DEVELOPING A DECISION SUPPORT TOOL FOR SUSTAINABLE URBAN WATER MANAGEMENT

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Abstract

Research in the area of sustainable urban infrastructure reflects the need to design and manage engineering systems in light of environmental, economic, social and technical considerations. In the water sector, the main challenge for the engineer is the development of practical tools for measuring and enhancing the sustainability of urban water infrastructure over its life cycle. The present study takes a major step towards this goal by developing a decision support tool for the sustainability assessment of urban water systems. The decision support tool takes the form of a dynamic water balance model coupled with environmental and economic sub-models. The various components of the model are described and selected results from a case study of the City of Toronto are highlighted.

Keywords

Sustainable urban water infrastructure, impact assessment, water balance, energy and chemical use, life cycle costs.

1 INTRODUCTION

Many regional and global environmental problems originate in urban centers. Changes in spatial distribution and the structure of human activities have lead to increased urbanization and associated negative environmental impacts. At the heart of issues of urban sustainability lie infrastructure systems. For the civil engineer, the major challenge is the development of practical tools to measure and enhance urban sustainability especially through the design and management of infrastructure.

The overall objective of this research is to develop a decision support tool for the assessment of system-wide impacts of potential changes in technology, production and/or consumption patterns implemented to enhance the sustainability of an urban water system. The quantitative framework will take the form of a dynamic water balance model coupled with economic and environmental sub-models. The sub-models can be viewed as layers where environmental and economic considerations can be addressed. The main flow model represents the flow of water through the urban water system from the water source to water production and distribution through to end use, wastewater collection and treatment. The economic sub-model will quantify the "flow" of economic resources using life cycle costing concepts while the environmental sub-model will focus on inputs such as energy and chemicals and outputs (or residuals) such as greenhouse gas emissions, nutrients and selected contaminants.

Ultimately, the model serves as an assessment and decision support tool, which simulates potential alternatives and scenarios envisaged to increase the sustainability of the urban water system and compares alternatives using sustainability criteria and valuation of environmental costs and benefits. The quantitative framework addresses the underlying factors which affect the sustainability of urban water systems namely population growth, climate change, aging infrastructure and associated environmental impacts such as greenhouse gas emissions and water contaminants. The model also includes uncertainty analysis to understand the impact of the final outcome and the variability of various parameters. The present study outlines model structure and algorithms and presents selected results for a base case simulation for the City of Toronto. The base case simulates the effects of population growth on total water demand and wastewater generated as well as energy usage and costs for wastewater treatment.

2 LITERATURE REVIEW

The focus of this short literature review will be on the application of models for urban water management. Computational models have become essential in modern urban water management (van Waveren 1999; Xu et al. 2001). As implied by the notion of sustainability, a systemic approach to modeling urban water systems is necessary in order to increase our ability to analyze environmental, economic and social impacts. Models of urban water management work 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, to support the decision making process and operational water management and to reduce the complexity of considering several different, and sometimes, opposing objectives (van Waveren 1999). Integrated models of urban water management are needed especially given that urban centers worldwide are faced with deteriorating water infrastructure, declining financial resources and increasingly polluted water sources.

Ideally, a model of the urban water system should include the interaction of the water supply-wastewater discharge network, and the rainfall-stormwater runoff network. These are rarely considered within the same modelling framework. The history and fragmentation of the water industry has meant that current research is dominated by detailed modeling of sub-components of the total water system (Mitchell et al. 2001). However, the idea of sustainability implies that extended temporal and spatial horizons as well as a more in-depth analysis of the synergistic effects among the different components of the urban water system are crucial (Larsen and Gujer 1997).

2.1 Environmental considerations

Historically, models of urban water flow focus exclusively on either water resource use or water quality. However, recent integrated models consider both issues simultaneously as they have important implications for environmental sustainability (Speers et al. 2001, Mitchell et al. 2000). Lundin and Morrison (2002) emphasize the need to include the analysis of energy and chemical usage and greenhouse gas (GHG) emissions to current models of urban water management. These analyses are crucial in order to provide a true measure of the use of environmental resources associated with the provision of water services.

2.2 Economic considerations

Economic considerations within urban water systems modeling focus almost entirely on the costs accrued to the operator of the urban water system. For the most part, life cycle costs are estimated (Xu et al. 2001). Life cycle costing takes into account all relevant economic factors, in terms of initial capital costs and future (estimated) costs. Initial costs include all investment costs directly related to the project or infrastructure (such as planning, design, construction and installation costs). Future costs comprise operating, maintenance, rehabilitation, demolition/removal costs and property and capital gains taxes (Speers et al. 2001). Current models lack proper analysis of public (or social) costs; those costs accrued to society as a result of the service provided by the operator but not accounted for by them. The identification and quantification of externalities or environmental costs and benefits are crucial in order to determine the true cost of providing water services to consumers.

2.3 Social considerations

Social issues related to urban water management are seldom included in modeling exercises mainly given the difficulty in measuring them. However, Speers et al. (2001) note that an analysis of customer needs and perceptions should be undertaken to ensure the levels of service are adequate and that services are delivered in an efficient manner. At the very least, a qualitative assessment of these issues should accompany any modeling exercise.

2.4 Other aspects

Integrated models of urban water management models have opened the door to more in depth analysis and discussion of what factors enhance the sustainability of an urban water system. Chief among neglected aspects of these models is the analysis of uncertainty. While some models include sensitivity analysis, few undertake comprehensive uncertainty analysis using statistical and probabilistic measures. Measuring uncertainty in projections and presenting them in probabilistic terms by including estimates of the likely ranges of different outcomes is helpful for planning and policy development. Potential users of such models can begin to assess the expected losses, costs and benefits that might occur in the absence or presence of measures to mitigate or adapt to changes in the urban water system.

3 MODEL DEVELOPMENT

Three major steps in the development of the model will be discussed in this section: (1) Problem definition, including selecting the components of the system and the modeling approach; (2) Conceptual model setup including model structure and relations between elements; and (3) Definition of model algorithms which characterize the interaction between components.

3.1 System boundaries

The target system to be modeled is the urban water system including water production, distribution, end use through to wastewater collection and treatment. Although traditional process-defined boundaries are useful and necessary for performance assessment of sub-components of the urban water system, extended boundaries are necessary for sustainability assessment. Figure 1 outlines various possible system boundaries in the study of urban water systems (Lundin and Morrison 2002).

Level 1(a and b) represents typical process-defined boundaries while level 2 depicts the system boundaries often defined by the management of a municipality or city-region. Level 2 encompasses the processes of level 1 but more importantly includes water use and ultimately water demand, which drives the entire system. Level 3 represents both the urban water system and surrounding systems. The main difference with layers 2 and 3 is that the extended boundary deals with a major residual of the urban water system. Processes for the treatment and disposal of sludge (or biosolids) and its links to agricultural land have important environmental sustainability implications related to energy recovery and the minimization of fertilizer usage.

The target user for the decision support tool is the municipal water manager or engineer. Consequently, level 2 system boundaries are used to accomplish the goals of the research. The model is meant to aid in planning and decision-making, therefore, water demand and use as well as the entire infrastructure related to the movement and treatment of water needs to be included. Even though level 3 system boundaries are desirable from the standpoint of sustainability, such boundaries fall outside the scope of the current research.

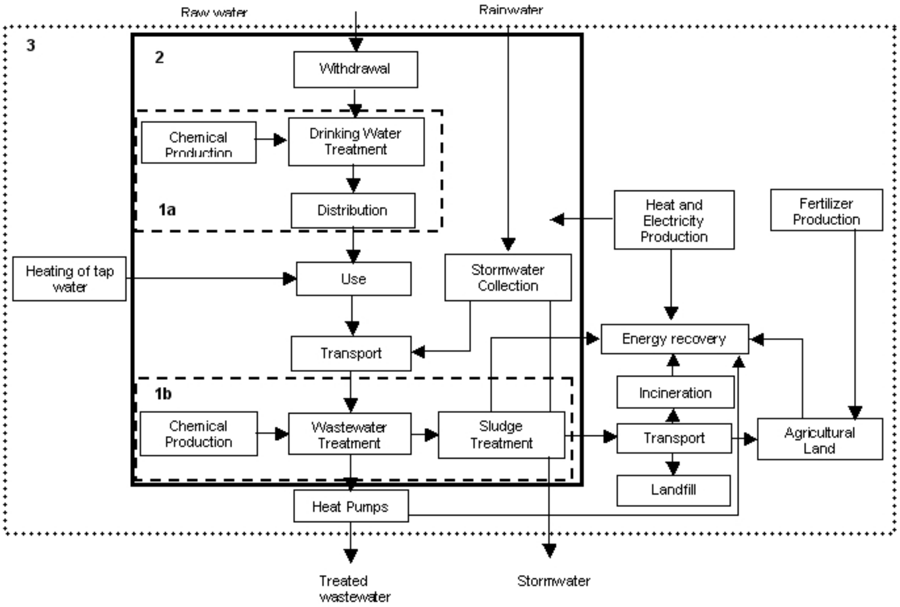


Figure 1. System boundaries for urban water systems (Lundin and Morrison 2002)

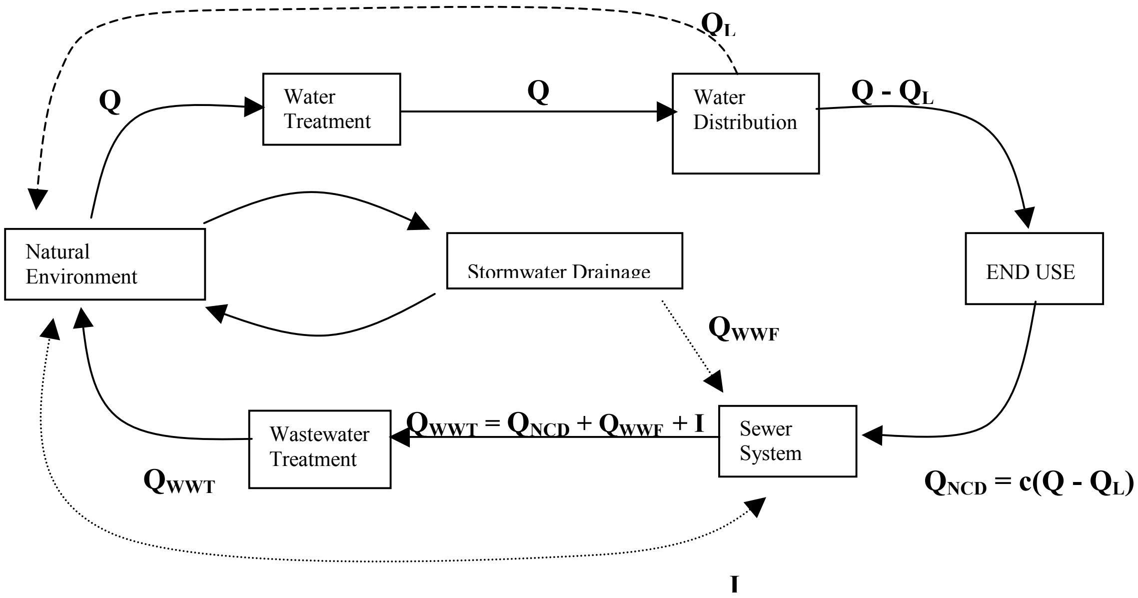
3.2 Modeling approach

A water balance approach is selected to characterize water flow through the urban water system. A water balance can be assessed using a range of methods, from the simple evaluation of the inputs and the outputs, through to complex modeling of all the processes that transform these inputs into outputs (Mitchell et al. 2001). Since the model is developed for use by water utilities, the water supply-wastewater discharge network of the urban water cycle is modeled in a more detailed fashion than the rainfall-runoff aspect. The model receives input both from precipitation and water demand, which together pass through the system and output in the form of lost water (i.e. distribution losses and outdoor water use), treated wastewater or combined sewer overflows (note: parts of the City of Toronto are serviced by combined sewers).

The water balance approach basically applies the principle of mass conservation to water. Generally, models using this approach are static and linear; that is they simulate a system at only one point or period in time, under the condition that outputs are in steady-state equilibrium with inputs (McLaren et al. 2000). Water demand drives the entire urban water system and varies with time both diurnally as well as seasonally. Consequently, the urban water system will be modeled on the basis of input characteristics that vary over time, but where inputs still remain in equilibrium with outputs. This approach is to be distinguished from a fully dynamic approach in that it does not include significant time lags. McLaren et al. (2000) describe this type of approach as quasi-dynamic. In order to account for seasonal effects but reduce data needs and the complexity of the model, a monthly time step was chosen.

3.3 Conceptual model and selected algorithms

Figure 2 depicts the conceptual model of the urban water system together with the main algorithms that characterize the interaction between components of the system.



NOMENCLATURE (All units in ML/month)

Q	= Total water demand
Q_L	= Water losses
Q_{WWF}	= Wet weather flow inflow/infiltration and collected combined sewer flows
I	= Base infiltration
Q_{NCD}	= Non-consumptive water demand
Q_{WWT}	= Wastewater treatment flow
c	= Non-consumptive use coefficient (dimensionless)

Figure 2. Conceptual model of urban water system

3.4 Total water demand (Q)

Sadiq (2003) developed a long-term daily water demand function for Toronto, which is used in this model. The function was derived using a stepwise regression technique as described in Brekke et al. (2002) (R^2=0.685). Various factors affect municipal water demand including population, water price, income, rainfall, temperature, garden size, and efficiency of water conservation measures.

A long-range demand model allows strategic planners to forecast water demand 5 to 10 years in advance. This type of model is essential for water supply planning and to understand the impacts of climate change on urban water. Because of the increased difficulty and uncertainty attached to long-term forecasts, it is essential that all explanatory variables can be determined or predicated with relative accuracy (Sadiq 2003). In general, socioeconomic variables such as population and climatic variables such as maximum daily temperature can be forecasted reasonably well with available statistical techniques.

BASE DEMAND (Oct. to April, T< 15 deg C)
Q^d= -283.92+0.63*POP (1)

SEASONAL DEMAND (May-Sep, T≥15 deg C)
Q^d= -668.82+0.63* POP+28.98*Tday (2)

Q^d = Total daily demand (ML/day)
POP = Population in thousands
Tday = Maximum daily temperature (deg C)

Population forecasts generated by the City of Toronto are used in the model (City of Toronto 2002). These forecasts assume a set percentage growth over the next ten years (on the order of 10%). 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.

MAXIMUM DAILY SUMMERTIME TEMPERATURE (deg C)
$X_t = \mu + \varphi*(x_{t-1} - \mu) + a_t$ (3)

X_t = Individually generated temperature at time t
μ ......= Mean daily maximum temperature
φ = Autocorrelation factor (0,6 for Toronto)
a_t ......= Independent and normally distribution random shock at time t

Equations 1 through 3 are utilized to forecast total daily demand from which total monthly demand can be derived and used as an input to the main flow model depicted in Figure 2.

Typical values for other parameters required to calculate losses, non-consumptive demand and wet weather flow components are based on empirical studies conducted by the City of Toronto and included in Table 1. Further research is required in order to characterize these parameters in a more detailed fashion as a function of the listed influencing factors.

Table 1. Selected parameters required for main flow model

Flow component (Figure 2)	Parameter	Influencing factors	City of Toronto estimate (as of 2001)
Q_L	Water losses as % of total demand	Condition, age of water distribution system	14%
Q_{WWF}	WWF Inflow/Infiltration and collected combined sewer flows as % of total wastewater generated	Condition, age of sewer Extent of combined sewers Precipitation	3-5%
I	Base infiltration as % of total wastewater generated	Condition, age of sewer system Precipitation	20-30%
Q_{NCD}	Non-consumptive use coefficient	Water demand patterns	0.70

3.5 Economic sub-model

The first version of the model includes costs incurred directly by the water utility in the form of fixed and variable costs. Fixed costs are considered constant regardless of flow through the system and are based on various sources from the City of Toronto. However, this assumption will no longer hold when considering the costs of replacing water infrastructure in future simulations. As for variable costs, the main assumption is that operation and maintenance costs including utility and chemical costs vary based on the flow through the sub-components of the system or some other explanatory variable. Variable cost functions are derived using regression analysis from historical data provided by City of Toronto. An example for variable energy costs for wastewater treatment is provided below (R^2=0.950).

TOTAL COST ($)

$TC = FC + \Sigma VC_{i,j}$ (4)

TC = Total costs
FC = Fixed costs incl. Administrative, labor costs etc
VC………= Variable costs of type I, component j.

GENERAL FORM OF VARIABLE COST FUNCTIONS

$VC = a X^b$ (5)

X = Explanatory variable
a, b…….= Regression parameters

VARIABLE ENERGY COST FUNCTION FOR WASTEWATER TREATMENT

$VC_{E, WWT} = 0.067 E_{WWT}^{0.99}$……………………………………………(6)

E_{WWT} = Total electrical energy use for wastewater treatment (kWh)

3.6 Environmental sub-model

The main components of the environmental sub-model are two-fold: inputs into the urban system and outputs (residuals). Inputs considered in the model are energy and chemical usage while outputs considered are GHG emissions, and in a more limited fashion, nutrients and selected contaminants. Similarly to the economic sub-model, regression analysis was used in order to derive relationships between environmental inputs and outputs and flow through the system. An example of such a relationship is shown below. The focus of future research is the development of such relationships for chemical usage and GHG emissions.

ENERGY INPUT TO WASTEWATER TREATMENT

$E_{WWT} = 426.7q + 373611$ (7)

E_{WWT} = Total electrical energy use for wastewater treatment (kWh)
Q_{WWT} = Total wastewater treatment flow (ML/month)

4 BASE CASE RESULTS

Results of a base case simulation, which evaluates the impacts of population growth, are included below to illustrate some of the model algorithms. Based on estimated population growth rates (approx. 10% over ten years), Figure 3 depicts an increasing trend in total water demand in the five-year period from 2001 to 2005. The increase in total demand is approximately in line with population growth. The impact of climate change is not considered here. However, Sadiq (2003) found that a 1°C increase in mean summer temperature would cause a 2% increase in average summer water demand and a 1.8% increase in peak day demand.

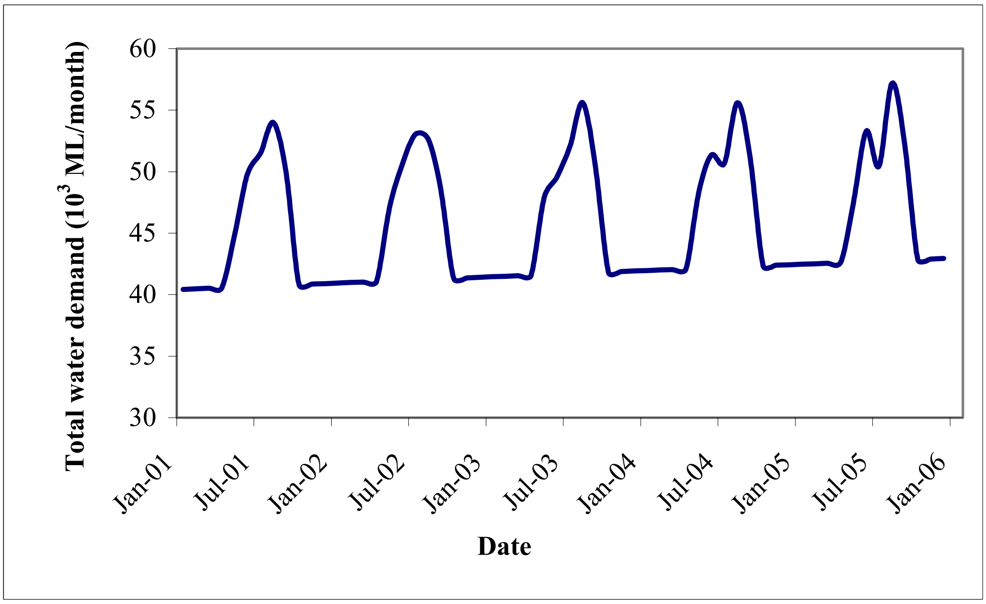


Figure 3. Simulated total monthly water demand (2001-2005)

Simulated wastewater flows were generated using the algorithms presented in Figure 2, the simulated total monthly demand in Figure 3 and the parameters presented in Table 1. For the purposes of this illustrative example, base infiltration and wet weather flow inflow/infiltration and collected combined sewer flow were considered constant over the period of analysis. In practice, these phenomena depend on various factors including rainfall and the condition of the sewer system. Table 2 summarizes the results of the base case simulation.

Table 2. Base case results

Year	Q (10^3 ML)	Q_{WWT} (10^3 ML)	E_{WWT} (MWh)	$VC_{E,WWT}$ (million $)
2001	535	454	204,241	12.56
2002	540	457	205,670	12.65
2003	547	461	207,631	12.77
2004	552	465	209,027	12.86
2005	559	469	210,918	12.97

Similarly to total water demand, total wastewater flow, total electrical energy usage and costs exhibit a gradually increasing trend approximately proportional to population growth.

5 DISCUSSION AND FUTURE WORK

The base case simulation demonstrates the ability of the model to link the drivers of water demand, namely population growth and temperature, to energy requirements and variable energy costs of wastewater treatment. From the perspective of the municipal manager, establishing and quantifying these types of links is crucial in order to better understand the system-wide impacts of potential changes in technology, production and/or consumption patterns implemented to enhance the sustainability of an urban water system. In addition, the future impacts of climate change, fluctuating infrastructure costs, increasing energy prices, aging infrastructure or combination of these can be accounted for. This will be the focus of future modeling exercises.

Future research steps also include:

1. Refining and expanding environmental sub-model to include inputs such as chemical usage and outputs such as GHG emissions;

2. Expanding economic sub-model to quantify externalities;

3. Measuring uncertainty in projections and presenting them in probabilistic terms using Monte Carlo simulation;

4. Moving towards a dynamic model of the urban water system where water storage can also be accounted for.

6 SUMMARY AND CONCLUSIONS

This paper highlighted the need for more integrated tools to promote the sustainability of urban water systems and outlined the basic structure and algorithms of such a decision support tool. The tool takes the form of a water balance model coupled with environmental and economic sub-models.

A base case simulation of the urban water system in the City of Toronto demonstrated the ability of the model to link the drivers of water demand, namely population growth and temperature, to energy requirements and variable energy costs of wastewater treatment.

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 municipal managers and engineers. A variety of scenarios can be tackled with much more vigor if a systems approach is utilized to model the urban water system. Consequently, not only internal components within the system but also external interactions between the urban water system and economic and environmental systems can be accounted for.

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