Life-Cycle Perspective on Residential Water Conservation Strategies

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Abstract: Motivated by the desire to understand the impact of water supply systems on the environment, a life cycle-based hybrid methodology is used to assess the performance of two conservation scenarios, water efficiency, and rainwater harvesting, relative to the base case. The analysis carried out for the City of Toronto's residential sector estimates the operational energy use and GHG emissions, and the embodied burdens associated with water-efficient devices and rainwater tanks. Hydraulic simulations, performed on a hypothetical network to expose the impact of demand peak factor on pressure distribution at nodes, revealed some of the rainwater scenario strengths such as hydraulic stress curtailment and capital investment postponement. While both strategies led to significant water savings, the associated energy expenditures and emissions varied with the selection of system boundaries. Nevertheless, both conservation strategies are worthwhile pursuing for rendering the existing water systems more sustainable.

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Introduction

Recently, many governments and municipalities have shown a greater interest in increasing the sustainability of products and services pertaining to the urban infrastructure. While much of this concern has been concentrated on energy conservation strategies and "greening" the electricity generation process, this environmental awareness is also benefiting the water sector. The requirement for safe and reliable water supply is a universal one, acknowledged as a basic necessity for human livelihoods. When, for example, the Canadian federal government acknowledged the need for adequate water infrastructure, as essential to sustain human health and economic growth, it encouraged innovative water conservation techniques (Environment Canada 1987). It has also been recognized that underpricing and the lack of consistent regulations and policies for pursuing and promoting efficient water use has led to excessive consumption, depletion of natural resources, and increased pressure on the infrastructure [Brandes and Maas 2006; Canadian Council of Ministers of the Environment (CCME) 2001; Canada Mortgage and Housing Corporation (CMHC) 1999].

Motivated by the desire to curtail the environmental burdens associated with water supply services, this study develops a framework for estimating the energy use and GHG emissions for urban residential water supply systems (WSSs). The focus on the domestic sector owes to its more homogeneous water use relative to commercial and industrial applications. The methodology is then applied to a typical "real-world" case study to serve as a guideline for designing and promoting water conservation programs. Broader sustainability issues related to the operation of WSSs are examined under three planning scenarios, base-case scenario (BCS) or "business as usual," water-efficiency scenario (WES), and rainwater-harvesting scenario (RHS). The key parameters of water savings, energy use, and GHG emissions are evaluated for activities examined within the system boundaries.

While life cycle assessment (LCA) has primarily been used to assess the environmental performance of products, LCA studies for water and wastewater systems have demonstrated the potential of this method for comparative analysis of services, processes, and technologies. Although in its incipient phase, this area of research is receiving a growing attention since the whole-life perspective can guide the selection of alternative systems and/or technologies by exposing activities/processes with the most taxing environmental loads. This selection will be based on informed decisions heeding the interconnectedness of water infrastructure with society and the ecosystems as it includes the environmental impacts associated with water supply services.

This paper broadens the analysis from Racoviceanu et al. (2007) to include the water distribution system (WDS) and end-user system (ES) in addition to the water treatment system (WTS). In so doing, a more comprehensive assessment of energy/GHGs associated with the production and distribution of potable water is accomplished while exploring the intricate issues of WSSs. The major questions addressed in this work are: (1) what are the energy use/GHG emissions and the water-energy trade-offs of pursuing the WES or RHS?; (2) how are the system boundaries influencing the analysis outcome?; and (3) from a

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whole-life perspective, what are the upstream/downstream impacts of different scenarios' uptake on systems they interact with, and what synergies are triggered by implementing these conservation strategies?

Setting the Stage

Environmental Metrics and Functional Unit

Focusing on system's environmental accountability, the scope of the study is to produce life cycle-based energy use/GHGs inventories of WSSs for typical North American urban residential developments and to use the results to comparatively assess the system under different planning scenarios. This work carries out a streamlined life cycle inventory (LCI), focused exclusively on two environmental indicators and the use phase of the system, an approach similar with that adopted in Racoviceanu et al. (2007). The conventional LCA is further adapted to suit the analysis of water systems by considering this commodity as having a source, transport, conversion, and use. In so doing, different stages within the life cycles of water could be assessed following the procedure used for materials.

The environmental metrics, i.e., total energy use and GHG emissions, defined in Racoviceanu et al. (2007), were selected based on their environmental importance to urban water systems as highlighted in previous LCA studies. These indicators are meaningful at the decision-making phase as they provide early warnings related to the environmental performance of existing water infrastructure and/or potentially harmful effects of new systems, but they also assist in simplifying and visualizing the phenomena of interest. Both in this study and in Racoviceanu et al. (2007), the LCIs account only for indirect GHG emissions arising from off-site generation of energy used for the production and distribution of drinking water. However, the indirect emissions due to off-site production and transmission of fuels, such as natural gas and diesel fuel used on-site (in WDS and WTS) for heat and generation of electricity, respectively, and direct GHG emissions from on-site combustion of these fuels were not included. Furthermore, because the processes/technologies involved in conventional water treatment and distribution are physical, the direct emissions associated with these systems (WTS/WDS) were also omitted. To consistently compare the different scenarios, the energy/GHGs flows are normalized to the functional unit of approximately 200 GL, representing the annual volume of potable water delivered at required parameters (i.e., quality and pressure) to the City of Toronto's residents.

Description of Scenarios

The scenarios proposed here were chosen for their easier and cheaper implementation compared with other water demand management strategies (e.g., recycled water and desalination). While in Toronto, efficient plumbing/appliances are already in use in a number of residences as a result of the water efficiency plan (City of Toronto 2002); for simplicity, the BCS assumes that there are no conservation measures implemented. In the WES the existing water fixtures/appliances are replaced with efficient toilets, faucets, showerheads, and clothes/dish washers, and the lawn is watered once a week with 2.5 cm of water (CMHC 1998).

The rainwater scenario builds on the water-efficiency scheme by adding a system for harvesting rainwater. To avoid pipe breaks from freezing, the rainwater is collected from March to October and is used for toilet flushing and lawn irrigation, the latter occurred during the growing season (June to September). The rainwater from the roof is stored in a 10-m^3 concrete tank located in the basement (RWT$_1$). While common materials for rain cisterns are plastic and concrete, the latter was chosen here for its lower embodied impacts (BlueScope Water 2008; Mithraratne and Vale 2007). When the harvested water does not meet the demand, the tank is supplemented with municipal water at off-peak times. An additional 0.5-m^3 plastic tank (RWT$_2$) placed in the attic (or roof) is sized to satisfy the household daily use for toilet flushing and irrigation. The pressure necessary to deliver water from RWT$_1$ to RWT$_2$ is achieved by provisionally using a Venturi tube. Although the technical aspects of this alternative, which replaces the local pump used in traditional systems, need to be further explored before prescribing its implementation, the configuration is advanced to underline the potential for additional energy savings. From RWT$_2$, the toilets and garden fixtures are gravity fed. In this work, rainwater is used exclusively for nonpotable purposes and, thus, the first flush diverter and filtration/treatment have been omitted. A logical extension of this study would be to explore additional impacts of filtration/treatment as well as the detailed design of using a Venturi tube in lieu of a local pump—topics beyond the scope of this work.

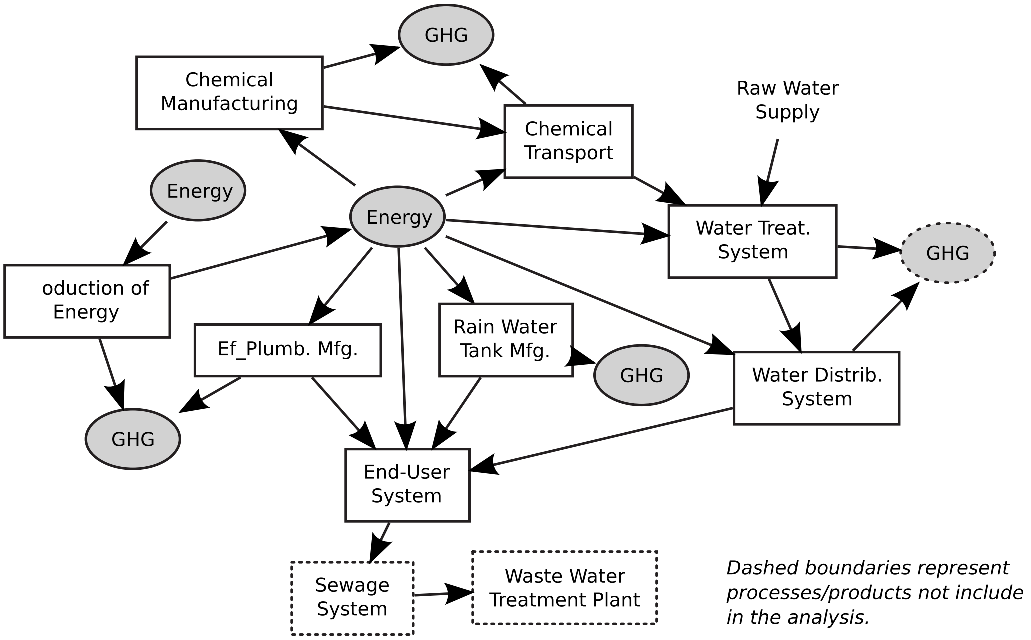
System Boundaries

To set the stage for drawing the system boundaries and allow for a flexible assessment, a model representing the WSS is constructed. The constituent units of interest for this work are the water treatment, water distribution, and ESs. The wastewater system is not included. The WTS includes all water treatment plants serving the City of Toronto. The ES represents the 418,000 single-family residential units with an average of three persons per household [City of Toronto 2002; Statistics Canada (StatCan) 2005]. Each system is modeled individually based on its own mass (i.e., water treatment chemicals) and energy balance. The overall burdens are calculated as the sum of these estimates.

The streamlined life cycle-based inventories carried out in this study focus on the operation phase selected for its dominant contribution to the total global warming potential, compared to construction and decommissioning-related impacts (Friedrich 2002; Stokes and Horvath 2006; Sahely et al. 2006). The exclusion of construction impacts can also be justified on the basis of major water infrastructure and buildings/equipment being common to all studied scenarios.

For both alternative schemes, the base-case plumbing configuration is modified by changing water devices with efficient models and by adding the on-site rainwater tanks. Thus, to gauge the magnitude of environmental consequences of pursuing these scenarios, the ES inventories account for both operational and manufacturing energy/GHGs associated with efficient plumbing/appliances and cisterns. To illustrate how the selection of system boundaries impacts the study results, the analysis is carried out with and without these embodied burdens. Similarly, the results with and without water-heating effects are discussed.

Fig. 1 depicts the life cycle energy/GHG flows within the system boundaries, which include the production of chemicals and electricity generation required in the treatment and distribution of water. In this way the analysis accounts for primary environmental effects of WSSs on the surrounding systems.



Dashed boundaries represent processes/products not include in the analysis.

Fig. 1. Life-cycle energy and GHGs flow diagram

Estimation Methodology and Data Sources

Estimating Water Demand

Prior to modeling energy use/GHG emissions, water demand is computed using the WATERGY model (deMonsabert and Liner 1998) and data from previous studies on residential end use of water (City of Toronto 2002; Mayer et al. 1999). The former is a spreadsheet tool, developed for U.S. facilities, to calculate water/energy savings, costs, and payback period related to various water conservation methods. Notwithstanding some engineering assumptions tailored for the United States, data sources can be used for Canadian venues due to similar technical characteristics of plumbing fixtures and water use habits (i.e., frequency of use).

The water demand is calculated as a function of fixture type and occupancy data for a typical North American household. For the rainwater scenario, the water mains demand is reduced by the volume of rainwater stored in-house. The annual hot water (HW) consumption is determined as a percentage of total water demand per fixture/appliance. Total annual residential water demand is calculated based on the daily consumption per household for main end uses of water (Table 1).

ES Impacts Modeling

Since water heating alone accounted for 21% of total residential secondary energy use [Eggertson 2005; Natural Resources Canada (NRCan) 2004], reducing HW consumption could significantly diminish the associated environmental impacts. With this in mind, the water-heating impacts are included in the ES operating burdens. At the household level, the energy consumption for other domestic activities using water (i.e., space heating/cooling and garden irrigation) is negligible [Natural Resources Canada (NRCan) 2004; de Monsabert and Liner 1998]. For the alternative scenarios, the inventories include the efficient fixtures/appliances and rainwater tanks manufacturing impacts.

In Canada, in 1997, the energy sources most commonly used for residential water heaters (WH) were electricity (52%) and

Table 1. Typical Household Daily Water Use

	BCS (L/c d)		WES (L/c d)		RHS (L/c d)	
Fixture	Water demand	HW	Water demand	HW	Water demand	HW
Toilets	82.5	0.0	30.0	0.0	0.0	0.0
Faucets	108.0	75.6	68.0	47.6	68.0	47.6
Showers	87.2	52.3	48.5	29.1	48.5	29.1
Clothes washer	43.2	10.8	32.4	8.1	32.4	8.1
Dishwasher	3.8	3.8	1.9	1.9	1.9	1.9
Leaks	13.0		0.0			
Capita indoor (L/c d)	337.7	142.5	180.8	86.7	150.8	86.7
Household indoor (L/H d)	1,082.6	456.9	579.4	277.8	483.3	277.8
Household outdoor (L/H d)[a]	670.0		464.3		0.0	

[a] Irrigation period is June to September.

natural gas (43%) [Natural Resources Canada (NRCan) 2004]. The combustion energy requirements for water heating, in kW·h or m^3 of gas, is given by $E_{WH}=HW\times(h_1\times\varepsilon_{WH}^{EL}+h_2\times\varepsilon_{WH}^{NG})$, where HW=hot water use (ML), ε_{WH}=water heater energy efficiency (kW·h/L or m^3 gas/L), and h_1 (h_2)=fraction of HW heated with electric (gas) heaters. To convert water-heating electricity (kW·h) and natural gas consumption (m^3) in energy use, energy intensities, specific for 1997 Ontario, of 8.8 MJ/kW·h (calculated as the ratio of total energy use to total electricity generated from natural gas, oil—diesel/light/heavy fuel oil, kerosene—coal, hydro, nuclear, petroleum products, wood, as defined in the Energy Use Data Handbook) and 37.5 MJ/m^3, respectively, are used [Natural Resources Canada (NRCan) 2004]. The GHG emissions are calculated as the product of energy use and emissions factor of 48-t CO_2 eq./TJ, representative for 1997 Ontario [Natural Resources Canada (NRCan) 2004]. These conversions allow for a comprehensive estimation, consistent with the models for water distribution and treatment systems. The assessment includes upstream impacts associated with mining, refining, and transporting fuels to their end use, and downstream environmental outputs, such as fuel consumption and its related combustion emissions.

Efficient devices and rainwater tank manufacturing impacts account for total energy use/GHGs associated with raw material extraction, material processing/production, and final product fabrication. The transportation impacts were omitted due to their insignificant contribution relative to the overall WSS impacts (Stokes and Horvath 2006; Racoviceanu et al. 2007). The environmental indicators were derived employing the economic input-output life-cycle assessment (EIO-LCA) model, as described in Racoviceanu et al. (2007).

The average purchase prices for concrete and plastic rain tanks and water-efficient devices retrieved from various sources (Texas Water Development Board 2005; Diverse Plastics Group 2005; Gleick et al. 2003; HydroOne Networks 2007) are discounted by 20% to account for the typical average freight and wholesaling cost. The producer price index used to convert above prices into 1997 producer prices was taken from U.S. Bureau of Labor Statistics (BLS) (2005) and Statistics Canada (2005). The 1997 producer prices in CAD are converted to 1997 U.S. dollar values (as required by EIO-LCA model) using purchasing power parities [Organization for Economic Cooperation and Development (OECD) 2004]. Last, the total energy use and GHG emissions computed by EIO-LCA are annualized to the useful operation life of each product: 20 years for toilets and cisterns, 12 years for appliances, and 10 years for showerheads/faucets (Gleick et al. 2003; BlueScope Water 2008). No allowance is made for the energy recovered from recycling of reinforcement steel used in concrete tanks or recycling of inefficient plumbing/appliances.

WDS Impacts Modeling

The WDS impacts are evaluated exclusively for operational activities associated with pumping. The assessment does not include the energy used for maintenance activities (i.e., pipe break repairs and pipe replacement) because of its insignificant value (on a per year basis) compared with the annual overall operational energy use. The life cycle energy requirements for pipe replacement, for the City of New York water supply tunnels, annualized to the planning period of 100 years, range between 1–4 kJ/m^3 (Filion et al. 2004) representing 2–5% of operational pumping energy reported in the literature (Cheng 2002; Sahely et al. 2003).

The pumping electricity is given by $E_{WDS\_OP}=W_{total}\times\varepsilon_P$, where W_{total}=water demand and ε_P=specific electricity use for water pumping (kW·h/m^3 of pumped water). Similar to the foregoing subsystem, the operational electricity is converted into total energy use/GHG emissions using energy/GHG intensities.

Assessing the Impact of On-Site Water Storage

The analysis of on-site water storage (RWT_2) is included here as it provides insights into the upstream impacts of rainwater-harvesting uptake and exposes the positive synergies arising out of integrating in one-scenario different conservation strategies, such as efficient plumbing, rainwater collection, and peak demand management. To evaluate the multiple benefits accomplished with this scheme, in addition to energy/water savings, the hydraulic performance of the distribution network is scrutinized. Since the in-house storage is expected to reduce the peak demand, the assessment focuses on the effect of peak factor (PF) on the water pressure at end users. To illustrate this, the performance of the hypothetical 20-loop network from Walski et al. (1987) is simulated for various PFs, running EPANET2 (Rossman 2000).

While the City of Toronto is of concern in this work, its WDS contains many different subsystems whose intricate examination requires a large amount of data, not readily available. Additionally, it is at the neighborhood level where individual household water use is most important. To this end, the Anytown system from Walski et al. (1987) was chosen for being representative of Toronto's subsystems and being well documented.

The model calculates the electricity intensity (in kW·h/m^3) for each scenario, while maintaining an equivalent service. Anytown topology rehabilitated as per Gessler's solution and with 2005 nodal demands, taken from Walski et al. (1987), represents the base-case layout. The pump supplies average flows at the nodal pressure of at least 40 psi (28 m) throughout the network, a hydraulic constraint obtained by adjusting the pump speed impeller so that under any scenario, pressures at the critical nodes are equivalent to those of the base-case configuration. A uniform pumping approach is adopted consistently over the 24-h cycle. The pump is assumed to have 100% constant efficiency. Demand multipliers of 0.6 and 0.5, applied to the base-case configuration, simulate the reduced demands of WES and rainwater scenario, respectively. The electricity use, corresponding to each case, is obtained by running extended period simulations of 96 h.

The pumping electricity of Toronto's WDS is calculated using the specific electricity use ε_P of 0.3 kW·h/m^3 for the base case and 0.27 kW·h/m^3 for the alternative scenarios. The electricity use is multiplied with energy/emissions intensities used in the end-user model to estimate energy use and GHGs.

The in-house tank (RWT_2) adoption is expected to lower the daily peak demand and thereby to distribute the use of water more evenly throughout the day. While this is true, calculating the reduction in PFs is beyond the scope of this study. Thus, three hypothetical scenarios, with the diurnal demand patterns shown in Fig. 2, were developed to expose the PF effect on minimum residual pressure in the Anytown network. Variations in nodal pressure are determined with EPANET2 for each case.

WTS Impact Modeling

The WTS impacts are modeled based on the water demand, W_{total}, energy and GHG intensities of 2.6 MJ/m^3 and 130-kg CO_2 eq./m^3, respectively (Racoviceanu et al. 2007). The activities examined within the system boundaries are chemical manufacturing and transportation, and water treatment plant operation,

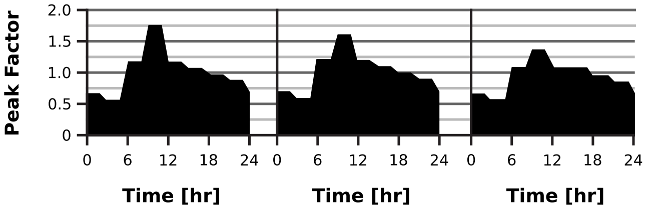


Fig. 2. Diurnal demand patterns

including pumping of raw water from Lake Ontario to the plant and pumping of treated water into the boosting stations (part of the WDS).

Case Study Area

Toronto's WSS provides services, such as filtration, pumping, distribution, and storage, for industrial, commercial and institutional (ICI), and residential sectors. Of this large infrastructure, the paper focuses on the single-family households (i.e., detached, semidetached, multiplexes with two to six units, and row housing), due to its more homogenous consumption pattern and data availability. In 2001, this study area, home to almost 1.34 million people (City of Toronto 2002), had approximately 418,000 active water accounts, using about 34% of the total annual water production (of 543,120 ML), 52% being attributed to multiunit residences and ICI accounts, and the remainder 14% to nonrevenue water.

The typical residence has a catchment area of 100 m^2 and an irrigable lawn of 130 m^2, values representative for Toronto [Natural Resources Canada (NRCan) 1995; CMHC 1998]. To test the sensitivity of the results, nine variation scenarios, combining these limiting parameters, were developed (Table 2). The concrete tank (RWT_1) volume of 10, 20, and 30 m^3, corresponding to catchment areas of 100, 140, and 180 m^2, respectively, were determined with the graphical method (Gould and Nissen-Petersen, 1999), using Toronto's rainfall normals for 1971–2000 [Environment Canada (EC) 2005).

LCI Results

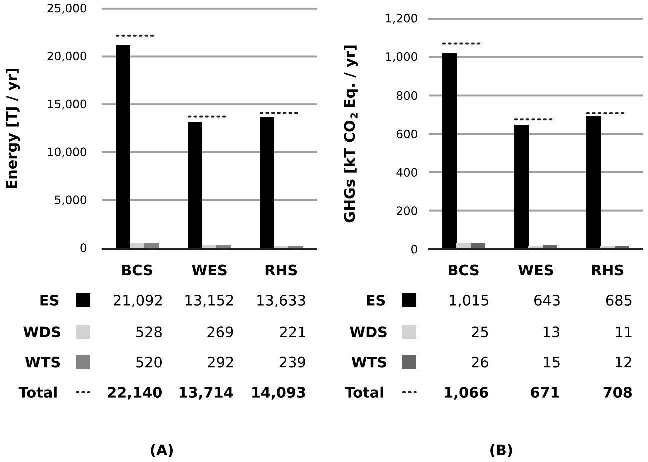
The results presented next are based on the assumption of a 100% uptake of alternative scenarios, across the case study area.

Water Demand

The base-case annual residential water demand was found to be about 200 GL of which HW represents 35% and outdoor use 38%. When modeling the garden water usage, variations due to watering behavior and daily climate changes (i.e., temperature and precipitation) were not considered.

Table 2. Sensitivity Analysis Scenarios

	Lawn area (m^2)		
Roof area (m^2)	130	200	400
100	RHS1	RHS2	RHS3
140	RHS4	RHS5	RHS6
180	RHS7	RHS8	RHS9



(A)

		BCS	WES	RHS
ES	■	21,092	13,152	13,633
WDS	░	528	269	221
WTS	▒	520	292	239
Total	---	**22,140**	**13,714**	**14,093**

(B)

		BCS	WES	RHS
ES	■	1,015	643	685
WDS	░	25	13	11
WTS	▒	26	15	12
Total	---	**1,066**	**671**	**708**

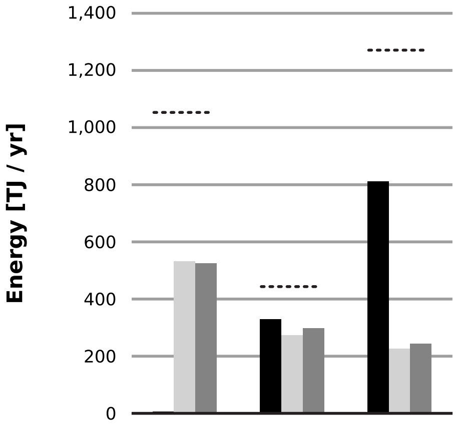
Fig. 3. (a) Annual energy use (with water heating); (b) annual GHG emissions (with water heating)

The water consumption was reduced to 112 GL for water efficiency and 92 GL for rainwater scenario. These significant water savings of about 44 and 54% could supply every year 325,500 new households fitted with water-efficient devices or 492,140 residences under the rainwater scenario.

The household water demand modeled here is slightly higher than the value reported by the City of Toronto (2002) due to different design assumptions. The average indoor daily demand per household is comparable with the results of a study conducted for the Region of Durham (Veritec Consulting 2005).

ES Impacts

The end-user impacts with and without water heating are summarized in Figs. 3 and 4, respectively. Water heating, when included in the analysis, is the dominant contributor to the end-user energy use/GHG emissions, the lowest impacts being achieved under the WES. Despite its largest water savings of 108 ML/year, the rain-



		BCS	WES	RHS
ES	■	0	325	806
WDS	░	528	269	221
WTS	▒	520	292	239
Total	---	**1,048**	**887**	**1,266**

Fig. 4. Annual energy use (without water heating)

water scheme has higher energy use/GHGs than the water efficiency, due to the cistern's manufacturing burdens. Nonetheless, the environmental load of rainwater scenario is lower than the base case yielding energy savings of 36% and GHGs reduction of 34%. The situation reverses when no allowance is made for the water-heating environmental expenditures: the rainwater impacts are significantly higher than the other two scenarios (Fig. 4), while the water-efficiency configuration has higher emissions compared to the base case.

To expose the impact that the system boundaries have on the results, the analysis is carried out without the embodied energy/GHGs from water-efficient devices. While the results with water heating improved marginally, the impacts without water heating changed significantly. These trends, echoed in the overall WSS results, are discussed later.

The analysis for RHS does not include the energy use associated with the local pump. Substituting the local pump with the Venturi tube lowers the end-user energy/emissions, but such savings are not evaluated in this study. Grant and Hallmann (2003), in a conventional LCA study on residential RWTs conducted for Melbourne, found that the operational impacts could be halved if the 600-W pump, used in their system, was eliminated.

WDS Impacts

The reduced water consumption of both alternative scenarios led to energy and GHGs savings, at WDS level, of 49 and 58%, respectively, rendering these scenarios more environmentally responsive compared to the base-case configuration (Figs. 3 and 4). Similar energy savings were achieved by leveraging water-efficiency programs in the United States [ICF International (ICFI) 2008].

When assessing the overall impact of water conservation initiatives on the distribution infrastructure, it is important to consider the potential benefits resulting from avoided upgrades. Water savings achieved with both alternative schemes are expected to reduce the freshwater resource depletion and the load on the infrastructure storage. While it is beyond the scope of this work to quantify the impacts from avoided capital works, it is worth noting that these savings are not likely to be significant enough to offset the additional burdens associated with RWT manufacturing (Grant and Hallmann 2003).

Climate change witnessed in the last years and anticipated to be greater in the future, in particular extreme weather events leading to extended dry and hot summers, and implicitly high lawn watering use affect dramatically the water demands. The distribution pipeline capacity is based on peak instant rate, and thereby, this parameter was included in the assessment. For a holistic understanding of the rainwater scenario synergistic benefits, the impact of peak demand reduction on minimum pressure at nodes was analyzed for Anytown system. The results indicate that as the PF decreases from 1.8 to 1.4, the pressure at the critical node in the network increases from 43 psi (30 m) to 50 psi (35 m). This translates into hydraulic stress curtailment throughout the network expected to increase the operational life of pipes, ultimately allowing significant expansion into fringe areas, while sustaining higher demands on the existing and finite water resources.

WTS Impacts

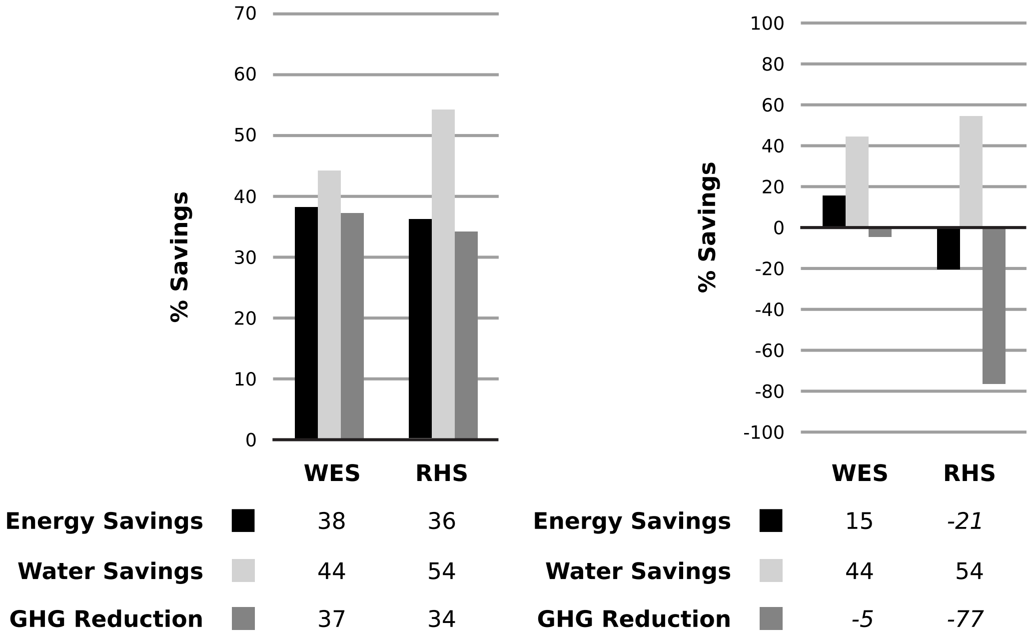
Similar to the distribution system analysis, the highest energy use and GHG emissions from water treatment activities were found for the base-case configuration. The alternative scenarios exhibited lower impacts due to their reduced flows (Figs. 3 and 4): WES and rainwater scenario environmental burdens were reduced by 44 and 54%, respectively.

WSS Impacts

When water-heating effects are accounted for (Fig. 3), the ES is the most energy/GHG-intensive system, accounting for 96% of the WSS environmental loading, dwarfing the effects pertaining to water distribution and treatment processes (at 2% each). These high burdens are mainly attributed to water heating. Thereby, including the environmental impacts of producing HW reveals the importance of water conservation programs in reducing the residential energy consumption. Similar results were reported by Cheng (2002) who identified the energy used for WHs at 84% of total consumption, the remainder 16% being split between electricity used by municipality for water and sewage treatment, and in-house pumping for delivering water to a six-story building.

In the assessment without water-heating impacts (Fig. 4), the ES share changes to 37 and 64% for WES and rainwater scenario, respectively, percentages attributed to the efficient plumbing/appliances and rainwater tank embodied effects. The water distribution and treatment systems had equal contributions to the total energy expenditures/GHGs. For the base case, the 50% of total energy attributed to the water treatment might seem high compared with the values for Sydney Water (Lundie et al. 2004), where the energy from water filtration is about one third of that associated with the distribution of water. The difference is defendable on two grounds. First, 60% of energy used for water treatment in Toronto is due to treated water pumping (Racoviceanu et al. 2007), which in Lundie et al. (2004) was included in the water distribution model. Second, the systems have different topology, water quality and boundaries, which might affect the final results. The electricity intensity of $0.3\ \mathrm{kW \cdot h/m^3}$ for water treatment and distribution is similar with the results reported for Taipei of $0.2\ \mathrm{kW \cdot h/m^3}$ (Cheng 2002) and the for United States of $0.4\ \mathrm{kW \cdot h/m^3}$ [Carlson and Walburger 2007]. Similarly, the electricity used in the boosting stations for a South African case study of approximately $2.3\ \mathrm{MJ/m^3}$ (Landu and Brent 2006) is comparable with the value estimated for Toronto of $2.6\ \mathrm{MJ/m^3}$.

The overall savings including water-heating burdens are given in Fig. 5(a). Notwithstanding rainwater scenario lower energy/GHGs savings relative to the water-efficiency scheme, harvesting rainwater benefits the WSS by curtailing the environmental output of the base-case configuration. A less favorable outcome arises when water-heating impacts are omitted: while the water-efficiency configuration has 15% lower energy use and 5% higher GHGs than the base case, the rainwater scenario is environmentally taxing with 21 and 77% increase in energy use and emissions, respectively [Fig. 5(b)]. When the embodied impacts from water-efficient devices are removed from the analysis, the overall results improved: the WES has energy/GHGs savings of 46% and the rainwater configuration yields 10% energy savings compared to the base case, while its emissions are 26% higher. Similar results were found by Grant and Hallmann (2003): the mains water only scenario showed the lowest energy use, while the rainwater system had better results for water use and nutrient emissions (eutrophication). In the analysis with water-efficient plumbing burdens, the negative impacts of alternative scenarios are expected to improve if lower producer prices are used in the EIO-LCA model. These results could further improve if the energy recovered from recycling the inefficient water devices is accounted for and the embodied burdens of base-case plumbing/



(A) **(B)**

Fig. 5. (a) Annual savings (with water heating); (b) annual savings (without water heating)

appliances are included in the analysis. While these refinements are beyond the scope of this work, future research is recommended.

An anticipated benefit of the rainwater scenario is the positive impact on the stormwater management system. The 10-m^3 tank (RWT1) captures all rainwater falling on the 100-m^2 roof, thus leading to a net reduction in the nitrogen load disposed in the stormwater system and, ultimately, discharged in Lake Ontario. Even in the case of smaller tanks, the nitrogen rich rainwater, occurring at the beginning of rain events, is harvested before it overflows (Grant and Hallmann 2003). The rainwater from tanks is used for garden irrigation, benefiting the plants, or in toilets, where the nitrogen is processed in the wastewater treatment facilities. The reduced water demand of both alternative scenarios also reduces the wastewater flows leading to operational energy/GHGs savings. The water-efficient devices may also result in higher effluent concentration and implicitly increase the amount of chemicals used for wastewater treatment. A quantitative assessment of these potential impacts on the wastewater treatment system is beyond the scope of this study and are recommended for future research. Current studies on energy savings associated with water conservation strategies focus on the positive impacts that these measures have on wastewater treatment system [ICF International (ICFI) 2008].

Despite its significant contribution to residential energy consumption, the energy used for water heating has a reduced visibility and thereby tends to be overlooked by consumers, as the same heating unit is used for both water and space heating (Eggertson 2005). In an effort to avoid this oversight, this paper accounted for the energy and GHGs associated with water heating. Similarly, Cheng (2002) included the water-heating impacts in his estimate of electricity consumption for residential water use. Conversely, Grant and Hallmann (2003) excluded the energy use/GHGs from water heating, an approach which is appropriate considering the exclusive focus on rainwater collection.

The rainwater scenario was developed to mimic the resource conservation strategy used by natural systems, the scenario's design elements (i.e., efficient plumbing, rainwater collection, and peak-leveling tank) achieving multiple benefits for both society and ecosystems. Had the water conservation been attained by exclusively collecting rainwater, the scenario was cost prohibitive and environmentally taxing as revealed in the literature (Grant and Hallmann 2003; Mithraratne and Vale 2007). This vantage point further justifies the inclusion of water-heating impacts in the analysis.

Sensitivity Analysis

Different roof-lawn combinations (Table 2) were developed to test the results sensitivity. The sensitivity analysis including water-heating impacts indicated that RHS7 had the highest water savings (61%) followed closely by RHS8 (60%). Since these scenarios have the largest cistern (30 m^3), their energy use of approximately 14,540 TJ/year and GHGs of 720-kt CO_2 eq./year, rank the highest due to rain-tank embodied impacts. The scenarios with best environmental performance are RHS1 and RHS2 with 13,630 TJ/year and 690-kt CO_2 eq./year. Therefore, configurations with large roofs are not necessarily the optimum solutions; despite their high score on water savings, these scenarios are not environmentally accountable. The combinations with the largest water savings for the lowest environmental impacts are RHS1–RHS3, corresponding to the smallest roofs and tanks.

Variations in savings with changes in catchment area, for a constant lawn area (at 130 m^2) are given in Fig. 6(a). As the roof area increases so do the municipal water savings, more rainwater being available for household consumption, while the energy/GHGs savings experience a slight downward trend, attributed primarily to larger cistern sizes and implicitly greater manufacturing

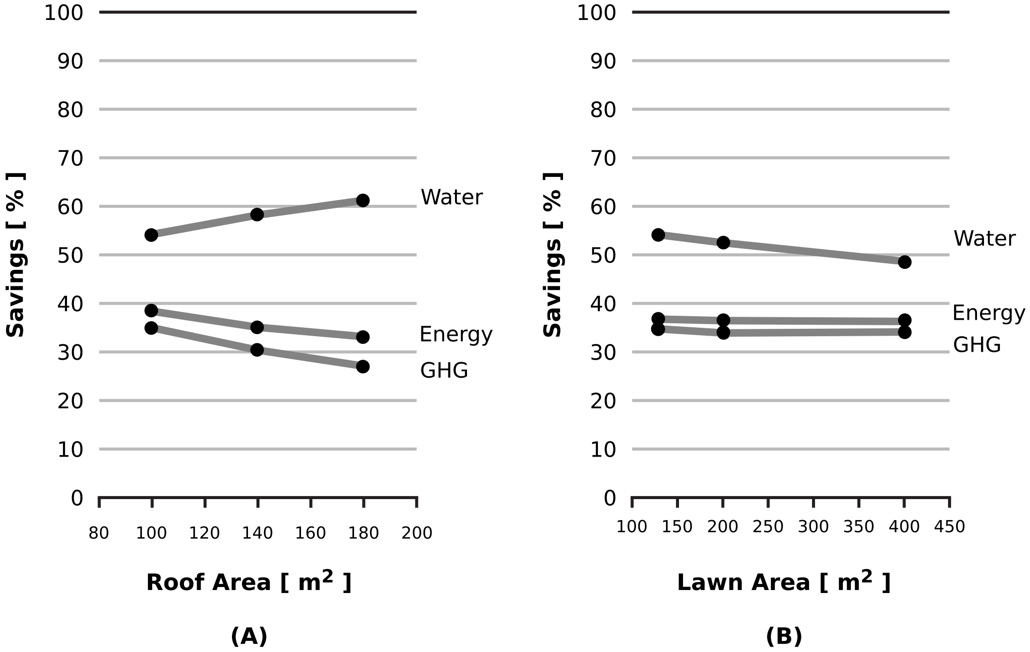


Fig. 6. (a) Savings for household with 130-m^2 lawn; (b) savings for household with 100-m^2 roof

impacts. Conversely, when the roof area is kept constant, the energy savings are not sensitive to variations in lawn area, as the energy consumption associated with the most energy/GHG-intensive system (end-user) remains unchanged [Fig. 6(b)]. Moreover, the reduction in water end-use exhibits a slight decrease due to larger quantities required for lawn irrigation.

The rainwater scenarios tested here are pure hypothetical and were selected for benchmarking the water-energy trade-offs. The sensitivity analysis indicated that municipal water and energy savings and GHGs reduction associated with WSSs were sensitive to catchment area and implicitly the size of the rainwater tank.

The reported results are also expected to be sensitive to the annual rainfall. An analysis evaluating the savings for above and below average rainfall years as well as for various Canadian locations, would be valuable for providing insights on the spatial and temporal applicability of the LCI methodology developed in this study. In search for optimum configurations from an environmental vantage point, future research investigating different tank materials (i.e., metal and plastic), alternative lifespan and tank disposal scenarios are also recommended.

Perspectives on the Results

Two scenarios integrating water conservation measures were developed for Toronto's residential sector and assessed against the base-case configuration, in terms of their life cycle-based energy use and GHG emissions, focused on the operation life-cycle phase of the system. Pursuing water-efficiency and rainwater scenarios led to substantial water consumption reductions of 44 and 54%, respectively, for a typical North American household. Similar reductions in the indoor residential water use were identified in the U.S. retrofit studies [ICF International (ICFI) 2008]. A 15% reduction in the domestic water demand is expected to be accomplished by 2011 in the City of Toronto, as a result of installing efficient plumbing/appliances (City of Toronto 2002). These lower target savings are due to different estimated participation rates.

In a study conducted for a typical residence on the Gold Coast, Australia, that uses rainwater for all household purposes, a 20-m^3 tank collecting water from a 140-m^2 catchment area, curtailed the municipal water demand by 78% (Gardner et al. 2001). Similarly, Mithraratne and Vale (2007) report 70% water savings for a system using a 9-m^3 rain-tank and demand management measures.

The analysis with water-heating impacts revealed that the water-efficiency scenario outperformed the rainwater scheme, and both alternatives had a better environmental performance than the base case, due to less energy and chemicals required for water treatment and distribution. Conversely, the rainwater configuration was the most energy/GHG-intensive when water-heating effects were omitted. Modifying system boundaries by excluding the water-efficient devices' manufacturing impacts improves the results. Higher impacts pertaining to the use of rainwater for nonconsumptive uses (i.e., toilet, irrigation, and cloth washing), relative to conventional systems using drinking water for the same purposes, were also found in previous LCA studies (Grant and Hallmann 2003; Bronchi et al. 1999).

When compared with other impacts, the rainwater tank or water-efficient devices manufacturing energy intensities of $0.6\ \text{kW}\cdot\text{h}/\text{m}^3$ of water used and $0.4\ \text{kW}\cdot\text{h}/\text{m}^3$, respectively, is almost equal to the wastewater treatment energy estimated at $0.5\ \text{kW}\cdot\text{h}/\text{m}^3$ for the City of Toronto (Sahely et al. 2003). Placed in an even larger context, the cistern's embedded energy, of 1 GJ/household, represents only 4% of the 2002 residential water-heating energy use (of 25 GJ/household) in Toronto [Natural Resources Canada (NRCan) 2004]. The energy intensity on a per capita basis of 0.9 MJ/s year, attributed to the rainwater scenario without water heating, is roughly equivalent to driving a car for a mere 400 m [Natural Resources Canada (NRCan) 2004]. This suggests that in absolute terms the "energy content" of the rainwater scheme is relatively small.

This work adopted a whole-system approach, scrutinizing not only the environmental but also the technical dimension of WSSs, particularly with respect to rainwater-harvesting impacts. Including parameters like peak demand and minimum residual pressure in the analysis shed a different light on the rainwater scenario sustainability, exposing some of its strengths such as freeing up system capacity, capital investment postponement, and stress abatement in the network, which might compensate for its weak score on energy and GHG emissions. Furthermore, scrutinizing WSSs in relation to systems they are intertwined with (i.e., stormwater and wastewater systems) and exposing the system boundaries' effect on the results helped create a more holistic picture, including the multiple benefits that could be accomplished upon the pursuit of different planning scenarios. These strategies can be viewed as options built into municipal engineering or urban planning—alternative paths to be taken to prevent potentially harmful consequences associated with conventional design and decision-making of using, by default, one path only. Adopting a water management approach focused on conservation and end-use efficiency offers a cheaper and more adaptively implemented alternative than supply-side solutions (Brandes and Maas 2006).

Exploring the potential of using the LCA beyond its traditional framework, that of an analytical process, this study seeks to provide designers with alternative tools incorporating the feedback loops ubiquitous in nature, a procedure that would ultimately render conventional thinking habits less linear. Analyzing different stages within water's life cycle, thinking of this resource as having a source, transport, conversion, and use, made it possible to conceptualize water services by using a source-to-sink approach. This life cycle perspective could form the basis for reorienting the engineering profession toward more preventive design and decision-making principles whose understanding and application are essential in creating a more sustainable world.

Conclusions

A life cycle-based methodology was used in this study for environmental benchmarking of Toronto's base-case system against sustainable alternatives for residential water supply services. The operational energy use and GHG emissions of each scenario were quantitatively compared.

While both strategies led to significant water savings, the associated energy expenditures and emissions varied with the selection of system boundaries. When water-heating impacts were omitted, the rainwater scenario proved to be environmentally taxing mainly due to the efficient plumbing/appliances and cistern manufacturing effects. The analysis including water heating and excluding the embodied burdens of water-efficient devices revealed that both alternative configurations had a better environmental performance than the base case. The rainwater scenario also reduced the peak demand, rendering a network with a better hydraulic performance, which in turn allows the existing water infrastructure to meet higher demands at current capacity. Additionally, collecting rainwater could benefit the ecosystems through reduced nitrogen load to lakes and rivers, and lower withdrawals. In summary, the results of both studied alternatives reinforced the essential role water saving measures play in energy conservation, pinning down the importance of raising public awareness of the water-energy nexus and its environmental significance when promoting demand management programs.

The whole-system approach helped identify positive synergies resulting from interactions between different infrastructure systems (water distribution, water/wastewater treatment, and stormwater) and their interconnectedness with the environment. Moreover, the life cycle perspective revealed the importance of including upstream and downstream environmental effects in strategic planning. Disaggregating the model into its constituent systems allows for transparent and easy alterations in analysis parameters and assumptions, as well as for scenarios and system boundaries adjustments.

Both water conservation strategies are worthwhile pursuing due to their substantial improvements that render the existing water supply services more sustainable. The LCIs produced in this work are intended as an information tool, to complement technical, economic, and social assessments, and to provide useful insights to strategic planners during the design and decision-making processes. While the design details pertaining to the studied alternative configurations were beyond the scope of this analysis, their scrutiny is commended for future research.

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