Leadership in Sustainable Infrastructure

Leadership en Infrastructures Durables

Vancouver, Canada

May 31 – June 3, 2017/ *Mai 31 – Juin 3, 2017*

LIFE CYCLE SUSTAINABILITY ASSESSMENT OF WATER AND WASTEWATER INFRASTRUCTURE SYSTEMS

Mohammadifardi, Hamed[1, 3], Knight, Mark A. [1] and Unger, Andre J.A.[2]
[1] Department of Civil and Environmental Engineering, University of Waterloo, Canada
[2] Department of Earth and Environmental Sciences, University of Waterloo, Canada
[3] h29moham@uwaterloo.ca

Abstract: The development of reliable, rational, and defensible renovation plans for water and wastewater systems requires a better understanding of the interrelated behavior of social, environmental, and economic systems, while ensuring compliance with existing and changing regulatory policies such as the Ontario 2010 Water Opportunities and Water Conservation Act (WOWCA, 2010), which requires water utilities to prepare long-term plans (10 plus years) for financial self-sustainability, or the Green Energy Act of 2009 (GEA, 2009), which calls public agencies, including municipalities, to prepare an energy conservation and efficiency strategy when planning their capital investments. Complying with these different requirements calls for comprehensive sustainability assessment that integrates social, environmental, and economic dimensions. The focus of this study is to discuss the implementation of sustainability assessment into a working system dynamics model that incorporates an environmental life cycle assessment perspective to appropriately consider the full spectrum of sustainability aspects (social, environmental, and economic). Scenarios are presented as alternative management strategies to discuss the utility/importance of considering environmental impact in the decision-making process. The strategic decisions are ranked based on their benefits to utilities, consumers, and the environment. Results of the applied models are discussed and conclusions are drawn.

1 Background

The strength of the System Dynamics (SD) tool in modeling the complex interconnections and feedback loops between economic and social systems attached to water and wastewater physical systems has been demonstrated in recent research papers (see Rehan et al. 2014; Rehan et al. 2015; Rehan et al. 2013). In these papers, the SD models are constructed for financial sustainability assessment of water distribution and wastewater collection systems. Guest et al. (2010) presented a hypothetical Close Loop Diagram (CLD) for sustainability assessment of decentralized wastewater treatment systems. They proposed the integration of SD modelling and LCA based tools within the Multi Criteria Decision Analysis (MCDA) framework for sustainability assessment. This current study builds on previous research by proposing and implementing a life cycle sustainability assessment (LCSA) framework to account for the life cycle energy of water and wastewater network systems.

2 Integration of LCA and SD: toward a comprehensive framework

LCA has been used in several environmental sustainability assessment studies of water and wastewater infrastructure systems (Corominas et al. 2013). Its key strength is that it considers the whole life-cycle processes, which prevents the problems of sub-optimization and shifting of impacts from one stage of a product's life cycle, or one type of impact, to another. However, its scope is limited to assess negative impacts, and it is not capable of considering the dynamic feedback from socio-economic system (Sala, Farioli, and Zamagni 2013). Modelling the non-linearities and dynamic features of social, ecological, and economic systems is one of the key feature of a complete LCSA framework (Sala, Ciuffo, and Nijkamp 2013).

One tool that has often been applied to model the socio-economic impact of strategic decisions is SD modelling, which has been regarded as a convenient simulation tool for water resource management problems (Mirchi et al. 2012) . The application of SD modelling within the LCA framework will add the benefit of time progression to sustainability assessment. The SD modelling tool brings the missing dynamic characteristics of systems in the LCA tools and provide as a platform for integrating LCA tools such as water footprint analysis, life cycle energy analysis, carbon footprint analysis, and life cycle cost analysis (Figure 1).

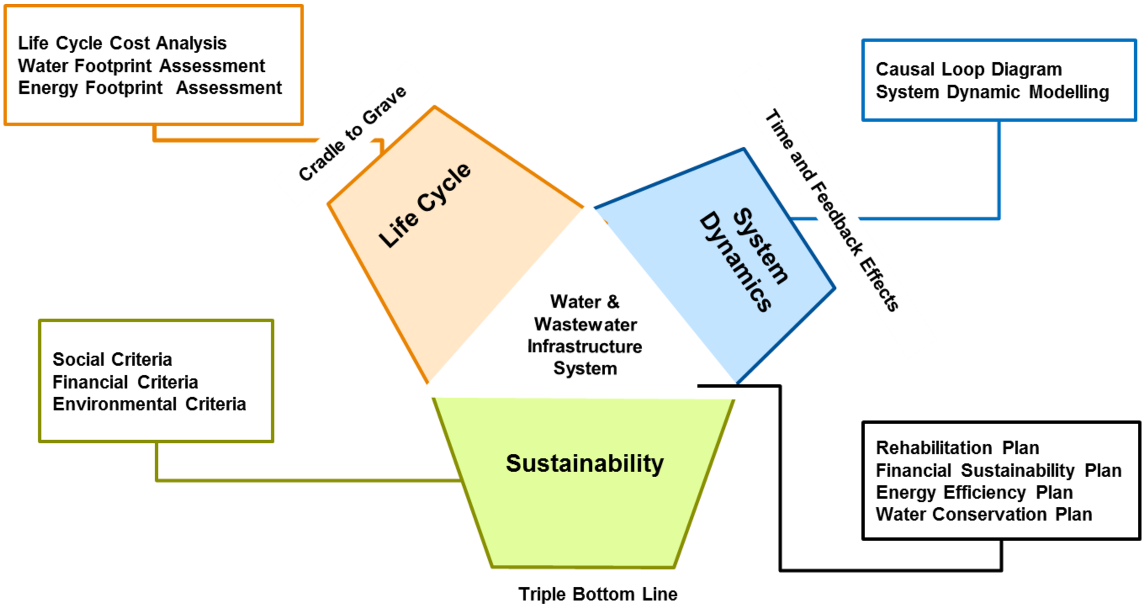


Figure 1 Integration of LCA and SD tools for LCSA of water & wastewater infrastructure systems

The LCA tools provide a set of quantitative environmental, social, and economic indicators and broadens the scope of the SD modelling tool to examine all the "cradle to grave" processes. On the other hand, the structured methodology of the LCA tools–in defining the system boundary, goal and scope, inventorying data, and characterizing the impacts–will limit the subjectivity SD modelling.

3 LCSA of water and wastewater pipe network systems

The proposed framework is demonstrated for the LCSA of the water-distribution and wastewater-collection pipe network system of a medium-sized municipality in Southern Ontario, Canada. It is shown that the framework is applicable for evaluating the social, economic, and environmental sustainability of water and wastewater infrastructure systems.

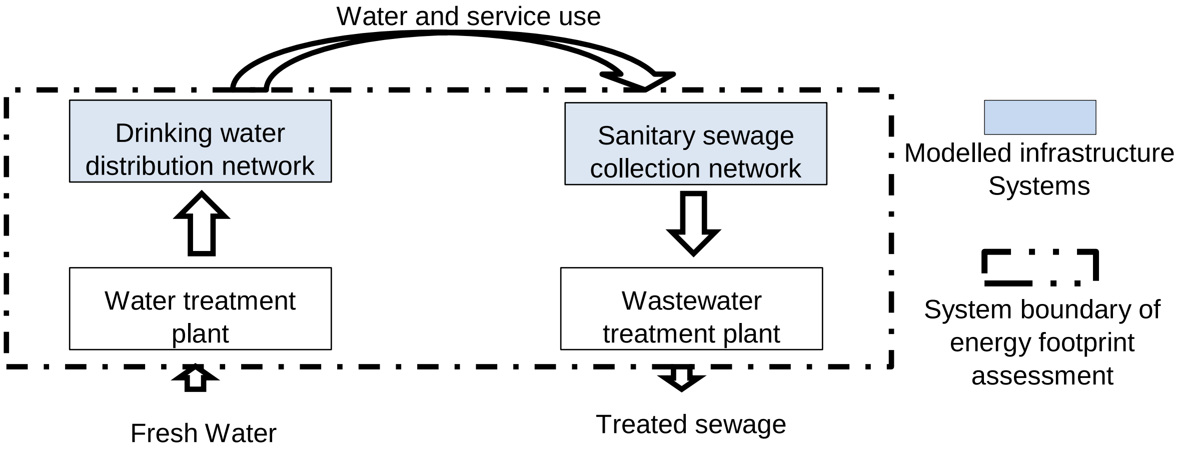
3.1 Scope and limitations

The scope of this study is limited to the municipality’s water distribution and wastewater collection systems and does not include its treatment plants or flood-collection system (Figure 2). The time frame of the assessment is 100 years in order to capture the lifecycle of the pipes, which exhibit the greatest longevity within the infrastructure system. The calculated sustainability indicators are limited to the life-cycle energy use, water and wastewater combined user fees, and consumers’ bill burden or affordability. These indicators are used to demonstrate the environmental, financial, and social sustainability, respectively. The selected indicator are presented per unit service of the system, the so called Functional Unit (FU), which is the water and wastewater services for a person expected to live and use the services for 81 years.

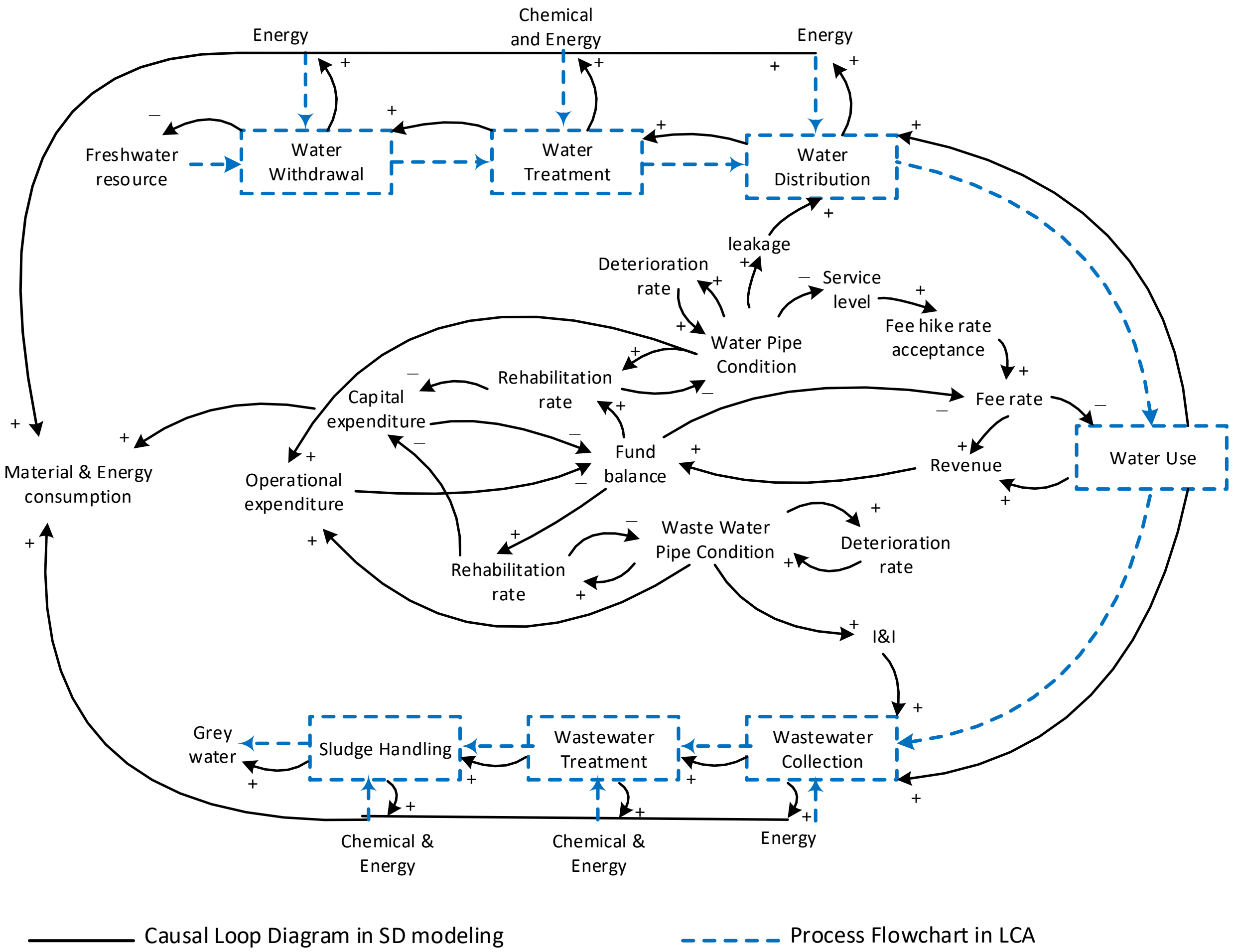
Figure 2 System boundary and the study scope

3.2 System dynamic modelling

3.2.1 Causal Loop Diagram (CLD) development



The qualitative relationships among the influencing parameters are depicted through a Causal Loop Diagram (CLD) in SD modelling. A plus (+) or minus (-) sign is used to represent the positive or negative influence of a variable (Sterman 2000). A positive link indicates that a positive/negative change in one parameter will cause a subsequent positive/negative change in the linked parameter.



A CLD, presented in Figure 3, is used to identify the interlinkages between various components related to the water and wastewater pipe network systems. As presented, the main driver of change in the modelled system is water-main or sewer-pipe aging.

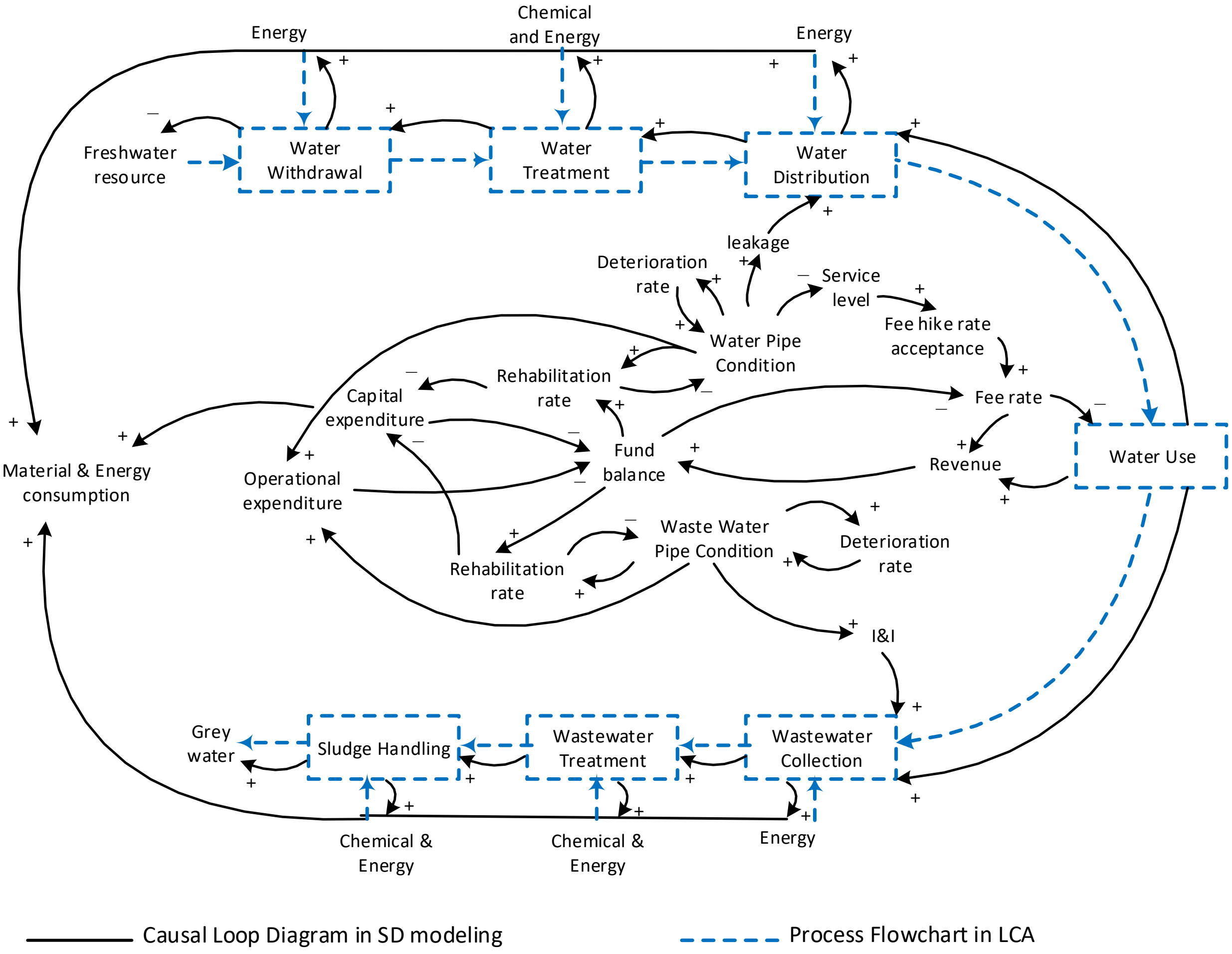


Figure 3 CLD of the studied system

Water and wastewater pipe deterioration rates are functions of pipe condition (i.e., if a pipe is in bad condition, it deteriorates faster). Water main breakage becomes more frequent as deterioration increases; hence, water leakage increases. To compensate for leaking water, more water needs to be abstracted, treated, and pumped into the distribution network, meaning that more energy must be used in upstream processes. Similarly, deterioration of sewers causes increasing infiltration of ground water into the sewer network, thus increasing the energy and material used to collect and treat the sewage downstream.

Operational and maintenance (O&M) cost is also a function of the structural condition of pipes. The deterioration of water-mains and sewer pipes results in more water main breakage and sewer pipe blockage, thus increasing maintenance cost. Detailed information on parametrizing the operational and capital expenses in relation to pipes' conditions is given in Rehan et al. (2015)

3.2.2 Quantitative modelling

The main components of quantitative modeling are flows representing the change of item quantities over time, stocks representing the accumulation of quantitated flows, convertors carrying the input and output variables or built-in functions used in defining the flows, and connectors joining the converters to flows. The relationship between flows and stocks is best represented as the following equation:

$$Stock(t) = \int [Inflow(s) - Outflow(s)]ds + Stock(t_0)$$

The basis for the physical and socio-economic modeling of the studied systems is taken from the joint water and wastewater SD model of Ganjidoost (2016). The main part of his model are briefly described next:

a) Physical system

Pipe inventories are modelled in the physical system. Water distribution pipes are categorized based on their ages and materials, and are distributed in 25-year incremental stocks. Sewer pipes are classified into five classes based on their Internal Condition Grades (ICGs), as defined by the UK Water Research Center (WRC 2011).The modelled city has 1550 Km of water mains made of polyvinyl chloride (PVC), concrete, ductile-iron, cast-iron, and steel; and 1430 Km of sewer pipes made of PVC, concrete, and vitrified clay. It is assumed that the network will not expand in the future.

b) Financial system

The revenue of the water and wastewater utilities should be equal to their expenses in order to be financially sustainable. Revenue is generated from collecting volumetric based fees for metered water and generated wastewater. Other revenue sources are the fixed monthly connection service charges, as well as the development charges, which are assumed to be zero. The expenses include the operational and maintenance costs associated with providing services, as well as the capital cost of rehabilitating the network systems. Fund balance is calculated from the difference between revenue and expenses, and it should remain positive during the 100-year simulation. In the studied system, the initial water and sewage fees are 1.63 (\$/m^3) and 1.45 (\$/m^3), and the unit price of water treatment and sewage treatment are 0.49 (\$/m^3) and 0.28 (\$/m^3) respectively.

c) Social system

Consumer behavior in response to incremental changes in water and wastewater fees is modelled on the social system. An increase in water and wastewater fees will cause a decrease in water demand due to the price elasticity of water demand, which is assumed to be -0.35 in Rehan et al. (2015). The minimum water demand is considered to be 150 liters per capita per day (lpcd) in Ganjidoost (2016). The water and wastewater infrastructure systems serve 377 thousand consumers with an initial 291 lpcd water demand. The population is assumed to be constant over the 100-year simulation period.

d) Environmental system

The energy footprint of the studied system is calculated to demonstrate environmental system modelling. From a life cycle perspective, energy is used in upstream processes such as manufacturing, construction, and installation of infrastructure components, as well as during normal system operation, which includes maintenance, renewal, and rehabilitation of the system; and the disposal of components after their end of life. The energy used in operations mainly consists of extracting water, conveying the water to water treatment plants, pressurizing and distributing the treated water to customers, collecting and conveying the generated sewage to wastewater treatment facilities, treating and discharging the treated wastewater to the receiving environment, and handling the remaining sludge.

An environmental and economic life cycle assessment study done by the United State Environmental Protection Agency (EPA 2014) shows that operational energy accounts for more than 98% of the life cycle energy use of the wastewater system. As with their study, the energy used in the construction and disposal of the water and wastewater infrastructure systems are omitted from this study.

Table 1 shows the energy use accounted for by operational activities in the model. The results of a life cycle energy assessment of a water treatment plant studied by Racoviceanu et al., (2007) for the City of Toronto are used in this study. The energy use for water distribution, wastewater collection, wastewater treatment and sludge handling are calculated based on the information sent by the studied water and wastewater utilities. The energy use for pipe rehabilitation work is calculated using the results of two studies that determined the life cycle energy use of PVC pipe manufacturing as well as the life cycle energy use of construction activities for pipe replacement.

Table 1 Energy use inventory

Energy use of processes that are accounted in the energy footprint assessment	Value	Unit*	References
Life cycle energy used for PVC pipes manufacturing	75.2	MJ/Kg	(Du, Woods, and Kang 2012)
Life cycle energy use for drinking water treatment	2.4	MJ/ m^3	(Racoviceanu et al. 2007)
Energy use for water distribution	1.224	MJ/ m^3	From data sent by utility
Energy use for wastewater collection	0.23	MJ/ m^3	From data sent by utility
Life cycle energy used for wastewater treatment (including sludge transportation, incineration, and disposal)	1.55	MJ/ m^3	From data sent by the WWTPs
Life cycle energy used for pipe installation	405	KWh/m	(Prosser, Speight, and Filion 2013)

* MJ/Kg: Mega joule per kilogram, KWh/m: Kilowatt hours per meter

3.3 Scenario development

Three alternative scenarios are compared with the current asset management practice of the water and wastewater utilities, denoted as the business-as-usual or zero scenario. The utilities plan for annual rehabilitation of 6% of the water main network and 1% of the sewage pipe network. In the simulation of the current system, the 1% rehabilitation rate is adapted for both water and wastewater networks. This means that the water and wastewater networks are totally replaced over 100 years. The 1.3% rehabilitation rate is adopted for the proposed scenarios, which are a pay-as-you-go strategy, meaning there is no debt or reserving capacity, a borrowing strategy, meaning the utilities can issue a debt of up to 12.5% of their annual revenue, and a capital-reserving strategy, meaning the utilities can reserve up to 2% of their network replacement value for their future capital expenses. The annual water and wastewater fee-hike rates in each scenario are determined through trial and error. These values are presented in Table 2.

Table 2 Asset management scenarios

Policy levers	Scenario 0	Scenario 1	Scenario 2	Scenario 3
Preferred Max. rehabilitation rate (% of the network length/year)	1	1.3	1.3	1.3
Max allowable water fee-hike rate (% per annum)	3	8.37	8.95	8.0
Max allowable wastewater fee-hike rate (% per annum)	3	8.1	9.7	9.20
Debt capacity (% of the annual revenue)	0	25	0	0
Reserve capacity (% of network replacement value)	0	0	0	2

The other policy levers applied in the studied scenarios are the maximum acceptable fraction of Highly Deteriorated Pipes (HDPs) and their desired elimination period. HDPs describe to water mains that are more than 75 years old, and sewage pipes in the ICG 5 group. The maximum acceptable fractions of HDPs in water and wastewater network systems are 5% and 10%, respectively. The desired elimination periods for the HDPs over the minimum levels are chosen to be 5 and 10 years, respectively. Rehan et al. (2013) presented these policy levers in more detail. In all the proposed scenarios, the utilities' target is to have a non-negative fund balance, and to keep the inventory of their HDPs within acceptable levels during the life cycle of their networks.

4 Results and discussion

Our simulation results are presented in Figure 4. Plot (a) shows that the average ICG of the sewage pipes will be improved by application of the proposed asset management strategies, while it will be increased toward the worst ICG in the business-as-usual scenario. Similarly, plot (b) shows that the average age of the water mains in the proposed scenarios will remain below 40 years, whereas it will increase to 100 years in the business-as-usual scenario at the end of the networks' life cycle.

In plot (c), it is shown that the utilities will need to increase their water and wastewater fees in all the proposed scenarios to rehabilitate backlog of deteriorated pipes. As a result of the price increasing, consumers start to conserve water, until they reach the minimum water demand level. Plot (d) shows that the minimum water demand level is reached in 30 to 35 years for the proposed scenarios and in about 60 years for the business-as-usual scenario.

It should be noted that the presented fees are discounted to the present values based on the risk-free rate calculated by Younis et al. (2016). As the fee-hike rate defined in the business-as-usual scenario is lower than the discounting rate, the combined water and sewage fee reduces over the 100 years simulation of this scenario.

The US-EPA standard recommended that combined water and wastewater fees should comprise no more than 4.5% of the median household income (Mack and Wrase 2017) . However, as the price of water and wastewater service is increasing at a higher rate than consumers' annual income, and they are not able to conserve more water, ability to pay for the water and wastewater services drops. It is shown in plot (e) that the water and wastewater bill burden will rise to 25% to 35% after about 30 years in the proposed scenarios, but it will remain below 1.5% in the business-as-usual scenario.

The life cycle energy use of the water and wastewater network systems in the proposed scenarios are compared with the business-as-usual scenario in plot (f).

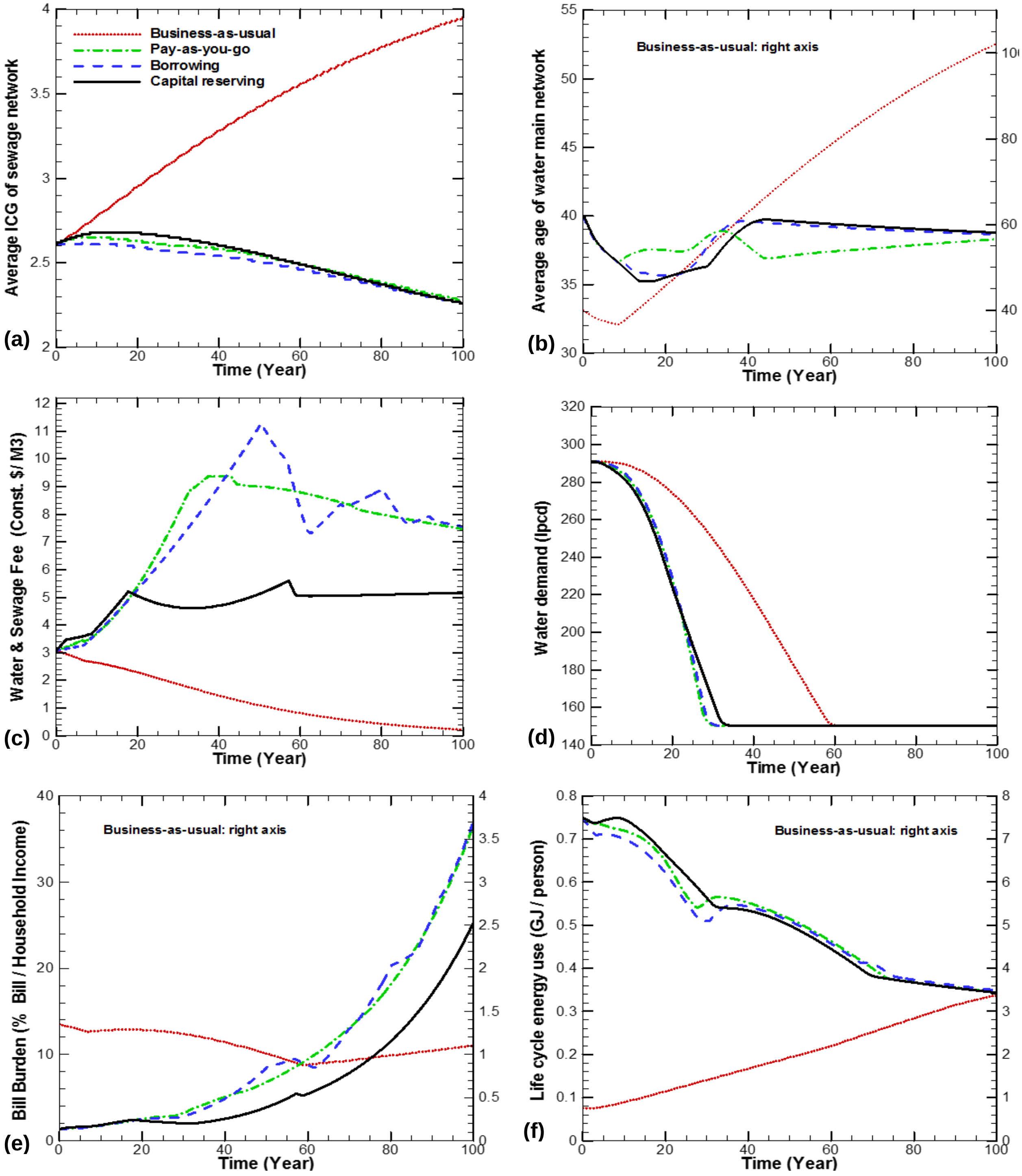


Figure 4 Simulation results

It is shown that the annual operational energy use of water and wastewater systems will reduce by more than 50% in the proposed scenarios, whereas it will increase threefold under the current asset management. The accumulated energy use of the studied water and wastewater infrastructure systems is calculated per one FU and presented in Table 3. These values represent the energy footprint of different asset management scenarios over the entire life cycle of the pipe network system.

Table 3 summary table of energy footprints

Scenario	Energy footprint GJ/FU*
Business-as-usual	197.884
Pay-as-you-go	51.103
Borrowing	50.235
Capital reserving	50.979

* GJ/FU: Giga joule per functional unit

Based on results, the energy footprint of the proposed scenarios will be much lower than the business-as-usual scenario, and the borrowing strategy will have the lowest energy footprint.

5 Conclusions

The integration of life cycle assessment with a system dynamics modelling tool provides an analytical framework to consider the interactions between economic, social and environmental systems, and to perform a complete life cycle sustainability assessment of strategic decisions on water and wastewater network systems. The advantage of the system dynamics modelling tool in capturing the energy footprint variations of the water and wastewater systems throughout the life cycle of the network systems is demonstrated. The scope of this study can be extended to include the other existing social and environmental indicators available in the LCA tool.

Acknowledgements

We gratefully acknowledge the financial support provided by the Natural Science and Engineering Research Council of Canada (NSERC), and the Centre for Advancement of Trenchless Technology (CATT) located at the University of Waterloo.

References

Corominas, Ll., J. Foley, J.S. Guest, A. Hospido, H.F. Larsen, S. Morera, and A. Shaw. 2013. “Life Cycle Assessment Applied to Wastewater Treatment: State of the Art.” *Water Research* 47 (15). Elsevier Ltd: 5480–92. doi:10.1016/j.watres.2013.06.049.

Du, Fei, Gj Woods, and Doosun Kang. 2012. “Life Cycle Analysis for Water and Wastewater Pipe Materials.” *Journal of …*, no. May: 703–11. doi:10.1061/(ASCE)EE.1943-7870.0000638.

EPA. 2014. “Environmental and Cost Life Cycle Assessment of Disinfection Options for Municipal Wastewater Treatment.” Unite States Environmental Protection Agency.

Ganjidoost, Amin. 2016. “Performance Modeling and Simulation for Water Distribution and Wastewater Collection Networks.” University of Waterloo.

"Green Energy Act, 2009, S.O. 2009, C. 12 , Sched. A | Ontario.ca." 2017. Accessed January 5. http://www.ontario.ca/laws/statute/09g12.

Guest, J. S., S. J. Skerlos, G. T. Daigger, J. R E Corbett, and N. G. Love. 2010. "The Use of Qualitative System Dynamics to Identify Sustainability Characteristics of Decentralized Wastewater Management Alternatives." *Water Science and Technology* 61 (6): 1637–44. doi:10.2166/wst.2010.880.

Mack, Elizabeth A., and Sarah Wrase. 2017. "A Burgeoning Crisis? A Nationwide Assessment of the Geography of Water Affordability in the United States." *Plos One* 12 (1): e0169488. doi:10.1371/journal.pone.0169488.

Mirchi, Ali, Kaveh Madani, David Watkins, and Sajjad Ahmad. 2012. "Synthesis of System Dynamics Tools for Holistic Conceptualization of Water Resources Problems." *Water Resources Management* 26 (9): 2421–42. doi:10.1007/s11269-012-0024-2.

Prosser, Monica, Vanessa Speight, and Yves Filion. 2013. "Life-Cycle Energy Analysis of Performance-Versus Age-Based Pipe Replacement Schedules." *Journal - American Water Works Association* 105: E721–32. doi:10.5942/jawwa.2013.105.0157.

Racoviceanu, Alina I., Bryan W. Karney, Christopher a. Kennedy, and Andrew F. Colombo. 2007. "Life-Cycle Energy Use and Greenhouse Gas Emissions Inventory for Water Treatment Systems." *Journal of Infrastructure Systems* 13 (4): 261–70. doi:10.1061/(ASCE)1076-0342(2007)13:4(261).

Rehan, Rashid, M ark A. Knight, Andreh J.A. Unger, and Carl T. Haas. 2013. "Development of a System Dynamics Model for Financially Sustainable Management of Municipal Watermain Networks." *Water Research* 47 (20): 7184–7205. doi:10.1016/j.watres.2013.09.061.

Rehan, Rashid, Mark A. Knight, Andreh J. A. Unger, and Carl T. Haas. 2014. "Financially Sustainable Management Strategies for Urban Wastewater Collection Infrastructure - Development of a System Dynamics Model." *Tunnelling and Underground Space Technology* 39. Elsevier Ltd: 116–29.

Rehan, Rashid, Andre J.A. Unger, Mark A. Knight, and Carl T. Haas. 2015. "Strategic Water Utility Management and Financial Planning Using a New System Dynamics Tool." *Journal American Water Works Association* 107 (1): 22–36.

Sala, Serenella, Biagio Ciuffo, and Peter Nijkamp. 2013. "A Meta-Framework for Sustainability Assessment Research Memorandum 2013-16 Serenella Sala Biagio Ciuffo Peter Nijkamp A Meta - Framework for Sustainability Assessment."

Sala, Serenella, Francesca Farioli, and Alessandra Zamagni. 2013. "Progress in Sustainability Science: Lessons Learnt from Current Methodologies for Sustainability Assessment: Part 1." *International Journal of Life Cycle Assessment* 18 (9): 1653–72. doi:10.1007/s11367-012-0508-6.

Sterman, John. 2000. *Business Dynamics: Systems Thinking and Modeling for a Complex World*. Irwin/McGraw-Hill.

"Water Opportunities and Water Conservation Act, 2010, S.O. 2010, C. 19 - Bill 72 | Ontario.ca." 2017. Accessed January 5. http://www.ontario.ca/laws/statute/s10019.

WRc. 2011. *Sewerage Rehabilitation Manual*. Swindon, U.K.: Water Research Centre.

Younis, Rizwan, Rashid Rehan, Andre J. A. Unger, Soonyoung Yu, and Mark A. Knight. 2016. "Forecasting the Unit Price of Water and Wastewater Pipelines Capital Works and Estimating Contractors' Markup." *Journal of Cost Analysis and Parametrics* 9 (1): 46–68.