WATER INFRASTRUCTURE:
LONG TERM SUPPLY, DEMAND MANAGEMENT AND PLANNING

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Canadian Water Network

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RESEARCH BACKGROUND

A great deal of Canada's water infrastructure was built in the 20th century, when urban areas were emerging, economic development was the main objective and abundant water was a requirement for growth. A shortage of water was an impediment to progress, rather than an obvious indicator of natural limits. Given this context, it is not surprising to find that certain design paradigms regarding infrastructure in general and water infrastructure in particular have become outdated. Water networks have historically been designed to meet predicted demands with sufficient pressure at minimum and maximum standards. These standards were set to be reasonable safety measures against contaminant intrusion under low pressures, and against higher burst and leakage rates during high pressures. However, the variation in standards between countries shows there is room for debate about the tension between sustainability and safety. Nevertheless, revising standards is never an easy task. Expectations have been created, infrastructure has been built, and private equipment has been installed based on these existing standards. Any modifications to the service delivered to users, including pressure and pricing, must consider multiple perspectives and wide stakeholder opinions as well as to allow sufficient time for adaptation.

The pioneering definition of sustainable development given by WCED (1987) established key concepts, such as inter-generational and intra-generational equity, needs, and limitations. Key resources should not be wasted or used in such a way that they become progressively less available then they are now. In an absolute sense, sustainability is an almost impossible standard; but practically speaking, it is certainly possible, and a key priority, for human activities to become "more sustainable" than they are at present. Limitations on the environment's ability to promote equity are imposed by the state of technology and social organizations. The three pillars of sustainability – economy, environment, and society – are explored in different ways within the proposed tools. But none of these are fixed and the overall goal is always that of becoming progressively more sustainable. It is this context that has informed this exploration into the sustainability of water systems.

The major source of revenue for many water utilities is the sale of water. Funds collected from water bills, along with some specific infrastructure grants and incentives, are intended to cover uncertain future operating and capital costs. Even though these systems have life cycles verging on a century, financial reports and business plans are completed yearly and every 5 to 10 years. Despite the large costs of reinvestment, deferring repairs and replacements is inevitably worse in the long run (AWWA, 2012). Yet merely optimizing present revenue might not be the most advantageous alternative. Long-term financial results and life cycle impacts should become both more nuanced and more routine, with incentives being aligned with the overarching performance goals of long-term reliable, resilient, and sustainable operation.

Other indicators of system performance include energy efficiency and water consumption, which can be benchmarked according to sector and land use type. Water utilities typically bill their customers according to sectors (i.e., residential, industrial, commercial, and institutional), or at a flat rate for all users. Although Canadian municipalities have access to land use and demographic data from the Municipal Property Assessment Corporation (MPAC) and Statistics Canada, at times little is known of the users except their billing class. Because this classification is not inherently descriptive, it does not allow for the definition of homogeneous groups of water users, which would be more suitable for establishing benchmarks, analyzing trends, and targeting both conservation and communication efforts.

Life cycle analyses of water infrastructure (Stokes and Horvath, 2011) have indicated that the operational phase contributes to 50% of total greenhouse gas (GHG) emissions due to energy use. According to EPRI (2002), approximately 80% of municipal water processing and distribution costs stem from electricity. Regardless of system size, the primary use of this electricity is for pumping treated water to the distribution system, representing 80 to 85% of the total electrical use for surface water systems. Groundwater systems generally require 30% more electricity. Water and wastewater services represent the single-largest source of electricity consumption in Ontario municipalities, comprising between one to two-thirds of municipal utility electricity costs (Maas, 2009).

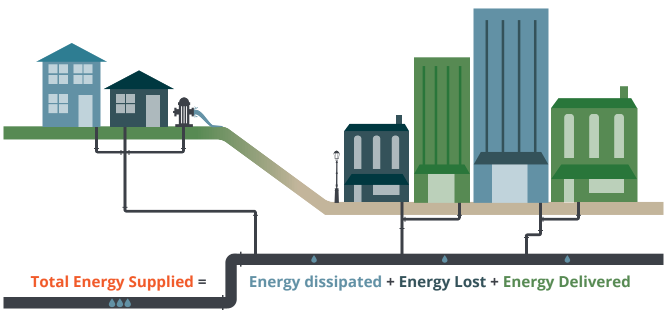
"By bringing these pieces of the water puzzle together, water service providers can look at how demand varies with the type of residence or business, age of the structure, and land area. A better understanding of local demands on water resources and usage allows for more accurate planning and helps ensure an adequate supply of clean water is always available."

The Honorable Jim Bradley, Minister of the Environment

RESEARCH METHOD

ENERGY AND PERFORMANCE METRICS

In water distribution systems, energy is a powerful metric, because energy use integrates not only a major financial and environmental cost, but also the two main products of the system (water flow and pressure) that control and evaluate design. The amount of energy used in water distribution, and its different forms, can be estimated with hydraulic simulators that are readily available, such as EPANET (public domain software provided by the US Environmental Protection Agency that models water distributions networks). Because energy is conserved there must be a balance: the total energy supplied to the water network must equal the sum of energy dissipated, lost, and delivered. Energy supplied is defined as that which enters the system through pumps or, in a few cases, from elevated water sources. Energy dissipated is defined as that which is converted from mechanical to thermal form (so called energy losses) through the passage of water in pipes, pumps, connections, and valves due to friction and inefficiency. Lost energy is a different category and is the energy that leaves the system through leakage of pressurized water. Finally, the energy delivered is that which reaches consumers or storage points as pressure and elevation. The ratio of energy delivered to energy supplied is thus a natural, useful but remarkably neglected indicator of system efficiency.



In order to expand the analysis of water networks and assess their performance under different operational conditions based on energy metrics (energy supplied, dissipated, lost and delivered), four performance metrics were defined and determined for hypothetical systems: reliability, vulnerability, resilience, and connectivity. Three scenarios were analyzed: normal demand pattern, fire flow during maximum demand, and pipe burst during peak demand. Reliability related to the performance of the system under different conditions was defined as the average energy efficiency over all scenarios. Vulnerability represents the severity of failure, and is the minimum efficiency reached by the system during emergency events or normal operation. Resilience, similar to reliability, is calculated as the average efficiency, particularly after emergency events. Resiliency represents the system's capacity to adapt to change and recover after a period of failure. Connectivity reveals the benefit of loops creating alternate flow paths, and is the minimum percentage of demand delivered given a pipe break.

DATA INTEGRATION

Water infrastructure – and the water it delivers – strongly affects a great many components of urban life: from system layout, to billing and municipal records, to fire-fighting and insurance premiums, to a community's quality of life. However, water infrastructure data reflecting this broad scope is often not available to municipalities and consultants, who deal with a bewildering array of standards, approaches, systems, databases, protocols and authorities.

> "We have the information technology infrastructure in Ontario that allows us to use existing technologies in new and innovative ways (...) it is not a big investment on the part of municipalities but is an opportunity to create powerful analytical tools and powerful information tools"
>
> *Jeff Evenson, Vice President of Urban Solutions, Canadian Urban Institute*

In order to better understand drivers of water use and quantify demand in different sectors, water billing records, land-use, and demographic data were integrated for the cities of Barrie, London, and Guelph. This information was collected from water utilities, MPAC, and Statistics Canada (StatsCan). Tables were created using common identifiers, that included the key data of address, roll number, parcel ID, and dissemination block ID. Roll numbers are the identifiers used by MPAC, while parcels are pieces of land generally equivalent to properties, and dissemination blocks (equivalent to city blocks), are the smallest geographic areas for which StatsCan releases population counts. The main variables analyzed were monthly water use (m^3), unit count, building footprint (m^2), year built, property area (ha), population, rate class, and property code. A spreadsheet-based summary tool comparing metrics from all three cities was developed to communicate these results to water utilities, and to assess and convey this information to policy makers and users. Water user clusters were also created through different techniques and selected according to internal and external validation.

RESEARCH FINDINGS

While predicting and managing demands is highly important, so is designing a system that can adapt to various scenarios. Demand management is potentially a huge design and performance tool for sustainable urban practice.

The proposed energy metrics (energy supplied, dissipated, lost and delivered) were applied to case studies of the Toronto and Hamilton water distribution networks. Aggregate results of the systems were used as indicators of overall system capacity, efficiency, GHG emissions, and costs. When mapped, the metrics provide a geographical snapshot of the system and allow for better and quicker identification of pressure districts, or even specific mains, pumps, and tanks, where dissipations are high or energy delivered is in excess, and changes are most beneficial. Overall, they quantify and qualify energy flows in the system.

Energy delivered to the consumer rarely equals the actual requirements for use. The system must function within the tension of pragmatic compromises between various requirements. Different types of consumers demand distinct pressures (particularly industries), and can be located throughout the system at different distances from supply and elevations. In order to meet one consumer's needs, for example, neighbouring users may receive excess pressure. This means that there is an energy surplus in certain areas and a tendency to deficit in others. The elevation of a customer's premises can significantly influence the amount of energy required to deliver water, and consequently the actual cost of the water they are receiving.

Energy dissipated increases with greater pipe roughness, and decreases with larger diameters. Although friction is not the primary cause of main breaks, greater roughness and smaller sections caused by corrosion also increase the probability of failure in two key ways, through weaker pipes and greater pressure variations. Therefore, energy dissipated can be used as an indicator of pipe susceptibility to bursts. Attention must also be paid to the variation of main diameter and roughness over time, as well as other causes of failure, such as temperature change, soil conditions, and loading.

The analysis of variations in energy supplied and delivered throughout the day can also reveal if pumps meet requirements, if tanks provide sufficient storage and if they are being used adequately to increase reliability while reducing energy consumption, costs, and GHG emissions. In Ontario, variation in emission factors is similar to variation in electricity rates. The emission factors of an electricity grid also increase during peak consumption. While energy generated from renewable sources remains fairly constant throughout the day, fossil fuels often meet peak demands. Reducing costs and environmental impacts are complementary objectives in this case.

Based on energy metrics, the four performance metrics (reliability, vulnerability, resilience, and connectivity) evaluate how the infrastructure responds to changes, whether intentional or not, in the system. Together they help assess and compare different network configurations, conditions, and systems. Increasing pipe diameters is more beneficial from an energy efficiency perspective, whereas adding more loops to the network provides additional resilience against bursts. With tanks, the availability of storage is important, as well as the rate of water delivery. Instead of inevitably filling tanks whenever possible, the focus should be on system equalization. Redundancy allows operations to occur in a range where efficiencies are higher and vary less. The costs of increasing redundancy, namely of pipes and their installation, must be compared to its benefits. The universal practice of creating pipe loops not only increases the available water pressure but also reduces pressure variations, making the system more tolerant to uncertain and variable water demands. Adding redundancy will decrease operational costs related to electricity consumption, as well as capital costs for maintenance, repairs, and replacements.

Integrating water, land use, and demographic data organizes information and makes inherent correlations easier to understand, reduces "silo mentality" and facilitates communication to policy makers. A decrease in gross and residential consumption from 2006 to 2011 was observed for all three cities studied. Residential water use during the winter remained fairly constant for all cities. The variation in yearly consumption was a result of higher summer (peak) water use. The rate of decrease per capita consumption was also similar for all three cities. Residents have been reducing their water usage to such a degree that it counteracts the increase in population. Different trends were observed for low, medium, and high density dwellings, as well as lower water use in more recent buildings.

Effective management relies on a deep understanding of system function and performance. So, for example, clustering of parcel level data helps to pinpoint that users under the same MPAC property code tend to group together, although there is no clear separation between property codes. Only two to five clusters were formed within each sector, whether the process was initiated with parcel data or property codes. Clusters of the parcel data of industrial, commercial, and institutional sectors correlated less to property codes, since water use varies more in these classes and the distribution of the metrics is more scattered. Although parcel data from identical property codes tends to cluster, sectors are not segregated through clustering. As technical as this sounds, the implications are profound for effective communication, establishing conservation measures and targets, and effective management of system performance.

RESEARCH APPLICATION

HOW CAN THESE TOOLS BE USED?

Modeling the water network through hydraulic simulators provides a greater level of detail about the system for informed decision-making and has the potential to make good decisions in the present for what might happen in the future. Given the results from the energy metrics, as well as identified target areas and potential solutions, alternatives can be easily simulated and compared to the base scenario to confirm effective solutions. Future studies can use these metrics to analyze different networks, scenarios, and alternatives for improvement. The metrics can also be complemented with more detailed data, such as break and leakage rates, to further study correlations. The ability to identify hot spots of energy use and compare scenarios according to simple metrics facilitates the assessment of system sustainability. The utility which provides the water distribution service can better understand what the user is receiving besides water, and what this entails operationally. As a result, cost and revenue can be allocated more appropriately and rate structures reviewed.

Excess pressure can cause higher burst rates, increasing leakage and costs, but can be curtailed by pressure management (Gomes et al., 2011). Installing valves is generally the solution of choice. However, in this case energy supply hardly changes. Additional benefits might be gained by extending pressure management to include a reduction in energy supplied. Even within AWWA (1995) recommendations of a minimum pressure goal range of 21 to 28 m, and a maximum pressure goal range of 56 to 70 m, space for improvement might be found. Alterations to operational standards will undoubtedly affect the manner in which the system functions. Depending on system design and current operations, pressure reduction may cause more cycling, starting and stopping of pumps. Frequent cycling of pumps is usually an indication that the system does not have adequate distribution system storage. Thus, the role of tanks in maintaining pressures could become more important.

Average energy metrics and system efficiency can conceal wide variations in energy efficiency. Comparing performance metrics (such as reliability and vulnerability) and the average and minimum efficiencies provides a better picture of the flexibility of the system. The daily profile of energy efficiency imparts further information. In addition to infrastructure performance, other criteria needed for effective decision-making are construction, operation, maintenance, and repair costs, as well as standard pressure ranges to ensure system safety.

The networks modelled, whether real or hypothetical, had pre-allocated and defined demands. However, when designing a real system, many more unknowns exist. Demands are estimated and junctions are located based on urban planning concepts, i.e., expected user types, their typical demands, location, and growth rate. Because design and demand are interrelated, discussion should surround the extent to which real customers are affected by the network designed, as well as how hypothetical customers affect design. For instance, the unmet expectation of high demands might cause pressures to be higher and efficiency lower. Therefore, while predicting and managing demands is highly important, so is designing a system that can adapt to various scenarios. Demand management is potentially a huge design and performance tool for sustainable urban practice, and one often neglected historically.

The method applied for integrating water, land use, and demographic data is based on data available to most Canadian water utilities. For those utilities which do not have access to such information, or are beginning to plan their database, this research can assist in understanding the value of different types of data and identifying which information should be collected. This study advocates a departure from the idea of simply collecting the maximum amount of information about the system, to collecting selective data that can support measures for system improvement. The result arising from this data mining process is that cities will have information to benchmark their water use, both internally and externally, and to target conservation, predict future consumption, review water rate structures and improve communication with consumers and policy makers. The metrics and charts proposed can be used by other utilities for similar purposes, and can enhance a knowledge base for implementing sustainable improvements. This proven methodology can also inform policy planners on which potential metrics should be reported by utilities, including targets and reasonable expectations.

Combined, these methods underline a holistic strategy toward improving water distribution system sustainability. Each tool addresses major challenges in most Canadian water systems: energy efficiency, infrastructure performance, demand management, and transients. With a lack of appropriate revenue allocation and full cost accounting, these cost generating issues contribute to the substantial infrastructure backlogs of municipalities. Inefficiencies in delivering water due to leakage, high pressure, and excessive demand, lead to wasteful energy and water use. The proposed methods provide insight to these issues through approaches that integrate infrastructure, cost, stakeholder, and environmental considerations.

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MEANING FOR MUNICIPALITIES

The proposed metrics and databases have been presented to city staff in Barrie, Guelph, London, Toronto and Hamilton, and have been important discussion starters. Comments and questions from these meetings inspired many discussions of the tools and their applications. These add a lens of sustainability to system analysis, invoking inquiries over concepts that were taken for granted or deemed immutable, including operational paradigms, maintenance strategies, rate structures, and standards. If expense reduction, or more holistically, sustainability is the goal, a decrease in energy consumption, as well as water use, and the use of more renewable energy sources is central. These objectives are achieved through the reduction of pressure and flow, perhaps via refurbished pumps, new pipes, increased conservation initiatives, and/or revised pressure requirements.

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FURTHER INFORMATION

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