Reducing Municipal Water Loss and Energy Consumption through Pressure Management

A project delivered by HydraTek & Associates and made possible through the financial support of the Independent Electricity System Operator (IESO)

Final Report | December 2021

Executive Summary

Leakage from municipal water systems is becoming a topic of increasing concern in Ontario and elsewhere. In addition to the waste of water which has been extracted from the natural environment, treated to meet stringent water quality standards for human consumption, transported long distances and pressurized for convenience of service, these processes also consume a considerable amount of energy, largely through pumping. Accordingly, the impact of leakage reduction often goes beyond the interests of a single municipality, transecting various jurisdictional boundaries as matters related to energy management are considered. In recognition of the integrated nature of water supply and energy consumption, Ontario's Independent Electricity System Operator (IESO) sponsored this cross-sectoral project.

This project involved the development and deployment of a mobile testing unit to measure selected performance characteristics of segments of municipal water systems commonly referred to as district metered areas (DMAs). Among these include the minimum night flow (MNF), a reliable indicator of leakage, as well as the direct measurement of the pressure-dependency of flow. These metrics can be used to characterize leakage and inform pressure management practices.

The project commenced in the first half of 2019 and concluded at the end of 2021. It involved raising water loss management awareness and interest among candidate municipalities across Ontario, eight of which ultimately participated, including the Regions of Durham and York, the Cities of Greater Sudbury, Markham, Ottawa and Vaughan as well as the Towns of East Gwillimbury and Georgina. Additionally, numerous industry interactions occurred over the course of the project, including conference presentations, webinars, workshops and meetings, papers and articles, across Ontario and internationally.

Owing to the project's success, it received the PEO York Chapter 2020 Engineering Research Project of the Year award and, along with York Region, the OWWA Water Efficiency Committee 2021 Award of Excellence in the Public Sector Category. This project and its impacts have also been independently referenced by other practitioners on the global stage.

Execution of this project established the proof-of-concept for the use of a mobile testing unit to enable accurate and reliable measurements of key performance characteristics to identify the existence of leakage and to provide an indication as to its quantity. As well, the mobile unit can be used to measure and verify the extent of any leakage reduction following system interventions. Given its unique assembly, the mobile unit combines the measurement accuracy and reliability of permanent infrastructure with the spatial flexibility and affordability of temporary testing schemes.

The mobile unit was deployed a total of 22 times, including twice on two particular sites where before- and after-intervention deployments were undertaken to locate and reduce leakage. The data collected from this project's testing was combined with additional data from 3 DMAs contributed from a participating municipality for a similar project and curated to the same standards. One of the key results of this data collection and analysis process was the development of industry benchmarks relevant to the Ontario context (as well as Canada and the U.S.). Selected benchmarks representing "healthy" residential DMAs showing minimal excess leakage, expressed as the 60-minute average MNF (MNF_{60}), are summarized as follows:

- MNF_{60} = 2.2 L/h/capita (R^2 = 0.83)
- MNF_{60} = 6.0 L/h/unit (R^2 = 0.81)
- MNF_{60} = 6.4 L/h/connection (R^2 = 0.73)

These benchmarks are intended to act as a surrogate baseline measure for the presence of excess recoverable leakage. Should MNF_{60} values recorded in the field be significantly higher in magnitude than these benchmarks, the likelihood and quantum of leakage can be discerned.

Applying the mobile unit and the benchmarking approach, two sites were subjected to leak detection and repair followed by subsequent re-testing. While both sites demonstrated meaningful leakage reduction, results from one of them were truly impressive, as summarized below:

- Measured and verified leak reduction: 4.4 L/s
- Water savings: 139,000 m^3/year
- Financial savings: $426,000/year
- Energy savings: 102 MWh/year (4.1 tonnes CO_2-equivalent/year)

Finally, the mobile unit is available for commercial application and industry duplication to support widespread adoption of its use.

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Introduction

The loss of water through leakage from municipal water distribution systems is wasteful in several respects. The expenditures required to extract, treat, pump and transport the water to the point of leakage are wasted. The chemicals used to treat the lost water is similarly wasted in this process of converting the more valuable potable water to a source of groundwater recharge, sewer baseflow or other less-than-productive uses. Quite importantly, the significant amount of energy required for pumping the water from its source, through treatment processes and to transport it long distances as well as pressurize it for use is wasted. Water is a heavy substance which is commonly used for generating power and energizing modern society but, at the same time and for the same reasons, requires considerable energy to move it.

The practice of water loss management is increasingly becoming recognized as an important element of prudent water distribution system asset and operational management. The simple reduction of water loss can simultaneously achieve multiple benefits on diverse fronts. That said, the practice of water loss reduction is anything but simple.

In fact, this lack of simplicity is the result of the complex nature of both the water supply and distribution systems themselves as well as the organizations that own and operate them. Amidst the competing interests of other municipal priorities, it is often not easy to allocate sufficient attention and resources to water loss if the problem is perceived to be minor and not as relevant or urgent as other matters municipalities are faced with.

Further, the successful management of water loss requires the cross-cutting through traditional divisional lines of planning, design, construction and operation. This presents challenges when pulling together projects or initiatives that require buy-in and resources from multiple divisions, departments, groups and sub-groups within what are typically large organizations.

At the same time, the industry is also fragmented with numerous service and equipment vendors whose offerings handle very narrow slices of what is needed for the application of a holistic approach to water loss management. Unsurprisingly, this fragmentation results in the promotion of devices or activities in and of themselves, rather than the development and execution of broader schemes which focus on their appropriate and logical utilization.

Admittedly, this project does not seek to solve the larger challenges associated with the development of a rational implementation strategy for comprehensive water loss management. Further, for any such plans to be truly successful, they must recognize and embrace the inherent and, in some cases, considerable uncertainties associated with such practices and have the ability to adapt to information as it is made available.

The central theme of this project concerns the reduction of an important element of uncertainty. It seeks to increase the ability of municipalities to test segments of their systems for the presence of leakage with accurate, reliable measurements that can be repeated and verified. Armed with the results of these tests, municipalities can then decide whether or not to expend additional resources and efforts in locating and reducing the leakage, or to re-allocate these resources to better uses. It is surprising how many municipalities engage in leak detection exercises with varying degrees of success without having an objective sense as to whether or not there is any leakage to be found. Similar to the concept of water loss itself, such an approach can be wasteful. At the same time, the results from these tests can be helpful to inform the high-level desktop exercises that are typically conducted annually to estimate the degree of water loss being incurred in overall systems, a process which is heavily dependent on the quality of information it uses.

Figure 1: Inaugural mobile unit test setup

Project Motivation & Contribution to Practice

This project was about collecting data to be used as evidence when informing leakage reduction activities and practices. It was born out of difficulties that manifested themselves in a more "traditional" water loss management project and which are common in the industry, as well as the opportunity to improve upon them. These common challenges include: (i) the relatively costly practice of installing permanent infrastructure to monitor flows and, hence, leakage levels; (ii) the challenges with obtaining accurate and reliable flow measurements with more affordable temporary metering methods; (iii) the general difficulty associated with finding leaks that do not otherwise present themselves at the ground surface; and (iv) the general lack of benchmarking data, particularly in the Canadian context, for municipalities to assess whether or not their systems might be exhibiting excessive leakage.

In fact, the concept arose at the tail end of that project as the final report was being assembled, during the 2018 Victoria Day long weekend. The underlying thought at the time was "there has to be a better way." A better way of obtaining data that is affordable, accurate and reliable. A better way to deploy capital such that the denominator in any benefit-cost ratio calculation is not unduly hampered by high costs relative to realized performance improvements. A better way to help municipalities understand, and advance their approaches to, water loss management practices.

The concept of the mobile unit combines the highly accurate and reliable flow measurement afforded by permanent installations (i.e., meters in chambers) with the affordability of temporary measurements. As a bonus, it also includes the ability to directly test the impact of pressure reduction on flow (and leakage) quantities, a feature which is not possible with traditional temporary measurement and even more costly with permanent installations that exclude such features. In essence, it is a "chamber on wheels" which allows for the broad and consistent deployment of reliable testing and measuring practices.

This is not the first application of a mobile unit for such field testing. For instance, experimental research in Ottawa in the 2000s (Hunaidi & Brothers, 2007) involved the development of a similar unit which was subsequently disassembled. Nevertheless, that experience provided confidence in the approach as well as lessons and insights that were leveraged when both designing the mobile unit developed for this project as well as the project itself. One of this project's aims was to develop both the mobile unit as well as a commercial service offering that would be available long after its completion.

This project was extremely fortunate early on when one of the initial test sites appeared to have a substantial amount of excess leakage which, following the subsequent identification and repair of the leak, a retest clearly and definitively showed a substantial reduction in flow. Apart from the proof of concept that this test site provided to the project, the resulting savings were remarkable, and which have been featured in various presentations and publications since, leading to awards and recognition for this project in the industry, both locally and on the international stage. More particularly, the repair of this single leak yielded an annual water savings in the order of 139,000 m^3 (139 ML) – the size of about 40 average-sized water towers – an annual energy savings of over 100 MWh and, quite notably, a financial savings accruing to the municipality of $426,000 per year!

This project has, for the first time (to our knowledge), collected and assessed data for the purpose of establishing performance benchmarks that are relevant to Canadian (and U.S.) water distribution systems and made them publicly available. This is important as industry practices have been traditionally anchored in international experiences where water loss management is generally more evolved than it is in North America, although the design and construction standards for, as well as development patterns associated with, those systems is often quite different than what is found in Ontario systems. Accordingly, it is unsurprising that benchmarks developed for such other jurisdictions may not necessarily be directly and universally applicable.

This project has also sought to raise awareness of, and reduce barriers to, the implementation of the field-based practices to support water loss management initiatives. The importance of determining whether or not there is meaningful leakage to be chased cannot be understated, lest a municipality's financial and human resources be deployed to hunt for problems that may not exist or may be too difficult to find or deal with. There is a logical hierarchy to be followed to assist in the judicious allocation of resources, and the testing conducted as part of this project represents an important element of that hierarchy.

About the Project

This project involved the development and deployment of a mobile testing unit to measure overnight flows into isolated sectors of municipal water distribution systems and to test the impact of pressure reduction on those flows. Given the reliable predictability of human behaviour, the degree of overnight water consumption is generally consistent everywhere, allowing for the use of this data to provide important characteristics on system performance, particularly in relation to potential excess system leakage.

Eight municipalities across Ontario formally participated in the project, providing a total of 20 test sites, of which two were re-tested following leak identification and repair efforts. The project was restricted to sites with predominantly residential land uses so as to develop statistics and benchmarks that are relevant therefor from as large a sample size as the project's scope allowed.

Testing took place in the autumn and spring seasons to mitigate from the influence of automated irrigation systems and extremely cold weather conditions. The first and last tests were conducted in May 2019 and October 2021, respectively. Along the way, numerous industry interactions took place via conferences, workshops and webinars as well as through articles in various industry publications. A full listing of the related materials is available on the project website for viewing and downloading.

This report and all other materials relating to this project are available and kept up to date on the project website: www.hydratek.com/mobile_dma_testing

As noted earlier, the results of this project, including the benchmarks derived and lessons learned, are being made available publicly through this report and the materials noted above. All of the data, results, information and insights related to the tested sites are, however, anonymized throughout, although participating municipalities have access to the specific results for their individual test sites.

Mobile Testing Unit

The "chamber on wheels," as the mobile testing unit (or simply, mobile unit) was referred to previously, was a tremendous success, not only for the control of the testing process and the quantity and quality of data it was able to collect, but also as a promotional tool for the service. It continues to be available for commercial deployment following the conclusion of this project, and applications for its use have expanded beyond what it was originally intended for, all of which are positive for the industry in general.

Moreover, the mobile unit may be duplicated as and where needed, without any restrictions. Accordingly, there are no legal or administrative obstacles to overcome in order to more broadly and more frequently apply this testing method. It is hoped that the outcomes of this project and the lack of restrictions to allow for the multiplication of these testing units will form the basis for, and motivate, more widescale adoption.

Awards & Recognition

The success of this project, including the novelty of the mobile unit and more particularly considering the demonstrated value of recovered leakage that fortuitously occurred during the course of its execution, has led to various awards and recognition. These have included the Professional Engineers Ontario (PEO) York Chapter (inaugural) 2020 Engineering Research Project of the Year Award as well as the Ontario Water Works Association (OWWA) Water Efficiency Committee 2021 Award of Excellence (Public Sector Category).

As well, there have been several industry references to the work, including having been included in presentations made by two independent U.S.-based practitioners to the IWA Water Loss 2020 conference held (virtually) in China. The results of this project were also included in a 2021 Residential and Civil Construction Alliance of Ontario (RCCA) report as well as in York Region's 2020 and 2021 publications relating to its Long Term Water Conservation Strategy. Additional information, details and related materials are also available on the project website.

Acknowledgments

The materialization and success of this project was the result of a timely and fortuitous alignment of interests among various organizations and individuals within them. This section attempts to identify most of the key participants and provides some "colour" relating to their involvement. It is recognized that some names may (will) be missed, particularly amongst the numerous individuals working "behind the scenes" within the municipalities that our project team may not have come in direct contact with or, if so, only briefly. Their contributions are gratefully acknowledged. As well, some names appear more than once in the discussion below, with only the first occurrence of each being emphasized by way of bold typeface.

Delivery Team

This project was delivered by HydraTek & Associates having been conceived and led by **Fabian Papa**. Serendipitously, the timing for the project coincided exactly with the arrival of **Bradley Jenks** to the HydraTek team in pursuit of his industrially sponsored Master of Applied Science degree at the University of Toronto under the supervision of **Dr. Bryan W. Karney**. In fact, this project formed the cornerstone of the research component of Bradley's degree and much of the theoretical underpinning and technical analysis relating to this project is covered in detail in the resulting thesis (Jenks, 2021).

Figure 2: Bradley Jenks in action

The field testing component of this project was certainly the heaviest in terms of the effort, diligence and fortitude required, characterized by many overnight tests in less-than-favourable conditions. The team members involved in that testing deserve special recognition and included, in addition to Bradley Jenks and Fabian Papa, the following individuals: **Steve Genser**, **André Brideau**, **Alexander Tonelli**, **Kelvin Meng** and **Alessandro Stefenatti**. Additional internal support for the project was provided by the skilled and experienced hydraulic specialists and interns: **Johnathan Nault**, **Djordje Radulj**, **Bryon Singh**, **Michael Metallo**, **Christopher Zuccaro** and **Michael Papa**.

Extended Delivery Team

Although not formally part of the HydraTek organization, several individuals contributed their expertise and insights at various stages of this project. In particular, the Italy-based British water loss expert, **Dewi Rogers**, was consulted during conceptual development of the project and as the project unfolded. His practical experience in field testing, hydraulic modelling and training in numerous international settings specifically relating to matters of leakage management were valuable to the delivery of this project.

Another example of serendipity occurred when the HydraTek team (along with its sister division, fabian papa & partners) visited London (UK) on its corporate retreat in February 2019, during which a visit was made to the hydraulic laboratory at Imperial College London and hosted by **Dr. Ivan Stoianov** (see Figure 3). While the project had yet to be formally awarded at that time, the interaction proved extremely useful as the project progressed. More particularly, Ivan visited Toronto in May of that same year, fortuitously after the first deployment of the mobile unit. When reviewing the experience and results, Ivan insightfully suggested the concept of pressure cycling during the testing process to avoid day-to-day (or, rather, night-to-night) demand stochasticity. This pressure cycling strategy was successfully applied on all remaining tests and whose results have become a recognizable characteristic of this service. As the project approached its conclusion, Bradley joined Ivan at Imperial College London to pursue a doctorate degree. While having migrated to become part of its extended delivery team, Bradley's pleasant disposition, work ethic, enthusiasm and competence will be missed in HydraTek's office.

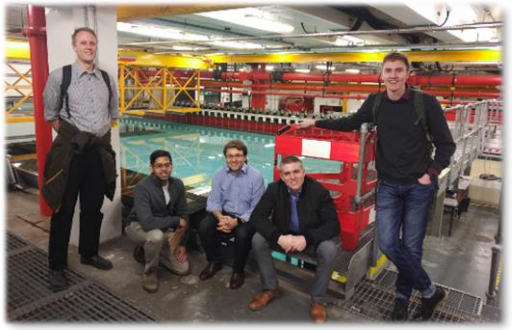

Figure 3:
The HydraTek team visiting the hydraulics laboratory at Imperial College London
(Left-to-right: Dr. Johnathan Nault, Bryon Singh, Dr. Ivan Stoianov, Alessandro Stefenatti and Bradley Jenks)

Sponsors

This project was made possible through the financial support of the **Independent Electricity System Operator (IESO)** through its Grid Innovation Fund. IESO is responsible for operating the electricity market and directing the operation of the bulk electrical system in Ontario, and it has recognized the potential within the municipal water (including wastewater) sector for improving energy conservation. This cross-sectoral collaboration provided the much-needed support to initially attract the interest of candidate municipalities and, quite importantly, to motivate the participation of those municipalities involved in this project. This is the second successful project undertaken by HydraTek with support from IESO (formerly the Ontario Power Authority, OPA). In 2011-2013, HydraTek characterized the energy efficiency of over 150 pumps in eight municipalities across Ontario to demonstrate the value, and encourage the adoption, of *in situ* field testing as well as to identify and objectively quantify the degree of energy savings that could be achieved through improvements such as pump refurbishments and/or changes in operating practices (HydraTek & Associates, 2013).

Additional financial support was provided by the **National Research Council Industrial Research Assistance Program (NRC-IAP)** and which is gratefully appreciated and acknowledged.

Industry Support

As noted above, the successful delivery of this project was the result of a collaboration between HydraTek and the **University of Toronto**, a long-standing relationship that has served both industry and academia well by effectively connecting engineering practice with fundamental theory and research. In addition to the efforts of Dr. Bryan Karney as Bradley's supervisor, the historical and ongoing advisory role played by **Dr. Barry Adams** (Professor Emeritus) is notable. To further demonstrate the strength of the connection between HydraTek and the university, the involvement of **Dr. David Meyer (né Taylor)** as the second reader of Bradley's thesis as well as general support throughout the course of the project, is appreciated. As a student intern at the time, David was instrumental in HydraTek's previous project relating to pump performance and energy efficiency which was similarly sponsored by IESO (formerly OPA), as noted above (HydraTek & Associates, 2013).

Many thanks are also deserved by the **Ontario Water Works Association (OWWA)** led by its Executive Director, **Michele Grenier**, for supporting this project at both the funding application stage as well as through conferences, workshops and trade publications where the project and its findings could be introduced and disseminated to the broader industry. These efforts will have long-lasting effects in terms of promoting the practices applied in this project for the improvement of water distribution system performance and the resultant conservation of both water and energy that it affords.

Of course, the planning, design and assembly of the equipment in the mobile unit were critically important to project's delivery. Top marks go to the skilled team at **Hard Rock Sewer & Watermain Ltd.** and the support, assistance and patience of **Michael Pedro** and **Mario Raponi** are gratefully acknowledged. Additional thanks goes to those consulted along the way and those who arranged for various key components, including: **Peter Sucharda** at **Devine & Associates** (pressure reducing valve), **Rob Derer** at **Municipal Metering Services** (ultrasonic flow meter), **Gary Fricke** at **SCG (Metcon)** (electromagnetic flow meter), **Domenic Villani** at **Tectonic Infrastructure** (industry advisory support), **Tom Moulton** at **EMCO Waterworks** (piping and accessories) and **Stacey Nichol** at **SCG (Flowmetrix)** (instrumentation and telemetry support).

Figure 4: Mobile unit equipment assembly by Hard Rock Sewer & Watermain Ltd.

This project was also fortunate to have access to data and experiences of Canada's leading water utility relating to water loss management practices, **Halifax Water**. Many thanks to **John Eisnor** for his assistance to obtain this information which helped shape the project's analytical processes.

Thanks also to **Allan Lambert** (UK) who became acquainted with this project and provided a considerable amount of thoughtful feedback as it progressed who, in turn, acknowledges the historical contributions of John May particularly in relation to advances in understanding the pressure-leakage relationship.

Participating Municipalities

This project was specifically designed for municipalities as owners and operators of water distribution systems. A sincere thanks is owed to those municipalities that participated in this project by providing access to their systems, staff time as well as financial support. This modest tribute is not at all commensurate with the scale of the efforts made to undertake activities that are generally atypical and require operational presence and support during tiring overnight (and overtime) periods. These municipalities are identified in Figure 5 and discussed below in the chronological order that they signed on to the project.

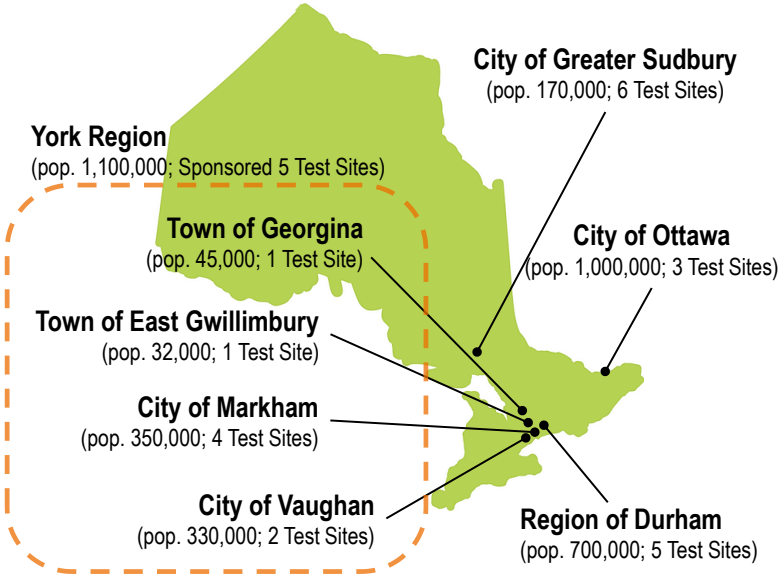

Figure 5: Participating municipalities

City of Ottawa

With a relatively long history in applying water loss management practices, Ottawa initially served as a sounding board for this project, particularly since it applied a similar diagnostic tool for experimental research in the 2000s. Many thanks go to **Joseph Hannewyk** and **Agi Motz** for supporting this project throughout its planning, application and execution stages.

Ottawa should also be commended for the show of strength (and enthusiasm) offered during each of the test nights, typically supplying five personnel and three heavily-equipped vehicles to assist with anything and everything. In an act of pure heroism, when it was discovered that the existing taps in a chamber had a thread pattern that matched nothing that either the City or HydraTek had available, the crew promptly dispatched themselves to obtain the necessary equipment and accessories from their yard and return to the site to install two new taps in record time.

Figure 6:
Mobile unit setup at Ottawa test site

A special mention has to be made for **Tim Lemieux**. This is not just for his exceptional listening skills to identify passing valves and leaks but, just as importantly, for the: (i) donation of a flexible corrugated pipe for purposes of re-directing vehicle exhaust fumes away from the work area, officially termed the TEPR (Tim's Exhaust Pipe Rerouter); (ii) the donation of a tiny three-legged camping stool; and (iii) comedic entertainment whilst conducting the work.

Other operational support was provided by **Mike Skelding**, **Quinn Broome**, **Jason St-Germain**, **Mike Bokman**, **Andrew Higgins**, **Eric Bottos**, **Warren Marleau**, **John O'Hara**, **Trevor Rolland**, **Jason Yang**, **Lance Nowak**, **Matt Steele** and **Donald Landry**. Thanks are also owed for contributing sample hourly Advanced Metering Infrastructure (AMI) customer consumption data, the use of which proved quite valuable.

Durham Region

HydraTek previously collaborated with Durham on the earlier municipal water pump performance and energy efficiency testing program supported by IESO (formerly OPA). The Region welcomed the opportunity to initially support and subsequently participate in this project, all of which is gratefully acknowledged.

Thanks goes to **John Presta** for facilitating discussions with the appropriate personnel at the Region and ultimately supporting the project. A special thanks goes to **Joeseph Green** who handled all of the internal coordination and attended the initial set up process for each of the testing nights with thoughtfulness, care and diligence. These efforts are very much appreciated.

Additional support was provided by **Dan Webster**, **Travis Hamlin**, **Luke Gerrow**, **Don Scott**, **Brent Seeley**, **Jack Steinsky**, **Greg Greenland**, **James Alexander**, **Dave Stewart**, **Eric Lamain**, **Shawn Downey**, **Dan Blakely**, **Tavis Nimmo**, **Greg Lymer**, **Brent Drew**, **Brent McKay**, **Brett Free** and **Denis Beaulne**.

York Region

This project was of particular relevance to York Region by virtue of it having among the greatest embedded energy in the water it purchases from the City of Toronto and Peel Region. That is, more energy is generally required to deliver water from its source (Lake Ontario) to York's customers as a result of both the elevation differences involved and the distance it needs to travel. Apart from the energy motivation, the resulting marginal cost of water to York Region and its local municipalities is among the highest in the province. Accordingly, reducing leakage is rightly a high priority for the Region.

Although York Region is not responsible for distribution within, but rather bulk supply to, its local municipalities, its primary role was to financially support those local municipalities that sought participation in the project. This was instrumental at lowering the financial barrier commonly associated with involvement in such projects. York also supported the project in other ways, including promotional efforts with its local municipalities, the coordinating of a presentation about this project to its Water Conservation Advisory Committee and securing the OWWA Water Efficiency Committee 2021 Award of Excellence in the Public Sector Category.

Special thanks go to **Tammy Silverstone** and **James Steele** – that name will appear again later – for initially supporting the project during the application stage. During execution, the project benefitted from the involvement of **Rosa D'Amico**, **Kristy Baidy** (now with the Town of East Gwillimbury), **Mahrukh Jawaid**, **Carlos Hurtado** and **Heather Macnab**.

City of Markham (York Region)

Quite interestingly, around the time that the funding for this project was approved, HydraTek was separately retained by Markham to design a pressure management system for one sector of its water distribution system. This led to the first test site for this project whose successful execution then provided the confidence for Markham to subsequently conduct an additional three tests within its system and for other municipalities to seriously consider participation.

Given that it was the project's first test site, particular care and attention was paid in the planning and execution of the field work. Many thanks to the support from amongst the staff and decision makers at the City, including **Shu Min Gao**, **Gord Miokovic** (now retired), **Aaron Smith**, **Eddy Wu**, **Peter Solymos** and **Celia Fan**. Additional support was provided by **Chris McCabe**, **Eddie Wong**, **Chris Farnell**, **Mario Puopolo** (now with the City of Richmond Hill), **Chris Bridson**, **Mark Jarvis**, **Bill Toleck**, **James Taylor**, **Luke Colangelo**, **Jesse Kang** and **Brendan Roffey**. As well, although outside of his field of practice, the support within Markham's organization of a collaborator on other assignments, **Robert Muir**, is very much appreciated.

City of Vaughan (York Region)

This project was a natural fit for Vaughan as it continues its evolution towards the implementation of water loss management practices. Interestingly, James Steele – mentioned earlier – had moved from York Region to Vaughan shortly after his endorsement of the project while at York. Of course, it was natural for him to support the project at Vaughan alongside the enthusiastic support of other staff there. (James has since moved on from that role.)

Additional thanks go to **Akter Hossain**, **Shathli Shaif**, **Fabian Plantamura**, **Mike Perin**, **Nolan Sherin**, **Gideon Manalo**, **David Frangella**, **Todd Sears**, **Matt Wiffen**, **Darren Darville**, **Doug McConnery** and **Diana Collura**. Additional acknowledgement is given to Vaughan for contributing data from its previous Pilot DMA project which involved the implementation of semi-

permanent DMAs – that is permanent infrastructure for periodic, rather than continuous, measurement – which was curated to the same standard as this project and further strengthened the benchmarking statistics.

Figure 7: Mobile unit setup at Vaughan test site

Town of Georgina (York Region)

Talal Latif was introduced to this project at a meeting of the York Region Water Conservation Advisory Committee and was an enthusiastic supporter of it along the way. Despite the modest resources available to the Town, Talal's efforts were instrumental in facilitating a successful test (even through unseasonably cold and snowy weather at the time of testing!).

Additional thanks go to **Miguel Wint**, **Dean Rurak** and **Craig Farmer**.

Town of East Gwillimbury (York Region)

Similar to Georgina, East Gwillimbury is a small municipality with limited resources. Thanks are owed to the following individuals whose patience and support allowed for the testing to be conducted successfully: **Joeram Vasquez**, **Larry Hollett** (now retired), **Matthew Hemmingway**, **Patrick Laforest**, **Dave Coulter** and **David Dodwell**.

The City of Greater Sudbury

Listed last due to the timing of its commitment to participating in this project, Sudbury is certainly not least as it relates to its involvement. In fact, Sudbury was the single largest participant in this project, having furnished sites for 6 tests. Again, in a case of serendipitous timing and following earlier interactions, Sudbury was re-contacted in late 2019, following the first year of tests and the impressive water savings at one test site noted earlier and at the time when **Cheryl Beam** returned from leave. Cheryl had seen a previously published article (Papa & Jenks, 2019) and enthusiastically committed to filling the remaining allocation of test sites available at the time. Cheryl's keenness and overall efforts towards this project were greatly appreciated.

Thanks for additional support goes to **Phil Gunthorpe**, **Jesse Bertrand**, **Luciano Valle**, **Larry Cormier**, **Roger Joanisse**, **Rob Snow**, **Chris Hannon**, **Dan Friel**, **Christopher McNeil**, **James Epple**, **Spencer Dailey**, **Joel Lavergne** and **Robert Matheson**.

Figure 8:
Mobile testing unit outside Sudbury water tower

Abbreviations

The following abbreviations are commonly used in this report:

AMI	Advanced Metering Infrastructure
AMR	Automatic Meter Reading
DMA	District Metered Area
GIS	Geographic Information System
HGL	Hydraulic Grade Line
IESO	Independent Electricity System Operator
MLD	Million litres per day
MNF	Minimum Night Flow
MNF_{60}	Centralized 60-minute average MNF
NRW	Non-Revenue Water
N1	Leakage exponent (used in orifice equation)
PMA	Pressure Managed Area
PRV	Pressure Reducing Valve

An additional resource for industry-standard terminology relating to water loss management is *Standard Definitions for Water Losses* (Pearson, 2019).

Theoretical Underpinning

Water Loss Management

The efficient and effective practice of water loss management and, more broadly, non-revenue water (NRW) management, requires an amalgam of disciplines, generally described as follows:

- **Hydraulic Engineering**: The modelling and analysis of water supply and distribution systems requires sufficient technical training and practical experience to properly understand and predict how these systems perform in practice. This also includes an understanding of the details and nuances of engineering design relating to these systems.
- **Operations & Field Testing**: Modelling and analysis are of limited utility without informing these processes with actual performance data and other forms of evidence that can only be gleaned through field testing and observation. Some common practical realities are the degree to which valves or other devices function as intended as well as actual conditions differing from official records.
- **Economics & Decision Making**: There is a trade-off between the amount of resources that can reasonably be afforded to be invested in the pursuit of NRW reduction and the reasonably expected return on such investments. These trade-offs cannot be formulated without financial information as well as reliable performance information. The rational and judicious allocation of capital demands the application of economic assessments and decision analysis on the basis of both the availability as well as the reliability of this information.
- **Probability & Uncertainty Analysis**: It is important to recognize that effectively all information used in the practice of water loss management – and engineering in general – is subject to varying degrees of uncertainty. It is therefore valuable to attempt the characterization of such uncertainties and to understand their potential impacts on analyses and resulting perceptions. The probabilistic characterization of data and incorporation into analysis methods can yield useful insights that can guide decisions.

The practical reality is that relatively few practitioners have the necessary blend of practical training, exposure and experience in these disciplines, although this is evolving. Further, and with the exception of only a few, the internal organization of most municipalities have not historically been structured to allow these practices to fully flourish. That too is evolving as the general industry trends towards the formal adoption of asset and operational management practices, including the optimization of infrastructure systems to deal with the combined influences of aging infrastructure, increasing densities and costs.

The efficient and effective practice of NRW management involves the intelligent application of two primary activities. The "top-down" assessment methods (e.g., water balances and audits) are relatively affordable desktop studies to conduct, being an inventory of system inputs and outputs over a defined period, but suffer from a lack of granularity and are heavily susceptible to estimation uncertainty. "Bottom-up" assessment methods, on the other hand, are undertaken at the pipe-level and naturally involve more complicated and resource-intensive activities to observe and measure the performance of systems and components thereof. Ideally, the appropriate ratcheting of these approaches, each progressively informed by its counterpart, will ultimately lead to their convergence. That is, the detailed, accurate and reliable information obtained from "bottom-up" analyses informs "top-down" assessments and *vice versa*. The result is a positive feedback loop between the continuous assessment of system performance, intervention efforts as well as the measurement and verification of the achieved leakage reduction. It is therefore important to understand the full spectrum of possible activities, their purposes, resource requirements and expected outcomes, in order to navigate the uncertainties associated with this practice.

This project was concerned with the collection of pipe-level data at a scale that can inform further, more detailed and costly pipe-level assessments (e.g., leak detection) and provide information to support top-down assessments. It also allows for the direct measurement and verification of interventions imposed to reduce leakage so as to evaluate such efforts and help guide the modification and improvement of the techniques applied. Put simply, this project was conceived to develop the tools and benchmarks that can increase confidence in the water loss management investment decision-making process.

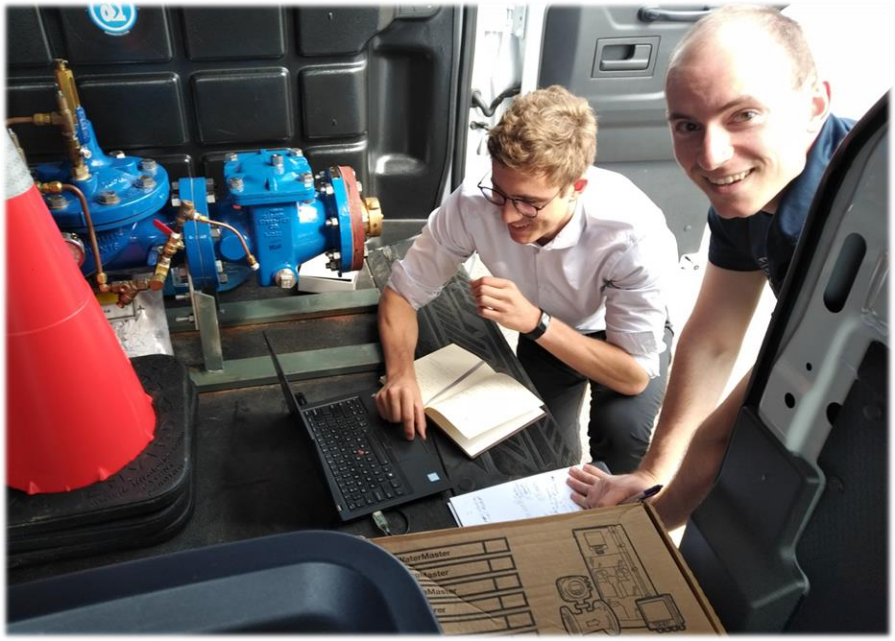

Figure 9: Bradley Jenks and Alexander Tonelli programming electromagnetic flow meter

District Metered Areas (DMAs)

The concept of district metered areas (DMAs) is to divide what are typically large, interconnected water distribution systems into smaller discrete sectors (see Figure 10). Implementation of DMAs enables the assessment of performance characteristics at a more detailed and granular level. From the authors' knowledge, the concept originates as far back as the 1980s (IWA Water Loss Task Force, 2007) and has been progressively applied in various forms and across many continents since. This disaggregation of the overall system allows for comparative assessments amongst DMAs. Such assessments can, in turn, inform decisions as to which system sectors warrant additional attention and resource allocation, whilst avoiding unnecessary investment in sectors where returns may be negligible.

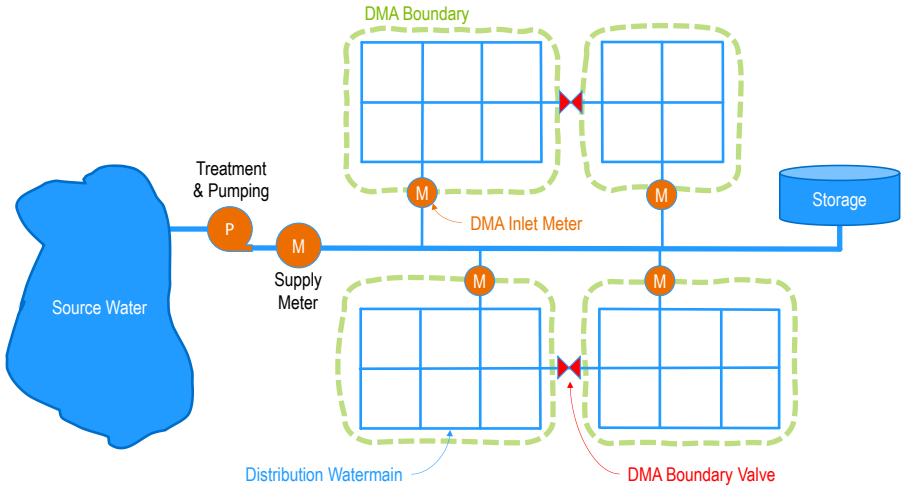

Figure 10: Conceptual diagram of DMAs within a water supply and distribution system

In addition to the possibility of conducting mass balance assessments by comparing the (net) volume entering the DMA with the consumption metered therein, certain valuable performance characteristics can be observed and measured. In particular relation to this project is the minimum night flow (MNF) performance characteristic.

Rationally speaking, the permanent installation of DMAs should be based on an economic assessment weighing the value of the estimated recoverable leakage against the cost of implementation. By testing DMAs on a temporary basis, the relevant information can be derived that will (or will not) support the generally high investment required for DMA implementation.

Minimum Night Flow (MNF)

As its name implies, this performance characteristic is based upon the measurement of the (net) inflow to a DMA during the overnight period when consumption is at its lowest. Given the typical variability observed in this data, averaging techniques are commonly applied to smooth the data. The overall industry often uses 60-minute averaging for the data, although smaller averaging periods are certainly possible and were explored in this study.

The inflow to a DMA is comprised of two components: (i) consumption, as noted above; and (ii) leakage. When consumption is at its lowest, leakage represents the largest fraction of total flow and, therefore, its characteristics can be more readily observed. This typically occurs between the hours of 2 and 4 am. This is demonstrated in Figure 11 based on sample DMA inflow data and an estimation of leakage therein based on the benchmarking statistics derived in this project.

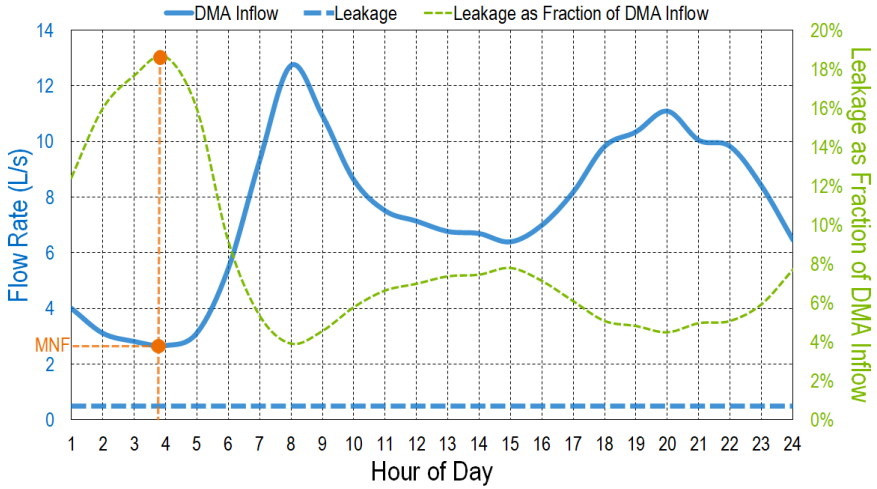

Figure 11: Sample DMA inflow data showing estimated leakage and corresponding leak-to-inflow ratio

Further, due to the regularity and, therefore, predictability of residential consumption patterns, the MNF can be a reliable indicator of the extent to which leakage exists in a DMA and to what extent. This topic is discussed further in the next section.

Predictability of Consumption Patterns

The predictability of consumption patterns in residential DMAs is clearly visible in Figure 12 where flow characteristics from three relatively "healthy" DMAs are compared. The variability among these results is quite small, lending confidence in the use of the MNF as a useful and reliable performance indicator.

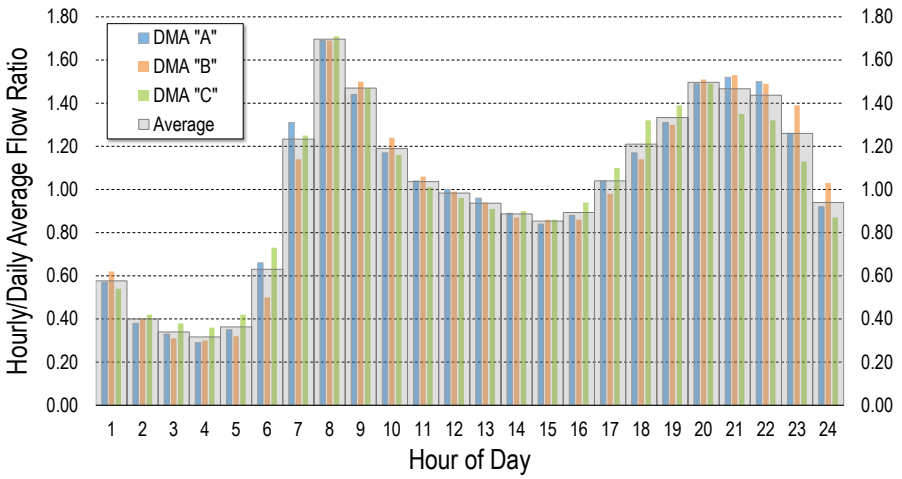

Figure 12: Comparison of flow patterns from three independent residential DMAs (Nault, Hossain, Panjwani, & Papa, 2019)

Influence of Irrigation

The use of automated irrigation systems during warmer months (Figure 13) will yield poor or useless results. Figure 14 presents a statistical analysis of hourly data for the same DMA for monitoring periods with and without automated irrigation, including both average hourly values as well as the measured ranges. Not only does the irrigation component of the demand have the potential to dwarf the diurnal peak demands during non-irrigation periods, the variability of measured flows is shown to also be considerably higher during irrigation periods. Accordingly, it is necessary to restrict any MNF measurements to periods with no irrigation. While this is possible (albeit often uncomfortably cold) in temperate climates such as Ontario, this approach (i.e., MNF analysis) may not be as directly applicable in warmer climates.

Figure 13: Example of irrigation discovered during night of testing

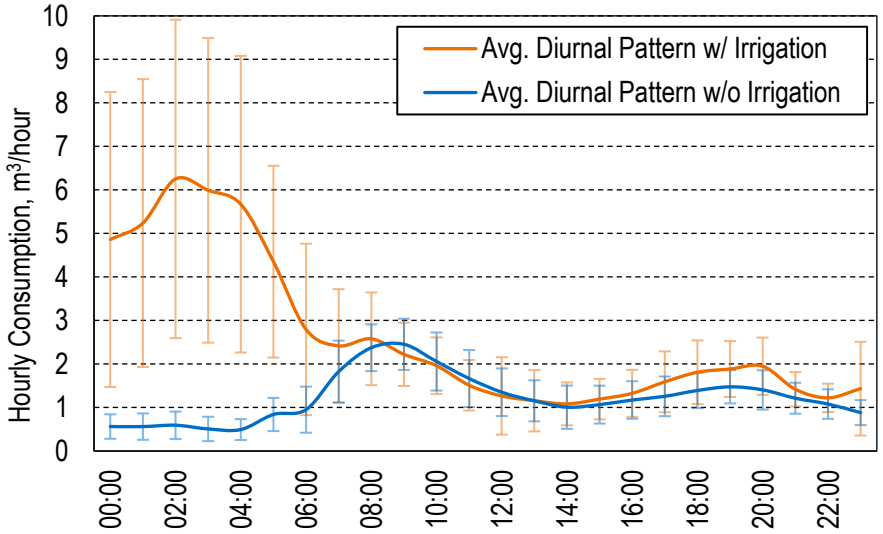

Figure 14: Analysis of sample DMA data during periods with and without Irrigation, showing averages and the range of measured values (Courtesy: Steve Genser, Infrastructure Initiatives)

It is noted, however, that such restrictions related to irrigation can be avoided when Automatic Meter Reading (AMR) or Advanced Metering Infrastructure (AMI) systems are present. In these cases, mass balances can be performed in order to directly calculate leakage quantities.

Pressure Management

One of the most effective approaches to controlling leakage, particularly if comprised of widely distributed small leaks, is through pressure management. That is, wherever leakage exists, the leak flow rate is higher when subjected to higher pressures, and lower with lower pressures.

While the concept applies to the broad-scale pressure zones of water distribution systems, typically through the control of pressures at pumping facilities and the sensible selection of service areas based on topography, this work focusses on the management of pressure at the neighbourhood scale. More particularly, a logical progression in the evolution of a DMA is to impose pressure controls, converting it to a pressure managed area (PMA). This is accomplished by introducing one (or multiple) pressure reducing valve(s) (PRVs) at the DMA inlet(s).

Pressure management may take both passive and active forms. In the case of passive pressure management, a PRV controlling pressure to a PMA may simply be set to a single (constant) value that will yield acceptable performance across the range of demands in the area it serves. This level of acceptable service is typically governed by ensuring pressures are above a minimum standard established by the municipality or governing agency. Active forms of pressure management, on the other hand, can take on varying degrees of complexity, including time-based pressure settings, or flow-modulated pressure control informed by hydraulic modelling and/or closed-loop telemetry systems in some instances. Pressure management accomplishes several objectives simultaneously, including: (i) limiting the amount of water exiting the system from existing leaks by virtue of the pressure-dependency of flow; (ii) significantly dampening or eliminating pressure transients (surges) that may be present in the system; and (iii) limiting the excess pressure and resultant stresses imposed on watermain piping and related components, thereby improving their longevity.

In 2014, Halifax Water received the Canadian Society for Civil Engineering (CSCE) Excellence in Innovation in Civil Engineering Award for the implementation of pressure management in a portion of its distribution system. That project achieved savings of 40 million litres per day (MLD) which, at the time, represented $600,000 in annual savings (CANAM Buildings, 2014).

The inclusion of a PRV in the mobile unit used for this testing program allowed for the direct measurement of pressure management effectiveness on each of the DMAs tested. This information was subsequently used as further evidence for characterizing any excess leakage, as well as to support the economic assessments relating to the consideration of PMA implementation.

Figure 15: Top of PRV with valve position indicator

Mobile Unit

Figure 16: Mobile testing unit

Anatomy

The mobile unit is effectively a "chamber on wheels" given that it contains the basic features found within a chamber used for a pressure managed area (PMA). More specifically, the mobile unit houses flow metering equipment, a pressure reducing valve, isolation/control valves, various taps and ports for pressure monitoring as well as air management and drainage functions.

The mobile unit was skillfully mounted onto a steel frame which, in turn, was securely fastened to the chassis of a commercial trade van, pictured above. The interior anatomy of the mobile unit is illustrated in Figure 17.

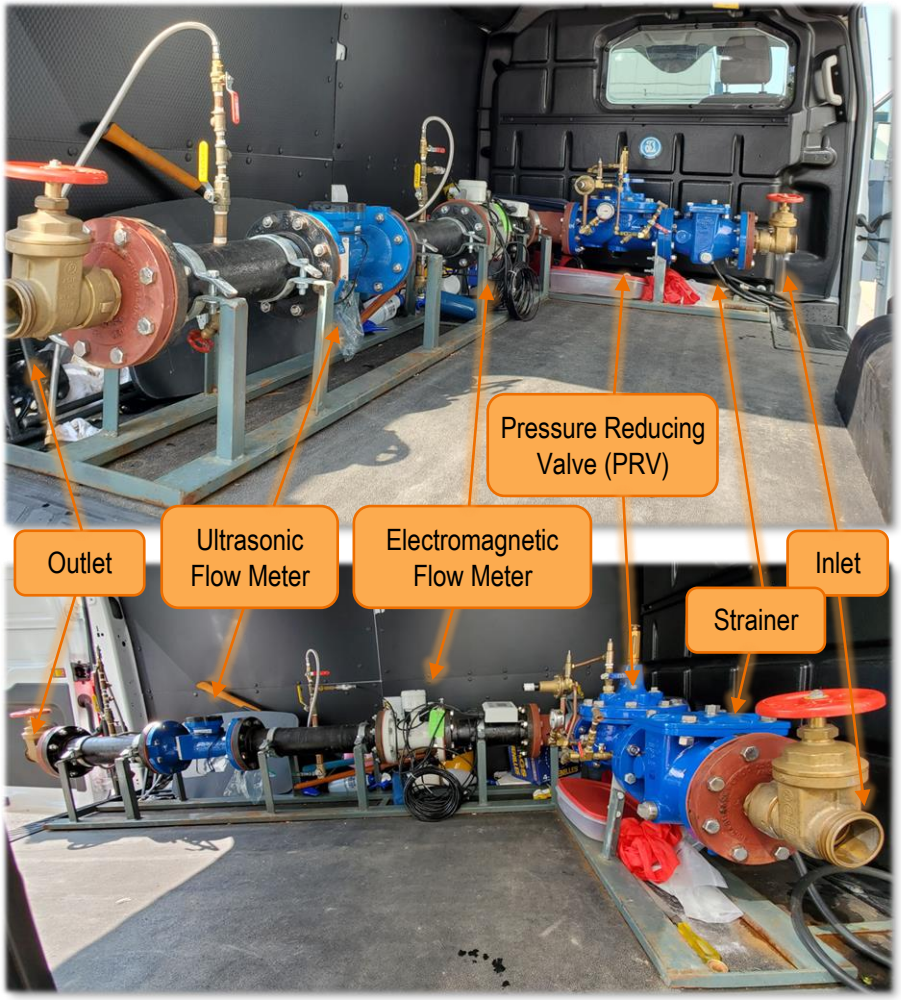

Figure 17: Anatomy of mobile testing unit

The subsequent pages discuss the various functions of the key devices within the mobile unit, additional equipment needs for its operation and practical hydraulic limitations relating to its use.

Flow Metering Function

The mobile unit was specifically designed to allow for the accurate and reliable measurement of flow rates into DMAs on a temporary basis where other temporary flow measurement technologies often experience challenges. It employs in-line flow meters – that is, the flow passes directly through the devices – which generally offer the highest degree of accuracy among available technologies. Such in-line meters, however, are typical of permanent installations within below-ground metering chambers as well as in treatment plants and pumping stations, all of which are fixed in place. The mobile unit allows for the application of this technology on a temporary as well as geographically independent basis.

In contrast to in-line flow metering, temporary flow metering is typically accomplished using: (i) insertion flow meters whereby velocity is measured through a probe extended into the flow path, commonly using electromagnetic technology; or (ii) clamp-on ultrasonic flow meters, a non-intrusive method whereby transducers, which emit and receive sound waves to determine flow velocity, are placed on the outside surface of the pipe. Under the appropriate installation conditions, each of these technologies are capable of producing accurate readings, although it is noted that such considerations are not always reliably achieved in the field for a variety of reasons. Apart from installation conditions, it is important for the proper application of these technologies that the flow velocity, particularly during overnight periods when demand is at its lowest, is within the applicable operating range (i.e., above their minimum detection limits).

These low flow velocity considerations become increasingly important for smaller DMA sizes. They are also often an inherent characteristic of Canadian (and U.S.) distribution systems whose pipe sizes are predominantly determined by fire flow capacity requirements. This circumstance differs from many other parts of the world where fire flow requirements are not as onerous.

Flow Meters

Although the mobile unit includes two flow meters placed in series, it is noted that only a single flow meter is needed. The two flow meters used employ different technologies: (i) an electromagnetic flow meter which employs Faraday's Law of induction, whereby the flow passing through a magnetic field imposed on it induces a voltage proportional to the velocity of the flow; and (ii) an ultrasonic flow meter which measures the time it takes for sound waves imparted on the flow passing through the device to calculate the average velocity thereof.

Figure 18: Statue of Michael Faraday in London (UK)
(Photo Credit: André Brideau, FP&P HydraTek 2019 Corporate Retreat)

The existence of these flow meters having differing technologies allowed for both the verification of flow measurements as well as the ability to compare and contrast their performance and other practical characteristics. Two key considerations for flow meter selection include: (i) the applicable flow range the meter is capable of accurately and reliably detecting; and (ii) the installation conditions. Concerning the latter, the mobile unit included upstream and downstream straight pipe lengths that exceeded the manufacturer's minimum specifications. This was to avoid hydrodynamic effects (e.g., non-uniform velocity distribution, swirling of flow, etc.) that may otherwise impair the accuracy of the flow measurement. Wherever practical, it is generally recommended to employ as much straight pipe length as possible, particularly on the upstream side. Flow straighteners may also be considered to promote a uniform flow distribution.

Pressure Reducing Function

Since leakage from a pipe system is directly related to the pressure of the contained fluid, an important concept in distribution system water loss control is pressure management. In this project, it was both valuable and straightforward to include a pressure reducing valve (PRV) in the mobile unit to directly measure the beneficial impact of pressure reduction on flow reduction.

A PRV allows for the pressure in the DMA to be controlled to a specific level and, in so doing, the relationship between pressure and flow can be measured. While there may be some pressure-dependent overnight consumption, this work applies the reasonable assumption that the vast majority of pressure-dependent flow (during the overnight period) is expected to be by way of leakage. Accordingly, the degree of leakage in a DMA may be both verified and characterized through the measured pressure-leakage relationship.

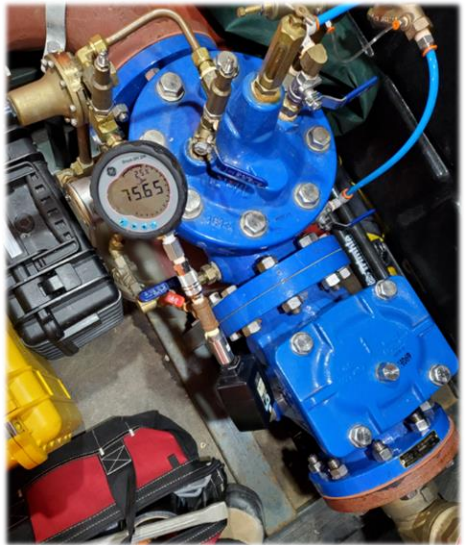

Figure 19:
Overhead view of PRV and strainer

Measuring the in-situ pressure-leakage relationship is an important value-added feature of the mobile unit when compared against traditional temporary DMA monitoring which is typically only able to measure flows. It also affords the ability to determine whether an investment in permanent infrastructure of this sort is expected to be worthwhile.

The PRV also played a key role in determining whether the boundary integrity of each tested DMA was achieved. After initial setup, and prior to the measurement period, a pressure drop test on the DMA was conducted to verify that the boundary valves were holding or if there were any connections to the system that were not adequately mapped when the DMA was designed. By lowering the pressure in the DMA with the PRV, a pressure differential across the boundary valves is created. If there is a lack of hydraulic integrity at any of these locations, the pressure in the DMA would not hold at the established PRV setpoint. Although this is a fast and reasonably reliable method of testing boundary integrity, preference is given to zero-pressure testing of each of the boundary valves. Additional discussion on these matters is provided in the Testing Methodology section of the report.

It is noted that a strainer is included immediately upstream of the PRV unit to prevent any debris or sediment which may be present in the flow from clogging the pilot lines or otherwise impairing the function of the PRV.

Additional Equipment

Apart from the key flow metering and pressure reducing devices noted above, the following additional equipment was included in the mobile unit:

- Gate valves at either end of the unit.
- Taps on the top and bottom of certain pipe segments to allow for the expulsion of air as well as draining of the unit.
- Ports for pressure gauges at various locations, including upstream and downstream of the PRV as well as at the downstream end of the piping within the unit.
- 65 mm (2.5”) and 100 mm (4”) fire hoses of varying lengths.
- Various fittings so as to allow for adaptation from site-to-site.

A digital listening device was also included as part of each deployment to assist with the identification of any DMA boundary valves that may be passing water. Such measurements were taken to improve matters for the sake of the testing data quality.

For this project, a considerable amount of data both within the unit and in the field was observed and collected, requiring the placement of pressure and flow logging devices within the unit as well as pressure logging devices at selected hydrants within each DMA.

Applicable Flow Range

When designing this (or any other) mobile unit, a balance must be struck between the size of componentry used and its resulting hydraulic impacts. That is, smaller componentry (e.g., flow meters, PRV) allow for the measurement and control of smaller flow rates relative to their larger counterparts. At the same time, however, smaller componentry results in increased friction (head) losses from the supply source into the DMA. Of course, smaller componentry is generally easier to manage as well in terms of space requirements, hose sizes, etc.

The mobile unit was designed to handle lower flow velocities than what could otherwise be achieved using traditional temporary flow metering technologies in order to cover the gap that exists in this regard. Considering the limitation noted above, the head loss characteristics were rigorously studied in advance of, and subsequently measured after, its construction. More particularly, the head loss characteristics for each installation type were measured and recorded in detail, noting that there were some key differences relating to matters such as tap size, piping configurations within chambers, hose diameters and lengths as well as whether the connection to the system occurred through taps in chambers or at hydrants or, in one case, a combination of each of these types. It is noted that the vast majority of hydraulic losses are attributable to the hoses and, accordingly, it is desirable to minimize the hose length required and maximize the diameter that can be used.

A sample of the resulting head loss characteristics is presented in Figure 20, which demonstrates the beneficial impact of larger tap sizes and the use of larger diameter hoses, wherever applicable. It is important to note that, the use of larger hose diameters was found to be constrained by the size of the chamber opening from the surface. A typical 60 cm diameter chamber opening was found to not be sufficiently large to allow for the pressurization of 100 mm (4") diameter hoses while still allowing for egress from (and ingress to) the chamber.

These results are helpful at identifying the applicable flow range that can be considered for each candidate DMA based on its particular size, access conditions and available pressure characteristics. These matters become increasingly relevant as the DMA size increases and, hence, so too does the anticipated overnight flow rate.

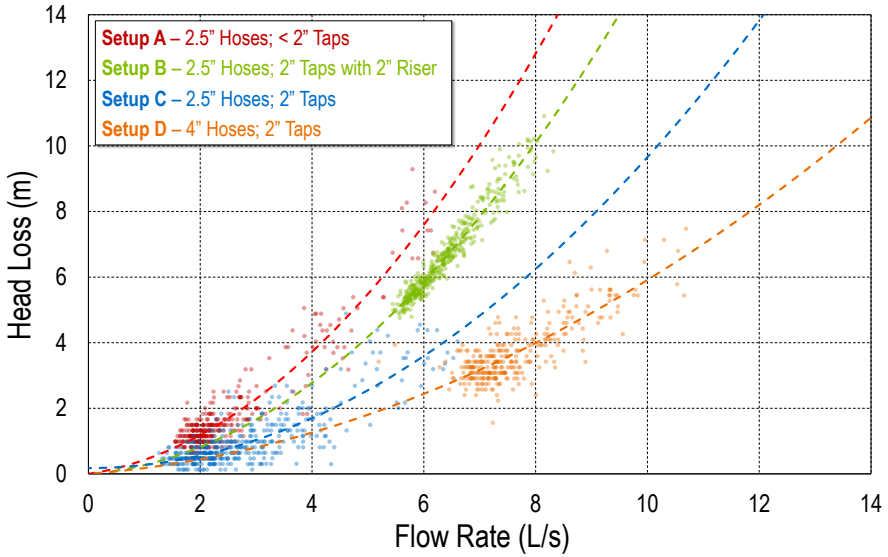

Figure 20: Measured head loss characteristics for various setup conditions (25' hose lengths)

Figure 21: Larger diameter hoses are used to minimize hydraulic losses where flow rates are high (left image) and in hydrant-based connections where hose lengths are typically long (right image)

Testing Methodology

DMA Planning

Planning is an important part of any field activities given the intensity of resources generally required and the potential impacts on drinking water systems for which there is deservedly a heightened level of awareness and control. While each circumstance is somewhat unique, there are some concepts which can generally be applied when identifying locations for, and configuration of, candidate DMAs. These may include:

- Prioritization of areas where leakage is known to occur and where there has been a relatively high historical frequency of watermain breaks.
- Prioritization of areas where common operation factors contributing to high leakage may be present, such as high operating pressures, wide fluctuations in dynamic pressures and a high frequency and/or magnitude of transient (surge) pressures.
- Prioritization of areas where the age and materials of watermains may tend to exhibit higher levels of leakage.
- The identification of DMA areas that are of a suitable size for the testing methodology being deployed.
- The identification of DMA boundary valves that need to be inspected, tested and operated for the work.

This is often an iterative process with several candidate sites being developed and whittled down to the identification of individual sites to be tested. Factors beyond those listed above may also influence the practicality of DMA testing, such as whether any other projects are planned or ongoing, such as watermain replacements or relining, for example.

DMA Preparation

There are three key components relating to the preparation of DMAs for testing using the mobile unit: (i) site reconnaissance; (ii) tap installation; and (iii) zero-pressure testing of boundary valves.

Site Reconnaissance

There is often no suitable substitute for site reconnaissance given that the available information sources and tools may be outdated, incomplete or inaccurate. Certainly, there have been great strides at improving the information available and tools to conduct such planning and preparation work, and these have had the general effect of reducing field-related efforts; however, site visits play a critical role in the DMA preparation process.

During the site reconnaissance process, practical matters such as mobile unit setup and exact boundary valve locations can be assessed for feasibility as well as for any traffic control requirements. Candidate valve chambers for the installation of taps to which the mobile unit will connect are perhaps the most important element to inspect. More particularly, the chambers should have sufficient interior space available on either side of the isolation valve to install suitably sized taps (e.g., ideal minimum of 50 mm or 2" diameter). As well, it is useful to understand whether the chamber drains freely or requires pumping (and at what frequency).

The results of the site reconnaissance process can either confirm (or inform alterations to) the DMA testing plan as well as provide the necessary information to the municipality for the arrangement of tap installations. Additional activities that may be conducted during the site reconnaissance include the checking of key valves and hydrants for suitable operability.

Tap Installation

As noted above, the installation of taps logically follows the site reconnaissance work. These installations may be done by the municipality's own forces or it may be subcontracted. Whatever the case, and as it relates to this project in specific, including threaded fittings and a ball valve on the tap with the ability to terminate the tap with a 65 mm (2.5") standard fire hose thread (male) is ideal. This setup allows for connection of the mobile unit with a swivel female hose end. Although compression fittings were used in some instances, restraint issues were occasionally encountered. Accordingly, this practice should be minimized or avoided to the extent possible.

Zero-Pressure Tests

Zero-pressure testing involves the closure of each DMA boundary valve and an immediately adjacent valve (or set of valves) whilst monitoring a hydrant in between. The objective of the test is to directly observe whether the intended boundary valve is tightly closed which, of course, improves the likelihood of success during the DMA testing process. While this is certainly the best method of eliminating a potential source of uncertainty and error in relation to confirming hydraulic integrity of the DMA, it commonly involves having a select number of customers being temporarily out of service. Accordingly, advance notice to impacted customers may be required before commencing such activities. Moreover, there is the need to flush the affected watermain segment thoroughly following this process to expel water that had been subject to depressurization and replace it with new water from the adjacent system for water quality maintenance purposes. When planning and conducting zero-pressure tests where more than one observation hydrant may be available, it is generally desirable to use the highest elevation hydrant such that the risk of complete depressurization of the watermain is minimized.

In conjunction with, and occasionally in place of, zero-pressure tests, the PRV in the mobile unit may be used to temporarily impose a reduced pressure in the DMA. In so doing, the hydraulic integrity of the DMA can be observed by its ability to maintain the pressure setpoint established on the PRV. The resulting pressure drop imposed by the PRV will result in a pressure differential acting on the boundary valves which, in the case of a valve that is not closed tightly, will result in water entering the DMA and seeking to re-establish the pressure in the system. This method, while convenient, is not always reliable. Further, if this method fails to confirm hydraulic integrity, it does not provide any information with respect to which of the boundary valves may be passing. As a result, additional efforts are required in the field to potentially check all of the boundary valves.

To assist with identifying the extent of water passing at valves, listening equipment may be used at the valves, particularly when a pressure differential is imposed. Such devices are useful to monitor the impact of operating the valve (e.g., cycling between partially open and fully closed several times to help seat the valve, colloquially referred to in the industry as a "crush-and-flush" process).

It is not uncommon to find that valves do not close tightly on their first attempt or after several attempts. In some instances, perfectly tight closure is simply not possible, and judgment is required with respect to whether or not the extent of water passing the valve is acceptable for delivering reliable test results. It may be necessary to re-configure the DMA with alternative valves in order to obtain data of appropriate quality.

Disinfection

A rigorous disinfection procedure was developed and followed prior to each deployment of the mobile unit, designed to exceed equivalent disinfection procedures for watermain systems. This involved the preparation of a 1% (10,000 mg/L) hypochlorite solution and placement of the solution within each of the mobile unit components, including its various ports and at each hose joint before making connection. Hand swabbing and spraying of such exposed fittings is also performed. The volume of the hypochlorite solution for each disinfection process was based on the total volume of the mobile unit's piping as well as the hoses to be disinfected with the aim of achieving a uniform concentration and a contact time in accordance with relevant regulations governing watermain disinfection. Dechlorination chemicals (e.g., pucks and/or crystals) were used following the disinfection process in the quantity necessary for the volume and concentration in question during the subsequent flushing of the unit. All exposed ends were closed and protected with disinfected caps and/or plugs until deployment.

Figure 22: All equipment is aggressively disinfected prior to each deployment

Mobile Unit Setup & Operation

The testing procedure applied for this project generally included more data collection than would be absolutely necessary, depending on the application at hand. This was done to properly characterize all aspects of the deployment and the resulting impacts on the system, in part to properly understand these matters, and in part to provide a level of comfort to the participating municipalities in relation to the ability of the testing method to not unduly impair operation of the system. As the number of deployments increased over the course of the project, the relative importance of data collection for purposes of appropriately interpreting results became increasingly clear.

The following is a list of data typically collected at the test sites in this project:

- Pressure in the supplying system, as measured at a nearby hydrant on the upstream side of the mobile unit.
- Pressure in the DMA as measured at:
  - A nearby hydrant on the downstream side of the mobile unit.
  - A hydrant at or near the location of highest elevation within the DMA, referred to as the "critical" hydrant.
- Pressure on both the upstream and downstream sides of the PRV.
- Flow in each of the flow meters.
- Elevations for each of the pressure gauges and transducers used for logging, using GPS-based survey equipment with high accuracy (i.e., typically in the order of less than 2-5 cm vertically, depending on measurement conditions).

Pressure and flow were generally collected at 1-minute intervals, although higher frequencies are certainly possible, if desired. It is important to note that elevation data is based on the location of the pressure gauges (and transducers), rather than ground elevations, in order to obtain an appropriate measurement of the hydraulic grade at these locations. Given that testing of each site occurred over multiple nights, the location of the mobile unit was marked with paint on the ground surface such that its location could be replicated each night.

With assistance from the municipality's operators, connections from the taps in the chambers (or hydrants) to the mobile unit were made with the disinfected hoses. The hoses were subsequently pressurized, followed by pressurization of the mobile unit, including the bleeding of air from the unit. Boundary valves were then closed to isolate the DMA, with the isolation valve located at the site of the mobile unit connection being the last to be closed. The closure of the last valve was generally conducted slowly such that the amount of flow passing through the mobile unit could be monitored, avoiding excessive losses from the supply side upstream of the unit to the DMA.

Following full closure of the final valve and stabilization of the system, the PRV was often activated to observe whether boundary integrity was achieved. In some instances, participating municipalities undertook zero-pressure tests of the boundary valves each night, while in others these tests were only conducted on the first night of testing or during the site preparation process. In either situation, activation of the PRV can be a useful technique as it imposes a pressure differential across each closed boundary valve. Passing flow (if any) can then be discerned through appropriate application of acoustic listening devices, serving to identify any boundary valves which warrant adjustments to achieve a better shut.

Once DMA integrity was duly established, the system was observed and data was collected, generally from 12 midnight to 6 am. Typically, the first night of testing involved collection of data under normal pressure conditions. In general, the objective of multiple nights of testing was to achieve reasonable duplicability of results and to test pressure reduction effectiveness. While up to 4 nights were allocated for each of the test sites, this included a contingency for sites where preparatory work may have been insufficient or incomplete, as well as to deal with any unforeseen circumstances – in one instance, there was an unmapped watermain connected to the DMA which needed to be located, consuming the efforts of the team for a complete test session plus a portion of the next.

Sample data for a typical test night is provided in Figure 23 for a DMA with rather stable pressures for the duration of the test. It is evident from the data that consumption starts to pick up at around 5 am as some residents commence their day. Further, it is noted that the pressure component of the data is represented as the hydraulic grade line (HGL) of the DMA, representing its

hydraulic head, being the combination of both pressure and elevation components, and which is commonly used for hydraulic calculation purposes.

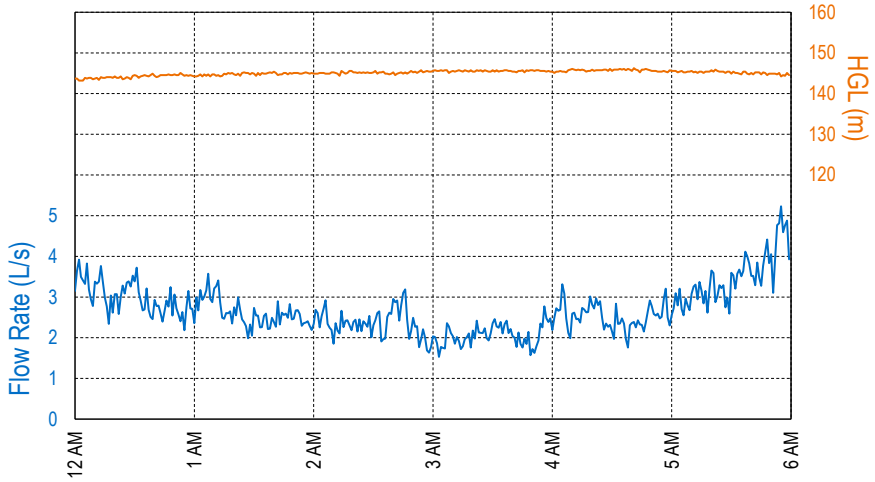

Figure 23: Sample data collected during night of normal (full) operating pressure

Pressure Cycling

The initial deployment of the mobile unit involved the collection of two nights of data at full pressure and two nights of data at reduced pressure. While a discernable difference between the resulting MNF at full pressure and at reduced pressure was evident, the degree of this departure was not clear, largely due to the stochasticity in the flow profile across the test nights. To improve the value of the testing results, the method of collecting data for the reduced pressure condition was altered such that pressures were cycled between full and reduced conditions at regular (typically 30 minute) intervals over the course of a test night. This eliminated the night-to-night stochasticity issue and yielded a useful representation of the pressure-dependency of flow (and, hence, leakage).

Sample data for a night of pressure cycling is provided in Figure 24, noting that more fulsome analyses of this data is discussed in later sections. Nevertheless, it is evident from visual inspection of this data set that there is some dependency of flow on pressure.

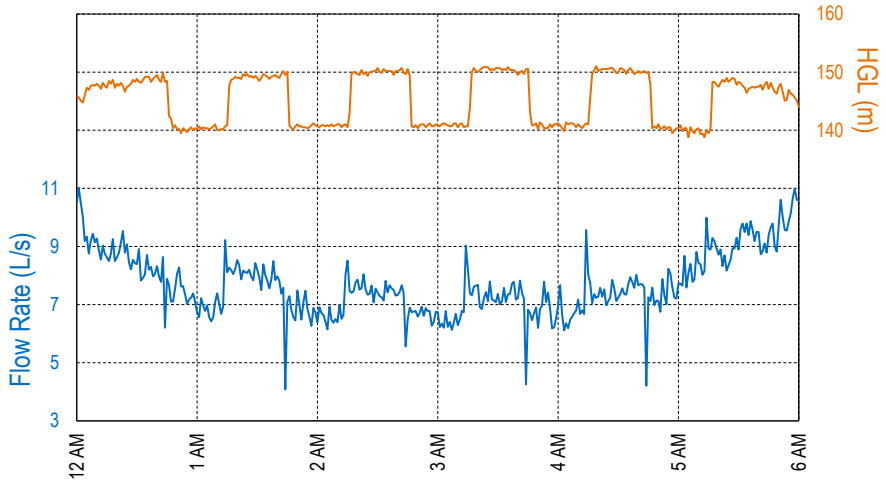

Figure 24: Sample data collected during night of pressure cycling

Test Efficiency Improvement

Over the course of the project, the testing method was continuously refined and improved such that, with appropriate advance planning and preparation, the number of nights required for testing could be reduced to two, or possibly one, depending on the results obtained as well as the level of granularity required. That said, two nights of testing would provide the opportunity for duplicability of the MNF estimate, with the first testing night typically being reserved for data collection under normal pressure conditions and the second night employing pressure cycling. On the other hand, if the first night of testing yields a very low MNF value, suggestive of little-to-no excessive leakage, then additional effort (and cost) may not provide additional value. Nevertheless, it is prudent to allocate at least 1 additional test night as a contingency to deal with unforeseen circumstances that could result in the inability to collect data.

By minimizing the number of nights required to obtain meaningful results, the amount of effort (and cost) required for this testing is significantly moderated. The project accordingly accomplished the indirect objective of improving testing efficiency, thereby improving the economic perspective relating to such activities and lowering barriers to implementation.

Analysis Methodology

Performance Indicators

Minimum Night Flow (MNF)

The key performance indicator for each of the DMAs tested was the minimum night flow (MNF) computed as a centralized 60-minute average (MNF_{60}). This averaging duration was selected in part to maintain consistency with the international water loss industry and in part to recognize that, wherever municipalities employ smart metering though Advanced Metering Infrastructure (AMI) or Automatic Meter Reading (AMR) systems, the available granularity of this data is often of this duration (thereby making it easier to make direct mass balance calculations on an hourly basis).

Wherever multiple, repeatable and reliable nightly measurements are observed, an average across all nights of similar testing is used for purposes of further analysis; otherwise, the lowest measured value is used. This value is used in each of the performance indicators discussed below for benchmarking purposes.

MNF_{60} per Number of Residential Service Connections

The number of residential service connections is derived from a review of billing records and GIS data for properties with residential land uses. For purposes of this project, predominantly residential land uses are defined as DMAs having at least 90% of its unique users being residential units and where there exist no significant overnight water users. Gas stations, coffee shops and grocery stores, for example, are not considered herein to be significant overnight water users. Further, gas stations with automated car washes are similarly not considered herein to be significant overnight water users given that their operation is intermittent (rather than sustained) and generally infrequent during the hours of testing, noting that modern facilities of this sort often make use of recycled water.

MNF_{60} per Number of Residential Units

The number of residential units differs from residential connections by accounting for multi-unit properties (e.g., apartment buildings) serviced by a single connection. The information used to obtain this number includes any available GIS-based information on the number of residential units per connection and, where needed, research into specific properties where this information is not readily available from information provided. An example of this is apartment buildings where estimates of unit counts were made based on observations and/or whose property managers were contacted for this information.

MNF_{60} per Population

The estimated population for each DMA was derived based on the most recently available census information acquired from Statistics Canada dissemination areas (DAs) which are contained within the DMA. For DAs which are partially contained in the DMA, the average population per unit (PPU) of the DA was applied to the number of residential units as determined above and contained within the intersection of the DMA and DA boundaries. In the absence of such information, population estimates could be based on unit population densities that may be available through, for instance, Development Charge Background Studies (in the case of Ontario municipalities).

MNF_{60} per Length of Watermain

The estimated length of the watermain in each DMA was estimated based on available GIS information.

Ratio of MNF_{60} to Average Billed Demand

The average billed demand (ABD), or average billed metered consumption expressed as a flow rate (including any outdoor water use associated therewith), is based on the following hierarchy, depending on available information: (i) billed demand (or consumption) records for the most recent 12-month period; or (ii) an estimated average demand based on 225 Lpcd for residential units, applying the same methodology for estimating population as noted above.

Benchmarking

One of this project's key outcomes was the establishment and/or confirmation of industry benchmarks for the performance indicators noted above. At the onset of the project, preliminary values were established from a combination of in-house knowledge derived from relevant project experiences, published industry literature as well as in consultation with other practitioners in the space.

As the project evolved, so did these values with the final benchmark values reported herein based upon a reasonable best fit of the data representing "healthy" DMAs – that is, those showing minimal excess leakage – and rounded to simplify their use without detracting from their relevance and accuracy. The differentiation between "healthy" DMAs and those with excess leakage was made through a combination of visual inspection of the data for the identification of obvious outliers and the consistency in the interpretation of the results across all performance indicators.

Excess Leakage

The estimation of excess leakage, measured as a flow rate, was calculated as the difference between the MNF_{60} value for each DMA and selected benchmark values. In addition to providing a sense of the physical scale of the leakage, these values were subsequently applied to various economic assessments, discussed below.

Annual Volume of Leakage

The annual volume of leakage is calculated using the excess leakage rate and applying it over a year consisting, on average, of 365.25 days (i.e., accounting for leap years).

Annual Value of Leakage

This is calculated by multiplying the equivalent annual volume of leakage and the marginal cost of water to the municipality. Specific to this project, the marginal cost of water (and wastewater, if applicable) was determined as either of: (i) the unit rate at which the municipality (utility) purchases imported water; (ii) the marginal or incremental cost for a utility to extract and treat each additional unit of water at its current rate of production (noting that this does not represent the average cost of production); or (iii) the appropriate blend of the foregoing, if applicable.

Annual Excess Energy Consumption

The calculation of excess energy consumption requires an estimate of the embedded pumping energy in the water supplied to the DMA. This is determined using the static lift (i.e., height to which the water level is raised), dynamic line losses (e.g., through transmission mains) from the source to the DMA, accounting for pumping energy efficiencies. These individual components were estimated as follows:

- The static lift was calculated as the difference between the hydraulic grade line (HGL) of the pressure zone in which the DMA lies and the source water surface elevation.
- The dynamic line losses are based on an average hydraulic gradient of 1 m/km based on the distance from the water source to the DMA.
- An average pump energy consumption rate of 4,000 kWh/Mm3/m (of total lift/head), being equivalent to a wire-to-water pump efficiency of approximately 70%, as determined in a study of the energy efficiency of water pumps in Ontario (HydraTek & Associates, 2013).

Accordingly, those DMAs that are higher than, and more distant from, the source of water they are supplied with have a higher embedded energy.

Annual Greenhouse Gas (GHG) Emissions

The equivalent annual GHG emissions resulting from the estimated excess leakage is calculated by applying an emission intensity factor of 40 g CO_2/kWh (National Energy Board, 2017) to the annual excess energy consumption calculation above.

Pressure Cycling

For the analysis of pressure cycling on flow characteristics, quadratic best fits of flow data in relation to time under conditions of both full and reduced pressure were developed. Given the volatility in the data during transitions to/from full and reduced pressure settings – periods during which elasticity effects relating to the water within the watermains and the watermain materials themselves occur prior to re-equilibration to a steady-state flow regime – the flow data used for this purpose was cleansed accordingly.

Use of quadratic best fit curves were generally found to represent the data reasonably well (that is, without over-fitting the data) and are easily used to measure the change in flow rate with changes in pressure. Figure 25 presents the analysis of sample results for a DMA with a relatively high degree of pressure-dependent flow, and Figure 26 presents similar results for a DMA with a negligible amount of pressure-dependent flow. The pressure cycling process allowed for sufficient data to be collected to characterize both the high- and low-pressure flow rate chords, with the vertical departure between them representing the difference in flow rate based on the pressure difference imposed on the DMA through the cycling process.

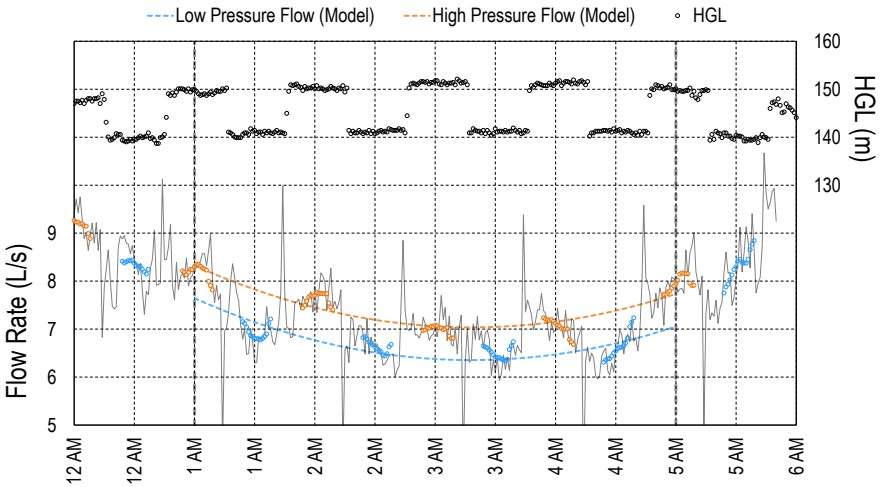

Figure 25: Sample pressure cycling analysis for leaky DMA

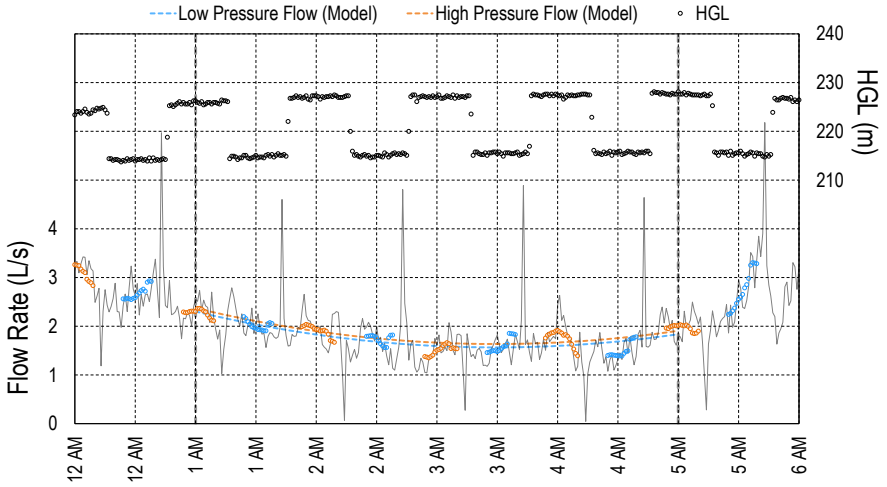

Figure 26: Sample pressure cycling analysis for "healthy" DMA

N1 Leakage Exponent

Derivation

A common metric applied in the water loss industry is the "N1" leakage exponent which may be derived from the orifice equation, commonly expressed as follows:

$$Q = K \cdot A\sqrt{2gH}$$

where Q is the flow rate, K is the orifice coefficient of discharge, A is the cross-sectional area of the orifice, g is gravitational acceleration and H is the driving pressure (head), measured as an equivalent depth of water. For instance, a 50 m depth of water is equivalent to approximately 490 kPa or 71 psi when accounting for the specific weight of water (9,810 N/m³).

This expression can be simplified by defining a constant C as follows:

$$C = K \cdot A\sqrt{2g}$$

This results in the following generic expression relating flow rate and pressure:

$$Q = C \cdot H^{N1}$$

For an orifice, the N1 value is 0.5. In this formulation, N1 is permitted to vary to account for practical variations in this value, including the pressure-dependency of the leak opening size. This value has generally been found in the industry to vary between 0.5 and 1.5 (and sometimes higher).

Derivation of the N1 term requires at least 2 pairs of Q and H values (i.e., Q_1, H_1 and Q_2, H_2) which, in this project, were obtained from the results of the pressure cycling testing for each DMA. Rearranging the original expression yields the following expression:

$$C = \frac{Q}{H^{N1}}$$

Given that the constant C applies to both Q-H pairs, an expression to explicitly calculate N1 can be derived, as follows:

$$C_1 = C_2$$

$$\frac{Q_1}{H_1^{N1}} = \frac{Q_2}{H_2^{N1}}$$

$$\frac{Q_1}{Q_2} = \frac{H_1^{N1}}{H_2^{N1}} = \left(\frac{H_1}{H_2}\right)^{N1}$$

$$N1 = \frac{\ln\left(\frac{Q_1}{Q_2}\right)}{\ln\left(\frac{H_1}{H_2}\right)}$$

While the flow rates (Q) for the different pressure conditions are directly measured with the flow meter(s) in the mobile unit, the driving pressure (head) requires some additional analysis effort, discussed next.

Average Zone Pressure (AZP)

For purposes of this work, and as largely applied in the water loss industry, the driving head (pressure) term (H) is typically defined as the average zone (or DMA) pressure (AZP) and is derived in this work as the difference between the measured hydraulic grade line (HGL) elevation and the average DMA (zone) elevation. The HGL, in turn, is calculated based on the pressure measured in the DMA downstream of the mobile unit and the elevation at which that pressure is measured. This is a simplification which can be comfortably applied for modestly sized DMAs in Canadian (and U.S.) systems – including those DMAs tested in this project – given that the HGL is generally "flat" across the DMA during overnight periods when demands (and therefore flow rates) are low. This is due to the relatively large pipes in these systems which are sized based on fire-fighting requirements, the flow rates for which can often be two orders of magnitude higher than overnight demands.

For this project, the average DMA (zone) elevation was determined based on the following hierarchy, depending on available information: (i) length-weighted average of ground elevations along watermains in the DMA; (ii) area-weighted average of ground elevations in the DMA; or (iii) average of lowest and highest ground elevations in the DMA.

(It is noted that the use of the term "zone" in this context refers to the DMA in question, rather than the pressure district in which it is situated and is used for purposes of maintaining consistency with industry vernacular.)

Calculating N1

Where pressure cycling was employed, the N1 value was computed from the relationship defined previously, with inputs of the minimum flow rates (Q values) from the numerical models representing the flow profiles for each of the normal and reduced pressure conditions and the corresponding AZPs during the relevant analysis time windows.

It is noted that the value for flow (Q) is intended to represent leakage and, for the purposes of this project, was initially estimated as the difference between the MNF value and the corresponding MNF benchmark value based on the residential unit count which was determined to be one of the more reliable estimation methods used. Later analysis of the test data (i.e., after the conclusion of all test sites) and consideration of the Advanced Metering Infrastructure (AMI) data made available to this project yielded more accurate and insightful results, presented later.

General Discussion

The practical reality is that the N1 value can be rather elusive to accurately measure and identify. Some reasons for this include:

- The influence of potentially leaky boundary valves that are undetected.
- The number, distribution and type of openings through which leakage is occurring, particularly considering the potential pressure-dependency of leak opening size.
- The degree of pressure-dependent flow within customer premises.
- The location, in terms of elevation, of any significant leak within the DMA, considering that the average zone pressure values may not adequately represent the actual pressures at the leak location.

In general, while the N1 is a useful concept, care must be taken in its measurement, interpretation and use in order to apply it effectively and appropriately for meaningful results. Despite the foregoing, some rather interesting results were generated from the testing conducted in this project as it relates to the N1 leakage exponent's relationship with DMA performance.

Economic Analysis

Models Applied

There is generally no standard approach adopted by municipalities in Ontario to conduct project economic assessments, including system interventions to improve performance. To assist in illustrating the potential beneficial economic impact of leakage reduction in each of the DMAs tested, several economic models were employed. These were not meant to be precise and reliable forecasts, but rather were intended to provide an indication of magnitude as well as to assist in the comparison of alternative investments under consideration.

Internal Rate of Return

The internal rate of return (IRR) value was calculated based on the assumption that leakage reduction benefits would carry on in perpetuity, and that the occurrence of any future leaks will have their own independent economic profiles. Accordingly, the amount that can be invested is equal to the present value of a perpetuity, being the estimated value of the annual recovery divided by the discount rate. For this project, a discount rate of 10% was applied for time value of money calculations and is conceptually comprised of the risk-free rate of return which, for purposes of municipal infrastructure investment as at the time of writing is assumed to be on the order of 2-3%, plus a risk premium of 7-8% to account for uncertainty.

Simple Payback Period

The simple payback period is the time required for any savings to offset the investment required without accounting for the time value of money (i.e., no discounting of future cash flows). For this work, a threshold simple payback period of 5 years was assumed to be appropriate for such municipal infrastructure investments.

Discounted Payback Period

The discounted payback period is the time required for any savings to offset the investment required, accounting for the time value of money using a discount rate of 10% (see IRR discussion above). For this work, a threshold simple payback period of 5 years is assumed to be appropriate for such municipal infrastructure investments.

Only Selected Results Presented

While all these models were applied for each of the test site reports, only the results from selected economic analyses are presented later for conciseness of presentation and generalization of results.

Basis for Assessment

Leak Repair

In cases where these models required an estimate of the amount of leakage to be recovered through detection and repair efforts, fractions of 25% or 50% were typically applied, depending on the degree of excess leakage estimated. For instance, for "healthy" systems, a lower potential recovery rate was applied, recognizing that it is increasingly difficult and costly to firstly locate, and secondly reduce, leakage when there is little (if any) available to be found.

As well, it is noted that the economic assessments do not account for future increases in the marginal cost of water over current rates (e.g., for future years) and, accordingly are likely to be somewhat conservative in this regard. This will

affect those municipalities that purchase water from adjacent jurisdictions more so than those municipalities that produce their own water. Additionally, apart from the trends and expectations relating to input cost increases, the ongoing progression towards full cost accounting of all infrastructure assets can be expected to result in higher marginal costs for all municipalities.

Pressure Management

To estimate the potential beneficial impact of pressure management, the N1 leakage exponent calculated for each DMA was used in conjunction with a target average zone pressure to be applied, the latter of which is typically constrained by acceptable performance standards. That is, for most Ontario municipalities, a lower pressure threshold of 40 psi is common with the lowest pressures occurring at the point of highest elevation in the DMA and in recognition that, during peak demand periods, operating pressures will generally be somewhat lower than during overnight periods.

In addition to the estimated volumetric and the resultant financial benefits associated with potential leakage reduction, it was recognized that there may be some reduction in consumption "past the meter" within customer premises. That is, there may be some pressure-dependent consumption which, by virtue of being reduced somewhat under lower pressure conditions, would also result in a reduction of the volume billed to the customer, thereby reducing the revenue to the municipality and affecting the economic assessment.

There is generally little in the way of reliable industry literature and/or guidance to firmly establish what fraction of total pressure-dependent flow is attributable to distribution system leakage with the remainder attributable to premise system leakage. For this project, it was assumed that 90% of the estimated leakage reduction was attributed to the distribution system in question. The resulting economic impact of the reduced billing volume was determined using a volumetric-based variable component of the retail water (and wastewater) rate paid by the customer.

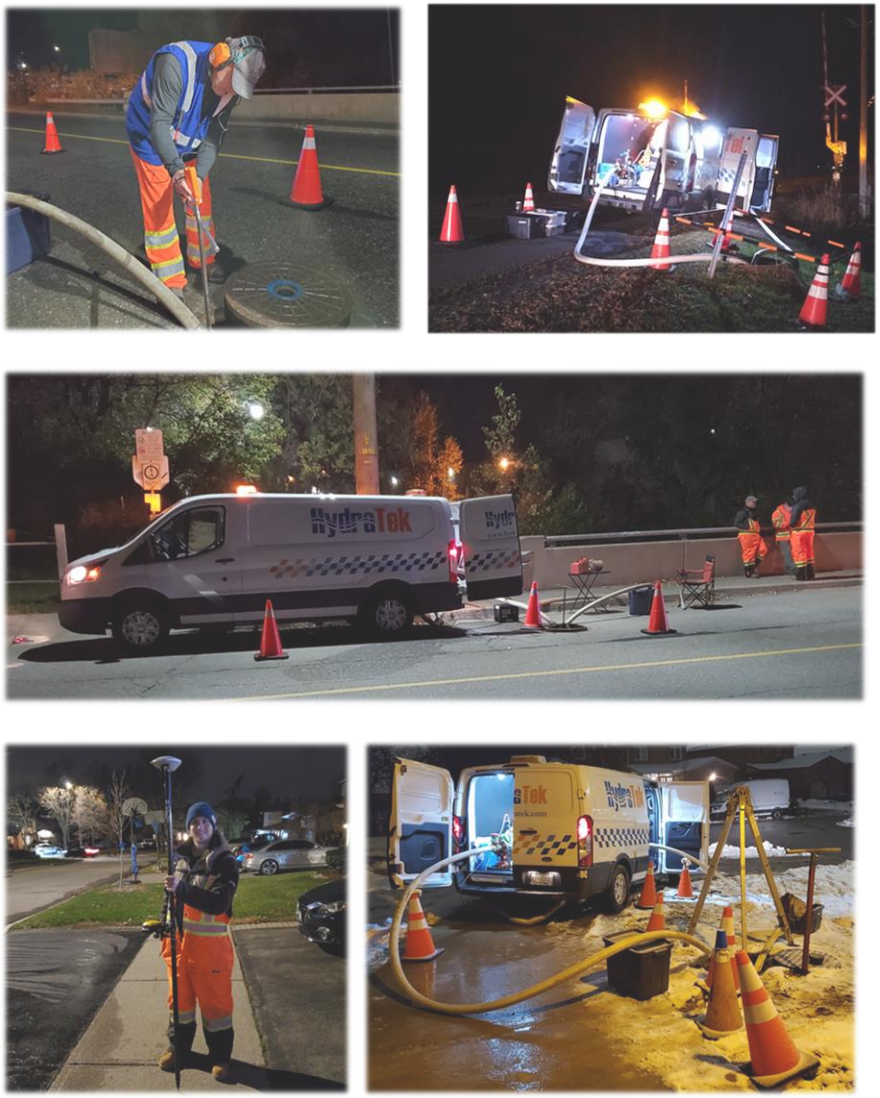

Figure 27: Photo gallery

Results & Discussion

Overall Results

In total, 25 sets of results formed the database used for purposes of characterizing DMA performance with respect to excess leakage potential through various benchmarking statistics. This data set comprises: (i) 20 sites where mobile DMA testing was conducted as part of this project; (ii) 2 sites where mobile DMA re-tests were conducted as part of this project and following leak detection and repair activities performed by the participating municipalities; and (iii) 3 sites from a separate pilot DMA project carried out by HydraTek for one of the participating municipalities and whose data was curated to the same standards as this project.

The overall 60-minute average minimum night flow (MNF_{60}) results are present graphically for each of the 25 DMAs noted above relative to population size in Figure 28.[1] Based on these results, the following observations are made:

- Most of the measured MNF_{60} values for the DMAs tested seem to track within a relatively narrow linear band extending from the origin, as would generally be expected. These are identified as "healthy" DMAs in the graphic (**blue** data points), although it is worth noting that there may indeed be some excess leakage within this collection of DMAs worth exploring further. This work, however, is more concerned with the identification of clear outliers as the "lowest hanging fruit" where substantial improvements are possible.
- Three of the DMAs tested with the mobile unit were found to be clear outliers (**red** data points).
- Of the outliers, two of the DMAs were subjected to leak detection and repair activities as well as subsequent retesting. In one case, these activities resulted in a substantial recovery of excess leakage (**blue** data point with **red** outline), resulting in the DMA's performance fitting nicely within the range of the other "healthy" DMAs. In the other case, approximately half of the suspected excess leakage was recovered (**green** data point with **red** outline) and, although still a positive result, there is expected to be more recovery possible therein. These examples are discussed more fully in the Case Studies section.
- While appearing to fall within the cluster of "healthy" DMAs, the results from two DMAs, identified by **grey** data points were suspected of not qualifying as such as a result of separate analyses relating to the fraction of consumption (see page 28) as well as on the basis of customer consumption variability prone in smaller DMAs (see page 39). As such, these points were excluded from the data set used to establish benchmarks.

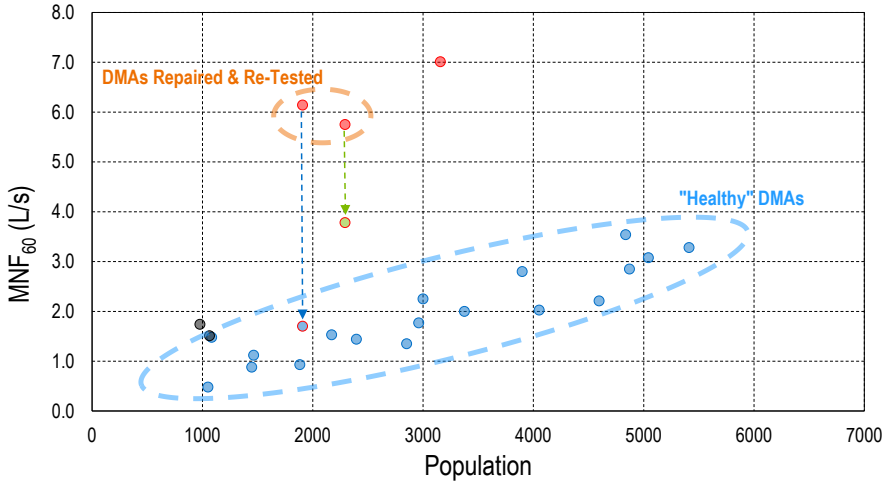

Figure 28: Overall results (MNF_{60} vs. Population)

In addition to relating the MNF_{60} values to DMA characteristics such as population, residential unit count, number of connections and watermain length, the fraction of MNF_{60} relative to average consumption rates (identified

[1] It is noted that comparable results for other bases for comparison (i.e., residential units, connections, watermain length) yielded similar results and are not presented here for the sake of conciseness.

as Average Billed Demand, ABD) within the DMA were also explored. This is similar, but not equivalent to, determining the ratio of MNF_{60} relative to longer-term average measured flow rates into the DMA. With respect to the latter, there is some experience available in the literature and the authors have successfully identified either high leakage or other system operational issues using such metrics on other assignments. For this project, longer-term average flow monitoring information was not available; however, consumption records were provided by the participating municipalities for the DMAs in question.

The results of this analysis are presented in Figure 29 which uses the same colour theme as Figure 28. The performance improvements made to the two DMAs are identified in the figure, and there is generally a distinct separation between those well performing "healthy" DMAs and those with suspected excess leakage. That said, there are two data points where the MNF_{60}/ABD value resembles a poorly performing DMA, despite these data points falling near the "healthy" cluster in Figure 28. These two DMAs, in addition to the outliers in Figure 28, were eliminated from further consideration with respect to establishing statistics to be used for benchmarking purposes.

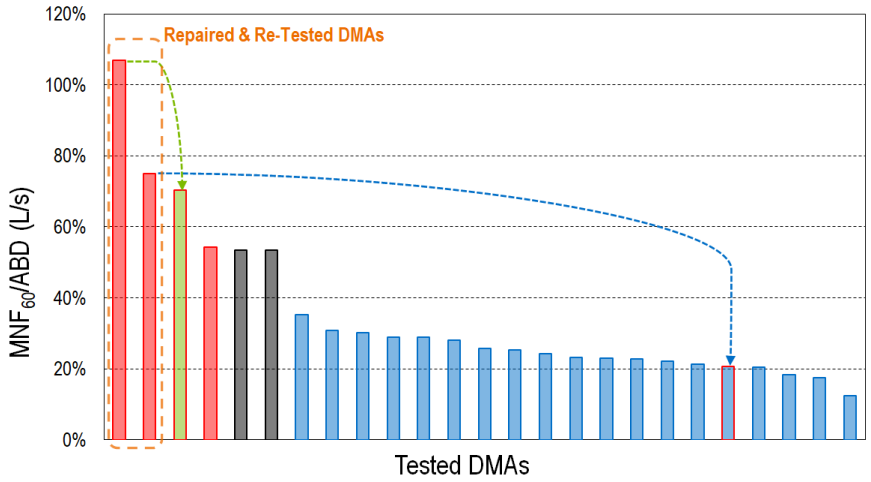

Figure 29: Overall results (MNF_{60} vs. ABD)

In total, data from 19 of the tested DMAs (i.e., identified with **blue**) are deemed to represent "healthy" systems and are used for benchmarking, discussed next.

Benchmarking Results

As noted earlier, 19 of the data sets were deemed to represent "healthy" DMAs, being those with little-to-no meaningful excess leakage. The resulting analyses of the MNF_{60} data relative to various DMA characteristics are presented graphically below in order of each benchmark's goodness-of-fit to the data (as measured by the calculated coefficient of determination, R^2). These results are summarized in Table 1, including figure references.

Table 1: MNF_{60} Benchmarks

Basis	MNF_{60} Benchmark	R^2	Reference
Population	2.2 L/h/capita	0.83	Figure 30
Residential Units	6.0 L/h/unit	0.81	Figure 31
Average Billed Demand (ABD)	24% of ABD	0.79	Figure 32
Residential Connections	6.4 L/h/connection	0.73	Figure 33
Watermain Length	525 L/h/km	0.49	Figure 34

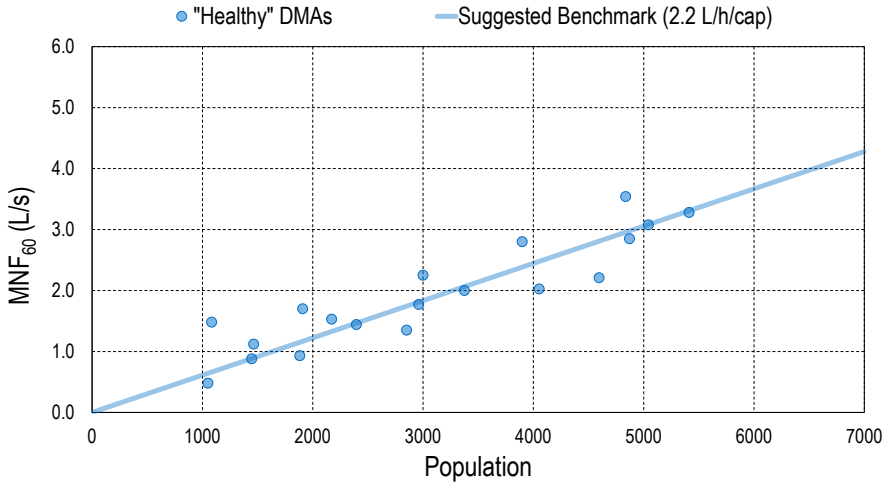

Figure 30: MNF_{60} vs. Population Benchmark

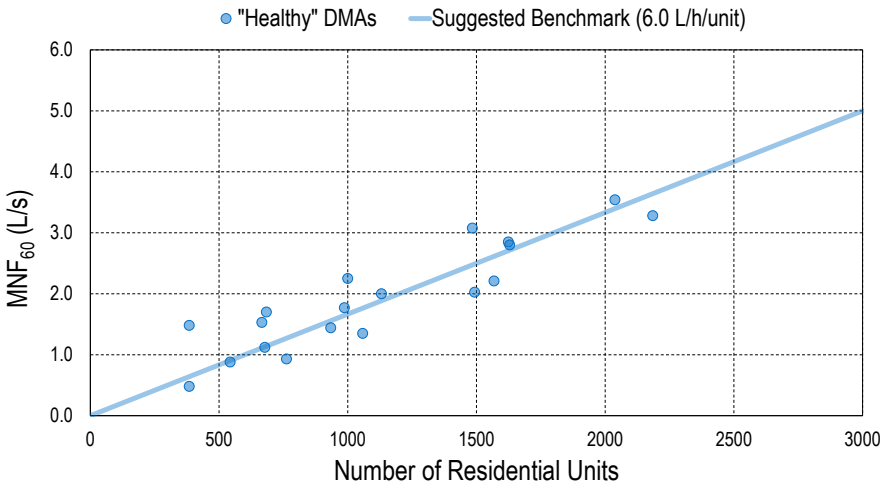

Figure 31: MNF_{60} vs. Residential Unit Count Benchmark

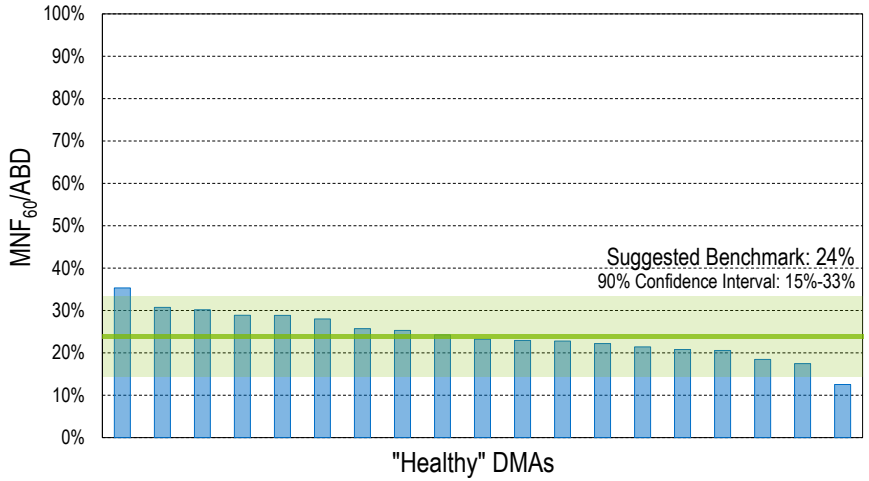

Figure 32: MNF_{60}/ABD Benchmark

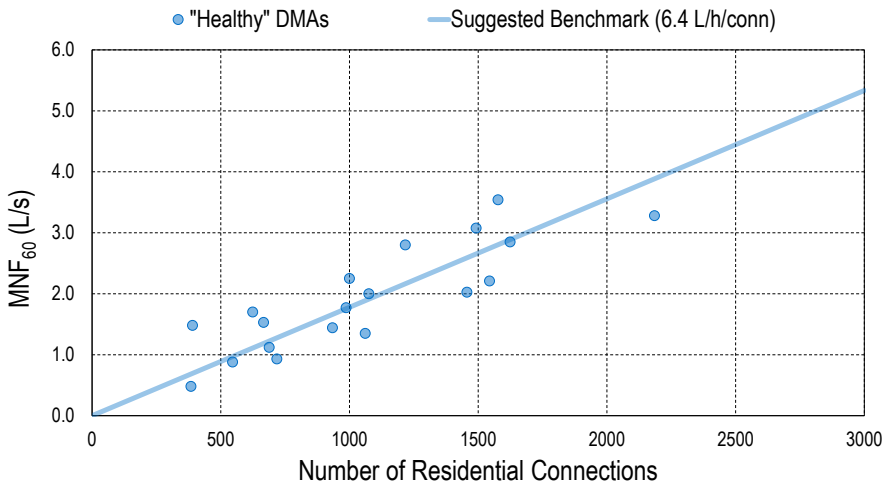

Figure 33: MNF_{60} vs. Residential Connection Count Benchmark

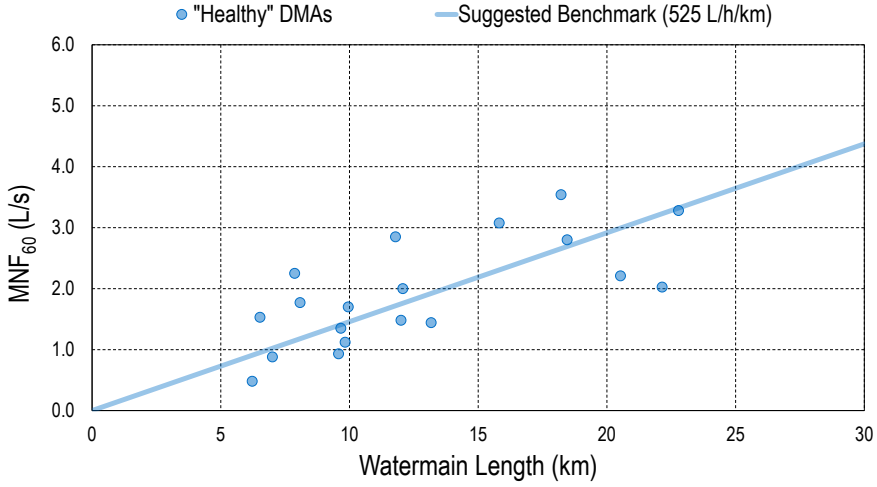

Figure 34: MNF_{60} vs. Watermain Length Benchmark

Case Studies

Case Study 1 | The "Big Win"

One of the project's early DMA test sites happened, fortuitously, to exhibit signs of excess leakage, estimated at the time to be approximately 5 L/s based on initially used values for benchmarking. It's MNF_{60}/ABD ratio was in the order of 75%. Accordingly, the participating municipality decided to carry out a leak survey and detection exercise employing acoustic technology and was able to identify the location of a substantial leak that was subsequently repaired. Interestingly, this leak had been undetected (for an unknown duration) since its discharge was entering a local storm sewer system and, as such, not surfacing as would commonly be the case where soils are generally dense.

This project benefitted from the ability to re-test this site after the leak repair and with impressive results, presented in Figure 35. While the impact of this leak is discussed below, it is important to recognize the impact that a single leak can have on the performance of a system. As the graphic indicates, the discovery and repair of this one leak resulted in the DMA's performance falling in line with its healthier peers.

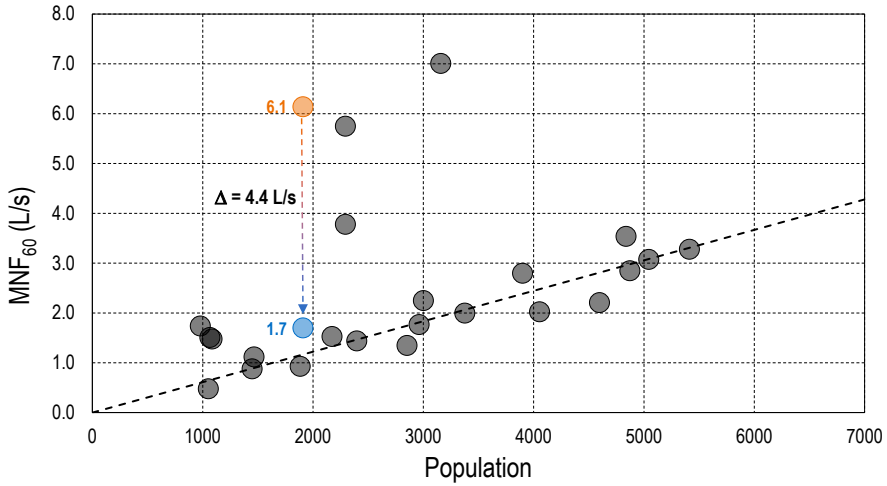

Figure 35: Case Study 1 leakage reduction quantification

The meaningfulness of this leakage reduction is better understood when viewed from perspectives other than flow rate alone as well as over the course of a reasonable duration, such as annually. The beneficial impacts resulting from this leakage reduction can be summarized as follows:

- The savings of approximately 139,000 m^3 (139 ML) of treated water annually. This is equivalent to about 40 commonly sized water towers of 3.5 ML each, or about 139 Olympic-size swimming pools. In another light, the water savings equates to the volume that would otherwise be consumed by a similar number of houses that were located in this particular DMA (~660).
- The savings of approximately $426,000 per year in water and wastewater charges borne by the municipality. This particular municipality purchases its water rather than producing its own, making its marginal cost of water quite high. Further, the amount of financial savings would increase over time as the unit charge also increases.
- The savings of approximately 102 MWh per year in energy used to pump the water from its source to its destination. This particular municipality happens to be located quite a distance from, and is situated quite a bit higher than, the source water.
- The reduction of approximately 4.1 tonnes in greenhouse gases (CO_2-equivalent) per year.

As a boon for this project, these results were realized within its first year and undoubtedly strengthened the perception of the mobile testing concept such that the project was over-subscribed shortly thereafter. As well, these results undoubtedly played a role in the awards and recognition earned by this project across the industry, within Ontario and internationally.

The participating municipality in question further benefitted from these results by deferring or avoiding the previously planned implementation of a rather costly pressure-management system for this particular DMA. The ability to collect accurate information and relating it to reliable benchmarks, coupled with the minimal reduction in flow rate under post-intervention pressure cycling, confirmed that additional efforts to pursue leaks in this DMA would likely not be worthwhile.

Case Study 2 | Step Testing

In another of the project's DMA test sites exhibiting significant excess leakage, a step test was conducted by progressively carving out segments of the DMA and measuring flows during the overnight period. Through this process, the segments within the DMA which demonstrated higher-than-expected flows, relative to key characteristics and related benchmarks, were identified. The step testing results are illustrated in Figure 36, with segments having various levels of potential excess leakage highlighted to facilitate further leak detection and repair efforts.

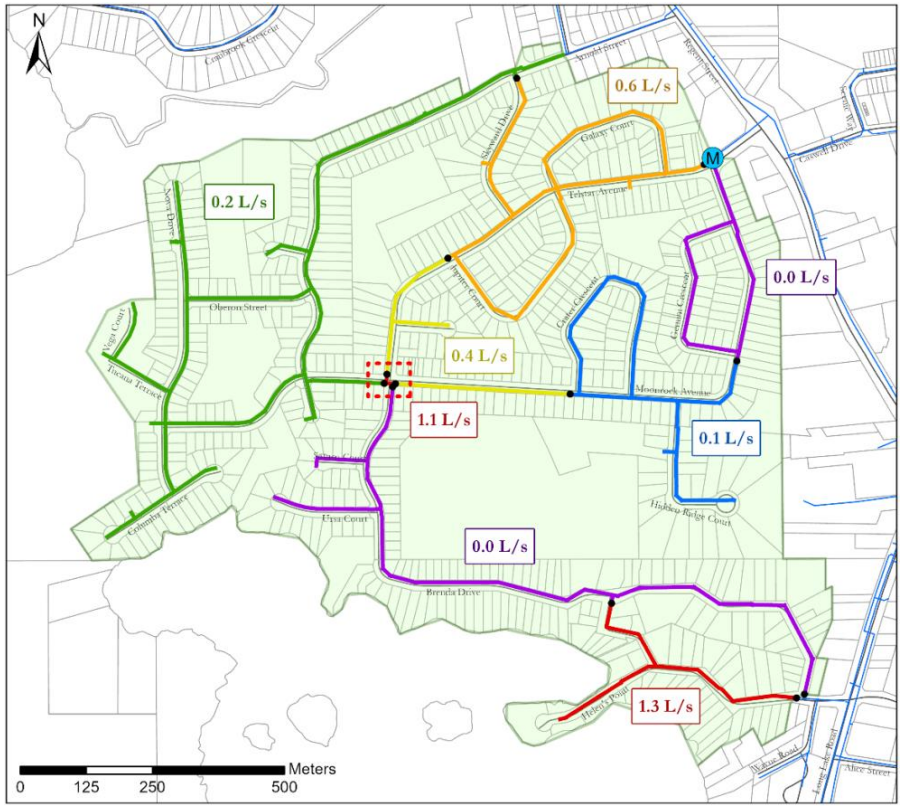

Figure 36: Case Study 2 step testing findings

Following the leak detection and repair activities, the site was re-tested. The original testing suggested excess leakage in the order of 4.3 L/s and the subsequent re-testing indicates that 2.0 L/s was recovered, as displayed in Figure 37. While these results are not as impressive as those presented in Case Study 1, suggesting that there may be approximately 2.3 L/s of recoverable excess leakage still present, it is still a rather positive outcome. A savings of 2.0 L/s alone equates to the following:

- Water savings of 63,000 m^3 (or 63 ML) per year.
- Financial savings of $50,000 per year.
- 16,300 kWh or 0.65 tonnes CO_2-equivalent per year.

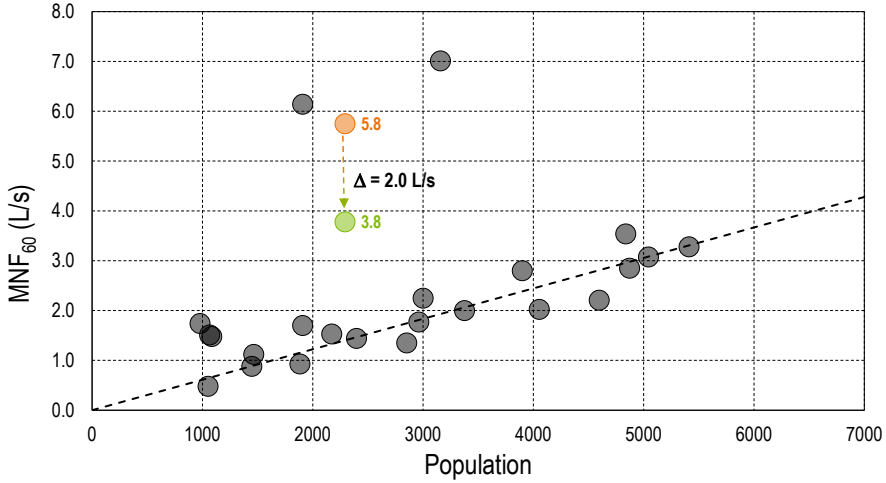

Figure 37: Case Study 2 leakage reduction quantification

At the time of re-testing, there continued to be segments of the DMA identified in the step-testing which required further investigation and, accordingly, there remains an opportunity to recover further leakage from this system. That said, the efforts required to do so are not insignificant and pose challenges for the participating municipality to move forward. One of the benefits of having the measurements afforded from this testing is that it lends confidence in the potential recovery volume and value which can be contrasted against the costs of intervention. In some cases, intervention may simply not be warranted.

Case Study 3 | Blow-Offs

In some instances, testing results were affected by the presence of blow-offs or other devices which constantly emit water from the system, giving the appearance of leakage. These elements are typically in place for purposes of maintaining water quality in the system by avoiding stagnation in areas where there may be insufficient demand or where discolouration risk is high. In some cases, an additional benefit can be derived by directing the discharge from blow-offs directly into sanitary sewer manholes to promote scouring and conveyance of solids such that they do not build-up and block these systems, creating other, typically more challenging operational problems.

While efforts were made to identify and close these sources of apparent leakage from the DMA, the practical reality is that these are not always discovered ahead of time. This may occur for a variety of reasons and is commonly due to the challenges in communications across relatively large and compartmentalized organizations that characterize most municipalities. Whatever the case, identifying and quantifying these sources of apparent leakage can be helpful to guide municipalities in their ongoing management, whether it be through their elimination, the reduction in flow rate emanating from their operation or perhaps the use of timer-controlled valves to accomplish the same benefits whilst moderating the amount of water used. Figure 38 provides examples of blow-offs discovered during this project while Figure 39 provides an indication of their impact.

Figure 38: Examples of constantly flowing blow-offs discovered during testing

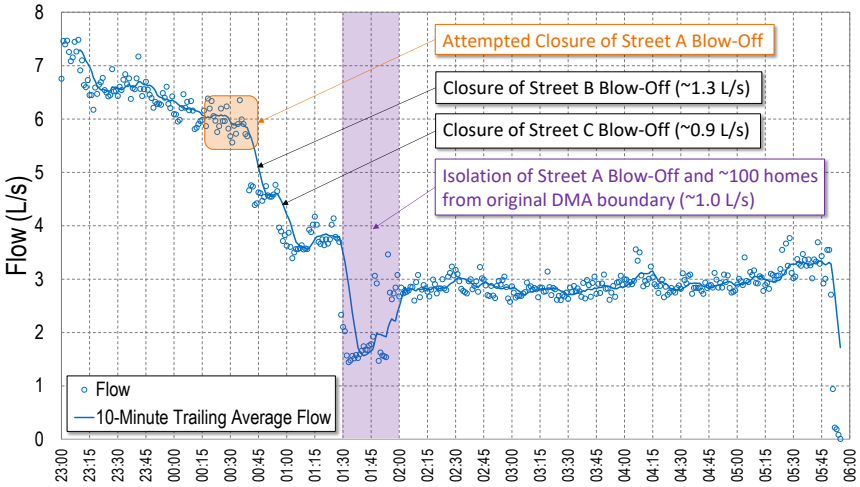

Figure 39: Impact of blow-offs on DMA inflow measurements

As can be seen in Figure 39, the flow from blow-offs identified in one particular DMA ranged from approximately 0.9 to 1.3 L/s which, in turn, amounts to about 28,000 to 41,000 m³ (28-41 ML) per year (each). In the above example, three such blow-offs were found in a single DMA. While this is not a common occurrence across all municipalities, it is nonetheless an important element to consider.

In addition to blow-offs, in one instance, a (throttled) hydrant was found to be running continuously. Pictured in Figure 40, this amounted to an apparent leak rate approaching 3 L/s (equivalent to about 7,800 m³ or 7.8 ML per month).

Figure 40: Constantly flowing hydrant discovered during testing

Whatever their necessity, blow-off locations, flow rates and volumes need to be accounted for with respect to water loss management.

Interpretation of Results on a Broader Scale

Project-Level Results

The following are the overall results from the testing program, excluding sites that were re-tested following leak detection and repair efforts:

- Total estimated excess leakage: 18.1 L/s — Or 570,800 m³ annually, enough to supply 6,900 to 7,800 people[2]
- Total estimated value of excess leakage: $781,000/year — Being paid by municipalities to produce or procure and waste potable water
- Total estimated excess energy consumption: 269 MWh/year — Or enough to supply 30 homes[3]

Province-Level Scaling

The estimated population of these DMAs is approximately 65,800, noting that the population of Ontario on municipal water services is in the order of 13 million persons.[4] If the results from this project are assumed to be representative of the entire province – which, admittedly is a stretch given that the test program represented ~0.5% of the entire serviced population, but is nonetheless somewhat useful for assessing the magnitude of the opportunity – the following may be expected:

- Total estimated excess leakage: 114,000 ML/year — Or enough to supply approximately 1.39 to 1.56 million persons[2]
- Total estimated excess energy consumption: 53,800 MWh/year — Or enough to supply 6,000 homes[3]

The 114,000 ML result is not unreasonable as its equivalent population of 1.39 to 1.56 million represents approximately 10.6% to 12.0% of the serviced population (respectively), fractions that lie comfortably within the range of what is commonly found when estimates of water loss in municipal systems are made. It is noted that any attempt at estimating the financial value of the excess leakage would be subject to the uncertainties associated with the wide disparity in marginal costs paid by the various municipalities.

Testing "Success Rate"

Of the project's 23 test sites (i.e., excluding re-tests), three of them exhibited significant excess leakage, yielding a fraction of ~13%. In terms of population, those DMAs with obvious excess leakage hosted an aggregate population of 7,360 people, representing ~11% of the total population across all DMAs tested. These fractions may be useful for developing business plans and testing strategies where a "success rate" associated with such testing can be applied. Given these results, and to lend a modest degree of conservatism to any such activities, a target "success rate" of 10% may be reasonable to apply. That said, it is also recognized that there is likely some degree of bias in these results given that the selection process for the test sites included some consideration for parts of the water distribution systems where leakage may have been suspected. Accordingly, considering a lower success rate (of, say, 5%) would provide for additional conservatism.

[2] Based on average consumption rates of 225 and 200 Lpcd (respectively).
[3] Based on an average of 9,000 kWh/year/household.
[4] Statistics Canada estimate for 2019 for population serviced by drinking water plants and for all source water types: 12,805,996. Table: 38-10-0093-01.

Economic Analysis Results

It is instructive to look at the estimated excess leakage results of the testing program in terms of the potential for financial- and energy-related savings (in addition to water savings potential). These results are presented in Figure 41 and Figure 42, respectively.

The data shown only includes those DMAs with anticipated excess leakage as determined using a uniform blend of estimates based on the MNF_{60} results of each DMA relative to benchmarks for unit count, population and average billed demand. Using a similar colour-coding convention as applied in Figure 28 and Figure 29, those clear outliers representing DMAs with excessive leakage are identified in **orange**, "healthy" DMAs are identified in **blue**, and inconclusive DMAs identified with the **grey** data points. The DMAs identified in **green** are those where leak reduction efforts and re-testing occurred following the initial testing results.

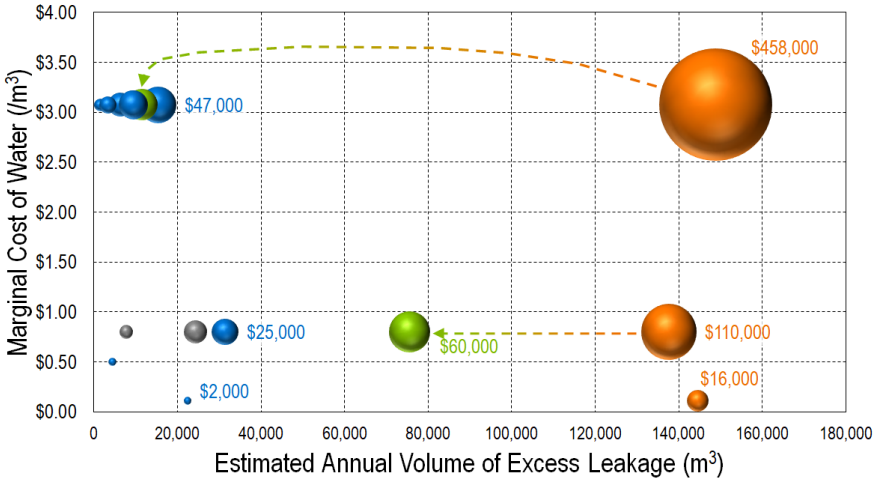

Figure 41: Value of excess leakage to municipality as a function of excess leakage volume and the marginal cost of water (annually)

As would be expected, the financial value of leakage is dependent upon the extent of leakage and the marginal unit cost of water borne by the municipality. The results shown in Figure 41 indicate that one DMA clearly stands out amongst those tested as having a substantial value of annual leakage. Fortunately, this is the same DMA where a significant leak was found and repaired prior to retesting (and which is featured as a Case Study on page 30). Figure 41 also displays the impact of the wide disparity in the marginal cost of water among the municipalities where testing occurred, with the lowest costs occurring for municipalities that draw water from abundant surface sources while the highest costs occur for those that purchase water from adjacent municipalities. It is quite telling that, although three poorly performing DMAs are shown to have high excess leakage (in **orange**), there is negligible financial incentive for one of them ($16,000 per year) and a modest, yet reasonable, incentive for the other ($110,000 per year). This is predominantly a function of the marginal cost of water paid by the municipality, and it should be evident that those municipalities with the higher unit costs have significant potential to benefit from leak detection and repair efforts as the case study clearly reveals.

Financial costs are only part of the picture. Apart from the obvious waste of treated water, energy wastage is also a matter of significant importance for which the largest component is attributable to pumping. The embedded (pumping) energy in water delivered is a function of both how high the water needs to be lifted above, and how far it must be transported from, its source.

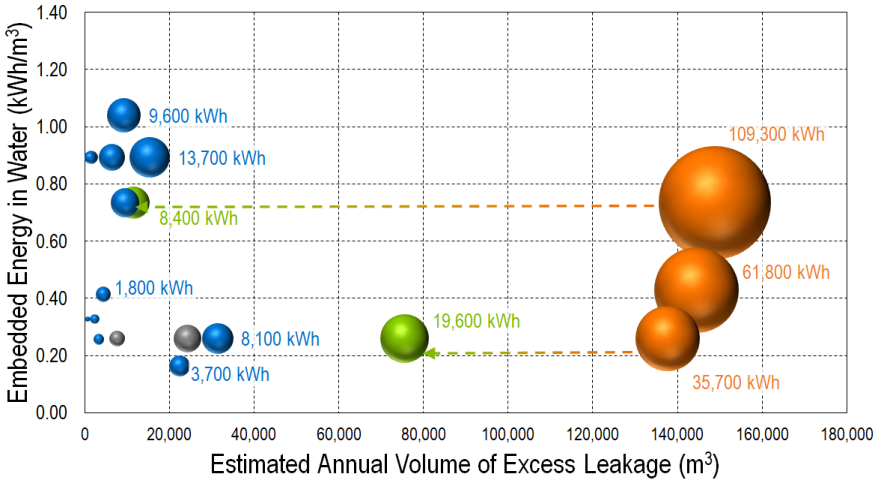

Figure 42: Excess energy consumption as a function of excess leakage volume and embedded energy in water (annually)

The results presented in Figure 42 show a narrower disparity in the values of embedded energy in water for the DMAs studied, with an approximately 6× difference between the lowest and highest values. This contrasts with the more than 33× difference between the lowest and highest values for the marginal cost of water illustrated in Figure 41. As a result of this narrower disparity, those poorly performing DMAs (in **orange**) are more closely clustered on the graphic and, while the same DMA dominates both figures, the order of the other two is reversed between the figures. That is, the poor performing DMA with little financial value ($16,000/y) in Figure 41 has a much more meaningful excess energy footprint (61,800 kWh/y) in Figure 42. Accordingly, business cases may be strengthened if the value of energy co-benefits are duly considered.

Benefit-Cost Analysis

The results of this project provide sufficient information from which benefit-cost analyses may be conducted. The following expression presents one potential model that may be applied, for illustrative purposes:

$$\frac{\text{Benefits}}{\text{Costs}} = \frac{L \cdot f \cdot M \cdot D \cdot S}{C_T + C_I \cdot S}$$

where
- L is the annual leakage volume (m^3/year)
- f is the fraction of leakage recovered
- M is the marginal cost of water ($/$m^3$)
- D is the duration of the benefit (years)
- S is the success rate (of finding excess leakage)
- C_T is the cost of testing
- C_I is the cost of intervention (if excess leakage is found)

For the purposes of this example the annual leakage volume is based on discovering a leak of 4 L/s (being representative of this project's findings) which amounts to about 126,000 m^3/year (L), and it is further assumed that only 50% of this amount can be recovered (f). The marginal cost of water (M) is used as a variable for this example with a 5-year duration of benefits (D) and testing success rates of 10% and 5% (S), as informed by the findings of this project. The cost of testing and intervention for each site are assumed to be $20,000 and $50,000, respectively.

The results of the analysis are presented graphically in Figure 43 which indicates the linear relationship between the benefit-cost ratio and the marginal cost of water (with all else being equal). These results suggest that, based on financial considerations alone, it may not be economically justifiable to conduct testing on systems where the marginal cost of water is $0.75/$m^3$ or less and a success rate of 10% (i.e., benefit-cost ratio < 1), and double that for a 5% success rate, unless there are known issues that need to be identified and characterized. For municipalities with a marginal cost of water of at least $2.50/$m^3$, for which the corresponding benefit-cost ratio is in excess of 3.0 with a 10% success rate and still in approaching 2.0 for a 5% success rate, these results suggest that regular testing should seriously be considered as the prospective financial benefits alone would outweigh the associated costs.

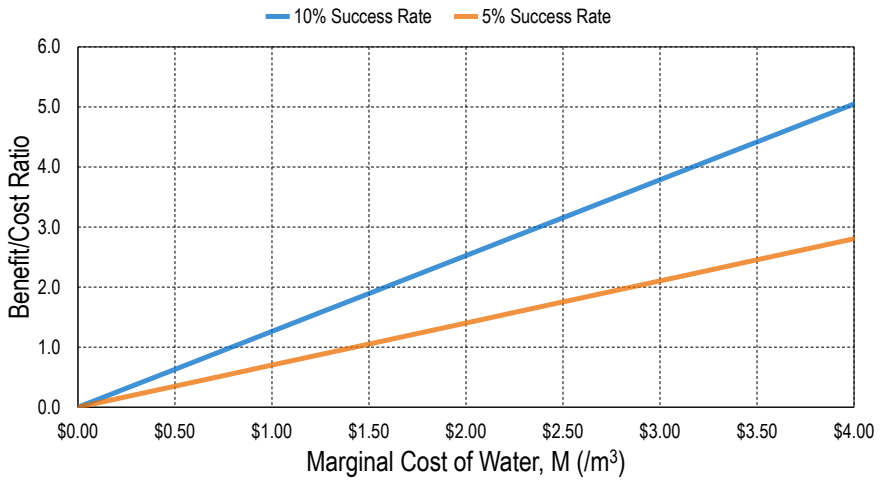

Figure 43: Benefit-cost analysis of testing

To account for environmental costs as represented by carbon pricing, the above expression can be expanded as follows:

$$\frac{\text{Benefits}}{\text{Costs}} = \frac{L \cdot f \cdot (M \cdot D \cdot S + E \cdot I \cdot C_C)}{C_T + C_I \cdot S}$$

where
- E is the embedded energy in the water (kWh/m^3)
- I is the emission intensity factor (g/CO_2)
- C_C is the price of carbon ($/tonne CO_2)

Based on Ontario's current emission intensity factor of 40 g CO_2/kWh (National Energy Board, 2017) and Canada's current pricing of carbon at \$40/tonne CO_2 (Government of Canada, 2021), the results presented in Figure 43 do not materially change, although this difference can be expected to grow over time given that the anticipated increase in carbon pricing. Of course, additional co-benefits can be expected to accrue, including the proactive identification of valves and other equipment in need of repair or replacement, the identification and improvement of system operations, particularly related to pumping energy and costs if not already accounted for in the marginal costs of water or energy components of the economic model identified above, amongst other matters.

It is noted that the above expressions do not incorporate time value of money considerations in relation to the discounting of future benefits. Such matters become increasingly of interest as the duration of assumed benefits increases. Ultimately, the degree of completeness and complexity in the economic analysis is subject to the discretion of the practitioner and depends on the particular circumstances relating to the analysis (e.g., scale, importance, expectations, etc.).

Warranted Investment Amounts

Each of the participating municipalities received a report for each individual test site which included an economic assessment identifying the amount of investment warranted in taking further actions for leakage reduction. There were two basic forms considered for these actions (interventions): (i) leakage detection and repair; and (ii) implementation of a pressure management system. The warranted investment amounts were calculated based on the anticipated financial savings using three economic models: (i) internal rate of return (IRR) using a 10% discount rate; (ii) simple payback period of 5 years; and (iii) a discounted payback period of 5 years.

Of course, results varied based on both the field testing results characterizing the presence and quantum of excess leakage as well as the marginal cost of water to the municipality. The general results are summarized in Table 2 for the 10% IRR model, excluding those sites that were re-tested.

Table 2: Selected intervention investment amounts warranted from test findings

Intervention Type	Warranted Investment Amount	
	Range	Total
Leak Detection and Repair	\$0 - \$1,214,000	\$2,043,000
Pressure Management	\$0 - \$349,000	\$1,700,000

The interpretation of these results on an aggregate basis may not be obvious, although the individual test results are more straightforward to understand. For instance, it can be reasonably estimated that leak detection and repair efforts may cost in the order of \$25,000 to \$50,000, depending on the level of effort needed. Using a threshold value of \$50,000, six of the test sites suggested that these efforts were warranted. Of the two sites that were re-tested following initial leak detection and repair, one of them continued to warrant these efforts based on this threshold investment.

Implementing a pressure management system, however, is considerably more costly with costs varying depending on complexity and market conditions (i.e., contractor availability and know-how). A threshold value of \$250,000 may not be unreasonable to consider and, in some cases, may not be sufficiently high. Nevertheless, using this value as a threshold, three of the test sites suggested that serious consideration of this type of intervention was warranted.

Leveraging AMI

Although this project focussed on the measurement of minimum night flow (MNF) data for identifying substantially leaky DMAs and for the purpose of establishing useful and reliable benchmarks, it is important to recognize that MNF itself is comprised of two basic components: (i) customer consumption; and (ii) leakage. While it is not commonly possible to simply conduct a mass balance between DMA input volume and consumption except over long timeframes corresponding to meter readings, thereby providing a more direct measurement of leakage, the trend towards smart metering, such as through Advanced Metering Infrastructure (AMI) or Automatic Meter Reading (AMR), is making this increasingly possible.

There are relatively few municipalities that have AMI or AMR systems in place, and those that do are not often exploiting the availability of data to its full

potential. While the ability to collect and leverage this data is expected to improve with time, this project benefitted from a sampling of AMI data from a participating municipality to help understand the potential division line between the customer consumption and leakage components of MNF. The analysis presented herein is not intended to be construed as definitive, but rather indicative. It is anchored in AMI data for select DMAs for a relatively short time period, noting that demographic factors will vary from DMA to DMA and, accordingly, so too will consumption. Nevertheless, it is a useful starting point.

For this analysis, hourly AMI data from three of the tested DMAs where testing occurred in this project was collected and filtered to remove unrepresentative data, including negative or unrealistically excessive consumption values as well as data from meters with too coarse a resolution for hourly analyses (i.e., greater than 1 m^3 resolution). As well, only weekday consumption was used for the analysis given that the MNF measurements were only conducted on nights leading into weekdays (that were simultaneously not holidays).

A comparison of hourly demand factors from the AMI data (i.e., consumption only) from the participating municipality (Municipality A) and a previous DMA study conducted by HydraTek (Municipality B) is provided in Figure 44. Although the DMA-based data includes a leakage component, the similarity of these results is striking, noting that similar results have been reported in the literature on a global basis. This lends confidence to the MNF approach for DMA leakage assessment.

To further assess the minimum hour consumption, including its variability as a function of DMA size, a bootstrapping resampling technique was performed on the filtered AMI dataset. This involved the random sampling (with replacement) of distributions varying in DMA size to estimate the statistical properties of the dataset. The results of this analysis are presented in Figure 45, showing the average values, as well as the 95% confidence intervals as observed from the data as well as from a Gaussian (normal) distribution using the mean and standard deviation from the data for DMAs ranging in size from 50 to 5,000 connections. The comparison of the 95% confidence intervals based on the data and the application of the normal distribution from that data's statistics suggests that the variability can reasonably be approximated using the latter.

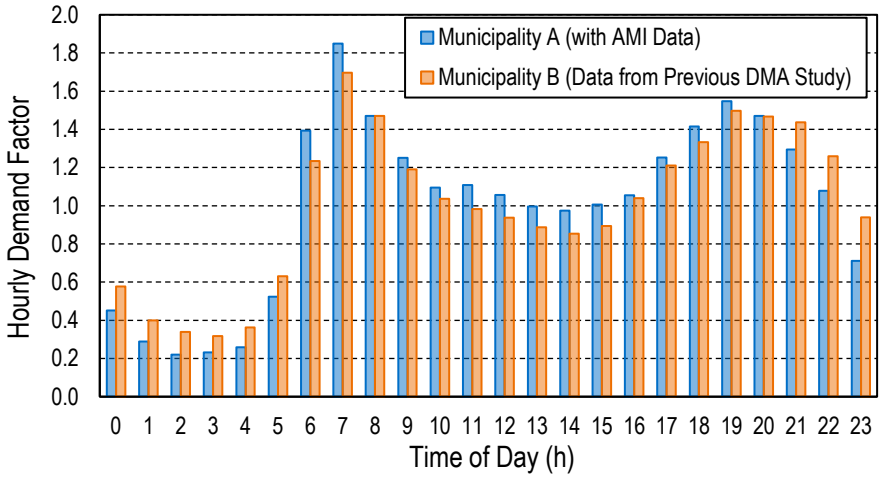

Figure 44: Comparison of selected AMI consumption and DMA flow data

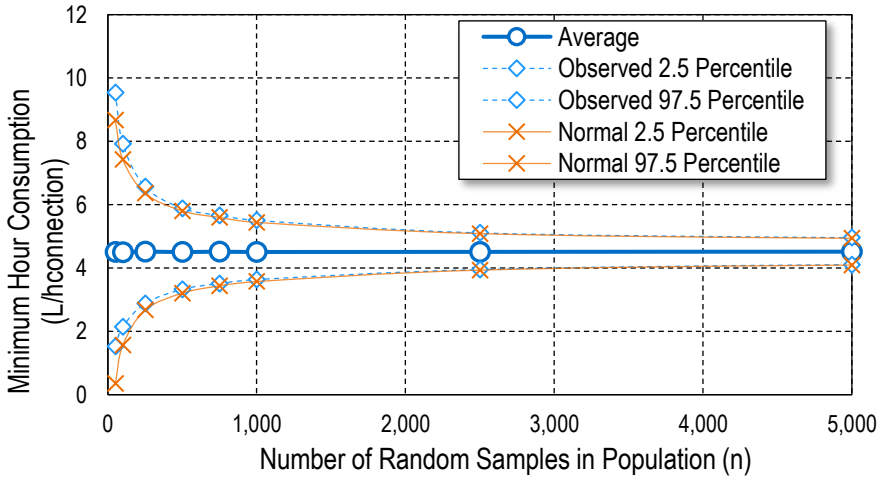

Figure 45: Results of bootstrapping analysis of AMI data illustrating the relationship between variability and sample size

These results demonstrate that the average consumption rate does not vary materially depending on DMA size, but that the variability of the data decreases significantly initially and tends towards the average as sample size increases. This is the basic premise of the law of large numbers and lends increased confidence when assessing the measured MNF from DMAs as they increase in size. These particular results suggest that there is significant narrowing in the variability for DMA sizes of approximately 500 connections (and that consideration of wider variability is needed for smaller DMA sizes). This project involved testing of DMAs ranging in size from approximately 380 to 2200 connections.

These particular results, relevant for the DMAs for which the AMI data was collected and analyzed, indicate an average minimum hourly consumption in the order of 4.5 L/h/connection. Note that this value pertains to a particular 1-hour period (i.e., starting on the hour and ending on the hour) and, as such, is not directly comparable to the measured 60-minute moving average flow used to determine the MNF_{60} value. Nevertheless, it does provide a reasonable indication of magnitude and, for one of the "healthy" DMAs from where the AMI data was derived, the measured MNF_{60} value was found to be 5.0 L/h/connection. Accordingly, the leakage estimate would amount to 0.5 L/h/connection (or 10% of the MNF_{60} value). It is noted, however, that this amount remains within the 95% confidence band identified in Figure 45 and, accordingly, has some uncertainty associated with it.

It is interesting to plot the results of this analysis alongside the performance of the "healthy" DMAs and relevant MNF benchmark identified through this work, as illustrated in Figure 46. Although these results are from a relatively small sample of AMI data from a single participating municipality and, as such, may not provide a true or fair indication of a frontier for all DMAs, it is interesting to note that none of the test results breach that frontier. The increased implementation of AMI and AMR systems, coupled with the analysis of data they collect, will be able to characterize and establish such a lower limit on site-by-site or broader-scale bases which, in turn, would be helpful at better characterizing leak quantities and reduction opportunities more firmly.

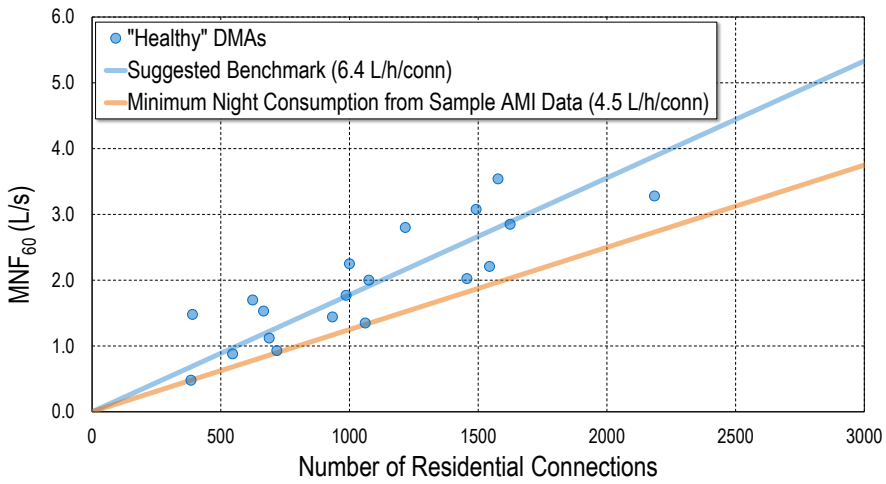

Figure 46: Minimum night consumption results from sample AMI data relative to test data and benchmarking r3esults

N1 Leakage Exponent Results

The pressure-leakage response, as represented by the N1 leakage exponent (see page 23 for explanation and derivation), was calculated for each of the test sites when pressure cycling was applied using the average high- and low-pressure flow rates nearest to the minimum hour period and having relatively stable demand. Estimates of the leakage flow rate were calculated by subtracting a value for the 1-hour minimum legitimate consumption of 4.5 L/h/connection based on the AMI analysis presented above, which represents the best information available for this project.

Figure 47 presents the average of several N1 calculations for the nights when pressure cycling was conducted, filtered to remove obvious outliers, plotted relative to the MNF_{60} value normalized based on the residential unit count for the DMA in question. Interestingly, this data generally shows that the N1 value is consistently low when leakage levels are high (based on the MNF benchmarks presented earlier), approaching the theoretical limit of 0.5 (i.e., orifice flow). For sites in the "healthy" DMA group, the N1 values become quite high, particularly as the MNF_{60} value approaches the minimum legitimate night consumption (LNC) value of 4.5 L/h/connection (i.e., zero leakage). In fact, many of the N1 values calculated are well above the industry's generally accepted upper limit of 1.5, many significantly (absurdly) so. These values are not credible and are likely

the result of customer-side consumption impacts due to the changes in induced pressure, the potential existence of very minor leakage at boundary valves and/or other matters. Whatever the case, that these values occur when leakage is minimal is of no practical importance.

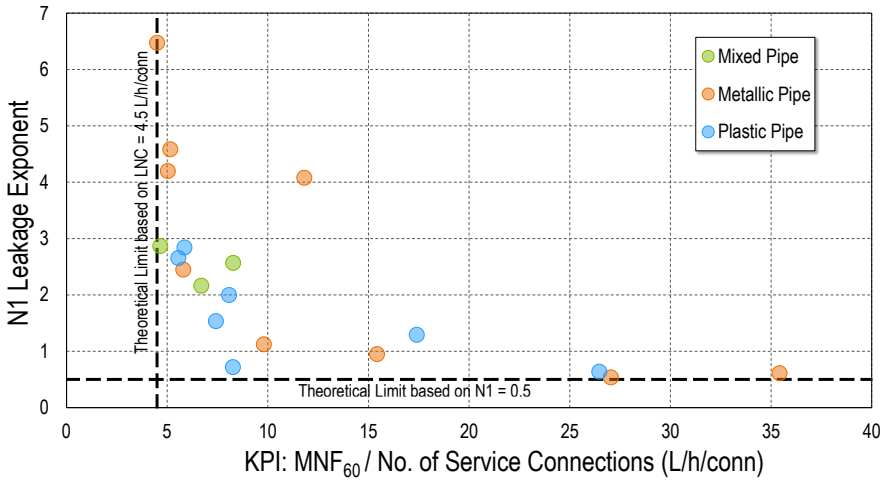

Figure 47: Calculated N1 values (filtered data)

It is noted that Figure 47 uses colour coded data points to differentiate between DMAs with different pipe material characteristics. For the purposes of this work, a DMA's watermain system was classified as "metallic" if its composition of metallic pipe was 70% or higher. If the DMA comprised less than 35% metallic pipe, it was classified as "plastic." If the fraction of metallic pipe in a DMA lied between these fractions, it was classified as having "mixed" pipe materials. The results do not suggest any causal relationship between pipe materials and calculated N1 values, noting that this is a rather limited data set, and the intention of the graphic is to simply present the results of the testing.

Figure 48 presents the unfiltered average and range of N1 values for each site when pressure cycling was conducted. These results indicate that there is generally a wider degree of variability in the N1 estimates for the "healthy" DMAs (see Figure 28), and those sites with high leakage (i.e., outliers) exhibit little-to-no variability. While this is not to be construed as causation, it is nonetheless and interesting correlation.

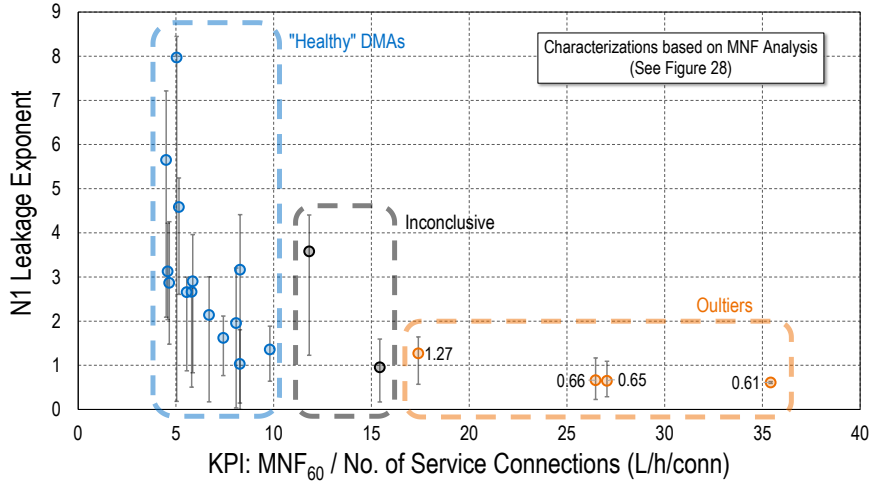

Figure 48: Calculated N1 values and ranges (unfiltered data)

The "Rule of Two"

During the course of testing, it became increasingly evident that, for "healthy" DMAs with little-to-no meaningful excess leakage, the flow rate into the DMA at approximately midnight would be about double the ultimately measured MNF value. While this ratio can be calculated from typical diurnal consumption and/or DMA inflow profiles such as those presented in Figure 44, a statistical analysis of the data collected as part of this project was conducted. For this analysis, only one night of measurement under normal operating pressure conditions at each "healthy" DMA was considered, subject to having complete data for the period from midnight to 6 am and subject to no obvious anomalies. This filtering process yielded 13 qualifying data sets, the analysis results for which are presented in Figure 49, based on 15-minute averaging windows.

As can be seen from the graphic, the field observations are roughly supported by the data, with the average ratio of midnight flow to MNF being 2.15 with a 90% confidence interval ranging from 1.80 to 2.75. That is, and practically speaking, the leakiness of the DMA may be roughly discerned around midnight. Based on the DMA's population, unit or connection count, an estimate of what the MNF ought to be if the DMA were "healthy" may be obtained using the benchmarks identified and, accordingly, the stable flow rate at midnight should

be roughly double that value. If the midnight flow rate is materially higher, then that difference could be an early indicator of what the night's testing will reveal in terms of excess leakage.

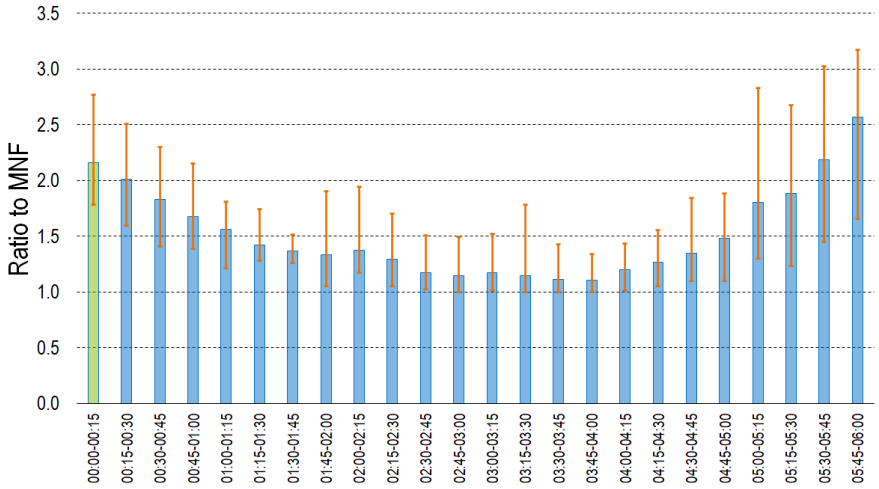

Figure 49: Ratio of measured flow rate, including average and 90% confidence intervals, relative to measured MNF at 15-minute intervals.

The benefits of such an early warning could include the proactive search for issues that might be giving rise to the high flow rate, such as blow-offs or valves passing to a lower pressure zone. As well, knowledge of the general pattern and error bands as presented in Figure 49 are helpful when planning and conducting step tests during overnight periods.

Shorter Averaging Windows

As part of this project, an exploration of the averaging time window used to determine the MNF value was undertaken. This study's results generally follow the typical industry practice of applying a 60-minute moving average to identify the MNF, and this exploration sought to review the appropriateness of this duration. More particularly, it sought to understand to what degree the MNF may be overstated as a result of the 60-minute duration relative to shorter durations while simultaneously preserving the reliability of the results given the increased volatility associated with shorter averaging periods.

For this analysis, MNF values were calculated for durations ranging from 1-minute to 60-minutes, with results normalized against the 60-minute value. This was undertaken for all "healthy" DMAs with the average and 90% confidence intervals plotted on Figure 50. As expected, the measured MNF decreases as the averaging duration decreases while the variance in the data increases. The results may suggest that averaging periods approaching 30-35 minutes may offer reasonable reliability of results and for which an approximate 6% reduction in the MNF_{60} value may be expected on average. That said, the 90% confidence interval at the 30-minute duration ranges from 2% to 11% reductions in the MNF_{60} value, which is quite wide.

Given that the results of this project have indicated that the presence of significant leakage is not uncommon, it does not seem worthwhile at this point to deviate from the typical industry practice of using a 60-minute averaging period. Any benefits in doing so, as it relates to short-duration temporary MNF measurement as in the case with the mobile unit, would appear to be small relative to the opportunities at hand, while the reliability of the results begins to suffer. Further, the use of the 60-minute averaging period dovetails well with typical AMI and AMR data for direct comparison. As the general industry practice evolves and it becomes increasingly worthwhile to focus efforts on such refinements, then these considerations can be resurrected at that point.

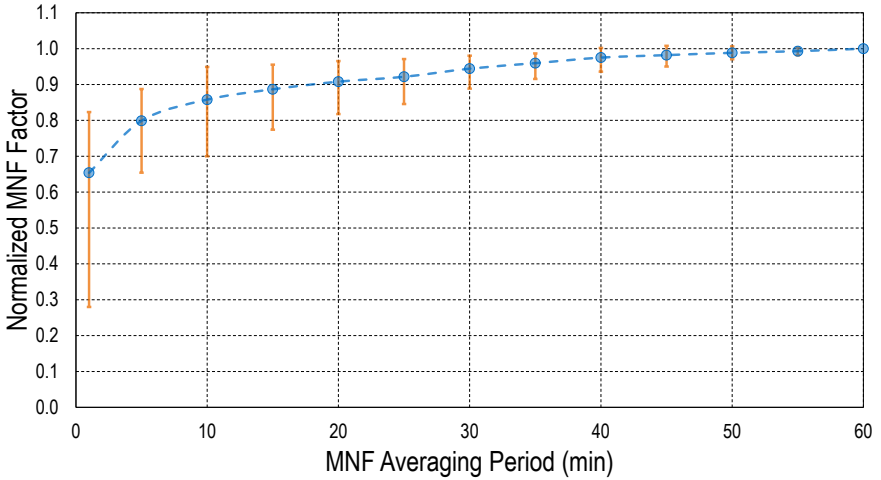

Figure 50: Analysis of shorter averaging durations for MNF determination

As alluded to above, the results presented in Figure 50 relate to deployment of the mobile unit for a limited number of nights in a given DMA and for which the value of employing shorter averaging periods is questionable. However, for permanent DMAs or other longer-term data sets (i.e., many nights of data) such as those obtained from temporary or semi-permanent DMAs, the reliability of MNF measurements based on shorter averaging periods will be improved by virtue of the number of overnight measurements available. This would result in higher confidence in the MNF estimate which would more firmly support a lower leakage estimate relative to that obtained using the MNF_{60} value. Such analyses are expected to be increasingly relevant after municipalities address any DMAs with more obvious signs (and quantities) of leakage (i.e., the "lowest hanging fruit"), as well as for municipalities with high marginal costs of water.

System Elasticity

To measure the pressure-dependency of flow into the tested DMAs, pressure-cycling exercises were conducted on certain test nights whereby the pressure reducing valve (PRV) in the mobile unit was activated and deactivated at regular intervals. During each of the transition periods – from full pressure to reduced pressure and *vice versa* – the effects of system elasticity were readily observed in the flow entering the DMA. That is, when transitioning from full to reduced pressure, the flow rate dropped considerably, often to zero, until the system stabilized. The opposite occurred when transitioning from reduced pressure to full pressure, with the inflow rate spiking for a period until stabilization of the system occurred. These occurrences are predominantly the result of two phenomena: (i) compressibility effects of the water within the DMA piping; and (ii) the expansion or shrinkage of the watermain system itself in the event of an increase or decrease in operating pressure, respectively.

To explore this matter somewhat further (and primarily out of curiosity), the frequency of selected flow and pressure recording equipment in the mobile unit was increased during one of the test nights in a DMA deemed to be "healthy" (i.e., little-to-no excess leakage). This particular DMA comprised approximately 433,500 L (V) of water contained within plastic and metallic piping materials (30% and 70%, respectively).

An example of the impact of pressure changes imposed by the PRV on the DMA inflow rate during these transitions is provided in Figure 51. The bulk modulus of water, being the measure by which its compressibility is characterized, is 2.15 GPa and can be used to estimate the volume change in the system due to the decompression (and re-compression) of water alone. During these transitions, the total change in volume of the system was measured by the flow meters which, for the testing conducted and after accounting for baseflow, was estimated to be generally in the order of 180 L. The difference between these two amounts was therefore estimated to be the amount by which the watermain system shrank (in the case of a reduction in pressure) and expanded (in the case of an increase in pressure). In general, it was found that approximately 15-20% of the volume change was attributable to water compressibility effects, leaving the remaining 80-85% of the volume change being attributed to system expansion (or contraction) and/or any other effects.

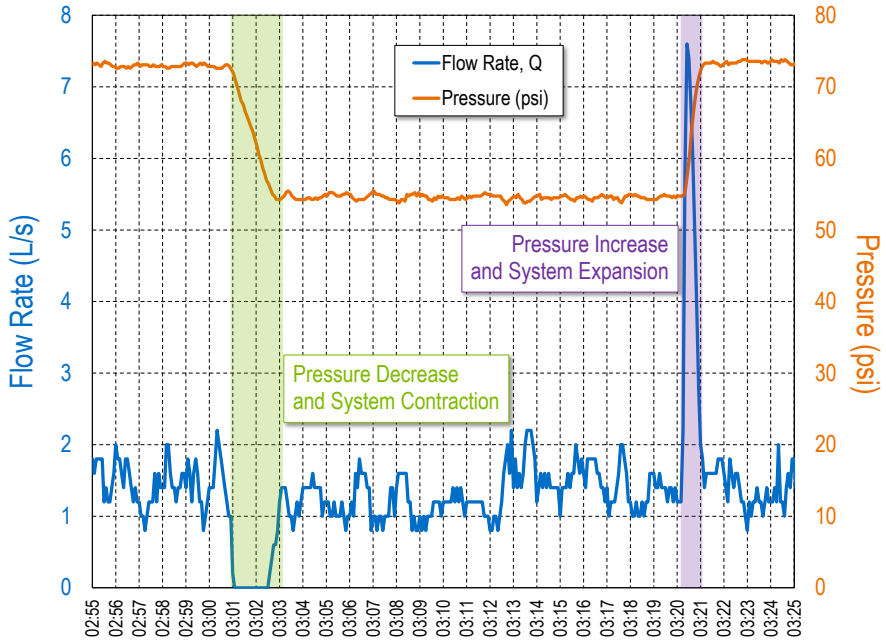

Figure 51: System elasticity effects during pressure transitions

While such analyses were beyond the scope of this particular project, it may be interesting to consider collecting more granular data and reviewing and contrasting the results for systems with varying degrees of leakage.

Lessons Learned

This section is intended to (humbly) identify some of the key lessons learned through this project to facilitate the efficient and successful future application of similar methods and tools.

Mobile Unit Development

Equipment Selection

The sizing of the componentry employed by the mobile unit, particularly hose lengths and diameters, in conjunction with flow rates and resultant velocities, dictate the degree to which hydraulic losses are imposed by the unit It is necessary to properly understand: (i) the range of DMA sizes that the unit is intended to be used for; and (ii) the impact of hydraulic losses on the system being tested including the impact on the test results.

Since flow measurement is critical to the purpose and function of the mobile unit, it is important to select a metering technology that is suitable for the configuration of piping and fittings within the unit itself to promote flow conditions that will yield accurate measurements thereof. Similarly, matching the applicable flow range of the PRV to that of the meter is sensible, noting that smaller PRVs tend to be more responsive than larger ones.

Material Sourcing & Assembly

Considerable effort was required through an iterative process of detailed design and related dialogue with material suppliers, fabricators and contractors for the assembly of the mobile unit. Given the small quantities involved and the uniqueness of the assembly, the appropriate level of attention and oversight of this process is important and recommended, as is the allocation of sufficient time to adapt to delays and unforeseen circumstances.

For this project, while working out the design details and sourcing components had some challenges, the contractor that handled the fabrication of the assembly within the trade van used was swift and masterfully accomplished. This process demonstrated the value of "social capital" within the industry as relationships with several individuals and organizations were leveraged to produce a solid, reliable and functioning unit without the need for adjustments. Over the approximately 2.5 years that the unit has been in existence (as at the time of writing), no repairs have been needed to the hydraulic assembly (or to the vehicle itself).

Acceptance Testing

A valuable component of the mobile unit development process followed in this project was the conducting of a thorough acceptance test which led to confidence in its deployment. For this testing, arrangements were made with a municipality to connect the unit to a fire hydrant where the unit was subjected to a wide range of flows. Pressure and elevation measurements were meticulously taken at key points (i.e., supplying hydrant, upstream and downstream of the PRV as well as at the downstream end of the piping within the unit) to characterize the hydraulic losses imposed by the unit. As well the function of the PRV was tested and confirmed, a procedure which identified issues with the pilot piping that were rectified during the acceptance test (i.e., before deployment).

Apart from the obvious benefits of preparing the unit for deployment including understanding its hydraulic behaviour and confirming its functionality, this was found to be a useful exercise to train team members on both the mobile unit as well as key hydraulic principles in a practical (quasi-laboratory) setting. Given the time spent on this process and the modest fees as well as the cost of water used paid to the municipality, this testing was well worth the effort.

Figure 52: Setting up for acceptance testing of assembled mobile unit

Data Integration

A sometimes frustrating reality of data collection from multiple devices is that the technologies for doing so, while generally similar in terms of data gathering, storage and communication, are often unique and not directly compatible. Selecting equipment (e.g., flow meters) with these matters in mind can save considerable efforts in relation to the testing work. As an example, one of the flow meters used for this project had the built-in ability to include a pressure transducer and logging capability which was found to be often relied upon.

Given that this testing generally occurs during colder months and overnight periods, the implementation of data integration and communication technologies could significantly improve the comfort level of those responsible for testing. As part of the testing process, periodic observations of data are made over the course of the evening to ensure that the testing is proceeding as intended and that the distribution system delivering service to the municipality's customers is performing acceptably. These periodic checks can also help to identify any issues that might arise such that they can be mitigated early, an excellent example of which is the potential freezing of the pressure sensing and PRV pilot lines within the mobile unit when ambient temperatures are below freezing. To the extent that data can be communicated in an integrated manner, benefits in terms of improving the process for the test operators, as well as the potential to log all relevant data together thereby improving the efficiency and quality of the data management and analysis process, would be expected.

Spare Parts & Supporting Equipment

Although there were relatively few issues (and all of which were quite minor) with the mobile unit's hydraulic assembly over the course of this project, there were instances when having spare parts on hand were beneficial. In general, various fittings, ball valves, gate valves, hoses, gaskets and seals (as well as Ziploc bags, zip ties, Teflon and duct tape) are recommended to be on hand and available if and when needed. Of the issues encountered, these were mainly due to freezing conditions affecting sensing and/or PRV pilot lines, noting that the hoses and main assembly did not suffer from freezing on account of both the temperature and velocity of the water passing through them. To deal with freezing conditions, a blow torch was periodically needed (see Figure 53).

Figure 53:
Special measures required to avoid freezing of sensing and pilot lines

Taps & Threads

On several occasions, the taps within the chambers were not installed in accordance with the instructions provided, resulting in the need for adaptation which in some cases was relatively easy (thanks to appropriate adaptor fittings being on hand). In other cases, these situations resulted in the loss of test nights as workarounds were sorted out.

DMA Boundary Integrity

It is not at all uncommon for watermain valves to not close tightly, although this is critical for the testing process. It is accordingly important for sufficient attention to be devoted to this matter and to duly prepare sites in anticipation of testing. The loss of test nights as a result of discovering and dealing with such issues represents a significant inefficiency in terms of human and financial resource deployment.

The value of zero-pressure testing in preparation of the test sites should similarly be communicated and encouraged or required. Recognizing that this can be laborious, the use of this technique to identify valves that seat tightly without extraordinary effort can be helpful at minimizing the number of times such tests are needed such that focus can be applied to those that require such efforts. Boundary integrity testing can be completed in a somewhat less intrusive manner than zero-pressure testing on each night of set-up through the use of the PRV within the mobile unit to temporarily reduce pressure in the DMA. This pressure reduction should be visible and maintained/sustained at all other locations within the DMA. Failure to do so reveals that there is a boundary integrity issue. While it is not a perfect substitute for zero-pressure tests, these two procedures can be used in conjunction with each other to reduce the overall effort required to ensure that boundary integrity has been accomplished.

Avoid Holidays & Weekends

Customer consumption patterns do exhibit some degree of variation between weekdays and weekends as well as around holidays. These effects were also noted to be a function of the DMA's population characteristics. Accordingly, understanding the DMA's demographics may help to avoid testing on nights that may not yield appropriate estimations of the MNF. As a case in point as it relates to this project, the data collected on Hallowe'en Night in 2019 demonstrated a strange and unexpected pattern that was of marginal utility for the project. It was found, however, that testing nights leading into workdays, particularly in working-class neighbourhoods, often yielded predictable and reliable results.

Avoid Automated Irrigation

Despite this project's relatively tightly defined temporal windows for testing, for the explicit purpose of attempting to avoid the influence of overnight irrigation, the surprisingly mild spring in 2021 required that a test site be postponed until later that year because of such activity. In addition to time of year, the presence of automated irrigation is often linked to the demographics of the DMA in question – particularly the affluence thereof – as well as the number of large-scale land uses, such as apartment complexes or commercial plazas. Nevertheless, testing in the presence of irrigation is a pointless exercise if the benchmarks developed in this project are to be applied.

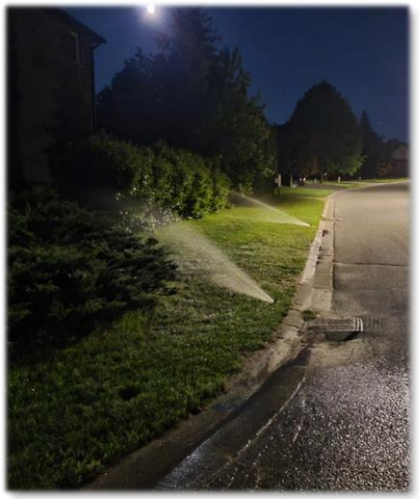

Figure 54:
Automated irrigation at 3:19 am

Beware of Compression Fittings

For some of the test sites, the municipalities installed taps on watermains in chambers that terminated in compression (rather than threaded) fittings. Such fittings can present challenges given that, without adequate restraint, the forces imposed upon them with or without the hoses connected to the mobile unit, can cause these fittings to detach. While the tests conducted using such fittings were largely successful, the few issues that were encountered suggest that it is simply more desirable and reliable to use tap installations with threaded fittings (for which no issues were encountered).

Beware of Blow-Offs & Automated Flushers

Some (but certainly not all) municipalities make prolific use of blow-offs at the end of dead-ended watermains and at other locations to maintain disinfectant residuals and manage discolouration risk of the water supplied and/or to provide continuous flow to flush their sanitary sewers in location where they may be prone to clogging. These blow-offs and flushers, when operating, contribute to higher flow measurements, giving the appearance of leakage. In some cases, blow-offs run continuously. In all cases, there is the resultant consumption of treated water and energy. Oftentimes, there may be poor institutional knowledge as to the location of these devices, requiring time to be consumed during the setup and, in turn, potentially compromising the testing period itself. As well, these devices have been found to not always close tightly and reliably to allow for accurate testing. As a result of these experiences, the following recommendations are made (in hierarchical order): (i) municipalities should be encouraged to identify and close all blow-off and automated flusher locations in the test areas in advance of testing; (ii) planning personnel should actively seek the existence of such devices during initial test planning and site reconnaissance; and (iii) testing personnel should also include such active seeking of blow-offs in their test setup process whilst operations staff are available and engaged for this purpose.

It is also noted that some of these blow-offs may have originally been intended as temporary measures, such as during the construction process until such time that sufficient build-out occurs or that water quality has stabilized. In one instance, a hydrant was found to have been flowing for numerous weeks following a watermain upgrade project and had apparently been forgotten about. Such occurrences support the general theme of testing, observation and discovery as they too were valuable findings in terms of identifying and reducing unnecessary water loss from these systems.

While a broader discussion on blow-offs is presented earlier in a case study (see page 32), the influence of an automatic flushing device on minutely flow measurements in a rather small DMA is evident in Figure 55. In this particular example, and despite the short duration that the automatic flusher was in operation, the resulting volume was approximately 6,700 L which amounts to about 2% of the DMA's annual consumption if operated every other day. Accordingly, there may be scope to consider reducing the run time of such devices in order to minimize wastage while still achieving water quality objectives through sufficiently high disinfectant residuals.

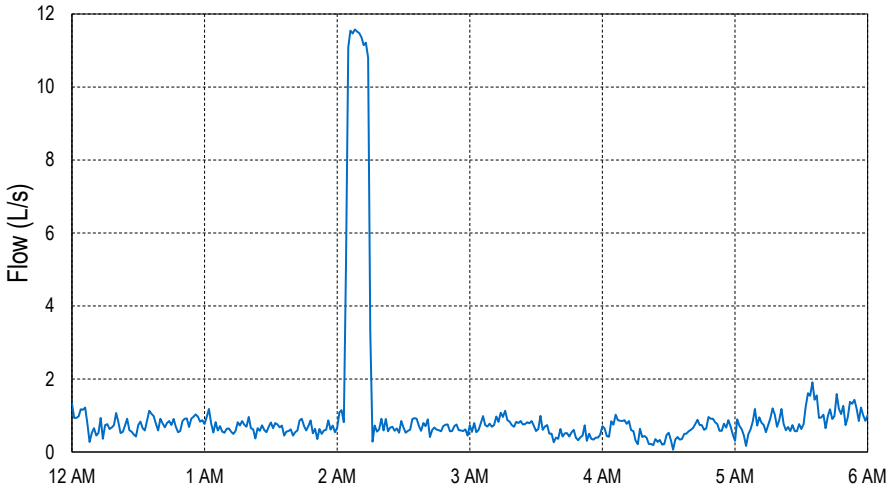

Figure 55: Impact of automatic flushing device on DMA flow measurement

No Substitute for Experience

All activities related to testing DMAs in general, and mobile testing of DMAs specifically, including planning, field work as well as data analysis and interpretation are interconnected and nuanced. While the concepts discussed in this report are generally simple and seemingly straightforward, successful application requires proficiency in all respects of the work. Proficiency, in turn, is related to the degree of experience of the practitioner, coupled with the appropriate and relevant training relating to matters of hydraulics, operations, probability and statistics, risk-based assessments and decision making.

As well, those procuring such activities can have a strong influence on the direction of any particular project. Improper procurement (or "asking the wrong questions") may present challenges for the delivery of a successful project before it commences. Accordingly, wherever needed, those responsible for procurement ought to consult with those with relevant knowledge and experience of this work, whether internal or external to their organizations. There is no "one size fits all" approach to water loss management in general and DMA testing in specific, and any individual projects should form part of broader-reaching programs logically organized to advance practices and progressively refine system performance knowledge. For instance, it is typically not sensible to procure leak detection work without knowledge of which areas have or are suspected to have meaningful detectable leakage.

Any gaps in knowledge and experience will shorten over time as these practices become increasingly adopted and more widespread. Through this process of evolution, the lessons learned and shared by practitioners and municipalities will help drive improvements and efficiencies. It is hoped that the results of this work, as documented in this report and on the project website, all of which is available for public consumption, as well as the numerous interactions across the industry along the way, will make a meaningful and lasting positive impact on the industry. It is recognized, however, that it is a vast and complex industry and that such efforts must be sustained on an ongoing basis for there to be acceptance and adoption.

Figure 56: "Experience is the teacher of all things." ~Julius Caesar

This report and all other materials relating to this project are available and kept up to date on the project website: www.hydratek.com/mobile_dma_testing

In Conclusion

To concisely conclude this report, the following is a brief distillation of its key findings and outcomes:

- The mobile unit offers the accuracy and reliability of permanent infrastructure with the flexibility of geographic independence and affordability of temporary testing.
- This project provided the proof-of-concept for the use of the mobile testing unit for diagnosing the "health" or leakiness of district metered areas (DMAs).
- As part of this proof-of-concept, two test sites were subjected to leak detection and repair efforts, followed by re-testing to measure and verify improvements which, in both cases, were meaningful.
- In one of the sites re-tested following the repair of a single leak, the resulting savings were truly impressive, summarized as follows:
  - Water savings: 139,000 m^3/year
  - Financial savings: $426,000/year
  - Energy savings: 102 MWh/year
  - Environmental savings: 4.1 tonnes CO_2-equivalent/year
- Strong and reliable benchmarks have been developed for industry use in Ontario, across Canada and in the U.S. (given the contextual consistency in these areas). These benchmarks are expressed in terms of the 60-minute average minimum night flow (MNF_{60}) for residential DMAs, and are summarized as follows:
  - 2.2 L/h/capita ($R^2 = 0.83$)
  - 6.0 L/h/unit ($R^2 = 0.81$)
  - 24% × Average Billed Demand ($R^2 = 0.79$)
  - 6.4 L/h/connection ($R^2 = 0.73$)
  - 525 L/h/km of watermain ($R^2 = 0.49$)
- The total estimated leakage from this project's test sites amounted to 570,800 m^3/year with an equivalent energy wastage of 269 MWh/year.
- Scaling these results up to the level of the province yields estimated leakage in the order of 114,000 ML (114,000,000 m^3) per year and an equivalent energy wastage of 53.8 GWh (53,800 MWh) per year.
- The "success rate" of finding test sites with significant excess leakage was in excess of 10%.
- The financial motivation to engage in leakage management practices is strongly driven by the marginal cost of water paid by the municipality. Those municipalities that purchase water from adjacent jurisdictions accordingly have strong incentives to advance these practices (although the awareness seems to either be low or to have not translated into strong initiatives). For municipalities with a high marginal cost of water, the benefits of regular testing clearly outweigh the costs of letting leaks go undetected and unrepaired.
- Business cases based on financial matters alone ignore the co-benefits associated with leakage reduction efforts which may include:
  - Pumping costs and energy usage, either within the municipality in which the site is located or in upstream jurisdictions.
  - Improved asset knowledge and early warning for repair needs.
  - Improved system operation knowledge.
  - Efficiencies realized by other asset systems (e.g., reduced wastewater volumes in the case of blow-offs directed to sanitary sewer systems).
  - Efficiencies with complementary initiatives and corporate-level goals within the municipality (e.g., water and energy savings).
- The mobile unit is available for commercial application and industry duplication to support widespread adoption of its use and, in a more general sense, leakage management and reduction practices.

This project was made possible through the financial support of the Independent Electricity System Operator (IESO)

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