Energy Metrics for Water Distribution System Assessment: Case Study of the Toronto Network

Rebecca Dziedzic, Ph.D.[1]; and Bryan W. Karney, M.ASCE[2]

Abstract: Descriptive energy metrics, calculated for each component, represent how the hydraulic state of a network evolves and how energy flows vary temporally and spatially. More specifically, these metrics describe how the energy supplied is partitioned between the energy that is dissipated, lost, and delivered throughout the system. The metrics are meant to support planning, from local (e.g., pump or pipe renewal) to system-wide (e.g., leakage or pressure management) decisions. Whereas aggregate results are indicators of system capacity, efficiency, greenhouse gas emissions, and costs, the comparison of component metrics allows for the identification of specific pipes, tanks, or pumps for which changes would be most beneficial. Furthermore, analysis of the temporal variation of energy flows facilitates the assessment of operation under multiple scenarios. The metrics are applied to a case study of the Toronto water distribution system and show, based on two scenarios provided by Toronto Water, that on average, less than 27% of the energy supplied is actually delivered to users. This system inefficiency has important economic and environmental repercussions. Nevertheless, changes to operations, such as improved pump maintenance or scheduling, have significant potential to lower costs and exploit lower greenhouse gas emission factors. **DOI: 10.1061/(ASCE)WR.1943-5452.0000555.** *© 2015 American Society of Civil Engineers.*

Author keywords: Water distribution systems; Energy efficiency; Costs; Emissions; Mapping.

Introduction

Central to the water-energy nexus is the fact that electricity is essential for supplying water, and water is an important energy carrier, used in generating electricity. Both water and energy are key inputs to a great many human activities and are important ecosystem services. Given the increasing global population and limited water availability, as well as high electricity and energy costs, the need for more efficient consumption is pressing. Furthermore, water distribution is usually at least partially powered by fossil fuels, the combustion of which emits greenhouse gases and contributes to both resource depletion and climate change.

Lifecycle analyses of water infrastructure (Stokes and Horvath 2011) have indicated that the operational phase is largely responsible for environmental impacts, viz, 67% of greenhouse gas (GHG) emissions. Energy use, specifically, contributes to 50% of total GHG emissions. Furthermore, according to the Electric Power Research Institute (2002), approximately 80% of municipal water processing and distribution costs stem from electricity use. Regardless of network size, the primary use of this electricity is for pumping treated water to the distribution system, which represents approximately 80–85% of the total electricity consumption for surface water systems. Groundwater systems generally require 30% more electricity (Electric Power Research Institute 2002).

In a broader context, water and wastewater services represent the single-largest source of electricity consumption in many municipalities, comprising between one- to two-thirds of municipal utility electricity costs in Ontario (Maas 2009). Therefore, reducing energy consumption and consequent GHG emissions in water distribution has large potential benefits on a variety of scales. Racoviceanu et al. (2007) established three major reasons for restricting the analysis of water systems to energy use and GHG emissions. First, energy use and GHG emissions occurring during the construction and demolition phases can be considered impulse actions; there are fewer opportunities to reduce impacts from these stages relative to those throughout operation. Second, construction and demolition energy use and GHG emissions are little affected by alternative treatment technologies or abatement strategies. Third, as mentioned, operations constitute the majority of the energy- and material-intensive phase.

According to Kumar and Karney (2012), energy is a practical and universal abstraction, for it is not only a commodity, but also a conceptual framework in which usefulness and viability, among other characteristics, can be gauged. Additionally, because energy is conserved and can be accounted for throughout the system, similar to currency, it has the potential to be used as a measure of a service's value. Specifically in water distribution, energy has the additional capacity of integrating the two primary products of the system, which control design: water flow and pressure. The amount of energy associated with water distribution, and its different forms, can be estimated with readily available simulators such as EPANET (Rossman 2000).

Pelli and Hitz (2000) define indicators of system energy use, although they are not based on hydraulic modeling. Rather, they are calculated using average differences in elevation and pumping requirements. Boulos and Bros (2010), instead, model network energy efficiency and carbon emissions. Energy losses are classified as diffuse (friction), discrete (valves), or tap (customer connection). Gay and Sinha (2012) also model network energy use, and compare minimal, ideal, and actual energy use. Cabrera et al. (2010) further distinguish between energy forms in the network: total energy input, dissipated, lost through leaks, and delivered. Energy efficiency indicators are defined according to ratios between energy supplied, energy lost, and useful energy or minimum required useful energy.

---

[1] Dept. of Civil Engineering, Univ. of Toronto, 35 St. George St., Toronto, ON, Canada M5S 1A4 (corresponding author). E-mail: re.dziedzic@mail.utoronto.ca

[2] Professor, Dept. of Civil Engineering, Univ. of Toronto, 35 St. George St., Toronto, ON, Canada M5S 1A4.

Note. This manuscript was submitted on November 5, 2014; approved on April 14, 2015; published online on June 10, 2015. Discussion period open until November 10, 2015; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Water Resources Planning and Management***, © ASCE, ISSN 0733-9496/04015032(11)/$25.00.

All of the aforementioned studies evaluate energy efficiency at an aggregated system level. Cabrera et al. (2010) recommend that the energy balance be calculated for 1 year to improve comparisons between systems. Although these indicators can be used to assess modeled improvements to the systems, they do not reveal where and which types of modifications are most beneficial. Although the forms of energy use are distinguished, the system is largely still seen as a black box.

Pflanz et al. (2009) convincingly assert that there is no single answer for every water system. The specific design, operation, and maintenance of each system must be analyzed with respect to system interactions, while balancing not only energy use, but also costs, greenhouse gas emissions, infrastructure performance, and safety. Clearly, modeling is instrumental in assessing the system in detail.

The present approach proposes metrics that can be used to assess the temporal variation, as well as the balance, of energy flows at both a component and network level to support system planning, and specifically activities such as the optimization of operations, the choice of pump and pipe renewal strategy, and issues of cost allocation. The metrics are applied to a case study of the Toronto water distribution system and mapped for which energy costs and greenhouse gas emissions are calculated. This motivates a discussion of potential improvements, as well as applications and limitations of the metrics given real utility practices.

Methodology

Metrics

Energy is needed to move water through the distribution system while meeting expectations and operational goals as well as minimum regulated requirements. Even though generally well known, for clarity of later developments, the essence of an energy formulation for a water system is briefly reviewed here. In essence, energy plays three essentially unavoidable roles in a water system: to overcome elevation differences, to compensate for energy losses, and to meet operating pressure requirements. Energy can be supplied as gravitational potential through relative elevation of reservoirs or tanks or, more commonly, through pumps. Part of this mechanical energy, however, is irreversibly dissipated, being converted to thermal energy by friction throughout the system. Furthermore, there is a fourth energy term that is definitely unwanted: energized water is lost through leaks. Thus, only a portion of the energy that enters the distribution system is delivered to the consumer, and this inefficiency depends on characteristics of the infrastructure and its operation. Energy can be calculated in several ways but can be thought of as a time integral of power, and consequently of head and flow, as

$$E = \int_0^t P dt = \int_0^t (\gamma H Q) dt \tag{1}$$

where P = power (watts), γ = specific weight ($\mathrm{N \cdot m^{-3}}$), H = associated change in head (meters), Q = flow ($\mathrm{m^3/s}$), and t = time (seconds). Modeling results almost universally unfold over a sequence of time steps. Then, an average energy flow, E, may be considered over the given period, t, as indicated by Eq. (2), where the overbar indicates a time average

$$E = \bar{P} t \tag{2}$$

Energy supplied to the water distribution system can be evaluated by the sum of its different forms as it passes through and leaves the system. The pipes and appurtenances constitute a control volume, to which water and energy are supplied, and from which they are also retrieved. Because energy is conserved, energy input equals energy output, an equivalence that can be confirmed as an accounting check that both sides of the following equation add up to the same values (as was done in the present study):

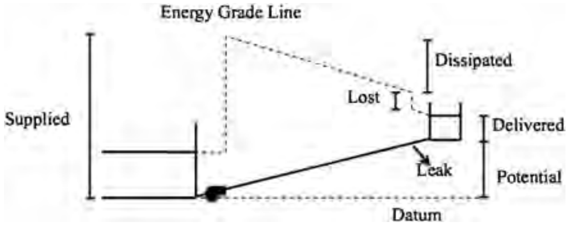


Fig. 1. Schematic representation of the different forms of energy in a water distribution system with a single reservoir, pump, pipe, and tank

$$\sum E_{\text{supplied}} = \sum E_{\text{dissipated}} + \sum E_{\text{lost}} + \sum E_{\text{potential}} + \sum E_{\text{delivered}} \tag{3}$$

where E_{supplied} = energy supplied at pumps, tanks, and reservoirs; $E_{\text{dissipated}}$ = energy dissipated in pipes, pumps, connections, and valves due to friction and inefficiency (Wh); E_{lost} = energy lost due to leakage of pressurized water (Wh); $E_{\text{delivered}}$ = energy delivered to nodes or tanks in the form of pressure and velocity, including requirements and excess energy (Wh); and $E_{\text{potential}}$ = the potential energy established by the difference in elevation between supply and delivery. These terms must be summed over all elements for each time step.

Each of the forms of energy, as dependent upon head, is represented in Fig. 1. The inefficiency of the pump is not reflected in the energy grade line, but is considered as part of the energy being supplied and subsequently dissipated at the pump. Therefore, the energy-supplied metric includes the wire power bought from the power company, and the energy dissipated includes the energy lost due to pump inefficiency.

Significant errors can be incurred if manufacturer curves are used to characterize pumps in the model, and an estimated constant efficiency assigned, without correcting for actual performance. HydraTek (2013) tested 152 pumps currently used in Ontario, Canada, and found that these have, on average, peak efficiencies 9.3% lower than their originally manufactured state. This gap further increases to 12.7% when accounting for operation away from peak efficiency.

The required energy parameters are simply retrieved from hydraulic models. Detailed leakage information, however, is usually only estimated by municipalities. Locating unreported bursts is cumbersome, for it requires expensive, specialized equipment, which makes it economically and technologically infeasible (Tabesh et al. 2009). Instead, leakage is generally equally distributed throughout the system or by district metering area (Thornton 2004). This means E_{lost} would be approximated as a percentage of $E_{\text{delivered}}$. Alternatively, if leaks were modeled, energy lost would be proportional to the product of flow through the leak and the difference in head between the inside and outside of the pipe at the leak location.

The location of the leaks affects energy requirements (Colombo and Karney 2002), and thus modeled pressures may be higher or lower than in reality. The error is inversely proportional to the size of the metered areas in the network, because in smaller areas, localized leaks are subject to less severe averaging. Information on pipe material and age can improve the allocation of leaks. Lambert and McKenzie (2002) found that, in general, a private pipe is responsible for more losses than water mains, and leak discharge varies linearly with pressure. Given these relations, the leakage indicators proposed by the International Water Association (Alegre et al. 2000) can be applied when estimating the current and unavoidable real losses of water distribution systems.

Energy dissipated is calculated according to Eq. (4)

$$E_{\mathrm{dissipated}} = \gamma H_{\mathrm{loss}} Q t \tag{4}$$

where H_{loss} = head loss (meters), which comprises local losses or friction losses, for each valve, pipe, or pump output from the hydraulic model; and Q = flow ($\mathrm{m}^3 \cdot \mathrm{s}^{-1}$).

Energy delivered and supplied are given similarly by Eqs. (5) and (6)

$$E_{\mathrm{delivered}} = \gamma (H_{\mathrm{node}} - z_{\mathrm{node}}) Q_{\mathrm{delivered}} t \tag{5}$$

$$E_{\mathrm{supplied}} = \gamma (H_{\mathrm{node}} - z_{\mathrm{datum}}) Q_{\mathrm{supplied}} t \tag{6}$$

where H_{node} (meters) = head delivered at or supplied by the node, depending on the direction of flow; $Q_{\mathrm{delivered}}$ = flow delivered; Q_{supplied} = flow supplied; z_{node} (meters) = the elevation of the node; and z_{datum} = the datum of the network. The net change in energy storage over an extended period should be zero and is not significant in an average network energy metric. In that case, energy supplied and delivered by tanks would be equal and would not affect the energy balance. However, the proposed metrics are intended to assess the system's temporal and spatial variations of energy. When considering small time steps, such as the hourly variations analyzed in the case study, storage exchanges affect the energy metrics and must be accounted for.

The elevation, responsible for potential energy, was subtracted from energy delivered so that it could be analyzed separately from pressure. With this approach, energy delivered represents the portion of energy that reaches the consumer and is readily available as pressure and flow. Potential energy is the amount of energy spent to overcome differences in elevation within the network:

$$E_{\mathrm{potential}} = \gamma (z_{\mathrm{node}} - z_{\mathrm{node}}) Q_{\mathrm{delivered}} t \tag{7}$$

The sum of energy delivered and potential indicates the energy requirements of each user. Accordingly, the energy efficiency of the system can be gauged by the ratio between the sum of energy delivered and potential and energy supplied.

Costs and greenhouse gas emissions associated with energy consumption are proportional to the energy supplied by pumps. Electricity rates vary by hour and season, as do the emission factors of the grid because energy is produced at different generators, operating at different intensities throughout the day. Therefore, apart from the consideration of varying electricity costs, the analysis of hourly fluctuations in GHG emissions can further inform operations (Bristow et al. 2011).

Potential Applications of the Proposed Metrics

Water utilities generally retain a hydraulic model to simulate system performance, compliance with pressure requirements, and provision of sufficient fire flow. Therefore, the proposed metrics can be easily calculated without representing great additional computational costs. Because the metrics are computed for each network component and time step, they can be mapped to show hot spots of inefficient energy use. Although not replacing detailed studies of operation and maintenance, these metrics and their graphic representation constitute a useful management tool for utilities. The metrics can motivate different responses from the utility, as explored hereafter.

Energy supplied is an indicator of the system's operating capacity. Energy supplied specifically at pumps is highly correlated to electricity costs and greenhouse gas emissions. Therefore, comparing hourly variations in energy demands, electricity rates, as well as emission factors, and adjusting pumping accordingly, can reduce financial and environmental costs. If pumping energy is high, and so are the pressures in an area of the network, pressure management is strongly motivated.

The partition of energy to each final form (dissipated, lost, or delivered) rather obviously implies which types of strategies should be prioritized. Energy hot spots prioritize areas and components for review. For example, if energy delivery to a specific area or a dead-end zone is high, lowering the pump set point or pressure management would be natural. Installing pressure-reducing valves increases local dissipation at the valve but reduces energy dissipated and lost through leaks thereafter. If energy lost is high, pipe rehabilitation and replacement should also be studied.

From the perspective of energy consumption, additional benefits might be gained with the extension of pressure management to include the reduction of energy supplied at pumps. Even within the American Water Works Association (AWWA; 1995) recommendations of a minimum pressure range of 21–28 m and a maximum range of 56–70 m, space for improvement might be found. Alterations to operational standards will undoubtedly affect the manner in which the system functions, however. Depending on system design and current operations, pressure reduction may cause more pump cycling. Frequent cycling of pumps implies the system has inadequate storage, and tanks might usefully assist in maintaining pressures.

The energy equation, Eq. (1), makes it obvious that high pressures are not the only factor responsible for excessive system energy demands, and that reducing flows in the system could minimize electricity costs. There is a major caveat to this statement, though. Water distribution networks are designed for a set of pressures and demands, and usually operate more efficiently with high demands. This trade-off must, thus, be analyzed, but conservation can also reduce treatment and expansion costs.

Energy potential, as separated from energy delivered, represents the portion of energy used dependent upon the elevation of the customer. This value thus depends on the topography of the system as well as its demands and is more difficult to control. Nevertheless, it indicates that users at higher elevations require more energy, an additional cost that could be included in water rate structures or at least inform future zoning practices.

If a lot of energy is dissipated through pressure-reducing valves and the supply is by gravity, the installation of turbines to recover energy should be explored. Otherwise, if flow is pumped, adjusting pressure zone boundaries should also be investigated. High levels of energy dissipation at pumps can motivate operational changes to pump combinations and scheduling or even pump refurbishments and replacements.

Excessive dissipation in particular pipes should prompt consideration of cleaning, lining, or even pipe replacement. Simply from an energy savings perspective, this type of rehabilitation is generally only justified for heavily tuberculated pipes with high dissipation (Walski 1985). High energy dissipation in pipes has not been shown to increase the probability of failure; however, it is often proportional to parameters that have been related to breakage. Dissipation is directly proportional to high pressures, which can increase the risk of breaks (Rajani and Kleiner 2001). It is also

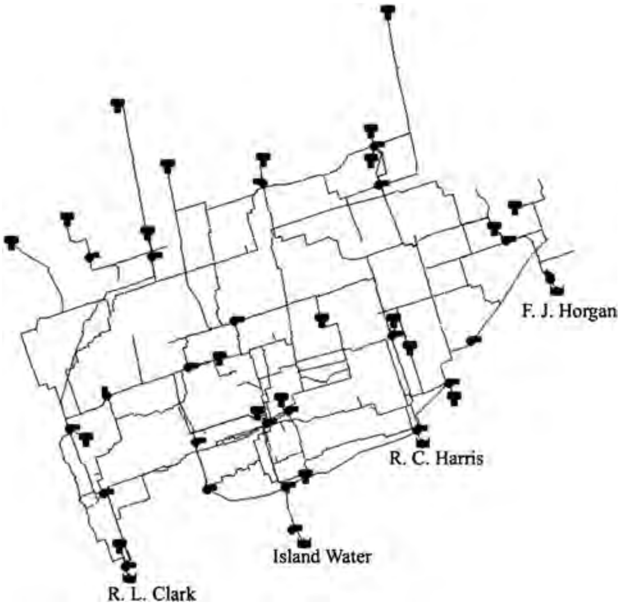


Fig. 2. Skeletonized Toronto water distribution network

inversely proportional to pipe diameter, and smaller diameters have been shown to cause a higher incidence of breaks (Kettler and Goulter 1985). Furthermore, although pipe roughness has not been linked to pipe failure, it increases (and C-factor decreases) with age, the main predictor of breakage (Rajani and Kleiner 2001). Therefore, energy dissipated per length of pipe can be applied as an indicator of pipe failure. This relation was confirmed by comparing energy dissipated and breakage rate maps in Toronto (Toronto Water, personal communication, 2012).

Case Study of the Toronto Water Distribution System

The proposed metrics were applied to a case study of the City of Toronto's water distribution system. The system is composed of nearly 6,000 km of water mains, 41% of which are over 50 years old, and 7% over 100. Partially due to such aging of the infrastructure, Toronto has a high rate of water main breaks, 21 breaks per 100 km of pipe (Toronto City Manager's Office 2012). This has prompted an ongoing leak detection and valve maintenance program. The distribution system currently comprises six pressure zones and more than 470,000 service connections. The model, however, shown in Fig. 2, contains only trunk water mains (which represent approximately 10% of total water main length), and demands are grouped into 1,582 junctions. This simplification means dissipation is somewhat underestimated, and energy delivered overestimated. Nonetheless, this greatly decreases the computational intensity of analyses. Furthermore, although Lake Ontario is the sole source of water in Toronto, the model contains four main reservoirs, corresponding to the city's four water treatment plants: R. C. Harris, R. L. Clark, F. J. Horgan, and Island Water.

Toronto Water provided the hydraulic models, in EPANET format, used in the case study. Two scenarios, maximum demand day (July 4th, 2011) and minimum demand day (January 21st, 2012), were simulated. Both have an extended period simulation of 24 h, allowing the visualization of operations throughout the day and the fluctuations in supply and delivery. Each model was based on the demands of the specific day and calibrated, also by Toronto Water, according to tank pressures. Minor changes were made to the infrastructure from July to January. One junction, five pipes, two pumps, and five valves were added to the 1,603 nodes and 1,833 links in the first scenario.

Because the modeled scenarios correspond to specific days of operation, the electricity rates and the GHG emission factors of those specific days were applied. Electricity rates were obtained from the Ontario Energy Board historical time of use energy prices (Ontario Energy Board 2012). GHG emissions from nuclear and coal generation were based on data from Ontario Power Generation (2010), whereas emissions from natural gas plants were estimated with U.S. EPA (2000) averages.

Results and Discussion

Summer and Winter Scenarios

The energy metrics described in Eq. (3) were applied to the analysis of two scenarios, summer (July 2011) and winter (January 2012), of the Toronto water distribution system. Because leaks are not included in the Toronto model, the sum of energy dissipated, potential, and delivered equals total energy supplied. The lost portion is not disaggregated from other metrics, and can be considered a percentage of energy delivered, even though this assumption has its flaws, as discussed earlier. Particularly in Toronto, the percentage of nonrevenue water is approximately 10% (Toronto Water 2005).

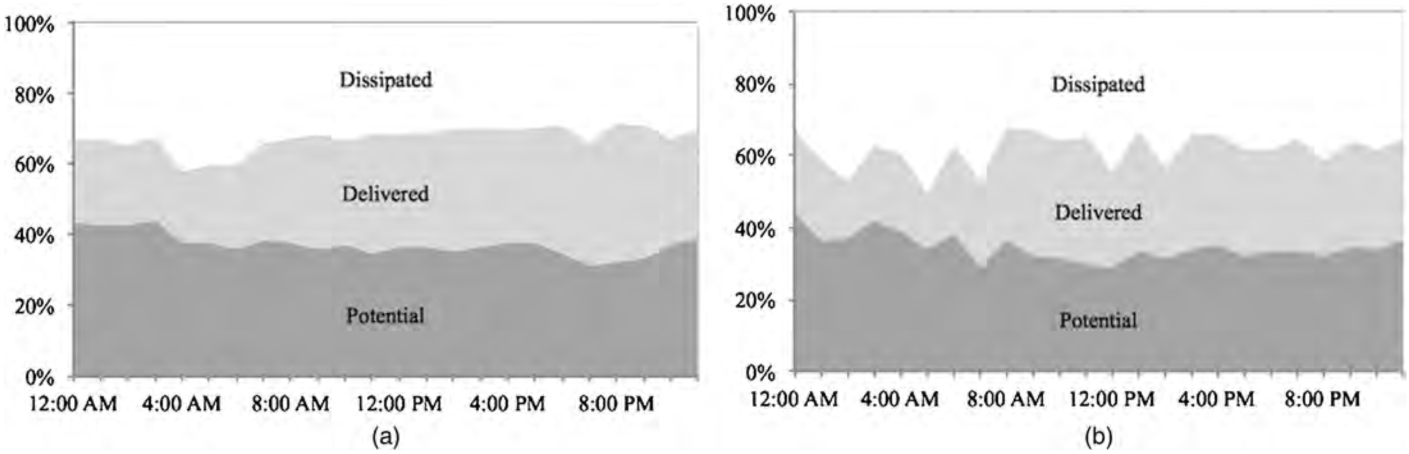
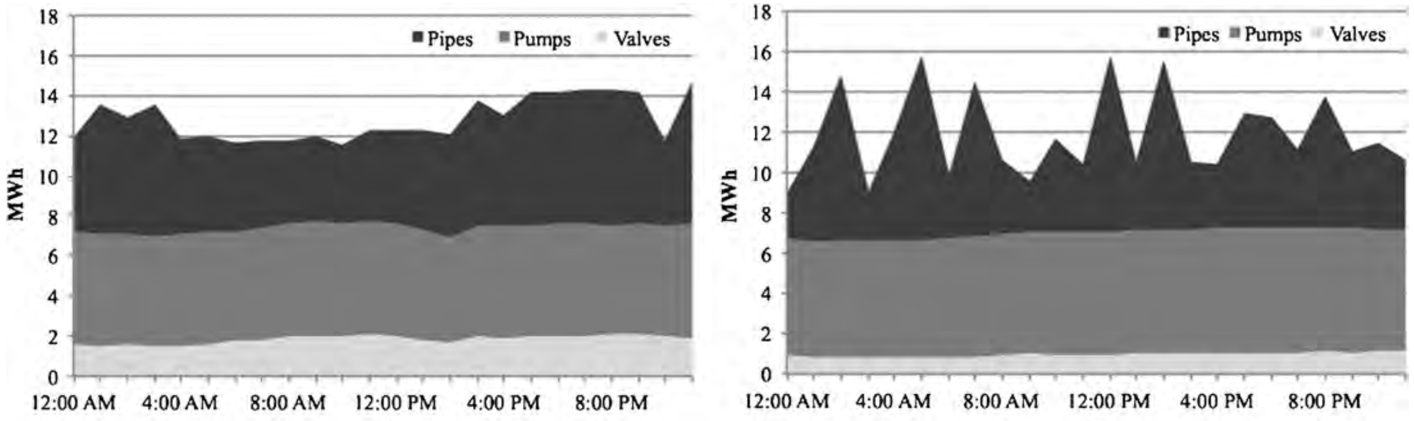


Fig. 3. Partition of energy supplied between potential, delivery, and dissipation during the (a) summer scenario; (b) winter scenario



(a) (b)

Fig. 4. Total energy dissipated per hour by pipes, pumps, and valves during the (a) summer scenario; (b) winter scenario

On average, approximately 28% of energy supplied is delivered to junctions, and 72% is spent in reaching them. Accordingly, 28% of energy supplied to the system is used in meeting pressure requirements, 35% in overcoming differences in elevation, and 37% in overcoming friction. Fig. 3 shows the hourly variation of energy dissipated, delivered, and potential. In the summer scenario, the increased demands generate higher energy requirements. However, the percentage of energy delivered is also higher. The lowest efficiency is observed at 5 a.m. on the winter day (49%), and the highest at 8 p.m. on the summer day (71%).

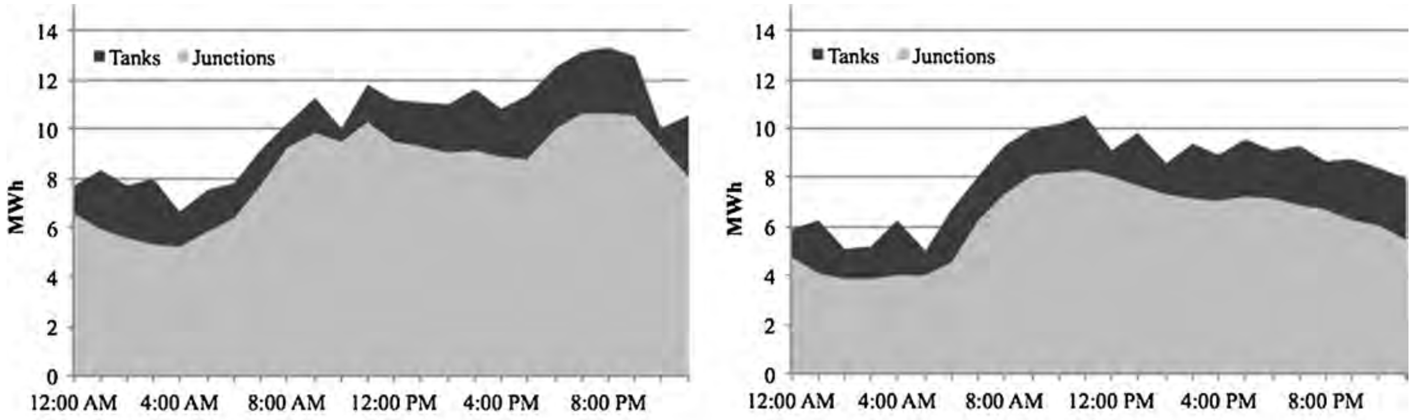
Because all of Toronto's water comes from Lake Ontario, reservoirs are at the lowest elevations of the network. Therefore, gravity flow is not prevalent, and pumping is fundamental. The calculations, however, consider the clearwell at the water plant as the source. Dissipation through the treatment plant is not included in the metrics. Tanks *supply* between 5 and 15% of energy requirements. Pumps are responsible for 80–90% of energy supply. However, 47% of dissipation already occurs at pumps, whereas 42% occurs in pipes (Fig. 4). In reality, however, dissipation is even higher because the model is skeletonized and manufacturer standard pump curves are used.

When gravity flow increases (that is, from tanks rather than from reservoirs at the lakeshore), energy potential decreases. This is observed in the winter day scenario, when tanks are supplying more energy than in the summer day. Energy potential at the junctions varies, yet is not similar to the fluctuations in demand nor energy delivered. Instead, it depends on pressure variations and how areas with distinct elevations consume water differently.

In both scenarios, the majority of energy delivered is for imminent use (80%) rather than storage (Fig. 5). As could be expected, energy delivered to junctions varies similarly to demand yet less intensely, because average pressure and velocity heads in the system tend to change inversely with demand, as displayed in Fig. 6. Pressures peak at nighttime, when demands are lowest and dissipation is reduced. Energy supplied, however, remains fairly constant. This causes higher leakage rates, which could be decreased through pressure management with control valves, more efficient pump operation, or installation of variable-speed pumps. The latter option, however, can increase costs in certain cases, such as dead end pressure zones or if flow is very low at times (Walski 2011).

The daily energy costs and greenhouse gas emissions of the given winter scenario are \$47,000 Canadian dollars (CD\$) and 116 $\mathrm{t\,CO_2}$, respectively. In the summer scenario, increased demands lead to greater energy costs (CD\$60,000). Emissions, however, are unexpectedly lower (107 $\mathrm{tCO_2}$), because less energy from coal and natural gas sources is used. Overall, energy use for water pumping represents approximately 10% of all energy used and 8% of greenhouse gases emitted by city facilities in Toronto (City of Toronto 2014).

Energy costs and, increasingly, GHG emissions are important factors in planning energy use. These are not necessarily opposing objectives. Electricity tariffs are generally highest during peak



(a) (b)

Fig. 5. Total energy delivered per hour to tanks and junctions during the (a) summer scenario; (b) winter scenario

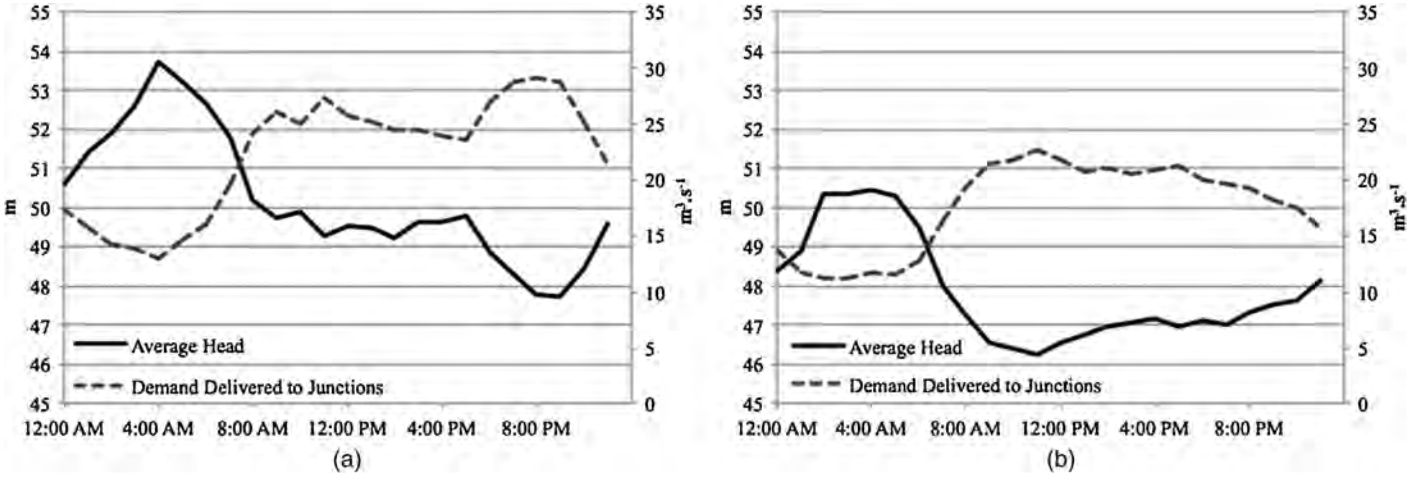


Fig. 6. Average head (pressure and kinetic) and total demand at junctions per hour during the (a) summer scenario; (b) winter scenario

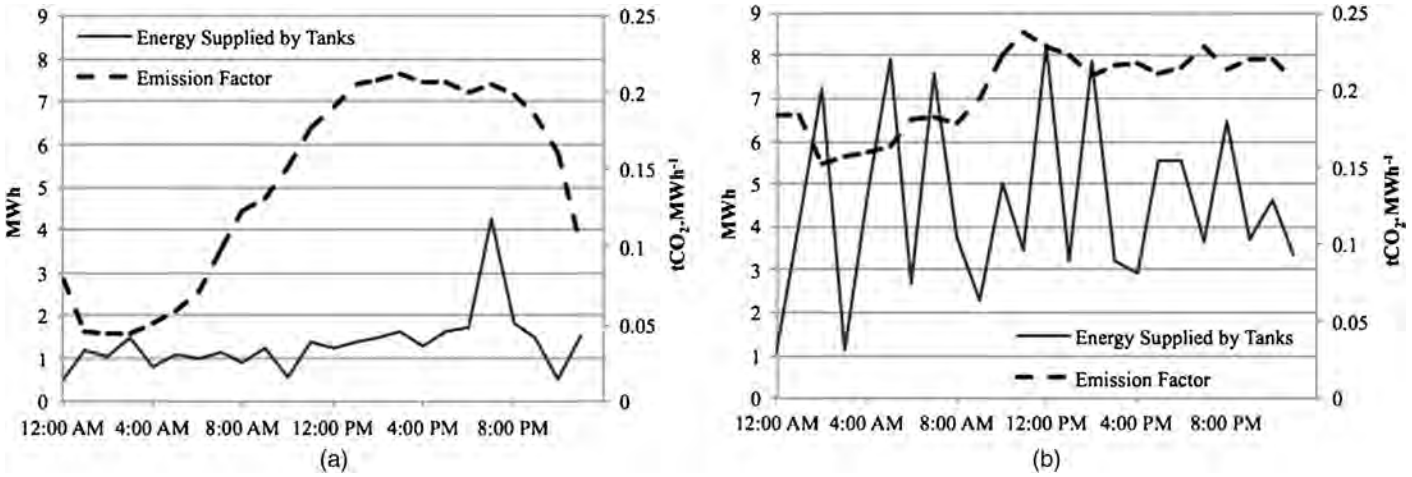


Fig. 7. Energy supplied by tanks and GHG emission factor per hour during the (a) summer scenario; (b) winter scenario

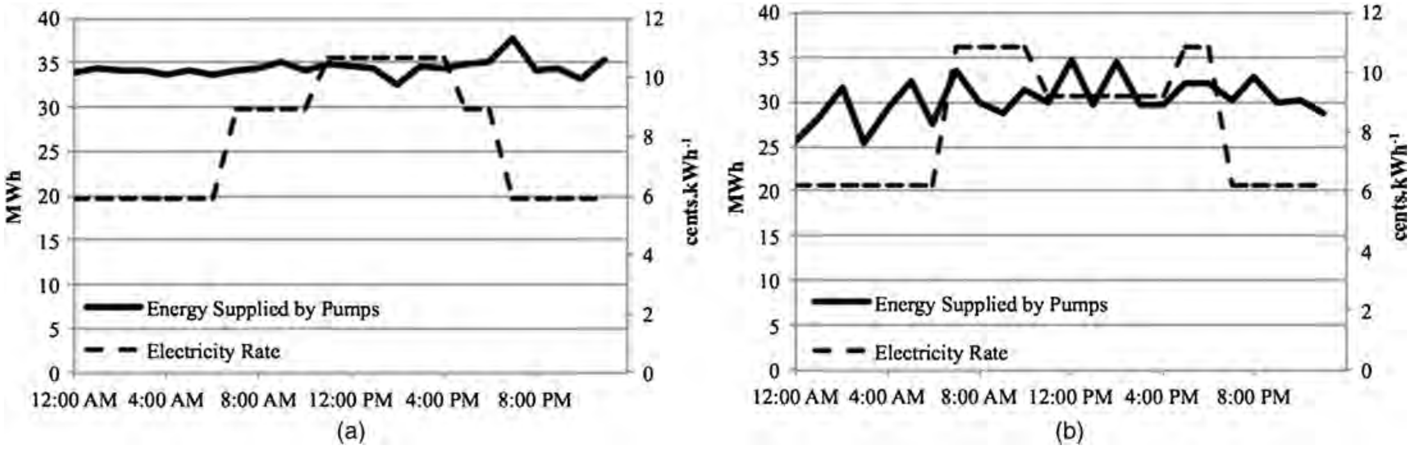


Fig. 8. Energy supplied by pumps and water rate per hour during the (a) summer scenario; (b) winter scenario

hours, and in Ontario, so are GHG emission factors (Figs. 7 and 8). Although energy generated from renewable sources remains fairly constant throughout the day, fossil fuels meet the peak demands. If reducing costs is the primary objective, as is generally the case, extra water should be delivered to tanks at night so that the system can rely on more gravity flow during the day. However, for the given scenarios, modeling results show that energy supplied by pumps varies little compared to the fluctuation in electricity rates.

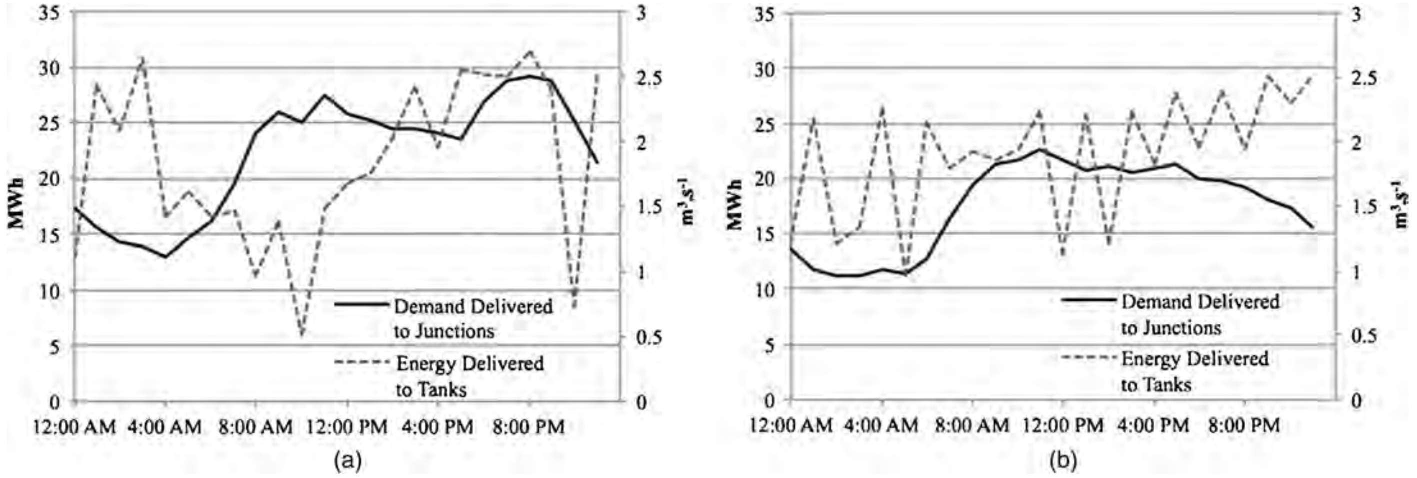


Fig. 9. Demand delivered to junctions and energy delivered to tanks per hour during the (a) summer scenario; (b) winter scenario

A small reduction in pumping is observed during peak hours in the summer scenario, but in the winter scenario, it even increases during the day (Fig. 8).

The energy supplied by tanks oscillates throughout the day, especially in the winter scenario, which also causes energy dissipated in pipes to vary intensely. This occurs because the network is designed for larger, summer flows. Therefore, during the winter, pumps are cycled more often, as shown in Fig. 8, and tanks often alternate between receiving and delivering flows.

Modified Summer Scenario

For energy supplied by pumps to increase at night, and for tanks to supply more of the peak demand, there must be sufficient pumping and storage capacity. Energy delivered to tanks would then vary inversely with demand. In the summer scenario (Fig. 9), this effect is observed at the beginning of the day, but as demand increases in the evening, more energy is delivered to tanks. In the winter scenario, despite the fluctuations, a trend can be seen as energy delivered to tanks increases as demands decrease.

Based on the given model scenarios, tank capacity is not the primary constraint to decreasing energy supplied by pumps during peak electricity hours. Almost half of the pumps are kept on during the whole day in these scenarios, despite available tank capacity, high electricity costs, and slightly high pressures in the system. Usual Toronto Water practice is to reduce pumping at peak times. Additional controls might need to be added to the model so that results better approximate operator practices.

To assess potential improvements, a modified version of the summer scenario was run. In it, 20% of the open pumps were closed between 11 a.m. and 4 p.m. Energy supplied by pumps consequently decreases during this period by 5%, as shown in Fig. 10(a), but tanks provide pressure equalization, and daily energy delivered to the junctions is only reduced 1% [Fig. 10(b)]. Electricity costs and GHG emissions are reduced by 6%. Over an extended period, however, even if tanks were maintained at lower levels, this temporary reduction in pumping would be offset by a subsequent increase to refill tanks. Therefore, significant changes could only be made to costs and emissions by altering pump scheduling. Even a 5% reduction in pumping electricity costs and greenhouse gas emissions could save approximately CD$0.9 million and 750 tCO_2 in one year (City of Toronto 2014).

Although the metrics can help uncover various types of modifications to the system, herein only one alteration to one scenario was modeled. This is meant to illustrate the usefulness of the metrics and how slight changes to the system can promote important benefits. Besides adjusting pumping hours, other alterations might include dividing pressure districts, reducing maximum pressures, cleaning and relining pipes, installing pipes, adjusting storage

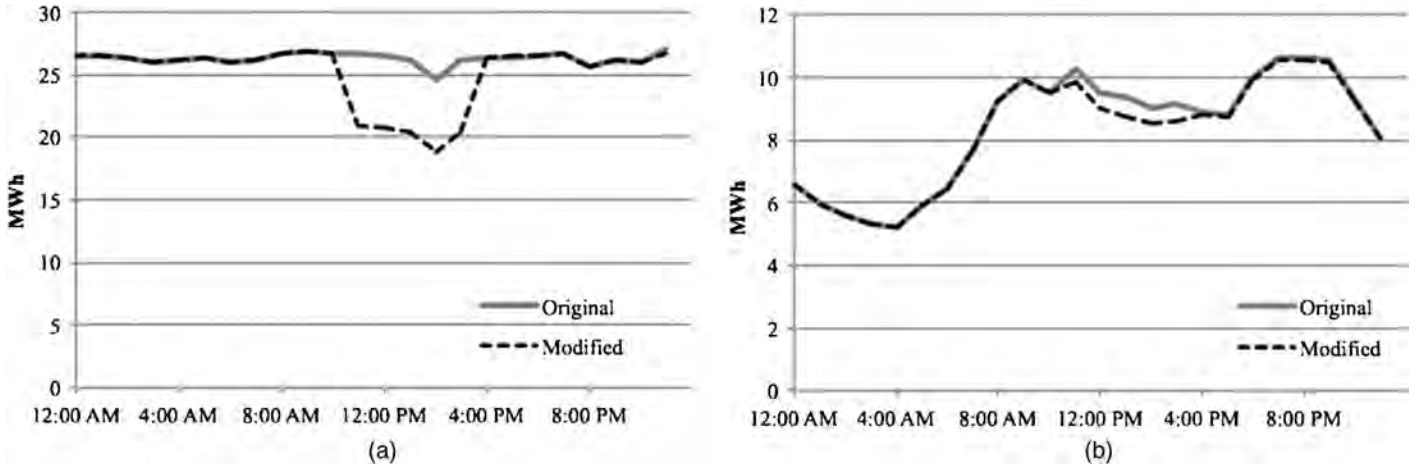


Fig. 10. Energy supplied by pumps (a) and delivered to junctions (b) during the summer scenario for the original and modified pump controls

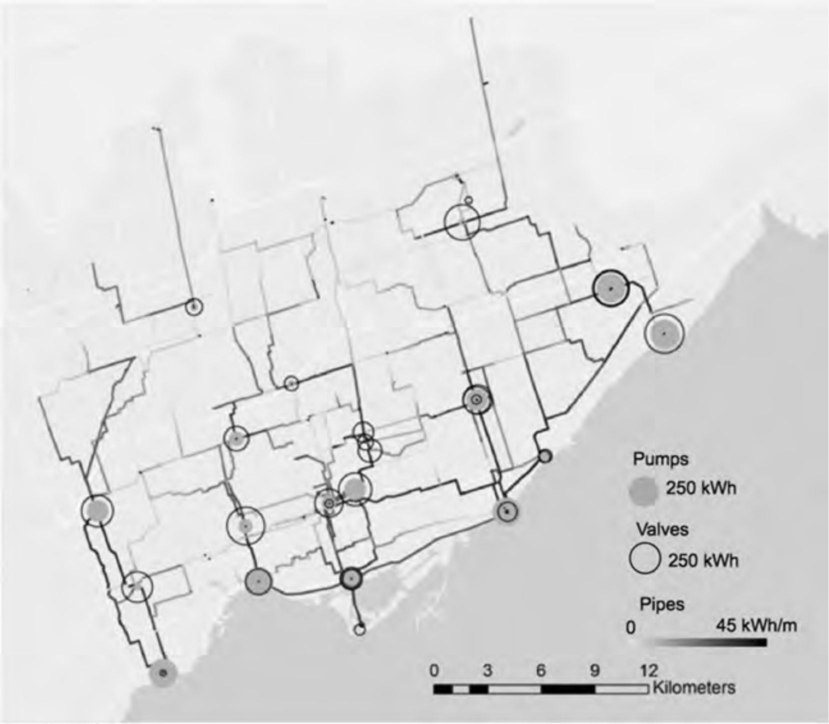


Fig. 11. Map of energy dissipated in the Toronto water distribution network during peak demand (8 p.m.) on maximum demand day

controls, as well as adding storage or pumping to the system. To support these modifications and assess their long-term effects, more scenarios would also need to be analyzed.

Mapping the Metrics

Calculating the energy metrics by network component, which is different from previous methods, allows for mapping. This novel approach facilitates the identification of specific target areas for improvement, be it through infrastructure renewal, pressure management, or conservation. Figs. 11–13 map the energy metrics of the system during peak demand in the summer scenario. Higher energy dissipation rates in mains, shown in darker gray in Fig. 11, indicate an increased probability of failure. These pipes, which, according to Toronto Water, have indeed experienced more bursts, are located mostly on the waterfront and downtown (central south), where water leaves the treatment plants. These should, thus, be

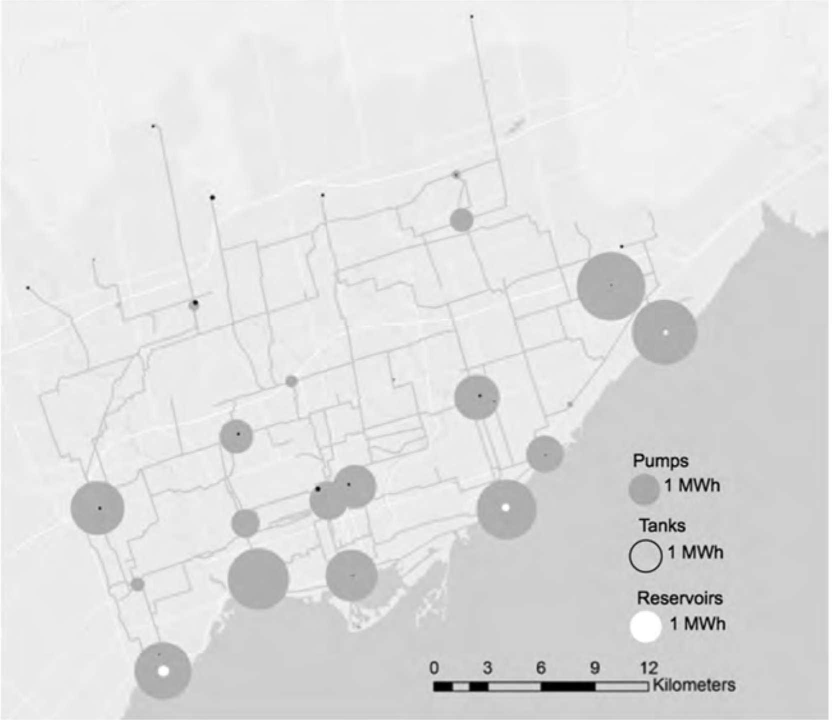


Fig. 12. Map of energy supplied in the Toronto water distribution network during peak demand (8 p.m.) on maximum demand day

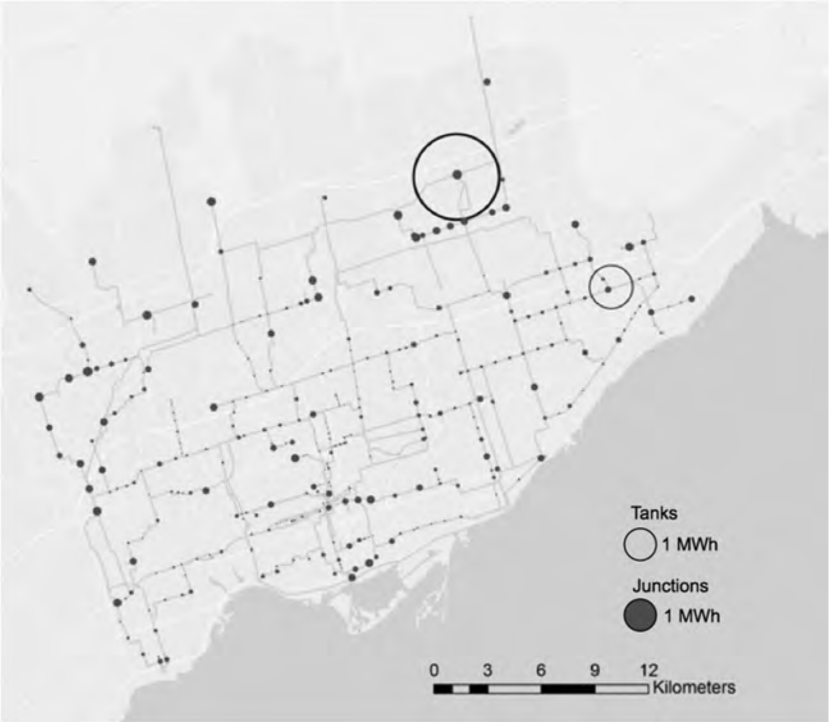


Fig. 13. Map of energy delivered in the Toronto water distribution network during peak demand (8 p.m.) on maximum demand day

further assessed and more closely maintained. Pumps that dissipate large amounts of energy are also key objects for refurbishment.

During this period, pumps provide most of the energy supplied (Fig. 12), whereas tanks predominantly receive water (Fig. 13). The highest energy delivery rates to junctions are observed downtown and in the northwest, prompting inquiries into pressure management and perhaps conservation. However, further away from the downtown core and the waterfront, there are fewer branches and delivery points in the system. Therefore, energy delivered could seem artificially high because of the larger populations supplied.

Improvements to the system can also be prioritized according to energy delivered, as areas that receive more energy generate greater costs. Whereas revenue is generally a function of demand (water rates in Toronto are based on volumetric consumption), expenses are a more complex function of multiple variables, creating the potential for ineffective cost allocation. The energy metrics can be applied in better understanding these expenses. The Electric Power Research Institute (2002) discusses some of the factors that can influence unit electricity consumption, such as system age, restrictions, standards, economies of scale, and equipment replacement. However, the extent of their impact on consumption depends on the system itself. Modeling the network with hydraulic models can also provide a greater level of detail to decision making. Given the results from the energy metrics, identified target areas, and potential solutions, alternatives can be simulated and compared to the base scenario to confirm they indeed solve the issue. 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.

Extensions of the Study

The metrics proposed herein have been presented to the Toronto Water staff. Comments and questions from these meetings inspired many of the previous discussions of the metrics and their applications. The metrics and the lens of sustainability they add to system analysis invoke inquiries over concepts that were taken for granted, such as operational paradigms, maintenance strategies, rate structures, and standards. If expense reduction is the goal, or, more holistically, sustainability, a decrease in energy consumption is central, as well as the use of more renewable energy sources. Both objectives are achieved through the reduction of pressure and flow, perhaps with refurbished pumps, new pipes, more conservation initiatives, and revised pressure requirements.

The present research and findings inspired further applications and studies. The energy costs and inefficiencies faced by the Toronto network motivated not only investigations into pressure management, but also a comparative study of international fire flow and residual pressure standards. These differ by country, as paradigms and practices regarding failure mitigation vary. North American standards are among the most restrictive, even though system safety is maintained with lower flows and pressures in other regions.

Although high pressures in the northern part of the network could be addressed through pressure management, the simultaneous occurrence of high and low pressures in the downtown pressure district prompted further research into the motivating factors and effects of dividing pressure districts. Whether by installing pressure-reducing valves, decreasing pumping, or dividing pressure districts, altering pressures, even within current standards, can affect customer satisfaction, demands, and utility revenue. Accordingly, the potential revenue impacts of pressure management were investigated as well as example cases of water rate structures that account for different delivery pressures.

Conclusions

The current paper proposes several integrated energy metrics and applies them to a case study of the Toronto water distribution system. These assess more than electricity consumption. Energy supplied is an indicator of operational costs as well as greenhouse gas emissions, and can thus be used to support a business case for reducing network energy use. Energy lost represents system leakage and the need for pressure management as well as increased maintenance, whereas energy dissipated also reveals the need for demand management. Energy delivered shows how much energy actually reaches the consumer and, accordingly, motivates improvements to zoning, design standards, and reducing pressures and demands.

Calculating the metrics by component disaggregates water distribution systems so that they are not analyzed as a simple black box with inputs and outputs, and allows for the identification of areas or specific system components, where changes are most beneficial. This novel approach enables the mapping of energy metrics, providing a geographical snapshot of the system.

In the Toronto case study, the amount of energy dissipated (37%), used in overcoming pipe and valve friction as well as pump inefficiencies, was found to be similar to energy potential (35%), used in overcoming elevation differences. This is in part due to the size of the network and the low elevation of the reservoirs. Only 28% of energy supplied is delivered to junctions in the form of pressure and flow. Consequently, users receive even less, and this inefficiency creates an important environmental and economic impact. In the modeled scenarios, pumping is not significantly adjusted to take advantage of off-peak electricity rates or lower GHG emission factors, a practice which Toronto Water seeks to follow. This prompted the development of a modified scenario, in which peak pumping was reduced by 20%, yet energy delivered was not greatly affected. This was shown to yield a reduction of 6% to electricity costs and GHG emissions, revealing the potential benefits of this practice. Nevertheless, an extended simulation would be needed to assess whether safe tank levels can still be maintained.

Mapping energy dissipated revealed key mains for retrofitting in the downtown. Energy delivered is also highest in this area, which means it could benefit from pressure management and conservation. Although the metrics have been shown to be useful indicators of energy efficiency, infrastructure performance, and costs, as verified by Toronto Water, additional data are required to support decision making. In future studies, as in the extended research being completed in Toronto, the analysis of different scenarios and network configurations can inform the revision of design standards, operational requirements, and maintenance scheduling. In addition, by systematically applying this methodology to a set of different systems, results can be compared and generalized between municipalities and benchmarks defined.

Acknowledgments

This paper is partly based on case study research conducted within the project "Integrated Water Mapping: Enhancing Decision Support for Sustainable Water Planning with Municipal Data," by Cities Centre and the Canadian Urban Institute, and funded by the Ontario Ministry of Environment through the Showcasing Water Innovation program. However, the findings, interpretations, and conclusions in this document are entirely those of the authors, and should not be attributed to the aforementioned organizations. The authors acknowledge the inputs of Katelyn Margerm, Kathryn Grond, Tom Weatherburn, Jeff Evenson, and the Toronto Water staff.

References

Alegre, H., Hirner, W., Baptista, J. M., and Parena, R. (2000). *Performance indicators for water supply services*, International Water Association, London.

AWWA (American Water Works Association). (1995). "Distribution system performance evaluation." Denver.

Boulos, P. F., and Bros, C. M. (2010). "Assessing the carbon footprint of water supply and distribution systems." *J. Am. Water Works Assoc.*, 102(11), 47–54.

Bristow, D., Richman, W., Kirsh, A., Kennedy, C. A., and Pressnail, K. D. (2011). "Hour-by-hour analysis for increased accuracy of greenhouse gas emissions for a low-energy condominium design." *J. Ind. Ecol.*, 15(3), 381–393.

Cabrera, E., Pardo, M. E., Cobacho, R., and Cabrera, E., Jr. (2010). "Energy audit of water networks." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000077, 669–677.

City of Toronto. (2014). "Annual energy consumption and greenhouse gas emissions." Energy and Waste Management Office, Environment and Energy Div., Toronto.

Colombo, A. F., and Karney, B. W. (2002). "Energy and costs of leaky pipes: Toward a comprehensive picture." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)0733-9496(2002)128:6(441), 441–450.

Electric Power Research Institute. (2002). "Water & sustainability." U.S. Electricity Consumption for Water Supply & Treatment—The Next Half Century, Palo Alto, CA.

Gay, L. F., and Sinha, S. K. (2012). "Measuring energy efficiency in urban water systems using a mechanistic approach." *J. Infrastruct. Syst.*, 10.1061/(ASCE)IS.1943-555X.0000072, 139–145.

HydraTek. (2013). "Toward municipal sector conservation: A pump efficiency assessment and awareness pilot study." Toronto.

Kettler, A. J., and Goulter, I. C. (1985). "An analysis of pipe breakage in urban water distribution networks." *Can. J. Civ. Eng.*, 12(2), 286–293.

Kumar, G., and Karney, B. W. (2012). "Natural cities, unnatural energy?" *The natural city: Re-envisioning the built environment*, I. L. Stefanovic and S. B. Scharper, eds., Univ. of Toronto Press, Toronto.

Lambert, A. O., and McKenzie, R. D. (2002). "Practical experience in using the infrastructure leakage index." *Proc., IWA Conf. on Leakage Management: A Practical Approach*, Water Board of Lemesos, Limassol, Cyprus.

Maas, C. (2009). "H2Ontario: A blueprint for a comprehensive water conservation strategy." Water Sustainability Project, POLIS Project on Ecological Governance, Victoria, BC, Canada.

OEB (Ontario Energy Board). (2012). "Regulated price plan (RPP) time-of-use (TOU) prices 2011." ⟨http://www.ontarioenergyboard.ca/OEB/Consumers/Electricity/Electricity+Prices#tou⟩ (Sep. 17, 2012).

OPG (Ontario Power Generation). (2010). "Sustainable development report." ⟨http://192.75.131.106/pdf/Sustainable%20Development%20Reports/003%20Sustainable%20Development%20Report%202010%20R1.pdf⟩ (Sep. 17, 2012).

Pelli, T., and Hitz, H. U. (2000). "Energy indicators and savings in water supply." *J. Am. Water Works Assn.*, 92(6), 55–62.

Pflanz, M., Walski, T., and Zheng, W. (2009). "Discovering energy bandits before they break the bank." *Proc., Texas Water 2009, Texas Section American Water Works Association*, Galveston, TX.

Racoviceanu, A. I., Karney, B. W., Kennedy, C. A., and Colombo, A. F. (2007). "Life-cycle energy use and greenhouse gas emissions inventory for water treatment systems." *J. Infrastruct. Syst.*, 10.1061/(ASCE)1076-0342(2007)13:4(261), 261–270.

Rajani, B., and Kleiner, Y. (2001). "Comprehensive review of structural deterioration of water mains: Physically based models." *Urban Water*, 3(3), 151–164.

Rossman, L. A. (2000). "EPANET 2 users manual." National Risk Management Research Laboratory, Cincinnati.

Stokes, J., and Horvath, A. (2011). "Life-cycle assessment of urban water provision: Tool and case study in California." *J. Infrastruct. Syst.*, 10.1061/(ASCE)IS.1943-555X.0000036, 15–24.

Tabesh, M., Yekta, A. H. A., and Burrows, R. (2009). "An integrated model to evaluate losses in water distribution system." *Water Resour. Manage.*, 23(3), 477–492.

Thornton, J. (2004). "Modeling water losses." Chapter 7, *Water loss control manual*, J. Thornton, ed., McGraw Hill, New York.

Toronto City Manager's Office. (2012). "2010 performance measurement and benchmarking report." Toronto.

Toronto Water. (2005). "Toronto water 2005 multi-year business plan." Toronto.

U.S. EPA. (2000). "Emissions & generation resource integrated database (eGRID)." ⟨http://www.epa.gov/cleanenergy/energy-resources/egrid/⟩ (Sep. 18, 2012).

Walski, T. M. (1985). "Cleaning and lining versus parallel mains." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)0733-9496(1985)111:1(43), 43–53.

Walski, T. M. (2011). "Tips for reducing energy use." *11th Int. Conf. on Computing and Control for the Water Industry, Urban Water Management: Challenges and Opportunities*, Exeter, U.K.