# Water Use Model for Quantifying Environmental and Economic Sustainability Indicators

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**Abstract:** A systems approach is used to model the urban water cycle. A model for analyzing the flows of water, energy, and chemicals and associated greenhouse gas emissions through the urban water infrastructure system is developed. A model is constructed to represent the City of Toronto urban water system from 2001 up to the year 2010. Scenarios are developed to assess the system-wide impacts of water distribution pipe renewal, sewer relining, demand management strategies, and energy recovery from anaerobically digested wastewater biosolids. Initiatives targeted at the early stages of the urban water cycle have greater positive downstream impacts on selected environmental indicators. Specifically, strategies aimed at reducing water demand produce more significant system-wide benefits. Demand management strategies aimed at reducing demand by 15% result in savings on the order of 12–18% for all environmental indicators. Demand management is also one of the most cost effective options.

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## Introduction

One of the challenges in building more sustainable cities is to develop more holistic approaches to urban design, which, for example, integrate greater recycling of materials, utilization of stormwater, energy capture from wastewater, and integrated land-use and transportation planning. In particular, the urban water system provides many opportunities for increased sustainability.

Urban water systems are complex, partly because they must provide a high level of reliability and safety to consumers. When water systems break down, the consequences are often severe and in some cases even fatal. Aging urban water systems within growing cities are feeling the "pressure" of having to provide high levels of service and are heavily burdened with fulfilling multi-objective, often conflicting, goals whether financial, environmental, or social which, left unmet, can compromise their vital role within the urban ecosystem. Fulfilling the high water demand of today's cities requires a myriad of physical infrastructure components including pipes, pumps, storage reservoirs, and treatment facilities. Utilities face enormous challenges related to the maintenance, rehabilitation, and development of this physical infrastructure, which have been highlighted by the growing awareness of sustainability issues. How can the principles of sustainability, of wise use of natural resources, cost effectiveness, and social acceptability, be incorporated into the process of strategic planning and decision-making for urban water systems?

This paper presents a methodology for incorporating selected environmental and economic considerations into the process of strategic planning. Specifically, the linkage between water and environmental indicators such as energy and chemical use and associated greenhouse gas emissions is explored. Scenario analysis is used to simulate system-wide impacts of various strategies designed to enhance the sustainability of the system, including demand management strategies, water distribution pipe renewal, sewer relining, and energy recovery from wastewater treatment facilities. Each strategy is compared to the base case scenario using four environmental indicators—water, energy and chemical use, and greenhouse gas emissions and one economic indicator—total costs. Although a variety of other indicators are useful in the context of sustainable urban infrastructure systems (Sahely et al. 2005), these decisive indicators are chosen to explore the water-energy-chemical nexus in urban water management.

## Literature Review

### *State of Urban Water Systems*

The conventional, linear urban water system in most cities of the developed world has served several important purposes, especially in terms of decreasing pollution, the incidence of major fires, and water-borne disease. Many would argue, however, that urban water is used unwisely in conventional systems and that valuable materials such as nutrients are not returned to the material cycle but destroyed (Otterpohl et al. 2004; Wilderer 2004; Johansson 2000; Larsen and Gujer 1997).

Energy use is also an issue for aging conventional, linear urban water systems especially as it relates to water pumping and distribution and water and wastewater treatment. James et al. (2002) estimate 2 to 3% of the world's energy consumption is used to pump and treat water. Leakage from distribution systems can have direct and indirect costs related to water losses, pumping

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energy, chemical and waste disposal. Leakage leads to increased energy use associated with pumping by exerting an extra demand. The American Water Works Association (AWWA) water loss control committee estimates 5 to 10 billion kW h of power generated yearly in the United States is expended on water that never makes its way to the consumer largely due to defective infrastructure (AWWA 2003).

In water and wastewater systems, treatment facilities account for a large part of energy use and emissions. For the Canadian municipal wastewater treatment sector, Sahely et al. (2006) demonstrated that on-site (i.e., within the boundaries of the wastewater treatment facility) processes account for 56% of the sector's overall contributions to GHG emissions, whereas upstream activities and on-site fuel use for heating and electricity account for 33 and 11%, respectively. Estimated energy use and GHG emissions using a life cycle approach for the City of Toronto water treatment facilities revealed that plant operation accounted for 94% of total energy use and 90% of GHG emissions (Racoviceanu 2005). Tarantini and Ferri (2001) found that water pumping had the highest environmental impact for the city of Bologna water and wastewater systems; whereas Friedrich (2002), in his study of water treatment facilities in South Africa, found that the generation of electricity involved the highest environmental burden. These studies demonstrate the impact of the operational phase of water and wastewater treatment facilities compared to the construction and end-of-life phases especially in terms of energy use and associated GHG emissions.

### *Models for Urban Water Management*

The focus of this section is on the application of computational models for urban water management. A systemic approach to modeling urban water systems has increased our ability to analyze a wider range of impacts. These models of urban water management help to increase and integrate knowledge about the urban water system, to highlight data gaps and research needs, to quantify and measure impacts of different strategies and to support the decision-making process and operational water management (van Waveren 1999).

Model-based assessments of the complete urban water cycle are relatively few. Models that look at the entire urban water cycle or alternatively at a regional water basin including a major urban center have been developed as a response to growing concerns about the sustainability of urban water systems (Lundie et al. 2004; Alegre et al. 2004; Soares and Bernardes 2003; Doll and Hauschild 2002; Jeppsson and Hellström 2002; Burn et al. 2002; Speers et al. 2001; Mitchell et al. 2003, 2001; Xu et al. 2001; Balkema et al. 2001; Foxon et al. 2000; Icke et al. 1999; Gao and Liu 1997; Huang and Chen 1990).

In general, models that seek to support the decision-making process and analyze the impacts of different urban water management strategies are spatially aggregated and adopt a systems approach in considering socioeconomic and environmental impacts. In contrast to detailed process-based models utilized in engineering design, an aggregated model allows for the study of various interacting processes within the whole system. Lundie et al. (2004) utilize a spatially aggregated life cycle model in order to enhance modeling of a large, complex urban water system which is useful for the examination of future scenarios and planning.

Environmental considerations have focused mostly on water resource use. Models also attempt to attack issues of water quality such as monitoring flows of contaminants, organic matter, and nutrients through the system (Jeppsson and Hellström 2002; Speers et al. 2001; Mitchell et al. 2001).

Many of the current model-based assessments of urban water systems focus primarily on environmental impacts and do not include an extensive treatment of economic issues. Environmental or social costs expressed in monetary terms are not usually estimated and included in systems models of urban water systems. Social issues related to urban water management are seldom included in modeling exercises mainly given the difficulty in measuring them.

Models that seek to promote sustainable urban water management use scenario analysis as a means for strategic planning and to identify opportunities to improve the sustainability of urban water systems. A comparison between the status quo and alternatives can then easily be made and improvements assessed using sustainability criteria (Sahely et al. 2005; Lundie et al. 2004).

## Model Development

A water use model has been developed to explore potential water, energy, chemical, and GHG emissions savings for the City of Toronto under various scenarios. The water-energy-chemical nexus is a complex relationship and this model offers basic guidelines and is useful for strategic planning. Further description of the City of Toronto water system can be found in Sahely et al. (2005).

### *Modeling Approach and System Boundaries*

A water balance approach has been selected to characterize water flow through the urban water system (Mitchell et al. 2003; Niemczynowicz 1990; Grimmond et al. 1986; Aston 1976). In order to reduce data needs and the complexity of the model, a monthly time step was chosen. The functional unit, defined as the volume of water output, is expressed in megaliters (ML).

The urban water system model includes water production, distribution, and end use through to wastewater collection and treatment. Fig. 1 outlines the boundaries utilized in the development of the systems flow model specific to the City of Toronto in this case. The indicators to be quantified in the analysis are listed on the left-hand side of Fig. 1 including water, energy, and chemical use indicators and associated greenhouse gas emissions. Dashed and shaded elements are not included in the analysis. Only the operational life cycle stage is examined as it dictates the construction process required, is expected to have the longest duration of the stages, and is the only stage that has been found to present significant opportunity for reducing long-term environmental and economic impacts (Sahely et al., 2006; Lundie et al. 2004; Suh and Rousseaux 2002). Further, Grant et al. (2006) found that operational impacts were much more important for key environmental indicators than capital infrastructure over the life cycle of urban water systems. The operational phase is ongoing compared to the long-lived nature of centralized capital infrastructure, which is provided only once.

The analysis is conducted from the perspective of the utility and thus the energy used for home hot water heating is not included in the analysis. Thermal energy expenditure (natural gas usage) for the wastewater treatment facilities is included in the system boundary. Given the biological processes involved in wastewater treatment, heating is a significant portion of on-site energy use. On the other hand, as water filtration plants include

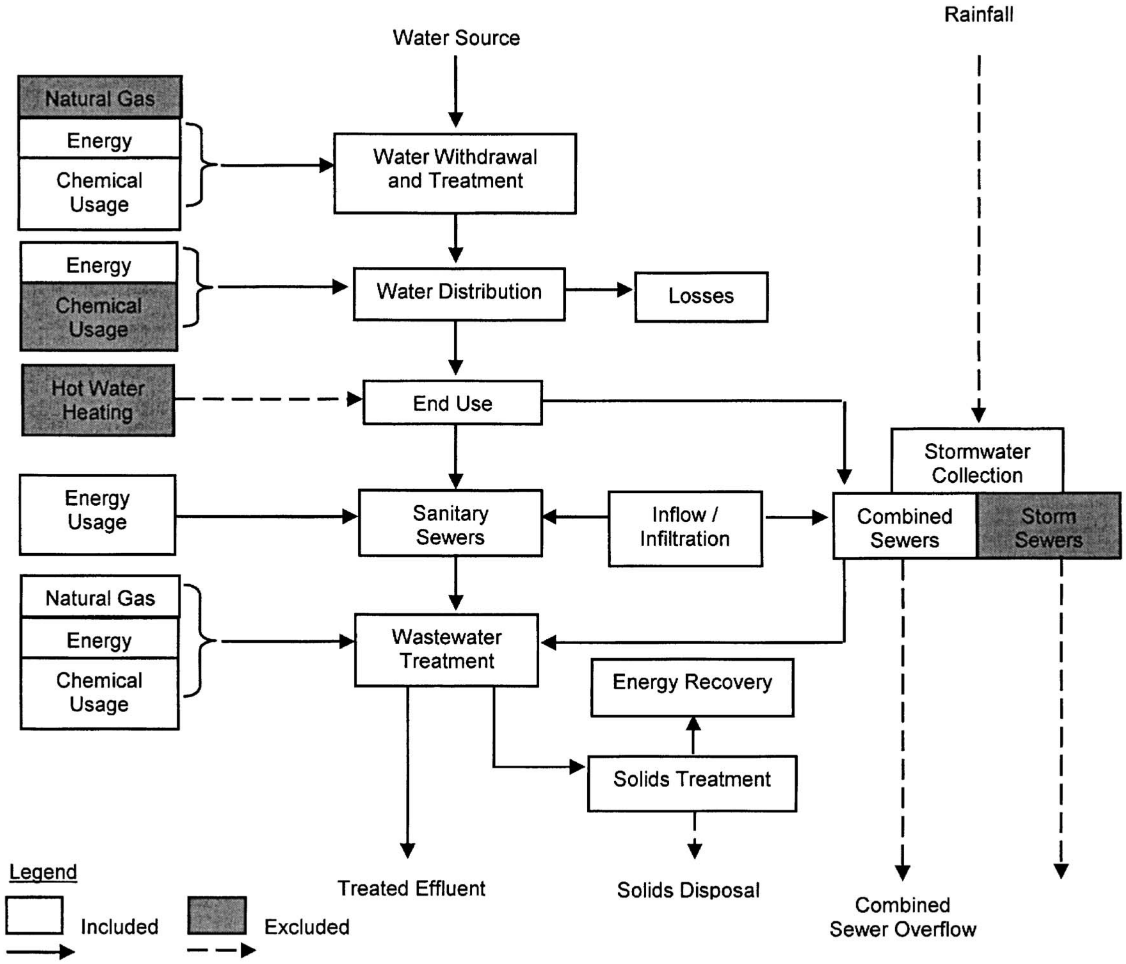


**Fig. 1.** Systems flow model boundaries for the use phase of the urban water system

mostly physical and chemical processes, heating is generally considered to be a small contributor (e.g., heating of administrative buildings) to overall energy use and is not included in the analysis. Total chemical usage at the water filtration plants and wastewater treatment facilities are included in the analysis. Chemical usage during water distribution is a small contributor to overall chemical usage and was excluded from the analysis.

On-site GHG emissions due to biological processes and due to fossil fuels (namely natural gas) combusted for heating of the wastewater treatment plant are included in the analysis. The rationale for inclusion of GHG emissions due to biological processes from wastewater treatment is discussed in detail by Sahely et al. (2006). Further, upstream GHG emissions related to off-site production and transmission of fuels used for heating, the off-site production of electricity and the off-site production of chemicals consumed by each component of the urban water system are included in the study boundaries. The downstream GHG emissions arising from the transport of solids for disposal and the upstream GHG emissions arising from the transportation of chemicals will not be considered in this study. Tarantini and Ferri (2001) showed that less than 7% of life-cycle GHG emissions from the City of Bologna drinking and wastewater systems were due to solids disposal and chemical transportation. Further, Racoviceanu (2005) found chemical transportation-related GHG emissions to be small (3% of total GHG emissions) compared to operational energy use-related GHG emissions for the City of Toronto water filtration plants.

As the main purpose of the model is to study system-wide impacts of demand management, pipe renewal, and other strategies, the water supply-wastewater discharge network of the urban water cycle is modeled in a more detailed fashion than the rainfall-stormwater runoff aspect. Although wet weather flow management has important sustainability implications especially in the case of combined sewers, a detailed analysis of stormwater flows is beyond the scope of the present research.

## *Conceptual Model and Equations*

### Water Demand, $Q$

Water demand drives the urban water cycle and dictates the volume of water withdrawn assuming that the water source is not in short supply. A long-range demand model that allows strategic planners to forecast water demand 5 to 10 years in advance was developed for the City of Toronto (Sadiq 2003). Therefore, a 10 year time span was chosen for this analysis. This type of model is essential for water supply planning and to understand the impacts of climate change on urban water. The function was derived using a stepwise regression technique as described by Brekke et al. (2002). The base and seasonal demand are shown in the following.

*Base demand* (October to April, temperature $<15°C$)

$$Q = -284 + 0.63 \cdot \text{POP} \tag{1}$$

*Seasonal demand* (May to September, temperature $\geqslant 15^\circ$C)

$$Q = -669 + 0.63 \cdot \text{POP} + 29T_{\text{day}} \tag{2}$$

where $Q$=total daily water demand (ML/day); POP=population in thousands; and $T_{\text{day}}$=maximum daily summertime temperature for that date (°C). Population forecasts generated by the City of Toronto are used in the model (City of Toronto 2002). These forecasts assume 10% growth over the next 10 years.

As for forecasting temperature, Colombo et al. (1999) developed a first-order autoregressive [AR(1)] algorithm to generate forecasts of maximum summertime (May-Sep.) daily temperature for Toronto

$$T_{\text{day},t} = \mu + \varphi(T_{\text{day},t-1} - \mu) + a_t \tag{3}$$

where $T_{\text{day},t}$=individually generated maximum daily temperature at time t (°C); $\mu$=mean daily maximum temperature (°C); $\varphi$=autocorrelation factor (0.6 for Toronto); and $a_t$=independent and normally distribution random shock at time $t$ (°C). Eqs. (1)–(3) are utilized to forecast total daily demand from which total monthly demand can be calculated and used as an input to the model.

### Distribution Losses, $Q_L$

Water utilities have been without consistent standards of water accounting resulting in an inability to accurately account for losses of treated water and a portion of the associated revenues due to leaky pipes. It is imperative to recover and minimize such losses as the water is already treated and ready for consumer use, is energized to provide adequate pressure to reach the consumer, and is possibly sufficient to provide for future population growth.

For the City of Toronto, it is estimated that 14% of treated water is considered nonrevenue water of which approximately 60% (or 8% of the total) is due to distribution losses (City of Toronto 2002). The remainder of the unaccounted for water is due to illegal connections and unaccounted-for water utilized by the city for various activities such as street cleaning. Generally, water losses are difficult to estimate and the City of Toronto is currently implementing more stringent water loss accounting procedures in line with AWWA standards. The reported 8% distribution losses for the City of Toronto is likely underestimated and is a source of uncertainty (City of Toronto, R. Kaszczij, personal communication, 2004). However, for the sake of consistency and for comparison purposes, all of the estimates provided by the City of Toronto are utilized in this analysis.

Distribution losses will be considered as the total volume of water lost due to leaks and breaks in the model. Leaks are defined as smaller volumes of water lost from loose joints and small main fractures (which are not replaced immediately). Breaks are defined as larger volumes of water lost from main fractures (which are usually replaced once they are detected) and from pipes that have burst or collapsed (O'Day 1982). Eq. (4) is used to calculate the total annual volume of distribution losses

$$Q_L = Q_{\text{leak}} + Q_{\text{break}} \tag{4}$$

where $Q_L$=total volume of water lost due to breaks and leaks per year. It is assumed that the number of leaks and breaks is a function of the average age of the system. Studies have shown a relationship between breakage rate and age. Shamir and Howard (1979) reported an exponential relationship between pipe breakage rate and age. Kettler and Goulter (1985) reported a moderate linear correlation between breakage rate and pipe age. Given the aggregate nature of the model and a limited data set, an exponential relationship between pipe breakage/leakage rate and age was not determined for the City of Toronto. Linear regression analysis was utilized to determine the appropriate function based on historical observed data as shown in Eqs. (5) and (6) which are used to calculate the number of leaks and breaks

$$n_L = 0.035y - 0.0315 \tag{5}$$

$$n_B = 35y \tag{6}$$

where $n_L$=number of leaks per year per kilometer; $n_B$=number of breaks per year; and $y$=average age of the system (years). $n_L$, $n_B$, and $y$ are measured and based on historical data. The volume of water lost from leaks and breaks can then be determined using

$$Q_{\text{leak}} = n_L L V_{\text{leak}} \tag{7}$$

$$Q_{\text{break}} = n_b V_{\text{break}} \tag{8}$$

where $Q_{\text{leak}}$=annual volume of water lost from leaks; $L$=total length of the water distribution system (km); $V_{\text{leak}}$=average volume of water lost per leak (for Toronto $V_{\text{leak}}$=7.5 ML/leak); $Q_{\text{break}}$=annual volume of water lost from breaks; and $V_{\text{break}}$=average volume of water lost per break (for Toronto $V_{\text{break}}$=23 ML/break). $V_{\text{leak}}$ and $V_{\text{break}}$ were calculated using data from leakage studies performed on the system between 1968 and 1987 and L=known measured quantity. $Q_{\text{leak}}$ and $Q_{\text{break}}$=modeled parameters.

### End Use, $Q_E$

The total volume of water delivered to consumers whether residential, institutional, commercial, municipal, or industrial is given by

$$Q_E = Q - Q_L \tag{9}$$

where $Q_E$=annual volume of water available for end use.

### Wastewater Inflows, $Q_{\text{WWT}}$

Three components make up the flow into wastewater treatment facilities as outlined in following:

$$Q_{\text{WWT}} = Q_{\text{WWE}} + Q_{\text{WWF}} + Q_{\text{INF}} \tag{10}$$

where $Q_{\text{WWT}}$=annual volume of wastewater treated; $Q_{\text{WWE}}$=annual volume of wastewater generated by end users which enters the sewer (sanitary and combined) system; $Q_{\text{WWF}}$=annual volume of wet weather flow that enters the wastewater treatment plant via the combined sewer system or inflow and infiltration; and $Q_{\text{INF}}$=annual volume of water, known as base infiltration, which enters the sewer systems during dry weather.

Approximately 75–80% of water delivered to end-users is not consumed but returned to the sewer system as wastewater. Consumptive water use includes mainly outdoor water use. The percentage of water demand that is nonconsumptive varies seasonally and was determined via calibration of the model against historical data. As a result, $Q_{\text{WWE}}$ is calculated as follows:

$$Q_{\text{WWE}} = \text{NCD}_i Q_E \tag{11}$$

where NCD=nonconsumptive demand coefficient during season $i$ (%). For Toronto, $\text{NCD}_{\text{summer}}$=0.67 and $\text{NCD}_{\text{winter}}$=0.87 were calculated via calibration of the model.

In practice, $Q_{\text{WWF}}$ and $Q_{\text{INF}}$ are difficult inputs to measure and dependent on several factors, including the proportion of combined sewers, the state of the sewer system, groundwater and soil characteristics, and precipitation. Wieb et al. (2002) observe that inflow and infiltration are often underestimated and this leads to inefficient performance of the sewer system. In their study of 34

**Table 1.** Values of Intensity and Emissions Factor for Toronto

| Term | Value | Source |
|---|---|---|
| Electrical energy for water treatment ($e_{WT}$) | 280 kW h/ML | Racoviceanu 2005 |
| Electrical energy for water distribution pumping ($e_{WDP}$) | 300 kW h/ML | Racoviceanu 2005 |
| Electrical energy for wastewater pumping ($e_{WWT\_PUMP}$) | 100 kW h/ML | Sahely and Kennedy 2003 |
| Electrical energy for wastewater treatment ($e_{WWT}$) | 450 kW h/ML | Sahely and Kennedy 2003 |
| Chemicals required for water treatment ($c_{WT}$) | 14 kg/ML | Sahely and Kennedy 2003 |
| Chemicals required for wastewater treatment ($c_{WWT}$) | 15 kg/ML | Sahely and Kennedy 2003 |
| Natural gas required in winter ($h_{WIN}$) | 47 $m^3$/ML | Sahely and Kennedy 2003 |
| Natural gas required in summer ($h_{SUM}$) | 28 $m^3$/ML | Sahely and Kennedy 2003 |
| Emissions factor—WWT biological process ($EF_{PROC\_WWT}$) | 480 kg $CO_2$ equiv./ML | Monteith et al. 2005 |
| Emissions factor—natural gas combustion ($EF_{NG\_C}$) | 1,890 g $CO_2$ equiv./$m^3$ | GaBi Software System 2004 |
| Emissions factor—natural gas transportation/production ($EF_{NG\_UP}$) | 2,360 g $CO_2$ equiv./$m^3$ | GaBi Software System 2004 |
| Emissions factor—electricity generation ($EF_{ELEC}$) | 348 g $CO_2$ equiv./kW h | Kuber 2005 |
| Emissions factor—chemical production for WT ($EF_{CHEM\_WT}$) | 740 g $CO_2$ equiv./ML | Racoviceanu 2005 |
| Emissions factor—chemical production for WWT ($EF_{CHEM\_WWT}$) | 1,860 g $CO_2$ equiv./ML | Calculated using historical data |

combined sewersheds in Germany, inflow and infiltration accounted for 35% of total inflow into treatment facilities.

In the case of Toronto and the aggregate water use model developed here, $Q_{WWF}$ and $Q_{INF}$ are considered constant and based on historical data and measurements for Toronto's main wastewater treatment plant, where inflow and infiltration during dry and wet weather flow accounted for approximately 30% of the flow into the City of Toronto treatment facilities (CH2M Gore and Storrie Limited 1997). $Q_{WWF}$ occurs mostly in the summer months between May and September and is approximately 3,000 ML/month, whereas $Q_{INF}$ is approximately 10,000 ML/month.

### *Environmental Indicators*

Definition of terms and value of environmental intensity factors are given in Table 1. Environmental intensity factors relate activity data (e.g., kW h of electricity or kg chemical utilized) and the functional unit [the volume of water output in megaliters (ML)]. Energy (electrical and thermal) and chemical usage are calculated using model determined flow rates and energy and chemical factors determined from historical data for the City of Toronto. In general, environmental indicator, $X$, is determined by

$$X = \sum_i x_i Q_i \tag{12}$$

where $x_i$=associated intensity factor for component $i$ and $Q_i$=volume of water through component $i$ as defined earlier.

In particular, taking a closer look at electrical energy as an environmental indicator, $E$, is determined by

$$E = e_{WT}Q + f e_{WDP}Q + (e_{WWT\_PUMP} + e_{WWT})Q_{WWT} \tag{13}$$

where $f$=adjustment factor, which accounts for the change in pipe roughness and hydraulic capacity as the pipe ages. As pipe renewal strategies are implemented, less energy will be required to pump water through newer pipes. The amount of pumping energy saved is defined as the savings in potential friction energy losses gained by replacing a pipe. This concept is described in detail by Filion et al. (2004). In this case, $f$ is set at 1 as insufficient data are available for the City of Toronto and more detailed network pipe modeling would be required, which falls outside the scope of this work.

On-site GHG emissions from activities such as biological processes (wastewater treatment) and combustion of natural gas for heating and upstream GHG emissions due to electricity generation, production and transportation of natural gas, and the production of chemicals are calculated using various emissions factors given by

$$GHG_{on\text{-}site} = \sum_i EF_i Q_i \tag{14}$$

$$GHG_{upstream} = \sum_i EF_i X \tag{15}$$

where $GHG_{on\text{-}site}$=GHG emissions due to onsite activities; $GHG_{upstream}$=GHG emissions due to upstream activities; and $EF_i$=emissions factor for component $i$.

A final note on the value of intensity factors in Table 1. The electrical energy for water treatment, $e_{WT}$, includes raw water pumping and treated water pumping up to the first water storage reservoir. Electrical energy for water distribution pumping, $e_{WT\_PUMP}$, includes all pumping from the first reservoir onwards in the delivery to consumers throughout the city. For the City of Toronto, the average pumping head for raw water is approximately 15 m. and the average pumping head for treated water up to the first storage reservoirs is 92 m (Kargel 1990a,b; Hargrove 1990).

### Costs

The annual installation costs and operating cost savings compared to the base case scenario (i.e., cost savings due to avoided energy and chemical use) are calculated over the 10 year period. For the scenarios that result in a decrease in water demand, the total annual volume of water saved is determined and is translated into energy and chemical savings as less water is treated and pumped through the system. Avoided energy and chemical use is calculated using the applicable intensity factors in Table 1 multiplied by calculated water savings. Unit costs of energy and chemical are utilized to determine the cost savings due to avoided energy and chemical usage. The net present value of all costs are estimated using a 5% discount rate, which is the rate currently utilized by the City of Toronto for this type of analysis (City of Toronto 2002). All costs are in 2001 Canadian dollars.

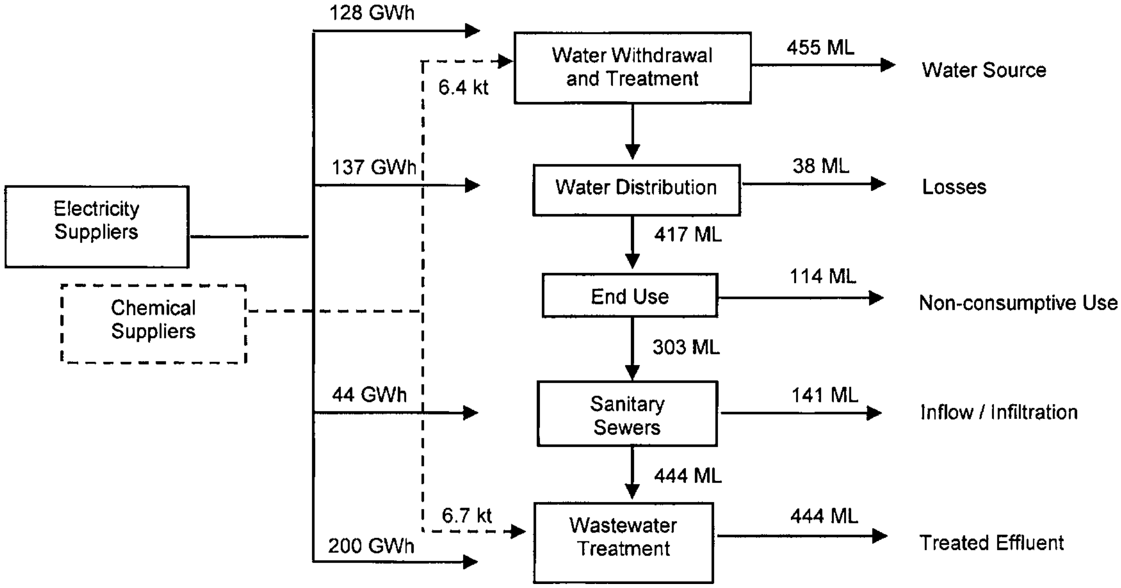


**Fig. 2.** Simplified flow diagram for the City of Toronto urban water system, year 2001

In addition to these costs, a cost-effectiveness analysis is undertaken as another technique of comparing the various scenarios. This analysis compares the costs and energy impacts of the scenarios to assess whether it is worth doing from an economic perspective. The cost-effectiveness ratio for each scenario is calculated, as the total installation costs of the scenario divided by the total avoided energy usage for the scenario ($/kW h).

## Model Application

The base case flow model was constructed to represent the City of Toronto urban water system in year 2001. Fig. 2 represents the simplified flow diagram within the defined system boundaries for the Toronto urban water system.

Several scenarios are investigated in order to compare the environmental and economic performance of alternative systems over a 10 year period up to 2010. For the base case, population growth of 10% is assumed over the 10 year period in accordance with planning estimates for the City of Toronto. For the base case, it is assumed that water distribution pipes and sewer mains are replaced only when severe breaks occur. This represents renewal rates of less than 0.5% of the total system and is supported by historical data from the City of Toronto (City of Toronto 2003, 2004).

### *Base Case*

Energy and chemical flows are characterized and represented in Fig. 2. Total electrical energy use per year is approximately 510 GW h (1,830 TJ), half of which is attributed to water supply and the other half to wastewater treatment. Taking a closer look at the water supply components, raw water pumping (15%) and treated water distribution (27%) as compared to water treatment (10%) are the main contributors to electrical energy use. On the other hand, wastewater treatment utilizing activated sludge and anaerobic digestion processes, as is the case for Toronto, is energy intensive. As a result, wastewater treatment accounts for 39% of total electrical energy use compared to wastewater pumping (9%). Natural gas usage accounts for a further 640 TJ of energy use.

A total of 13 kt of chemicals are utilized per year, split roughly equally between water and wastewater treatment. Ferrous chloride represents 30% of total chemical flows followed by alumi-

**Table 2.** Comparison of Scenarios against the Base Case for Environmental Indicators

| Scenarios | Water demand ($Q$) (ML/year) | Distribution losses ($Q_L$) (ML/year) | Treated wastewater ($Q_{WWT}$) (ML/year) | Total electrical energy used ($E$) (GW h/year) | Total mass of chemicals used ($C$) (kt/year) | On-site GHG emissions ($GHG_{onsite}$) (kt/year) | Upstream GHG emissions ($GHG_{upstream}$) (kt/year) |
|---|---|---|---|---|---|---|---|
| Base case (2010) | 514,400 | 43,200 | 483,900 | 564 | 14 | 268 | 242 |
| Percentage change in environmental indicators for each scenario | | | | | | | |
| Demand management (DM) | −1.2 | −8.8 | 0.0 | −0.6 | −0.6 | 0.0 | −0.5 |
| Pipe renewal 0.5% (PR0.5) | −1.9 | −13.7 | 0.0 | −1.0 | −1.0 | 0.0 | −0.8 |
| Pipe renewal 1% (PR1) | −3.6 | −25.9 | 0.0 | −1.9 | −1.8 | 0.0 | −1.6 |
| Pipe renewal 2.5% (PR2.5) | 0.0 | 0.0 | −1.2 | −0.6 | −0.6 | −1.2 | −0.7 |
| Sewer relining 10% (SR10) | −17.5 | −18.2 | −12.5 | −15.1 | −15.0 | −12.5 | −14.7 |
| Energy recovery from biogas (ER) | 0.0 | 0.0 | 0.0 | −9.0 | 0.0 | 0.0 | −7.3 |

**Table 3.** Costs of Scenarios against the Base Case for the 10-Year Period

| Scenario | Total installation costs (million \$) | Operations costs savings (million \$) | Net costs (million \$) |
|---|---|---|---|
| Demand management (DM) | 55.1 | 37.2 | 17.9 |
| Pipe renewal 0.5% (PR0.5) | 182 | 1.67 | 180 |
| Pipe renewal 1% (PR1) | 365 | 2.68 | 362 |
| Pipe renewal 2.5% (PR2.5) | 912 | 5.26 | 907 |
| Sewer relining 10% (SR10) | 839 | 3.01 | 836 |
| Energy recovery from biogas (ER) | 31.9 | 28.8 | 3.15 |

num sulfate (alum) (23%), chlorine (14%), hydrofluosilicic acid (12%), and sodium hypochlorite (7%). The remaining 14% comprise various polymers and buffers.

Total GHG emissions are equivalent to 465 kt of $CO_2$ equivalents per year with 53% of emissions due to onsite activities and 47% due to upstream activities. Upstream GHG emissions are equivalent to 219 kt of $CO_2$ equivalents per year with 80% due to electricity generation, 19% due to the production and transportation of natural gas and 1% due to the production of chemicals. On-site GHG emissions account for 245 kt of $CO_2$ equivalents per year with 87% due to biological processes and 13% due to on-site combustion of natural gas, both of which occur during wastewater treatment.

### *Scenario Analysis*

Each scenario deals with one or more of the major components of the urban water cycle. Demand management (DM) initiatives focus on consumption by end users, pipe renewal (PR) strategies target distribution losses, whereas sewer relining (SR) aims at reducing inflow and infiltration. The results of the scenario analyses are summarized in Tables 2 and 3 and Fig. 3. Each of the scenarios is discussed in more depth in the following, including key assumptions and comparison against the base case for environmental indicators.

#### Demand Management Strategies

The benefits of demand management strategies are numerous including: (1) the benefits of deferring and reducing capital works, and downsizing treatment plants and distribution upgrades; (2) the reduced cost of pumping due to decrease in frictional energy losses; and (3) the flexibility of demand-side solutions in terms of adjusting a given program to meet changing circumstances.

The City of Toronto water efficiency plan outlines a variety of initiatives aimed at achieving a 15% reduction in demand by 2011 (City of Toronto 2002). The initiatives include system leakage detection and computer controlled irrigation at the municipal level, toilet replacement, clothes washer replacement, and outdoor and indoor water audits for all other user types. The demand management scenario creates savings on the order of 12–18% for all indicators shown in Table 2. Lundie et al. (2004) found a similar result for the City of Sydney in that reducing demand by 6% resulted in savings of approximately the same scale across all impact categories. It is important to note that the initiatives outlined in the City of Toronto water efficiency plan are not as aggressive as other plans implemented worldwide where savings on the order of 25% have been achieved. The positive impacts of a more aggressive strategy are potentially significant.

Savings across all indicators are achieved most cost effectively using demand management versus all of the other scenarios explored (Table 3). A large portion of the implementation costs of demand management is offset by the cost savings for energy and chemicals. The costs per unit of water saved is approximately \$36 per ML, whereas the costs per unit of energy saved is 0.04 \$/kW h (Fig. 3).

Demand management effectively demonstrates that initiatives targeted at the early stages of the urban water cycle have greater downstream impacts and in many cases can be implemented more cost effectively and can lengthen the lifetime of infrastructure systems.

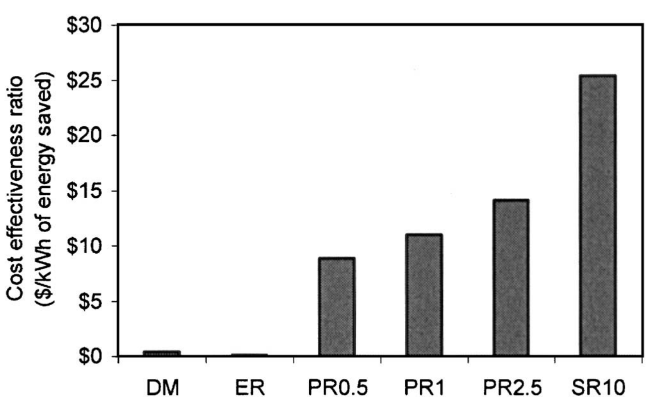


**Fig. 3.** Cost effectiveness ratio for energy impacts for selected scenarios

#### Pipe Renewal Strategies

USEPA (2002) outlines the characteristics of a deteriorating water distribution system including: increased frequency of leaks and breaks, taste, odor, and red water complaints, reduced hydraulic capacity, and increased disinfectant demands due to the presence of corrosion by-products, biofilms and microbial regrowth.

Liabilities associated with pipe breaks and leaks are significant and go beyond just lost revenues. Direct and indirect costs related to water losses, pumping energy, chemical, and waste disposal can be significant. Leakage leads to increased energy costs associated with pumping by exerting an extra demand and through greater dynamic losses that result from having to provide equivalent service (Colombo and Karney 2005).

Pipe renewal as well as leakage repair could become a valuable hedge against premature capacity expansion in light of increased urbanization and population growth. According to Grigg (2005), the average replacement rate in U.S. cities is approximately 0.5% and it is clear that this is not sufficient. Therefore, renewal rates of 1 and 2.5% were also utilized as part of the scenario analysis to assess what may be the environmental and cost impacts of such strategies.

Although environmental and cost considerations are only two of a variety of influencing factors attached to developing pipe renewal strategies, these are explored in a bid to further understand the system-wide impacts of infrastructure renewal and how to possibly incorporate such an understanding into a larger sustainability framework.

The main positive outcome of pipe renewal strategies is the reduction of distribution losses as outlined in Table 2. Reduction in losses between 8 and 26% and in total water demand between 1 and 4% can be accomplished with pipe renewal rates between 0.5 and 2.5%, respectively.

As distribution losses represent less than 10% of total water use, the overall system-wide impacts in terms of the other environmental indicators are not as significant as anticipated with energy and chemical savings and GHG emissions reduction of less than 2% for all renewal rates. In general, reduction in distribution losses on the order of 15% must be achieved in order to reduce energy and chemical usage and GHG emissions by 1%.

In terms of capital costs, the pipe renewal strategies are amongst the most expensive. Such strategies are not the most cost effective solutions in terms of reducing energy and chemical loadings and associated GHG emissions, but there may be other benefits of pipe renewal beyond those assessed here (e.g., reduced costs of disruption due to pipe breaks etc.).

### Sewer Relining

Downspout disconnection and repairing and relining old sewer pipes are two ways to reduce inflow and infiltration. Approximately 8% of the City of Toronto sewers are older than 80 years old and inflow/ infiltration (I/I) is a major component of wastewater inflow (Fig. 2). It is assumed that half of base infiltration is due to damaged sewers and is equivalent to 5,000 ML/month (Snodgrass 2001). With a total of 5400 km of sewers, an average volume of 0.93 ML of I/I enters per kilometer of sewer per month. A sewer relining rate of 10% is chosen for this scenario and is equivalent to a reduction of 500 ML/month in I/I.

Table 2 outlines the minimal impact of a 10% relining rate for sewers. Inflow into the wastewater treatment plants is reduced by less than 1.5%, with energy and chemical savings and GHG emissions reduction of the same scale. Other options for mitigating inflow and infiltration such a downspout disconnection are likely more cost effective.

Although sewer relining at a rate of 10% is an unlikely option for any utility, the scenario demonstrates that taking such a drastic option later in the urban water cycle carries few benefits. Although sewer relining is a necessity to assure continued performance of the system and effective and safe wastewater transportation, it should not be viewed as an option that would contribute beneficially to other sustainability goals.

It is not surprising that the costs of relining 10% of the sewer system annually are quite high. Comparing sewer relining (SR) to the pipe renewal scenarios (PR2.5), for an equivalent investment, more tangible benefits occur with the pipe renewal option (Table 2). The main reason, which is consistently reflected in the results, is that initiatives targeted at the early stages of the urban water cycle have greater positive downstream impacts.

### Energy Recovery from Anaerobically Digested Wastewater Biosolids ER

Three of four wastewater treatment facilities in the City of Toronto produce biogas from anaerobic sludge digestion, which can be used onsite for the production of renewable energy. Historical data on biogas generation rates were taken from the annual reports of the individual wastewater treatment plants (City of Toronto 2001a,b,c,d). This scenario assumes only the facilities that currently anaerobically digest solids are retrofitted with energy recovery systems. Given the biogas generation rate for each of the plants in Toronto, the minimum required capacity for the energy recovery system was calculated and an appropriate technology chosen. The costs of implementing these technologies are summarized by Liu (2005). In this case, it is assumed that a combination of gas turbines cogeneration gas engine are installed and that all recovered energy is used in the form of electricity on-site, thus decreasing the amount of electricity purchased from the grid.

Energy recovery from wastewater solids provides approximately 9% energy savings and an associated 7.3% reduction in upstream GHG emissions due to using less fossil-fuel based energy. Although such an option is implemented at the last stage of the urban water cycle, it has significant impacts on energy use for a reasonable cost compared to other scenarios, namely because wastewater treatment is one of the most energy-intensive processes within the urban water system.

Although such energy recovery is not generally viewed as being cost effective (Bagley et al. 2004), by utilizing a systems approach and comparing various alternatives, the benefits of such an investment become more evident especially if anaerobic digestion of solids is already in place. In terms of energy savings, it is the most cost-effective option with a cost per unit of energy saved of less than \$0.01/kW h. As the technology evolves, the amount of energy generated may be increased and the cost reduced further. In addition, if wastewater treatment facilities were included in future GHG emissions trading schemes, the economic attractiveness of producing energy from biogas would increase (Bagley et al. 2004). With the anticipated peaking in world oil and gas production worldwide and the increased energy costs in the aftermath of natural disasters such as Hurricane Katrina, energy recovery from wastewater treatment makes sense from a variety of standpoints.

## Model Limitations

A high degree of model segmentation was chosen in order to enable modeling of a large, complex urban water system, which is useful for the examination of future scenarios and planning. However, such model aggregation has its drawbacks, especially in terms of performance assessment of the water distribution system. Representation of pipe breaks, leaks, and associated water losses, the energy impacts of replacing pipes and demand management initiatives (e.g., installing water meters and other devices) and inflow and infiltration in the model is crude compared to available methodologies in the hydraulics literature. Such issues could be attacked more rigorously if a pipe network model of the City of Toronto's distribution system is integrated. This would be especially useful if more in-depth analysis of pipe rehabilitation and renewal strategies and other initiatives aimed at enhancing performance efficiency are needed.

In its present form, the model considers only selected environmental indicators, notably water, energy and chemical use, and GHG emissions. It could be expanded to include other factors such as nutrient and contaminant loadings. Taking a closer look at energy and chemical usage, the model is limited to tracking average material flows. Seasonal and peak variations in the electricity generation mix and the impact this may have on GHG emissions are not taken into account. In order to incorporate the impacts on human health into the model, these limitations would need to be addressed in more detail.

## Summary and Conclusions

Through the assessment of system-wide effects, the use of scenarios, and the inclusion of selected costs, this study has achieved its goal of incorporating wider sustainability criteria into the assessment of alternative strategies for urban water systems. Application of the model to the City of Toronto urban water system produced the following main findings: (1) initiatives targeted at the early stages of the urban water cycle have greater positive downstream impacts on selected environmental indicators; (2) demand management strategies aimed at reducing demand by 15% result in savings on the order of 12–18% for all indicators. The results suggest that savings from demand management can be achieved at a reasonable cost and may be enough to offset increases in demand due to population growth over the next 10–15 years. (3) Pipe renewal rates between 0.5 and 2.5% yield a reduction in distribution losses between 8 and 26% but have only minimal influence on environmental indicators. (4) Energy recovery from wastewater solids provides approximately 9% energy savings and an associated 7.3% reduction in upstream GHG emissions due to using less fossil-fuel based energy.

Overall, the model is flexible and permits a utility to capture environmental effects associated with the consumption of materials, something which does not usually occur in the strategic planning process. The use of scenarios allows for benchmarking of current practices against potentially more sustainable alternatives and can be used for policy-setting and communication to relevant stakeholders and community members.

The practicality and usefulness of operational tools to enhance urban water system sustainability cannot be overstated. They serve as a platform for rational decision-making by policy-makers, municipal engineers, and urban planners alike and are a necessary component for the sustainable development of today's water industry.

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