and are reported in Section 4.

3.4 Pressure Reduction Testing

Pressure management has been widely tested and applied outside of, with some modest implementation within, Canada. Conventionally, empirical relationships are used to estimate the potential leakage rate (L) reduction resulting from lowered pressures (P), with the most accepted concept being the Fixed and Variable Area Discharge (FAVAD) method (Lambert 2001):

[2] Pressure-Leakage Relationship: $\frac{L_1}{L_0} = \left[\frac{P_1}{P_0}\right]^{N1}$

In the absence of field data, this approach relies on an estimate of the power exponent N1 which has been reported to vary significantly in practice. A unique feature of the mobile unit, though, is its ability to conveniently test the effectiveness of pressure reduction on reducing leakage through the activation of a PRV. In other words, an in-situ N1 exponent specific to each system can be derived. This approach evidently provides an increased level of confidence to decision making in relation to any investment to be made in implementing permanent pressure management infrastructure whose costs can be formidable.

It is also important to note that the benefits of pressure reduction go well beyond that of leakage reduction. That is, by generally reducing and controlling pressures using a PRV, the supply system is subjected to generally lower stresses and often significantly reduced variations in pressures, including common dynamic pressure fluctuations during normal daily operations and often more severe short-duration hydraulic transient (i.e., surge) events. The result is that break frequencies and the occurrence of new leaks have been shown to reduce significantly, thereby effectively extending the useful life of such assets.

4 Interim Testing Results

The mobile testing unit was assembled in April 2019 and has since been deployed at 19 of the project's 22 allotted DMA sites. For each site, project activities consist of (i) training workshops to inform and prepare participants of the project and specific testing details; (ii) testing over multiple nights at both full and reduced pressure; and (iii) the reporting of results and recommendations both to the municipality and a wider audience through publications and industry colloquia. The testing setup is depicted in Figure 5.

Figure 4: Mobile testing unit set-up (left); and winter condition testing (right)

4.1 Evidence-Based Performance Benchmarking

The measured MNF_{60} for each tested DMA is plotted relative to certain DMA characteristics, such as the number of service connections or the average billed demand (ABD), as shown in Figure 5. Sequentially, the performance of any individual DMA can be assessed relative to their peers and what is estimated to be a healthy performing system of similar characteristics, denoted in this work as the MNF frontier.

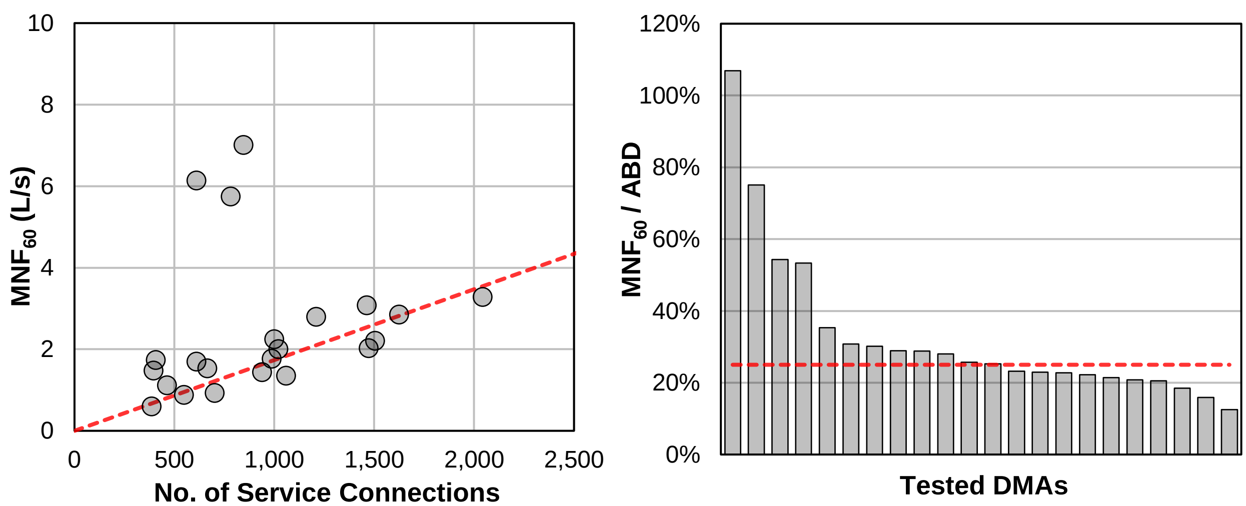

Figure 5: Sample evidence-based performance benchmarking metrics

The MNF benchmarks, represented by the red lines in each of the Figure 5 plots, represent "healthy" DMAs with minimal (or reasonably acceptable levels of) excess leakage. In turn, this level of normalized flow forms the basis for the reported recoverable leakage estimates. Table 2 outlines the values and rationale used in the development of each MNF benchmark. Note that, for the sake of brevity, only two of the several benchmarking metrics considered are displayed in Figure 5 for the purposes of illustrating the underlying concept.

Table 2: MNF_{60} benchmark development (values tentative and subject to change)

Benchmarking Basis	Benchmark Value	Rationale/Reference
Number of Connections Number of Residential Units	6.25 L/connection/h 6 L/unit/h	Analysis of test data and in-house records, verified through communications with industry practitioners
Population	2.2 L/person/h	Analysis of test data and in-house records
Watermain Length	550 L/km/h	Analysis of test data and in-house records
Ratio of ABD to MNF_{60}	25%	Analysis of test data, in-house records and in consideration of *IWA Water Loss Task Force District Metered Areas Guidance Notes (Version 1, 2007)*

In application, the measured MNF_{60} value is plotted and assessed relative to the cohort of well-performing systems clustered around the relevant benchmark. The departure from the benchmark indicates potential recoverable leakage and, when this amount is appreciable, intervention efforts become increasingly valuable. A compelling case study from the testing program is explored in the following section.

4.2 Case Study: Leak Repair Measurement and Verification

Testing results in a particular DMA revealed strong potential for recoverable leakage as a large departure was observed between the measured MNF_{60} and several benchmarking metrics. Accordingly, the municipality decided to extend its efforts and carry out a leak survey and detection exercise. This work, which employed acoustic detection technology, was able to identify the location of a substantial leak that was subsequently repaired. Thereafter, post-intervention testing was conducted using the mobile unit to measure and verify the recovered leakage. Figure 6 (left) shows the observed difference in MNF_{60} between pre- and post-leak repair testing of approximately 4.4 L/s. Furthermore, the results plotted on the project benchmarking statistics revealed the DMA returning to a performance level in the region of its healthier peers, verifying the reduction in leakage.

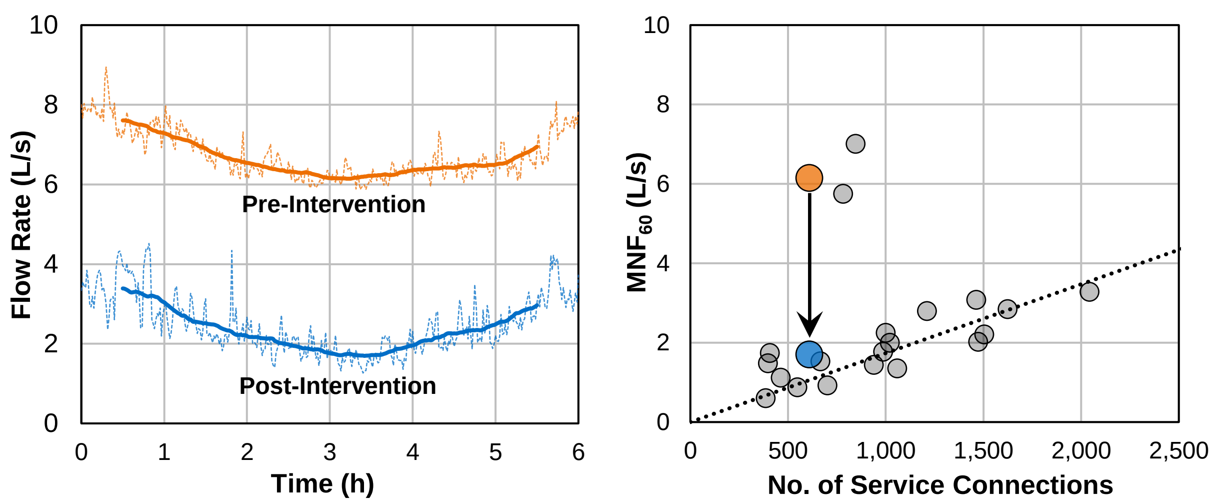

Figure 6: Pre- and post-intervention flow profiles (left) and benchmarking results (right)

The magnitude of the leak repaired resulted in the measured benefits shown in Table 3. To put these values in perspective, the measured water savings was equivalent to an annual consumption of about 505 typical single-family households (assuming 250 Lpcd consumption and 3 persons per dwelling), which amounts to nearly the size of the tested DMA itself.

Table 3: Measured and verified savings informed through the mobile testing unit

Type of Savings	Value
Treated Water	139,000 m^3/year
Financial	$426,000/year
Embedded Energy	102 MWh/year
Mitigated Environmental Impacts	4.1 tonnes of CO_2/year

The significant benefits were a result of informed intervention in only a small segment of the municipality's watermain infrastructure, suggesting further savings from proactive water loss management, both financially and environmentally, are reasonably attainable.

5 Leveraging AMI Data

Advanced metering infrastructure (AMI) provides two-way communication between the user endpoint (e.g., meter) and a fixed network, thereby allowing for near real-time meter readings. The increased granularity of consumption data – often hourly and sometimes sub-hourly – offers a wealth of customer meter information, including that of overnight demand values critical to the basic assumptions of the MNF method. Therefore, to support the project's methodologies, AMI data for residential connections was collected and analyzed from a participating municipality with AMI fully-deployed in its distribution system (one of the few cases in Canada). The objective of the AMI analysis was twofold: to document the repeatability of legitimate night consumption and, more specifically, to evaluate the magnitude of minimum consumption levels in the Canadian context to support the benchmarking metrics developed in this work.

The AMI dataset includes predominantly residential connections from three DMAs that were tested using the mobile unit as part of the IESO leakage assessment program. Furthermore, the data was collected over the period of 10 September to 26 October 2019. As with any analysis, initial efforts were focused on filtering unrepresentative data. Filters were applied to discard data associated with meters reading negative consumption, having resolutions over 1 m^3 (resolution too coarse for hourly analyses), recording overnight consumption greater than 250 L/connection/h – the 99th percentile of the dataset – assumed to be uncharacteristic of typical residential connections, and weekend demand.

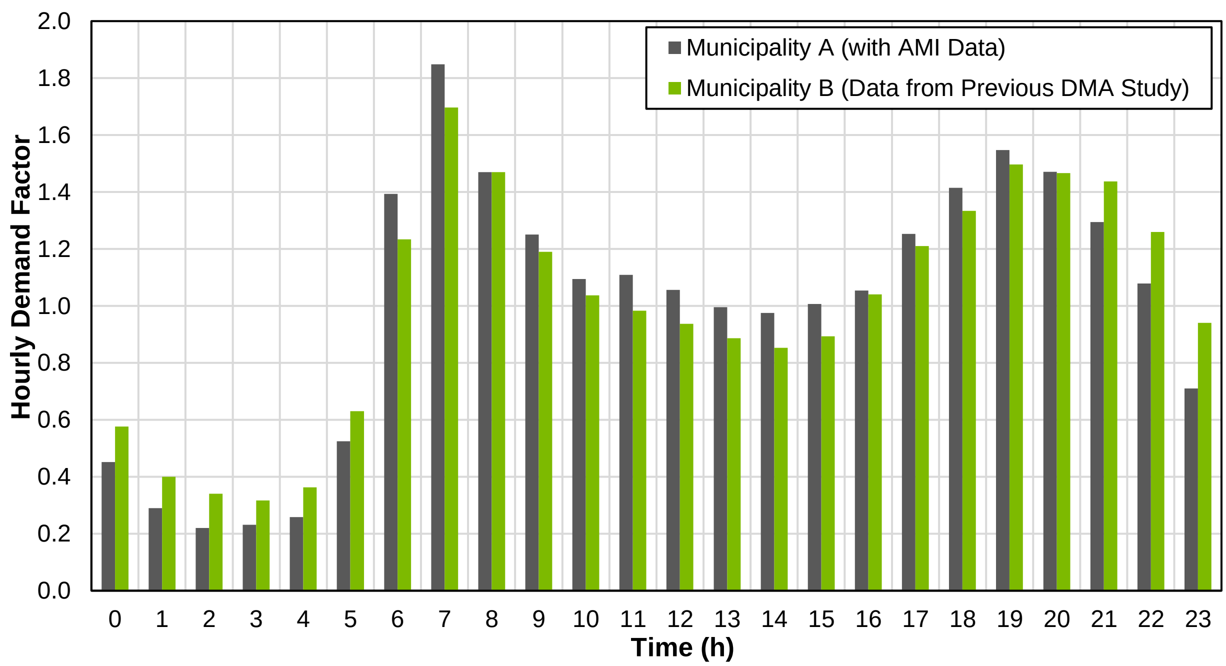

Figure 7: Diurnal AMI consumption and flow profiles

Figure 7 above shows the average diurnal consumption profile for the DMAs characterized by AMI data as well as a previous DMA study conducted by HydraTek. These profiles demonstrate how residential demand is consistent and at its lowest during the overnight period, noting that similar results have been reported globally, thereby imparting confidence in the MNF method for leakage management applied in this work. Moreover, the minimum hourly demand factor ranged from 20 to 30%, which generally agrees with values reported in the literature. Note that the data from the previous work ("Municipality B") was measured at the DMA inlet, instead of at the customer meter, and therefore accounts for any leakage present in the system.

With respect to the magnitude of minimum hourly consumption for typical residential users, analysis of the filtered AMI dataset revealed an average of 4.5 L/connection/h, surrounded, though, by an amplitude of variability. The wide range of minimum hour consumption is influenced most by the extremes of the dataset: zero registered consumption from approximately 70% of the user base or, on the other end of the spectrum, large consumption ranging between 10 and 250 L/connection/h (the filtered maximum) from just under 10% of users. Because of these principal influences, the average minimum hour consumption for a relatively small sample size (or DMA) can vary considerably from one case to another.

To further demonstrate the concept of (minimum hour) consumption variability as a function of DMA size, a resampling technique known as bootstrapping was performed on the filtered AMI dataset. The exercise involved the random sampling (with replacement) of distributions varying in size (n) to estimate the statistical properties of the dataset (n ~ 53,000). Figure 8 shows the average and degree of variability for several distributions ranging in size from 50 to 5,000 connections.

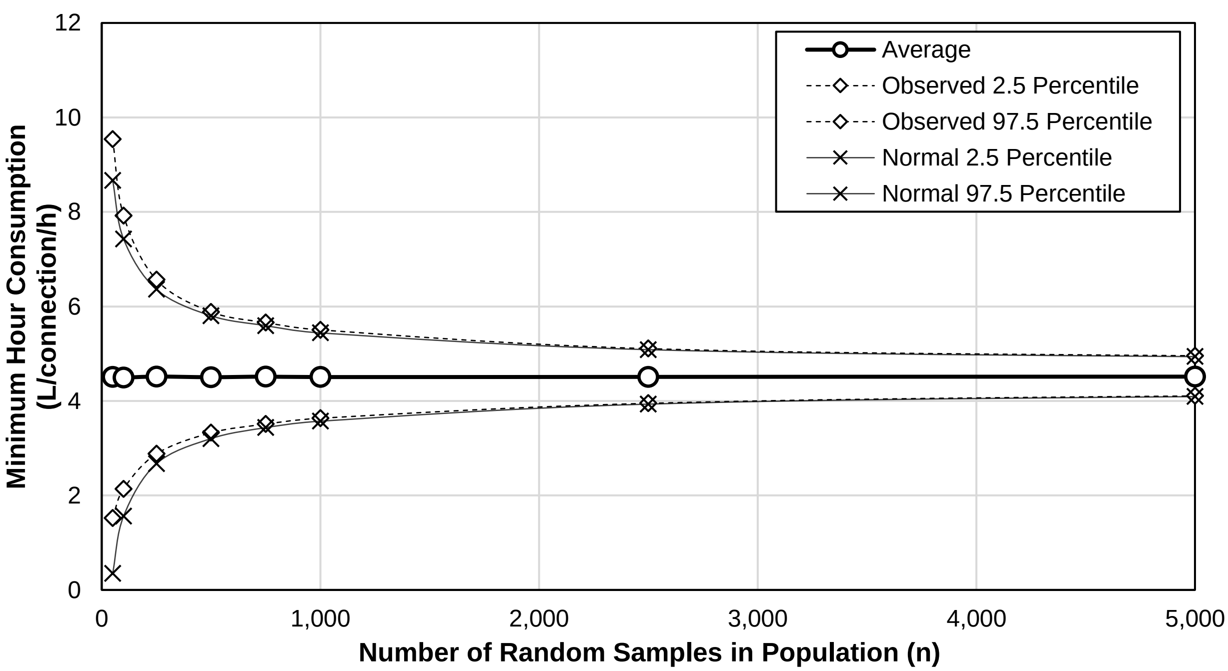

Figure 8: AMI bootstrap analysis results illustrating the relationship between variability and sample size

Results of the bootstrapping analysis suggest that as the sample size of overnight users increases, the variability in average minimum hour consumption decreases, supporting the initial findings which framed the exercise. In application, this implies that as DMA size (e.g., number of connections) increases, greater confidence is bestowed on the estimated actual consumption element of the MNF_{60} frontier. Naturally, the opposite is true for smaller DMAs where a more considerable degree of uncertainty needs to be accounted for, as depicted by the diverging 95% confidence bands in Figure 8.

Although only a starting point, the analysis of AMI data supports the lower envelope of healthy MNFs reported in this work (Figure 5 and Table 2) and helps to inform the inexorable presence of uncertainty surrounding the MNF method, especially for smaller DMAs.

6 Conclusion

Through the support of the power industry in Ontario, a mobile testing unit has been developed and deployed across district metered area (DMA) sites in several municipalities to promote water loss reduction practices. Equipped with flow metering technology capable of accurately and reliably measuring minimum night flow (MNF), and a pressure reducing valve (PRV) to test the effectiveness of pressure reduction on leakage reduction, the mobile unit serves as a cost-effective diagnostic tool used to reduce uncertainty in water loss decision-making. At the time of this writing, data collected from 19 of the project's 22 sites have been used to inform the development of evidence-based benchmarking that can assess the performance of DMAs relative to their peers. Moreover, an assessment of AMI data has imparted greater levels of confidence in the lower MNF benchmarking limit, which allows for reliable estimates of excess recoverable leakage.

Quite interestingly, the deployment of the mobile testing unit, and calculation of the associated MNF benchmarking metrics, have already been used to successfully inform intervention efforts which ultimately resulted in the remarkable savings of nearly 140 ML/year (or $426,000/year) to a participating municipality. The value of this outcome in and of itself, on a present value basis, significantly exceeds the project's costs. To this end, results from the Ontario-wide project have contributed to not only water conservation and long-term sustainability goals, but also in energy conservation and associated environmental benefits.

Acknowledgements

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