Resource recovery strategies for municipal water planning and management: a system dynamics modeling approach

by

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Abstract

The true value of water has not yet been captured in municipal water planning and management, despite the increasing availability of technologies designed to create value from wastewater. Adapting system processes for water reclamation, energy generation, and production of other outputs (such as fertilizers) can transition wastewater treatment facilities into economically viable resource recovery facilities. Although resource recovery is an appropriate solution for municipal water management, its success depends mainly upon techno-economic feasibility, environmental sustainability, and public acceptance. Both the public and private sector face several barriers to advancing resource recovery, such as operational challenges, inappropriate regulatory frameworks, and a lack of capacity to develop or evaluate business plans pertaining to resource recovery and water reuse. A variety of possible solutions can be defined based on the principle of resource recovery, such as decentralized treatment and reuse, co-digestion with organic waste for energy, and nutrient recovery through struvite precipitation. A broad range of products can potentially be generated from wastewater at different time scales into the future.

The purpose of this study is to represent and analyze the value of products that impact the feasibility of both established and emerging resource recovery strategies for municipal water planning and management. A decision support tool developed using system dynamics modeling software represents the various system components that are important to decision makers. The dynamic simulation model permits testing of the economic feasibility of specific resource recovery strategies and facilitates planning of resilient water systems. The system dynamics model represents real world processes through nonlinear feedbacks, changing variables, and delays – and is intended to increase understanding of the effects of feedbacks between resource recovery sub-systems with external drivers and variables. The model presented runs at a weekly time step and simulates the performance of user-specified resource recovery strategies into the future under various population growth, climate change, and water consumption/conservation scenarios, revealing trade-offs in the medium- to long-term. Simulating potential future scenarios by altering important input parameters helps to identify the most important variables to the economics of the specific strategies considered.

The model is applied to the City of Calgary, Alberta to explore the impact to the City’s overall per capita water demand, based on the theory of diffusion of innovations framework and population served by source-separated resource recovery systems. The model was calibrated with financial data from existing utilities that have successfully integrated resource recovery strategies, in some cases recovering the entire costs of the capital investment required to upgrade in less than 3 years. This thesis includes a description of model characteristics and capabilities, as well as results that highlight the value of system dynamics modelling methods, which simulate system behaviour and shed light on cause-and-effect relationships, representing resource recovery systems in a realistic, comprehensive way. Decentralized wastewater systems with greywater reuse could help the City achieve its goal of reducing per capita water use below 350 liters with either the “intermediate” or “fast” adoption rates. The final result for the average per capita daily municipal water demand at the end of 2043 was 302, 348, and 391 liters per capita per day (Lpcd) for each of the three strategies tested (“fast”, “intermediate”, and “slow” rates of adoption). Retrofitted stormwater systems can also offset water production (up to 25 Lpcd of savings).

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Chapter 1 - Introduction

Water is life: essential for survival, environmental sustainability, and the global economy. Societies depend on the reliability of water systems for the provision of clean water and the safe management of stormwater and wastewater. People living in municipalities (both urban and rural settlements) depend on safe and reliable water systems for the provision of clean water and the responsible management of wastewater and stormwater. Communities around the globe are facing challenges to the sustainability and resiliency of their water related infrastructure. Climatic changes cause water scarcity and droughts, while flooding devastates communities by disrupting both linear and non-linear water infrastructure. The age and centralized design of municipal water systems pose significant economic, social, and environmental risks to the communities they serve.

The World Health Organization (WHO) reports that in the last two decades two billion people gained access to safe drinking water, and that the return on investment for clean water projects are estimated at more than three times their cost in urban areas, and more than six times their cost in rural areas (World Health Organization, 2022). Despite the encouraging progress and the known benefits these investments bring, an estimated two billion people still go without clean water. On the 25th of September 2015, Member States of the United Nations adopted the 2030 Agenda for Sustainable Development. The 2030 Agenda comprises 17 Sustainable Development Goals and 169 targets addressing "social, economic and environmental aspects of development, and seeks to end poverty, protect the planet and ensure prosperity for all" (United Nations Children's Fund & World Health Organization, 2017). An urgent call to action report published by WHO in October 2022 emphasizes that in order to meet the Sustainable Development Goal target of universal access to safe drinking water by 2030 the current investment in water infrastructure must be quadrupled (World Health Organization, 2022). A similar urgent call report for sanitation states that the world is "alarmingly off-track to deliver sanitation for all by 2030" and that over half of world's population (4.2 billion people) use sanitation services that leave contaminated waste untreated, threatening both human and environmental health (World Health Organization, 2021). With less than 10 years left to achieve the 2030 commitment, the current rate at which sanitation coverage is increasing will also need to quadruple (World Health Organization, 2021). With this required rapid rate of development municipal water systems will be built conforming to conventional practices and standards to ensure the efficient delivery of projects. It is important that decision makers and governments do not undermine the sustainability and resiliency of projects as to not experience the same problems that conventional water systems currently undergo.

Municipal water systems and responsible waste management systems are the most important components of our infrastructure systems that must be transformed in order to achieve a circular economy. The majority of water-related infrastructure systems (including stormwater and wastewater systems) in developed nations were installed over 50 years ago and typically involve inefficient resource-intensive processes that can result in negative societal impacts. The replacement value of water, stormwater and wastewater assets in fair, poor, or very poor condition in Canada has been estimated to be over $173 billion (Canadian Infrastructure Report Card, 2016). The required investment in water-related infrastructure should involve engineering and economic analysis that consider alternative systems prior to the commitment of infrastructure spending.

Most municipal water utilities are typically classified as “centralized” systems, characterized by large treatment plants and expansive distribution and collection networks that serve entire municipalities or regions. Decentralized water systems are characterized by numerous smaller systems that service localized areas closer to the site of water production or wastewater/stormwater generation. Both types of water systems can be designed based on the principle of “resource-recovery”, a strategy that is defined by the effective use of waste streams as an input to other processes that create valuable products as new outputs. There is a clear need to improve municipal water systems – yet the environmental, economic, and technological trade-offs pertinent to designing and operating new systems are still poorly understood. A major factor affecting the implementation rate of resource recovery strategies and technologies is the uncertainty regarding the value of the products produced. Stakeholders must be able to estimate the return on investment for emerging or established resource recovery technologies but the lack of an established market for the value-added end products being produced make this a difficult task. This information is needed to establish an economic basis for the minimum cost design of resource-recovery systems suitable for implementation.

The province of Alberta, Canada has only 2.2% of the freshwater supply nationally, and while approximately 80% of the province's population resides in the South, 80% of Alberta's freshwater is in the North (Government of Alberta, 2010). Southern Alberta is at risk of both water quality and quantity problems due to a combination of different factors, including the dry climate, settlement patterns, intense irrigation, and unevenly distributed water resources. In Alberta, potable water is currently used for all applications including outdoor use and toilet flushing. The net amount of water withdrawals and the amount treated to potable quality standard could be reduced with the recovery and reuse of municipal wastewater for "non-contact" household, commercial and institutional, and landscape purposes. However, the capacity and threshold values of water treatment plants are location specific. In Southern Alberta, there are several unique factors that contribute to the heightened concerns regarding securing adequate long-term water supply, treatment, and distribution. For example, during drought conditions the capacity of water treatment plants can be reduced, creating a shortfall in some cases that puts the system's ability to provide full fire protection in the community at risk. The Province of Alberta has stopped accepting applications for new water allocations in the Oldman, Bow, and South Saskatchewan sub-basins in southern Alberta, in accordance with the Water Management Plan (approved in 2006). This license closure has had a significant effect on future development plans and water supply strategies available to municipal water users, as many communities currently hold water licenses that are not adequate for their projected growth (Pernitsky & Guy, 2010). In 2010, Pernitsky et al. highlighted many communities in the South Saskatchewan River Basin, including the City of Calgary, that could face water shortages by 2030 if water conservation measures were not taken.

Three main options exist for municipalities facing water shortages in southern Alberta: 1) Given that irrigation districts hold the largest water licenses in the Bow Basin, these licenses are good candidates for reassignment for municipal purposes; 2) A municipality could purchase raw or treated water from another municipality that has extra capacity; or 3) A community's water supply could also be augmented through alternative water supply source extensions such as groundwater extraction and the use of reclaimed wastewater/greywater (Pernitsky & Guy, 2010). Although irrigation is by far the most significant use of freshwater in Alberta (accounting for 75% of consumptive use and 75% of water licenses) (Belayneh, 2018), the focus of this research is to explore individual actions a municipality can take to conserve water and further develop the resources available to them, such as source-separating wastewater for greywater recycling. Transferring or amending irrigation licenses for municipal use is not considered as a strategy, given the socio-economic controversy and the tendency of irrigation districts to maintain long term control under any water sharing agreements. In Alberta approximately 75% of the province's population is served by tertiary-level wastewater treatment, providing ample opportunity for municipalities to reuse wastewater effluent and stormwater for non-potable end-uses (Government of Canada, 2011). The increased awareness and stewardship of a "one water" approach has the potential to extend the capabilities of an existing water license significantly, providing the ability to serve thousands of additional homes by more effectively managing finite resources.

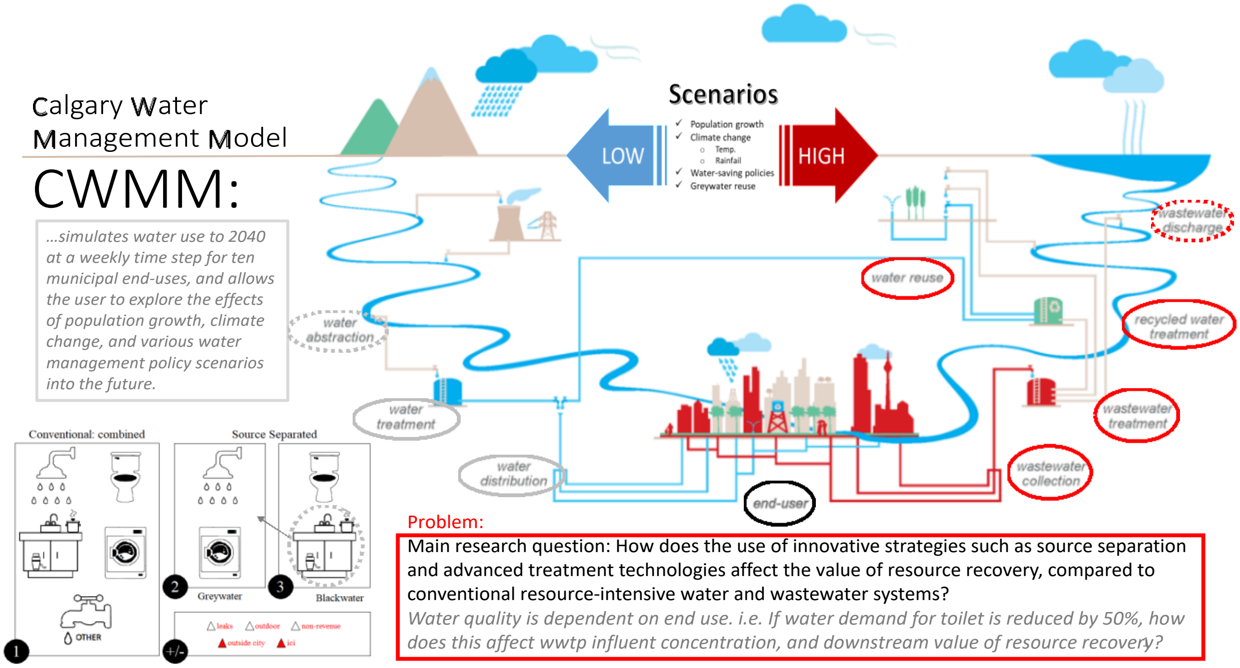
1.1 Research Objectives

The purpose of this research program is to evaluate leading resource-recovery based municipal water systems and provide a model to test the effectiveness of various strategies under a wide range of possible future scenarios relating to water and wastewater infrastructure decisions. This thesis explores the opportunities and implications of pursuing new municipal water management strategies and systems, specifically source-separated wastewater treatment options within a Canadian municipality. The main questions this research aims to answer are:

1. What is the value of specific resource recovery products created by implementing source-separated wastewater collection and water distribution systems?
2. How much water and other value-added products could be recovered from source-separated systems and what is the monetary and environmental value of these products within the selected study area?
3. How does the value of these products compare (economically and environmentally) to existing resource recovery facilities integrated within centralized systems employing combined wastewater collection and treatment?

The main research problem is represented graphically in Figure 1 below. How do water systems that are designed based on the principle of resource recovery compare to conventional systems in terms of 1. resource intensity, 2. economic analysis, and 3. other environmental performance metrics. The variables circled in grey represent the focus areas of the pre-existing Calgary Water

Management Model. The variables circled in red outline the scope of this research; expanding end-use simulation data to analyze the value of resource recovery products.



…simulates water use to 2040 at a weekly time step for ten municipal end-uses, and allows the user to explore the effects of population growth, climate change, and various water management policy scenarios into the future.

Problem:

Main research question: How does the use of innovative strategies such as source separation and advanced treatment technologies affect the value of resource recovery, compared to conventional resource-intensive water and wastewater systems?

Water quality is dependent on end use. i.e. If water demand for toilet is reduced by 50%, how does this affect wwtp influent concentration, and downstream value of resource recovery?

Figure 1 - Graphical Abstract: Permission to adapt figure granted by Jose C. Porro (Energy Performance and Carbon Emissions Assessment and Monitoring Tool).

The objective of this research is to use an end-use based water demand system dynamics model to simulate and analyze the effects of broader water-related resource recovery strategies focused on downstream reuse. The intent is to simulate combined and source-separated wastewater and stormwater streams quantitatively as dynamic variables that can be assigned user-defined quality characteristics, exploring various treatment/recovery levels applied to individual water streams.

1.2 Thesis Structure

The thesis is structured as follows: Chapter 2 provides an introduction to integrated municipal water planning and management, including a review of decision support tools for sustainable municipal water systems. Chapter 3 explains the study methods and provides a description of the study area and the data sources. Chapter 4 contains a description of the employed model followed by an explanation of recent updates including resource recovery sub-systems for each of the main resource streams: water, energy, and nutrients. The results of scenario-based simulations in

Chapter 5 shed light on the trade-offs of the various resource recovery options tested. Chapter 6 concludes the thesis with a summary of the results, modelling limitations, and ideas for future research.

Chapter 2 - Integrated Municipal Water Planning and Management

The definition of “integrate” is to bring together or incorporate (parts) into a whole. Fully integrated municipal water planning and management requires the consideration of all aspects that make-up and relate to municipal water systems. The implementation of integrated planning and management principles is difficult, specifically when it comes to transforming qualitative ideas into quantitative models and action plans (Prodanovic & Simonovic, 2010). An integrated system can be partially represented by a model that involves multiple sectors, making it an “integrated model”. Water supply, stormwater and wastewater subsystems with possible centralized and decentralized water reuse and resource recovery represents an integrated ‘one-water’ modeling approach.

The main systems that comprise a complete municipal water system may seem easily identifiable and linear at first, but the sub-systems are deeply interconnected and make municipal water assets an increasingly complex area of infrastructure asset management (Vieira, 2020). This chapter provides a review of the different aspects of integrated municipal water planning and management and explains how the various parts of the water sector are deeply interconnected with many other human and natural earth systems. This chapter begins with a review of conventional municipal water, stormwater and wastewater systems, followed by an introduction to more sustainable systems based on the principle of resource recovery. This chapter also provides a review of other decision support tools and studies that have tried to further understand and improve municipal water planning and management.

2.1 Water Resources Planning and Management for Municipal Water Systems

Mismanaged water resources and aging water infrastructure are the root cause of many environmental and public health disasters such as flooding, water quality degradation, and water scarcity concerns ; Vieira, 2020). Many local governments and utilities are failing to provide total water services and are struggling to manage water conflicts that exist amongst various water users (Poff et al., 2016). This section includes an overview of conventional water, stormwater, and wastewater systems and the risks they face, followed by an introduction to more sustainable municipal infrastructure strategies, including decentralization and source-separation.

2.1.1 Background and Limitations of Conventional Water Systems

Municipal water management includes potable water systems, stormwater management systems and wastewater collection and treatment systems. Conventional water systems are typically centralized, requiring extended distribution and collection networks that extend from large treatment plants (Chung et al., 2008; Leigh & Lee, 2019). Established water systems in developed countries demonstrate that water infrastructure is not a one-time investment and that they require continuous input of resources for operation and maintenance (Canadian Infrastructure Report Card, 2016). Current operational challenges exacerbated by neglected reinvestment of infrastructure have led to many inefficiencies (Bianchi & Montemaggiore, 2008). Although these conventional systems help protect human and environmental health, they depend on resource-intensive processes that can lead to negative effects (Jeyanayagam et al., 2016). Many systems are nearing or past their design life and desperately require remediation or replacement. Increasing urbanization, population growth and climate change raise concerns over the ability of conventional water systems to meet future capacity reliably (Kaur et al., 2020). Pollutants found in potable water, wastewater, and stormwater systems threaten human health and environmental ecosystems in both urbanized and rural areas alike. This subsection provides a brief description of conventional water, wastewater, and stormwater systems, followed by the limitations and risks these systems face.

Potable (drinking) water systems begin with the abstraction of water from the natural environment followed by treatment systems and distribution infrastructure that delivers water to the various end-users who depend on it. As distribution systems grow so does the risk of water containing potentially toxic contaminants. Contaminated water in conventional distribution networks is the cause of nearly all boil water advisories. Chlorine has been used to disinfect drinking water and prevent waterborne disease since the early 1900s, preventing millions of deaths and making potable water widely available at a low cost. However, when disinfectants such as chlorine encounter naturally occurring organic matter they form carcinogenic compounds called disinfection byproducts (DBPs) such as trihalomethanes (THMs) and halogenic acetic acids (HAAs) (Richardson et al., 2007). Mazhar et al. (2020) reviewed 52 studies about DBP toxicity and epidemiology to understand the relative hazards caused by exposure of DBPs, finding that DPBs dermal and inhalation exposure routes actually have greater risk compared to ingestion and that many innovations and methodologies can be used for the removal of DBPs. Decentralized systems are inherently less risky than centralized systems because the distance that potable water extends from the treatment plant is significantly reduced.

Sewer systems were introduced in the 1800s to improve community health and relieve concern caused by the challenges of controlling the outbreak of pathogens that arise from poor sanitation. Although sewers alone served their purpose (reducing the risk to humans through the improved conveyance of waste), simply transporting the problem to another location soon became inadequate to meet the demands of a world experiencing rapid population growth and developmental change (Burgess et al., 2015). Wastewater not treated adequately causes downstream increases in dissolved organic carbon and inorganic nitrogen and phosphorous resulting in algal blooms that can majorly impact the environmental and economic prosperity of urbanized coastal, lake, and river systems (Yoon et al., 2017). During the mid-20th century, gross environmental impact became the main driver for municipalities to make an effort to reduce pollution and implement wastewater effluent regulations (Canadian Water Network, 2018). Activated sludge processes and high rate anaerobic digestion were employed by many utilities prior to discharging wastewater back to the environment and disposing biosolids separately to land (Jetten et al., 1997). Priorities once again transitioned in the 1980s when regions impacted by the effects of eutrophication began to speak-out about the importance of nutrient removal prior to discharging wastewater effluent back to the natural environment. This resulted in utilities expanding their treatment systems to include conventional biological nutrient removal processes (Burgess et al., 2015). The problem with aerobic systems is that they produce excess sludge which must be handled responsibly prior to disposal, increasing costs (Stazi & Tomei, 2018). The growth and transformation of biological removal technologies continues to this day, with a present-day focus on considering the carbon and nutrients as resources that can be recovered as energy, valuable fertilizers, and various other value-added products.

In addition to the inadequacies associated with the treatment processes themselves, conventional potable water and wastewater systems create diseconomies of scale where long distances must be covered by vast networks of pipelines, forcemains, manholes, and lift stations (representing up to 80% of the cost of centralized water systems) (Philip et al., 2019). Utilities have historically prioritized building more supply to meet increasing demand, but if water use is not increasing linearly with population this could lead to investments in facilities that are ultimately not needed. A problem shared by both conventional drinking water and wastewater processes is the amount of energy consumed. As cities sprawl the amount of energy and underground infrastructure required to service the outer limits of the municipality increases significantly. In many cases extensive transmission lines and sewer force-mains are constructed to also service numerous peri-urban local governments who may struggle to provide adequate water services on their own (Ravetz et al., 2013). Energy intensive total water services can represent 40% of a municipality's energy bill due to processes such as aeration, pumping, and solids processing (Congressional Research Service, 2017). These systems are heavily dependent on electrical energy supply, putting them at risk in economic/political and natural crisis times – such as overflow events caused by heavy rainfall or flooding which can lead to destructive conditions and potentially fatal consequences (Capodaglio et al., 2017).

Stormwater systems should also be considered to evaluate complete water systems holistically (Xue et al., 2015). Precipitation control (stormwater management) is an extremely important aspect of municipal water management. The quantity and quality of runoff produced by municipal and industrial developments pose significant risks to the health of the environment and our communities (Schneider & Null, 1975; Codner et al., 1988). Natural land is extremely absorbent – vegetation and soil will retain most of the precipitation throughout the year, while developed land (often referred to as grey infrastructure) is typically impermeable which creates significantly more run-off than pre-developed land. Rainwater and snowmelt collect many pollutants as they flow to the nearest stormwater management system (through either ditches or pipelines), leading to the degradation of water quality (Goonetilleke et al., 2005). Many stormwater collection systems are combined with wastewater conveyance networks that experience overflows during rain events. Toxic contaminates flow directly into our rivers, lakes, and oceans every day due to the limitations of conventional systems. The stormwater generated within municipalities could be captured, treated, and reused to offset the resource-intensive production of drinking water for non-potable end-uses such as irrigation.

2.1.2 Sustainable and Resilient Municipal Wastewater Systems

Local governments are struggling to maintain their water systems under severe fiscal pressure and competing infrastructure requirements (Chung et al., 2008). The water sector is pressured by population growth, increasing demand for natural resources, uncertain environmental conditions, and rising costs along with community expectations. Water systems face many risks, and as large population centers continue to expand, decision makers are becoming increasingly aware to the concepts of sustainability and resiliency prior to the commitment of long-term infrastructure spending (Rehan et al., 2011). The infrastructure managers of many water-related utilities have made significant efforts to reduce operating costs, enhance plant revenues, address regulatory challenges, and promote environmentally conscious practices such as reducing the consumption of resources and recovering value-added products (Remy & Jekel, 2012; Pikaar et al., 2022).

Determining the priority level of each subsystem within the overall municipal water system is a primary challenge for the decision makers of local governments. Several constraints currently limit the uptake of more sustainable water management strategies including a lack of human and economic resources, governance structures, and regulatory mechanisms (Poff et al., 2016). Solutions to this problem must satisfy the demanding societal, political, and financial requirements associated with marketing and distributing new ideas and products. Juan-Garcia et al. (2017) conducted a critical review of studies in the wastewater treatment literature and found there are limited studies that directly addressed the resiliency of municipal wastewater systems (where resiliency is represented by metrics that describe the performance of the system under changing conditions). Conveyance systems (sewer infrastructure) have been shown to have a larger environmental impact than both the construction and operation of wastewater treatment plants (Risch et al., 2015). The construction and operation of sewer systems must be considered in the environmental assessment of centralized versus decentralized options for municipal water systems. Schoen et al. (2015) studied the technologic resilience of various water and wastewater system options including a comparison between conventional centralized systems and a range of decentralized wastewater options (including source-separated strategies). Resiliency was measured by the robustness, adaptive capacity, rapidity, and resourcefulness of each system. Although the service options utilizing source-separated systems (such as a pressure sewer and local digester) were considered the most robust, no one system was the clear resilient choice given the selected events and assumptions.

2.1.3 Decentralization and Source Separation

Historically the approaches for decentralized treatment of sewage have been limited to conventional septic tank systems which include a tank, an optional distribution box, and a drain field comprised of perforated pipe and gravel or crushed stone. Traditional septic tanks provide a simple treatment method but have a low performance in the removal of biodegradable organic matter (only 30-50%), depending on the nature of the wastewater and sedimentation efficiency (Santiago-Díaz et al, 2018). These systems convert a major part of the organic matter in wastewater to methane gas, which dissipates into the atmosphere. Moreover, septic tanks release high concentrations of nutrients such as nitrogen and phosphorous to receiving surface waters, which can cause eutrophication contributing to the degradation of the natural environment and devastation to local economies (Wood et al., 2015). Septic systems also provide no level of treatment for many other toxic pollutants including contaminants of emerging concern. Several academic and industry sources are pointing towards a shift towards more decentralized reuse at the community scale, and source-diverted streams for enhanced resource recovery and adaptive management to control emerging issues. In recent years, decentralized concepts have been re-designed to achieve maximum possible sanitation while minimizing negative environmental impacts (Verstraete et al., 2009).

Source-separated collection systems can improve resource recovery by providing treatment facilities with more nutrient- and energy-rich streams to maximize energy recovery and minimize sludge production and the release of contaminants to waterways (Tervahauta et al., 2013).
Blackwater-only sewer systems comprised of wastewater from toilet flushing (and potentially kitchen food streams) opens the door to a number of readily available options, such as anaerobic treatment strategies designed to recover combined heat and power while at the same time minimizing sludge production and contaminant release to waterways. Greywater refers to wastewater collected from all other end-uses, including the shower/bath and laundry. Separation of municipal wastewater into blackwater and greywater has proved to be an efficient strategy to prevent contamination of greywater, reduce the volume and increase the concentration of

blackwater, as well as reduce the overall cost of treatment (Abdel-Shafy et al., 2009; Guest et al., 2010). 80–95% of the nutrients from wastewater can be recovered by diverting black water from grey water (Kujawa-Roeleveld & Zeeman, 2006). The separate treatment of greywater offers significant potential for the reused water to meet the demands of appropriate end-uses (such as toilet flushing and outdoor use) following less intensive treatment processes since it is of a "lighter" quality, free from feces, urine, and pathogens. Source-separated systems have also been shown to reduce hazardous substance flows to receiving water bodies compared to conventional combined systems (Malmqvist and Palmquist, 2005).

Source-separated systems paired with low-flow appliances provide an opportunity for the elimination of excessive distribution and wastewater conveyance systems which have been found to constitute approximately 75% of the costs of a municipal water system (Rehan et al., 2011; Cohen et al., 2004). Pumping water and wastewater through extended piping systems accounts for approximately 80% of the total electricity used in municipal water/wastewater systems (Goldstein & Smith, 2002). Greywater treatment and reuse strategies generally receive a more positive acceptance by the public than combined wastewater reuse and there are currently many different options available to achieve greywater reuse (Verstraete et al., 2009).

For rapidly expanding urban population centres decentralized wastewater systems are a viable alternative to extending piping networks well beyond city limits to convey wastewater to centralized treatment facilities. Hue et al. (2016) found that localized treatment systems can also satisfy and even exceed the increasingly stringent effluent regulations for major urban population centres, also helping alleviate the growing concerns of global resource shortages in the energy, nutrient, and water cycles. Decentralized water and wastewater systems can be designed to operate in conjunction with existing infrastructure; therefore it is possible to create synergies to reap the benefits of decentralized systems while minimizing the effects on centralized wastewater infrastructure (Libralato et al., 2012). For some water utilities, expanding sanitation systems in phases with autonomous decentralized units that operate closer to the source of waste production and actual demand can be more cost effective strategy than one large scale centralized design, especially when communities are scattered spatially or located at elevations where pumping costs may be prohibitive (Chung et al., 2008). A semi-centralized infrastructure approach developed for rapidly growing cities that require expansion to meet their challenges regarding water supply and wastewater treatment was implemented in China (Tolksdorf & Cornel, 2017). Model calculations of the system showed that compared to conventional systems without source separation, uncertainties for the source-separated system are considerably higher, due to significant differences between the measurement of influent concentrations compared with design values, and possible variation of load distribution between greywater and blackwater streams, underscoring the importance of building full scale systems to increase the wide-spread implementation of such source-separated strategies.

The embedded energy in used water can be more efficiently captured using innovative anaerobic treatment methods, which are much more efficient than outdated aerobic systems commonly used today. Wastewater treatment using anaerobic biotechnology with simultaneous energy recovery is a promising solution for decentralization initiatives such as sewer-mining developments. Upflow anaerobic sludge blanket reactors (UASB), and anaerobic membrane bioreactors (MBR) are commonly used to treat domestic wastewater (Puyol et al., 2017). The UASB reactor provides good removal efficiency of organic matter using a dense sludge bed at the bottom of the reactor. The sludge bed is formed by accumulation of suspended solids from the influent and from the biomass produced by microorganisms during the biological treatment process (Kujawa-Roeleveld & Zeeman, 2006). Lutterbeck et al. (2017) investigated the performance of a wastewater treatment system consisting of a UASB, four subsurface flow constructed wetlands, and two photoreactors and found the reductions in chemical oxygen demand (COD) varied between 93% and 97%. Additionally, 100% of the ammonia nitrogen and more than 90% of total phosphorus were removed from the wastewater. The capital cost of UASB systems are similar to conventional primary treatment plants but the operational costs are lower, as the UASB relies on less mechanical components and generates substantially lower quantities of sludge (Sandino et al., 2011). Bhatti et al., (2014) reported that the total cost of an integrated UASB system (with post-treatment using hydrogen peroxide) has approximately 50% less cost than conventional aerobic wastewater treatment and was found to be very successful with the effective treatment of wastewater (99% chemical oxygen demand, 95% ammonium). Despite the effective COD removal by the UASB and other anaerobic biotechnologies, some challenges still exist.

Currently the uncertainties for new decentralized systems (such as source-separated greywater and blackwater treatment) are considerably higher, due to the limited number of working systems and lack of design criteria, regulations, and relevant standards required for engineering guidelines and regulatory requirements. Innovative investors, increased awareness of available alternatives, and revision of legal frameworks and technical standards are all required to advance more sustainable solutions. Designs based on the principle of resource recovery need to be integrated into the beginning of the planning process, especially in cases where there is currently no wastewater treatment system in place and raw sewage is discharged directly to the natural environment (Werner et al., 2009). Another one of the main obstacles associated with decentralized facilities has historically been the lack of human resources (such as water operators and engineers) available to local governments looking to upgrade or construct their first treatment plant. There are decentralized systems that can now be controlled from a distance, facilitating the implementation of remote monitoring technologies which has resulted in a reduction of operational and maintenance requirements (Capodaglio, 2017). Economic and environmental assessments are an important part of the decision-making process as accessing funding is typically required for the implementation of new systems for most local governments.

Decentralized municipal water systems for isolated communities and rural areas struggling with water supply and wastewater management can be designed to accommodate the simple constructability, operation, and cost efficiency that most local governments are seeking. Decentralized and source-separated systems also facilitate the integration of low impact development infrastructure and nature-based systems improving waterways and supporting water reduction and reuse goals. In smaller communities and isolated areas, passive wastewater treatment systems such as wastewater stabilization ponds and constructed wetlands are typically preferred. Rural areas implement these types of systems because they are inexpensive and require little energy, maintenance and operational expertise (Liang, 2018). The performance of these passive systems is strongly influenced by both environmental conditions and water quality parameters, factors that are both unique to a specific location and climate. Generally, all biological treatment systems are affected by environmental conditions that the biomass is exposed such as dissolved oxygen, pH, and temperature (Abou-Elela et al., 2016). In cold climates like Canada, the effect of a seasonal temperature variations on the overall performance of the treatment system is critical, specifically in regions where the temperature range of the raw wastewater in the summer and winter vary significantly (Liang, 2018).

Garrido-Baserba et al., (2018) tested the feasibility of three different potential types of source-separation compared to the current wastewater management paradigm using techno-economic terms, expanding the understanding of the economics of decentralization and source-separation. The alternatives were evaluated for both new developments and retrofits (due to aging of existing infrastructures) and the results indicate that source-separated alternatives designed based on the principle of resource recovery can be cost competitive options despite existing drawbacks. Leigh & Lee (2019) found that stormwater is another potential source of usable water that can be incorporated into decentralized systems, and that underserved residential areas, mixed-use developments, and industrial developments are identified as high-opportunity areas for decentralized water systems.

2.2 Resource Recovery

The prioritization of sustainable planning and development is causing a paradigm shift in municipal infrastructure industry. Resource recovery has been an emerging theme in the water sector in recent years, complementing the overall progression of a clean energy transition framework being established by different levels of government around the world. Some water and wastewater utilities have transformed into “resource recovery facilities”; focused on enhancing efficiency and recovering valuable resources such as clean water, energy, and nutrients. The maximum valorization of used water has not been realized, despite numerous established technologies available to capture value from wastewater, and the wave of innovation that is emerging with advances in big-data analytics (Kehrein et al., 2020). Resource recovery for a circular economy involves next generation (digitally enabled) connected water management systems driven by advanced biological technologies. Water systems designed based on the principle of resource recovery should be considered for all new developments.

Utilities that leverage resource-recovery opportunities have achieved cost effective, energy producing plants that create a surplus of valuable products. Mateo-Sagasta et al. (2015) estimated that the resources embedded in the municipal wastewater generated globally could theoretically provide enough resources to irrigate and fertilize millions of hectares of crops and produce energy for millions of households. The main resource streams include water, energy, and nutrients as shown in Figure 2 below. An integrated water management approach based on the principle of resource recovery will lead to an increase in the overall acceptance of projects such as water recycling, co-digestion of waste, energy-positive utilities, and an elevated awareness of lifecycle impacts and community resiliency and sustainability (Burgess et al., 2015).

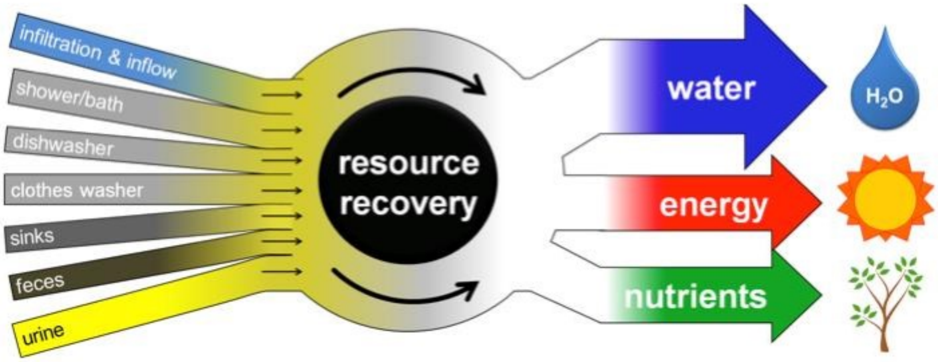


Figure 2 - Source-separated wastewater collection for the recovery of resources including water, energy, and nutrients

Both the public and private sector face a number of barriers to advancing resource recovery, such as operational challenges, inadequate regulatory frameworks, and a lack of capacity to develop or evaluate business plans pertaining to resource recovery and water reuse (Wichelns et al., 2015). A variety of possible solutions can be defined based on the principle of resource recovery, such as greywater treatment and reuse, blackwater co-digestion with food waste for energy recovery, and nutrient recovery through struvite precipitation which can be sold for local agricultural uses (Xue et al., 2016). Although these alternatives are currently available, the environmental and economic trade-offs in the process selection of these systems are poorly understood. Another critical barrier to advancing resource recovery system development has been the lack of understanding of how detailed design decisions influence system sustainability, a barrier stemming from the lack of functional resource recovery treatment systems. Municipalities with competing infrastructure priorities are generally reluctant to building new water systems if they have already made substantial investments to provide the existing centralized systems and conventional piping networks.

The existing literature shows an increasing number of publications providing frameworks for evaluating the benefits and costs of sustainable strategies in the water sector. However, a larger gap exists regarding analysis of the trajectory from cost recovery to business opportunities, taking into account options for water, nutrient, and energy recovery in sewered and unsewered systems (Wichelns et al., 2015). Efforts taken by municipal water managers to improve resource recovery vary widely depending on the local conditions of the utility (Khiewwijit et al., 2018). Voulvoulis (2018) emphasized the importance of the public safety of water reuse through the application of different water quality standards for specific end-uses, suggesting the adoption of appropriate regulatory enforcement to ensure the reliable operation of resource recovery systems. The following sub-sections provide a review of literature focused on the main products that can be recovered from wastewater systems (water, energy, nutrients, and other value-added products).

2.2.1 Water

Municipal water systems serve residential, industrial, commercial, institutional and public clients, whose demands are affected by both short and long-term impacts. The amount of water treated to drinking-quality standards can be reduced through a number of technological and policy-driven changes. Water conservation efforts such as the adoption of more efficient fixtures and appliances, water reuse, and water metering are all effective measures that can be taken to reduce total water demand (Wang & Davies, 2018). An example of how technological change impacts water use trends is the adoption of low flow appliances like toilets, that have been shown to reduce flush volume by up to 80% compared to typical toilets from the 1980s (DeOreo, 2016). The quantity of water that can be saved from water conservation efforts can be accurately simulated using an end-use based model. The value of water has the potential to change the focus of wastewater design from pollution abatement to resource recovery. However, social acceptance of recovered water and the challenges associated with marketing the resources produced creates larger risks for investment (Hall et al., 2018).

The value of water varies depending on location-specific factors that influence the cost to extract, treat, and distribute potable water. These factors include both capital and operational expenditures and can be separated into potable water, stormwater, and wastewater sub-systems. The main expense is the cost of energy required to pump and treat water and wastewater, including the life cycle energy for all the chemicals used in both treatment processes in addition to the energy required to transport required materials. Treated greywater or wastewater for agriculture, domestic reuse, or to recharge environmental flows is a viable option for all water utilities, especially those in water-stressed areas. Greywater reuse offers a variety of context specific opportunities and challenges, and reuse technologies and policies vary widely around the world (The International Water Association, 2018). While greywater and wastewater reuse are common in other countries around the world, an increasing number of water-stressed regions in Canada are considering water reuse schemes, while some municipalities are being forced to prioritize other pressing matters such as addressing the impacts of eutrophication, stormwater capture, and flood risk mitigation.

2.2.2 Energy

The energy consumed by public water systems has been increasing significantly (Alexandratos et al., 2019), prioritizing new strategies that reduce energy to achieve environmental targets and reduce costs. Advancements in energy recovery from wastewater has been an emerging theme within municipal water management in recent years, complementing the overall progression of a clean energy transition framework being established by different levels of government and lead by municipalities (Hanjra et al., 2015). Utilities may alleviate treatment costs by integrating well-established energy recovery methods including the utilization of biogas and thermochemical conversion of biosolids generated during the treatment process (Wang et al., 2018). Energy recovered from the wastewater treatment process can provide a surplus of heat or electricity, reducing the overall lifecycle cost of the treatment process and creating opportunities for further developments in energy recovery from end-use (source-diverted) wastewater streams (Roefs et al., 2017). Municipal water systems can be designed to be net-zero and in some cases energy-positive when innovative strategies are employed such as heat-exchange technologies. It is projected that future municipal water systems could recover more thermal energy than is required for the treatment process itself (Englehardt et al., 2016). Part of integrated municipal water planning should involve testing different management strategies for the recovery of the embodied energy in wastewater, comparing different methods of energy recovery to the BAU case typically employed by larger, conventional biological treatment systems.

It is estimated that 60-80% of organic material in wastewater could be converted to methane, and subsequently used for electricity and heat generation (Logan, 2004). Energy generation is already included and implemented in many conventional activated sludge systems, often supplemented by techniques such as enhanced primary treatment or other high-rate processes to increase the amount of organics that are sent to the anaerobic digester, where the organics are converted to biogas. Sludge-derived resource recovery options involve emerging treatment methods such as anaerobic digestion, thermochemical conversion, wet air oxidation, and hydrothermal treatment. The specific power consumption of current conventional wastewater treatment plants should range between 20 and 45 kWh per PE (population equivalent) per year, translating to between 0.41 to 0.87 kWh/m^3 of wastewater treated (Gandiglio et al., 2017).

The energy contained within wastewater can be classified as either chemical, thermal and kinetic. The chemical energy contained in wastewater has been estimated by different studies as ranging from approximately 10 to 14 kJ/g COD (1.67–2.33 kWh/m^3 assuming a diluted COD concentration of 600 mg/L), while thermal energy could yield about 21 MJ/m^3 (5.8 kWh/m3) for a drop of 5 °C in wastewater temperature (Capodaglio & Olsson, 2020). Anaerobic digestion produces approximately 0.075 m^3 of digester gas per m^3 of wastewater treated. Digester gas contains between 40% and 75% methane, with 60% being common, resulting in an energy value of 22,000 kJ/m^3 (Sandino et al., 2011). Typical energy recovery systems typically provide approximately 20–40% of the energy requirements for an activated sludge wastewater treatment plant, depending on the type of treatment system in place (Sandino et al., 2011). McCarty et al. (2011) evaluated the potential benefits of anaerobic domestic wastewater treatment compared to a conventional activated sludge system with sludge digestion, finding that with full anaerobic treatment methane production is double to what is typically achieved with conventional aerobic processes, giving anaerobic wastewater treatment processes the potential to be net energy producers. Verstraete et al. (2009) reported that conventional activated sludge processes consume 25 kWh per person annually, while source-separated anaerobic processes could potentially produce 5 kWh, representing a 30 kWh potential increase in energy recovery. For anaerobic digestion, the amount of biodegradable particulate matter (measured by chemical oxygen demand) and fraction of active biomass are the most important parameters, as they constitute the fractions which are converted to methane.

The utilization of sludge as a resource for energy recovery is the appropriate solution to advance resource recovery for sustainable water management, but the success of sludge-derived resources depends mainly upon the technical and economical feasibility, environmental sustainability, marketing facets and public acceptance of the proposed system and the products produced (Tyagi & Lo, 2013). Callegari et al. (2018) showed that microwave-assisted pyrolysis of sludge could be utilized to produce oil, syngas, and biochar, eliminating the need for conventional disposal of sewage sludge which may constitute approximately 50% of the total cost of operation of a treatment plant and have a serious negative impact on the environment. Other analysis has shown that the generation of biogas is not typically viable until a treatment plant reaches mid-range size, approximately 50 ML/day (Burgess et al., 2015), largely due to the high capital cost associated with gas production and storage systems required for retro-fitting centralized wastewater infrastructure. Electricity costs, government policies, environmental regulations, and waste discharge costs for the region are all major variables impacting the viability of resource recovery within a utility.

Higher strength source material such as liquid and solid organic waste improve the energy production and economic feasibility of anaerobic digestion. Water and wastewater utilities can boost the amount of energy production through a variety of supplementary strategies, for example co-digestion, which involves the addition of food waste in the anaerobic digestion process. Xue et al. (2016) found that the electricity generated from blackwater and food residuals co-digestion was estimated to offset at least 40% of life cycle energy consumption for total water/waste services. Gao et al. (2019) operated a UASB and achieved higher biomethane recovery per m^3 of reactor installed than the values from the reported literatures, reporting an average methane production of 0.68 m^3 of methane per m^3 reactor per day and a corresponding specific energy of 27.34 MJ per m^3 reactor per day as heat. Although alternatives are currently available, the environmental and economic trade-offs of these systems are poorly understood. Macro environmental factors such as housing density, condition of existing infrastructure, and regional climate affect technology decisions for source-separated domestic wastewater treatment regarding reactor volume, weight of outputs, energy consumption, atmospheric emissions, investment cost, and net revenue (McConville et al., 2014).

2.2.3 Nutrients

Wastewater contains valuable nutrients such as nitrogen and phosphorous that are required for agriculture. Nutrients are being recovered in the form of fertilizers and can be produced from both biosolids and side-stream processes. Phosphorous is a critical raw material used in the formulation of many important chemical fertilizers that are applied around the world, though it is unevenly distributed globally, with up to 75% of the reserves located in Morocco (Cooper et al., 2011). Experts believe that economically viable phosphorous reserves are being consumed faster than the geologic cycle can replenish it (Jeyanayagam et al., 2016), making phosphorous a valuable product that should be recovered by municipal wastewater utilities. The phosphorous lost in human waste could satisfy approximately 20% of the global need for phosphate (Wang et al., 2018). Reducing the need of mining phosphorous is a critical step towards closing the nutrient cycle and advancing global environmental stewardship, but the barriers and opportunities to implement effective nutrient recovery systems differ widely from one country to another (Ross & Omelon, 2018).

Producing fertilizers from used water can be achieved using a wide range of technologies, ranging from simple biosolids land application to reactors that produce more refined fertilizer products, such as struvite. The annual production of struvite (a phosphate material that can be recovered) from a wastewater treatment plant that processes only 100 m^3/day (approximately 300 population equivalent) could fertilize 2.6 hectares of land (Kumar & Pal, 2015). Although nitrogen recovery is not practical at this time given the value of nitrogen and the intensive inputs required to make nitrogen available in a fertilizer-ready form, phosphorous recovery through struvite production has multiple benefits, including 1) nutrient removal from wastewater effluent reduces eutrophication in receiving waters and helps protect the environment, 2) reduced maintenance costs associated with avoiding nuisance struvite formation and blockages in wastewater treatment plant facilities, and 3) revenue stream from the sale of high quality fertilizer for agricultural purposes.

Utilities are demonstrating the advantages of the life-cycle costing approach for phosphorous recovery by accounting for the avoided cost benefits. These avoided costs include a reduction in chemical use, landfill tipping (reduced sludge disposal), and operating and maintenance costs associated with fouling caused by unwanted struvite formation in piping and equipment. Burgess et al. (2015) performed a financial study for the case of struvite recovery and showed that for the production to be economic in Australia, on its own and without considering avoided costs, struvite prices are required to be in the range of $1000 to $2000 AUD per tonne. Although the market value of the recovered phosphorous products alone is generally not high enough to justify the cost of recovery, when the total value of phosphorous recovery is considered, additional incentives emerge (Mayer et al., 2016). High rates of return on investment were demonstrated by an analysis of six case studies of nutrient recovery projects in North America (Burgess et al., 2015). For example, the decision to implement a struvite reactor for Clean Water Services water utility in Oregon was simple, as the ongoing cost of removing phosphorous was significantly greater than the initial investment in a struvite recovery system. In the City of Edmonton, EPCOR Water Services Inc. and Ostara Nutrient Recovery Technologies recently partnered to build and operate the largest nutrient recovery facility in Canada. The facility recovers up to 85% of the phosphorous and 25% of the nitrogen from the biosolids settling lagoons for the City of Edmonton and surrounding area. The new facility is expected to produce 1000 one-tonne bags of struvite fertilizer annually, which is marketed as an environmentally friendly high-quality product to farmers across the country.

Struvite reactors are scalable and offer promising return on investment value. Torre et al. (2021) reported that four times more phosphorus and over 30 times more nitrogen can be recovered by wastewater source separation systems than with conventional systems given the higher concentration levels of nutrients in the wastewater streams. Although previous struvite recovery studies have identified optimal conditions for phosphorus recovery, limited information is available on the process optimization to minimize the potential risks. Yee et al. (2019) show that downstream application of recovered struvite inevitably contains co-precipitated hazards that if not assessed can result in undesirable public health outcomes. All of the economic, social, public health and operational factors must be taken into consideration when comparing alternatives within the integrated water resources planning and management decision making process.

2.2.4 Other Value-Added Products Derived From Wastewater

The potential generation of various other resource recovery products depends primarily on the economic feasibility of the proposed solution to achieve specified environmental or socio-economic goals. Holistic evaluation of possible strategies should consider the expected production of raw materials, the value of the products, the cost of generation, and any cost avoidances that result from the implementation of the new processes. Water reuse, energy recovery (biogas for electricity, heat), phosphate products, and both wet and dry biosolids application are well-established products derived from wastewater. Innovative and embryonic potential products include ammonium products, next generation fertilizers, commodity inorganic chemicals, various microbial products, advanced biofuels, and biopolymers (Burgess et al., 2015). Recent reviews have identified and compiled a wide range of technologies that enable resource recovery by concentrating and transforming resources from wastewater into valuable products (Zhang et al., 2018; Puyol et al., 2017). Additional prospects for value-creation from wastewater include non-conventional products and processes such as single cell protein development, recovery of metals, and bioproduction in bioelectrical systems (Puyol et al., 2017). Van der Hoek et al. (2016) applied material flow analysis for Amsterdam's wastewater chain including several resource recovery products such as alginic acid, bioplastic, cellulose, phosphorus and biogas, demonstrating that adaptive policymaking presents a good approach to deal with the wide variety of possibilities and uncertainties associated with resource recovery strategies.

2.3 Decision Support Tools for Municipal Water Systems Decision Makers

For new developments and upgrading old infrastructure, municipalities require user-friendly tools to assess alternatives that are more sustainable and cost effective. Decision makers and utility managers must consider wide-ranging factors at different scales when considering the implementation of new infrastructure. Pilot projects and full-scale resource recovery systems are scattered around the globe - things that impact one system/utility are not necessarily relevant to all other projects. Municipalities and other forms of local governments are also forced to deal with competing infrastructure requirements such as energy supply and transportation systems. Although more sustainable and resilient strategies/technologies are available, decision makers require tools to assess alternatives to the "flush-and-discharge" paradigm for water, as researchers have demonstrated the many problems of these systems. The need to improve demand forecasting is increasing, and part of that forecasting is planning for climate change and its impact on demand, something that many water agencies have yet to incorporate successfully. This section reviews some common tools that have been used by researchers and decision makers in the water sector to support the planning and management of their utilities.

2.3.1 Traditional tools

Most decision support tools developed in the past are based on multiple criteria decision-making frameworks, which involves the aggregation of multiple objectives, alternatives, and individual criteria into one overall assessment. Multiple criteria decision analysis studies often rely on traditional methods of optimization, but many researchers conclude that it is not possible to find an alternative that optimizes all criteria simultaneously when considering the wide range of metrics or indexes that are selected for evaluation (Balkema et al., 2001). Traditional tools used in the water sector also includes a wide range of softwares that rely on water balance and water quality models combined with financial analysis tools to track construction and operation costs. A common aspect of these traditional tools is that they often rely on strictly defined boundary conditions and linear equations that don't always allow the interaction of inter-related sub-systems such as the connections that exists amongst potable water, wastewater, and stormwater systems. Other decision support tools rely on rule-based systems and include tools like decision trees, which lack the ability to consider multiple criteria simultaneously and represent the interactions of complex systems, necessitating the development of dynamic scenario-based decision support tools (Kalbar et al., 2012). The tools reviewed below differ in many ways, including the inputs required and outputs expected. The individual tools vary widely due to the selection of different criteria and the use of different knowledge bases for the analysis.

User-defined inputs and information about the study area (such as legislation) can reduce the amount of alternatives that decision makers should consider. Garrido et al. (2010) developed a complex tool based on a hierarchical decision approach that breaks down a complex design problem into a series of smaller issues that are easier to analyze and evaluate. The tool relies on two knowledge bases regarding the main features of various treatment technologies (removal efficiency, costs, reliability) and the compatibility of technologies in combination with one another (high, low, non-compatible).

There are many multi-criteria analysis frameworks that rank alternative scenarios and suggest strategies such as the application of a policy or implementation of a treatment systems. The different criteria established for each tool depends on the desired outcomes. Many tools apply a scoring system to assess the relative strength of one alternative over another based on the selected criteria (such as health indicators, environmental standards, and economic feasibility) (Hidalgo et al., 2007; Malmqvist and Palmquist, 2005).

Behzadian & Kapelan (2015) developed a model for the metabolism-based assessment of the integrated urban water system performance. The model quantifies both water and energy flows/fluxes which are used to derive sustainability-based performance metrics. Chamberlain et al. (2014) presented a decision support tool that takes in descriptions of treatment components and integrates community sustainability goals to automate the design of alternative wastewater systems, providing the ability to visualize the trade-offs of various strategies. Coats & Wilson (2017) investigated, characterized, and described nontechnical socio-political barriers to realizing wastewater resource recovery. Principal actors in the water sector were interviewed and results revealed that economics were the primary barrier to implementation/expansion of the resource recovery facility concept.

Analysis of environmental metrics for municipal water systems have benefited from the development of life cycle assessment (LCA), a methodology used to determine the environmental impacts of a product or process across its life cycle. LCA metrics utilized in the wastewater literature are either “inventory-based” or “impact-based.” Inventory-based metrics quantify the inputs (resources) and outputs (emissions) of a process across its life cycle, while impact-based metrics predict an environmental impact that would result (based on characterization factors) from the metrics identified during the inventory stage (Guest et al., 2010). Impact-based metrics present data in more relatable terms but their uncertainties can be much larger. Although traditional tools like LCA have been applied to elements of municipal water services, Xue et al. (2016) argue for the importance of developing more system-based tools to holistically evaluate complete water systems based on the concepts of integrated resource management.

Kalbar et al., (2012) provided a scenario-based decision making tool using life cycle sustainability assessment framework for assessing technologies from environmental, economic, and social perspectives. Marinoski & Ghisi (2019) also used LCA to assess the environmental performance of hybrid rainwater-greywater systems in comparison to a residential building serviced by conventional centralized water system. The average potential for potable water savings using the hybrid system was 42% and the total energy reduction in comparison to the conventional system scenario was 36%. Wood et al., (2015) estimated a household nitrogen mass balance combined with life cycle cost assessment to calculate the cost-effectiveness of nitrogen mitigation from the local watershed, finding source-separated systems demonstrate the lowest life cycle cost (dollars per kilogram of nitrogen removed from the watershed) and in all cases centralized wastewater treatment plants the least cost-effective option in all cases.

2.3.2 Systems tools

Specific systems thinking tools include systemic root cause analysis, system archetypes, main chain infrastructures, causal loop diagrams with feedback and delay; stock and flow diagrams; behavior-over-time graphs, and computer modeling of system dynamics (Monat & Gannon, 2015). These tools can be categorized as brainstorming tools, dynamic thinking tools, structural thinking tools, or computer based tools (Kim, 1990). The focus of this sub-section is dynamic thinking tools and computer based tools for simulating municipal water systems.

The flexibility of system dynamics provides modelers with a considerable amount of integration capacity, such as building models in combination with hydrological process models, ANN models, or socio-economic sub-systems (Zomorodian et al., 2018). The dynamics of wastewater systems make reliable predictions using traditional tools difficult, therefore it has been proposed by researchers to use methods that systematically account for future uncertainty in the planning and design phase of projects (Dominguez & Gujer, 2006). The development of innovative integrated water system models provides utilities the opportunity to bridge the gaps related to the nexus of water, energy and other environmental factors. However, because municipal water systems are complex and involve interactions between numerous factors – including population growth rate, government, climate, wastewater characteristics, environmental regulations, economics, etc. – a method is required to identify and understand the interactions and feedbacks between the various system components in order for decision makers to plan appropriately an incorporate resource recovery into current operations and future design criteria .

In 1956 Jay W. Forrester began applying the principles of feedback and control to economic and management problems, pioneering the field of System Dynamics. Since then, the field has grown and system dynamics has been used widely to model complex systems for decision making purposes. System dynamics provides both conceptual and quantitative methods to represent, simulate, and investigate complex feedback and non-linear interactions among system components, management actions, and performance indicators (Elsawah et al., 2017). Winz et al. (2009) discussed the theoretical and practical evolution of system dynamics in water resources management over the past 50 years, and argue that system dynamics combined with stakeholder involvement provides an appropriate methodology to address the significant challenges resource planners and managers are facing. Findings from the review indicate that careful use of system dynamics modeling presents an important opportunity to improve water management strategies and enhance the resiliency of the system as a whole. The study indicates that prospects for success are maximised when the group itself constrains the definition of the problems to be addressed, and participatory procedures are applied in scoping, development and testing of the model (Winz et al., 2009).

System dynamics modeling focuses on the interactions/feedback among disparate but interconnected subsystems in determining a larger system's behaviour, to identify and understand its root causes for change (Mirchi et al., 2012). This makes it a good method to integrate the physical components (water supply, distribution networks, treatment technologies) and the socio-economic components (consumer behavior, economic feasibility, various water policies, etc.) to capture the big picture of the water system to support integrated water management and holistic decision making. Sahin et al. (2016) reviewed different methods for modeling integrated systems and considered system dynamics to be the most appropriate approach for modelling municipal water systems.

Altarabsheh et al. (2019) modelled a wastewater system as a "system of systems" rather than a stand-alone system to simulate and compare various funding and rehabilitation scenarios for the wastewater system under population and water demand uncertainty. Mohammadifardi et al. (2019) developed a system dynamics model to better understand the feedback mechanisms between the wastewater collection systems and wastewater treatment plant systems by representing the relationships between variables within physical, financial, and consumer sectors. Only recently has system dynamics been applied to complete water services (i.e. integrating trade-offs between drinking water, stormwater and municipal wastewater treatment) to address the urban water industry's evolving one-water management approach. Applications of system dynamics to municipal water management have allowed decision makers to investigate changes in both human behavior and technology, by assembling various model parameters and changes in policy into scenarios and then comparing their results (Wang & Davies, 2018).

Breach & Simonovic (2018) explored the water-energy nexus and potential for investments in energy recovery from wastewater to increase treatment levels and thus improve surface water quality. This was done by examining the relationships between nutrient over-enrichment, wastewater treatment, and energy recovery at a global scale using system dynamics simulation as part of a global integrated assessment model. The results show that a significant amount of energy can be recovered from wastewater and concluded that a finer spatial scale should be used to increase the utility of the simulation that includes regional treatment, economic, and water quality information (Breach & Simonovic, 2018).

System dynamics models can be developed quickly and are typically easy to modify and understand. The fast run time allows modelers to present sets of simulation results clearly to a wide audience of users and decision makers. System dynamics models are often used for educational purposes, participatory planning and modelling, and public engagement, and can be used to assess different options easily and inexpensively through alternative scenario building, sensitivity analysis, and the recently emerging gaming approach (Winz et al., 2009). Therefore, system dynamics models are powerful tools to analyze water management policies under future uncertainties such as population growth and climate change. Simulation gaming is a modification of the standard simulation approach that has been adopted by disciplines such as the military, education, policy analysis, economics, and engineering with an increasing recognition of its effectiveness as a tool for the management of limited resources. Simulation gaming models support decision-making by illustrating the comprehensive results of management decisions, and thus promoting the understanding of the connected water resources systems, management trade-offs, and various stakeholders' positions (Wang and Davies, 2015). Simulation games are experimental, rule-based, interactive environments, where "players" (users of the model) learn by taking actions and by experiencing their effects through feedback mechanisms that are deliberately built into the model (Mayer, 2009). Although gaming approaches are used for a wide variety of applications, this research focuses specifically on computer simulation models, which are used to represent physical and socio-economic systems and provide an effective and collaborative environment for water policy analysis and integrated water management. Bianchi & Montemaggiore (2008) use the system dynamics methodology to model the distribution system, sewer systems, human resources sector, and financial sector of a water utility – making use of a "dynamic balanced scorecard" to assist with the strategic management of the utility. Running simulations help decision makers and stake holders discuss options more effectively, negotiate priorities, and reach a cross-sectoral consensus under a multi-disciplinary context.

There have been a limited number of studies published evaluating resource recovery systems using the system dynamics framework (Phan et al., 2021). Prouty et al. (2018) employed the system dynamics modeling framework to identify strategies that will improve the adoption and sustainability of resource recovery systems. The framework is informed by literature-based theories, such as the well-known and widely used Theory of Diffusion of Innovations, which represents the transition from an initial knowledge about resource recovery technologies through the confirmation phase where utilities demonstrate behaviours to sustain the implemented technologies and report the relative performance of the system under various loading conditions. The selected factors, definitions, and equations used to formulate the model are not easily transferable to other studies, considering key metrics are derived from local survey responses and participatory observations for a specific region. There are no known models to date that allow users to simulate the "per capita" quantitative impact of adopting decentralized greywater systems on the overall water demand of an existing region (that is currently dependent on centralized water infrastructure).

2.3.3 The Calgary Water Management Model

The main strength of the system dynamics modeling methodology is its ability to explore questions that are often case-specific or problem oriented. The model components and capabilities discussed in this thesis add to an existing model developed by Wang and Davies (2018) for municipal water forecasting, the Calgary Water Management Model (CWMM). The model was created to test the effects of implementing broad-scale water saving/reuse strategies of various intensities. The model has been calibrated, validated, and applied for the City of Calgary within the water-stressed region of southern Alberta, Canada.

Municipal water systems serve all sectors, including residential, industrial, commercial, and institutional. The demand for water from these sectors is affected by both short and long-term impacts that are specific to each localized water system. The CWMM aims to understand the demand for water at a deeper level by simulating water use into the future. The CWMM is based on ten specific end-uses, including seven residential and three non-residential uses. The existing simulation model includes interactions between multiple variables important to integrated municipal water management and simulates "per capita water demand" based on the number of water fixture uses per day and their associated water requirements, which are affected by water conservation policies, as well as appliances and fixtures. The CWMM includes interactions between increases in municipal water demands with population growth, the available water supply, and the effects of climate change and water conservation policies (Wang & Davies, 2018).

Wang & Davies (2018) tested four scenario groups under various degrees of implementation to analyze whether Calgary's "30-in-30" goal could be achieved. This goal targets the same volume of water withdrawal in 2033 as in 2003 by reducing per capita water demand by 30% (from 500 lpcd to 350 lpcd) over 30 years (The City of Calgary, Water Resources, 2007). The model was validated against historical water demand data for Calgary and a series of scenario simulations showed; 1) potentially large changes to both seasonal and non-seasonal water demands with population growth, 2) a need to enhance historical water management policies with new policies such as xeriscaping and greywater reuse to achieve water management goals, and 3) the value of an end-use based model simulating management policy effects on municipal water demand and use (Wang & Davies, 2018). The model runs at a weekly time step and allows the user to explore the effects of variations in specific factors such as population growth, climate change, and the application of various water management policies into the future. The model is adaptable and allows for the simulation of water demand for any size municipality – given the required data is provided or can be reliably assumed for the new study area. This research project focuses on the extension of the CWMM for the analysis of stormwater/wastewater treatment and reuse, an exciting field that has gained attention in recent years due to advancements in digitalization and innovative resource recovery technologies.

Chapter 3 - Model Approach

This chapter explains how the system dynamics modeling methodology reviewed in the last section is used to simulate municipal water systems and explore the value of resource recovery products within a major Canadian city. The chapter begins with an explanation of the main tools used within the system dynamics modeling methodology followed by an introduction to the selected study area to which the model is applied. The chapter concludes with an explanation of the regulatory structures considered within the development of the model.

3.1 Methodology

In this study tools of the system dynamics methodology are applied to test the value of specific resource recovery strategies employed in Canada. This section further describes the system dynamics methodology and model development approach. This section references the software used for modeling followed by an explanation of the two main tools of system dynamics (causal loop diagrams and stock and flows). For investors and stakeholders, such as companies seeking public-private partnerships with local government owned utilities, standard economic valuation and financial modeling methods are employed so that new investments can be put into perspective over time based on the revenue generated from resource recovery products plus the benefit of avoided costs that come along with alternate strategies. The list below describes the steps taken to address the research questions presented in Section 1.1:

- Extend the existing model with a user-defined "stream selection" input option that automatically combines the various end-uses that produce specific wastewater streams

- Create a dynamic stormwater stock that represents the potential quantity of water available for reuse weekly, based on input data for the selected study area

- Develop algorithms that allow the simulation of multiple wastewater/stormwater stream scenarios depending on selected resource recovery infrastructure options

- Determine the main parameters considered within wastewater system effluent regulations and how to best represent them

- Create wastewater characterization variables that change depending on the specific stream selected by the user of the model (i.e. combined wastewater, greywater, blackwater, etc.)

- Develop a treatment technology selection module to represent primary, secondary, tertiary, and advanced wastewater treatment options with regards to user-defined removal efficiencies

- Define a list of simulation scenarios and a table of values that show the variation in model variables for each individual scenario

- Use the inputs of the technology selection module to simulate the quantity of resources recovered for each simulation scenario

- Translate the quantity of resource recovery products to a per capita monetary value, based on results from the literature and locally relevant market data

- Run the model with baseline conditions and generate comparative figures that represent the typical value of resource recovery products obtained from conventional municipal water systems

3.1.1 System Dynamics Modeling as a Framework for Municipal Water System Simulation

Simulation modeling has been used widely in research to improve the understanding and interconnectedness of municipal water systems. Figure 3 below describes the four main steps followed for the development of the model; 1. Conceptualization, 2. Formulation, 3. Verification & Validation, and 4. Application (Elsawah et al., 2017). The initial phase of the modelling process is the conceptualization phase which involves defining the reasons and motivations for the creation of the model. Prior to model formulation key aspects such as important data, information and knowledge elements must be identified. The next step in the modeling process is the formulation phase, which involves the selection of model features, including performance criteria, algorithms, and the identification of model structure and parameters. This step is followed by verification and validation which involves diagnostic testing to quantify uncertainty and evaluate the model. The final step is application, where the model is used to explore the systems represented and gather insights to the problem that may not have been easily identifiable using other techniques.

The double ended arrow at the base of the figure symbolizes the iterative process of model development (i.e. the extension of the existing model involved the conceptualization of new research questions and formulation of new model sub-systems, even after the model had already been validated and applied). Running simulations provide results that represent the modelled systems over a specified period of time. The VENSIM computer program used for this study is capable of simulating future scenarios by allowing the ability for the user to input values that interact with key system variables. Mathematical expressions and logical coding algorithms represent the relationships and feedbacks between variables and are specific to the study area and the defined overall boundary of the system analyzed. Scenario-based simulation modeling provides the ability to explore the economic and environmental effects of implementing and operating alternative solutions to reduce risk and improve public health. System dynamics models are typically used to answer "what if" questions rather than find the best option, which would be answered instead with methods of optimization.

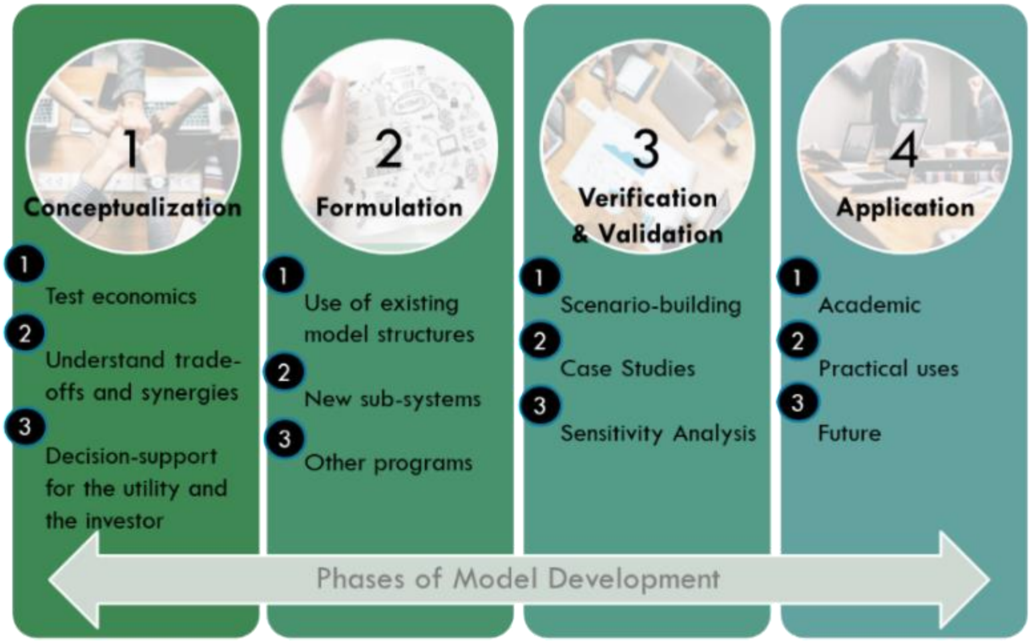


Figure 3 - Phases of model development

This system dynamics model incorporates Net Present Value (NPV) analysis and "real options theory" for the economic evaluation of disruptive resource recovery projects compared to the baseline. NPV analyses consider the full cost of projects and requires the inclusion of revenue streams that are linked to markets, and capital and operational costs that are incurred as a result of the investment. "Real Options" is a new framework in the theory of investment decision-making that modifies the traditional NPV method by involving the impact of future choices (Kenton, 2018). Municipal water utilities could potentially make decisions to alter the development plans and operations of infrastructure projects based on changing economic, technological or market conditions. Throughout the lifetime of an infrastructure investment decision makers have options to change the state of the project's initial intended utility. Real options refer to actual choices or opportunities of which the invested entities may take advantage; therefore factoring in real options affects the valuation of potential investments because it includes the consideration of benefits that commonly used financial valuations (such as NPV) fail to account for (Kenton, 2018). Incorporating economic analysis into the system dynamics approach is an effective tool to explore "Real Options Theory", allowing an opportunity for modelers and stakeholders to test the effect of different possible options in the future (using simulation and gaming). Decisions regarding the timing of a project are important, considering new data can provide an opportunity to learn more about the system and reduce uncertainty. Decision makers look to the future to evaluate growth opportunities, but they must also consider the flexibility of assets in place and whether there are options to abandon a process or switch to an alternative option if need be.

3.1.2 Causal Loop Diagrams

Qualitative system dynamics makes use of causal loop diagrams (CLDs) to represent feedback thinking and provide model developers and involved participants the ability to define relationships between system variables and identify the possible unintended consequences of various management actions (Wolstenholme, 1999). Representation of these relationships is referred to as mental modelling and involves explicitly mapping out all the components of the system to increase the understanding of the problem and make it transparent and visible for others (Haraldsson, 2004). CLDs are the core tool in systems thinking and can facilitate participatory diagramming to analyze cause-and-effect relationships, enabling decision makers to further explore and explain changes within a system (Sterman, 2000). The effect of compounding interest rate on an investment account can be used to represent one of the most well understood examples of feedback; Figure 4 below shows a positive feedback loop (often referred to as “reinforcing”) with positive signs of polarity on each of the variables. Positive signs indicate that the change of a specific variable causes an increase in the state of the variable that is directly connected with it.

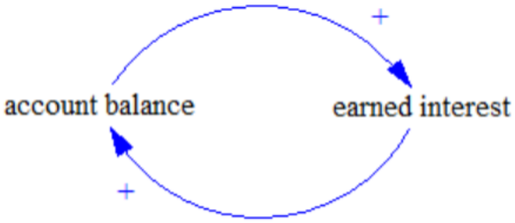


Figure 4 - CLD representing the relationship between account balance and earned interest over time

A “balancing” (negative) feedback loop occurs when the increase of one variable leads to the decrease of another or vice-versa, precisely when the amount of negative polarity signs in a multi-variable loop is an odd number. In reality the “account balance” and “earned interest” variables introduced above are complex systems that are made up of multiple sub-systems comprised of several circumstantial variables. These variables depend on relevant case-specific information, such as factors encompassing the owner of the account and the state of the economy, amongst others. As causal loop diagrams expand multiple feedbacks may interact with each other leading to various modes of dynamic behavior exhibited by variables (i.e. exponential growth, goal seeking, oscillation, S-shaped growth, overshoot and collapse) (Mirchi et al., 2012).

Another important concept relevant to the development of the model is shifting loop dominance. This behavior is represented with a causal loop diagram shown in Figure 5 below. The model presented in the following chapter is routed in the Theory of Diffusion of Innovations (TDI) for both the water management policies section and the additional components for the implementation of various resource recovery options. Recovering resources from wastewater streams is considered an innovation, and in 1962 Rogers stated that diffusion is the process by which an innovation is communicated over time amongst the participants in a social system. The rate of adoption is defined as the relative speed by which innovations are adopted by members of a social system and is typically quantified as the number of people who adopt a new idea or technology in specified period of time (Rogers, 2010). According to Rogers, TDI describes how innovations are adopted and the adoption rate is accelerated through a "word of mouth" positive feedback loop. The theory also describes how the level of adoption will eventually start to approach the saturation level and taper out, making the saturation level the stabilizing factor in the figure below. This behavior, when represented in graphical format typically displays an "S-shaped" curve, which can be simulated using the equation of a sigmoid curve.

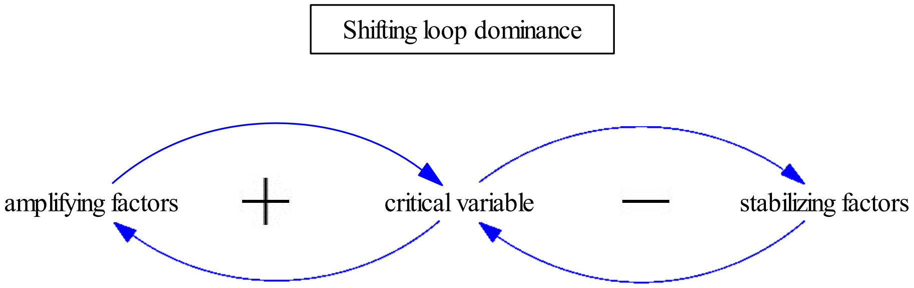


Figure 5 – CLD representing shifting loop dominance

3.1.3 Stock and Flow Diagrams

Stock and flow diagrams (SFDs) are another key tool of system dynamics that allow modelers to represent balances and rates of change over time through the extension of CLDs to further define the system and create model structures that are capable of dynamic simulation. Figure 6 below demonstrates a functional SFD representation of the CLD presented in the last sub-section regarding the simulation of the relationship between account balance and earned interest over time. In this simplified model, earned interest is now shown as a rate of change and the account balance is a stock that is assumed to have no outflows. Seemingly simple sub-systems must be expanded to accurately represent real life, such as the necessary inclusion of variables that describe depreciation and economic uncertainty. Nonetheless, this section serves to introduce and provide an image of CLDs and SFDs, the two main tools used within system dynamics modeling.

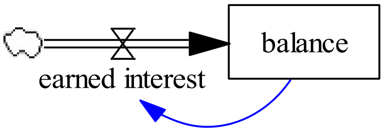


Figure 6 - SFD used for the simulation of the stock "balance", dependent on the inflow "earned interest"

3.2 Study Area

Planners (such as engineers, utility managers, politicians and suppliers) depend on data and relevant case studies to make informed decisions. Sustainable systems designed based on the principle of resource recovery need to be critically evaluated before they can be seriously considered. The selected study area significantly influences the development and structure of the applied system dynamics model. Specific relationships between people, the environment, and the government always exist and must be identified within the conceptualization phase of model development (Daley et al., 2015). Trends such as rapid population growth, climatic changes, and increasing regulatory mandates are often specific to an area and must be incorporated into the model. This section includes an overview of the selected study areas and the location-specific drivers that necessitate further research and analysis, such as the development and application of decision support tools.

3.2.1 Calgary, AB

The City of Calgary, Alberta has implemented a number of water conservation initiatives in the last few decades, including water metering, incentivized adoption of water-efficient appliances, improved leak detection, and educating citizens about water use and conservation. The City's "30-in-30 Water Efficiency Plan" plan identifies water efficiency targets and outlines how various strategies will reduce water use, water loss and wastewater volumes within the municipality (The City of Calgary, 2007). The plan presents a wide range of water management strategies that are incorporated into the CWMM model used for this research. An update of the plan published in 2016 reported that the city was on track to achieve its goal, but the relative effect of each of the various water management strategies is unknown. One of The City's core water efficiency strategies is to match water quality to water use. The plan makes specific mention of reusing stormwater and wastewater streams for specific end-uses to reduce water abstraction, treatment, and distribution. The model presented in the following chapters tests the relative impact of water reuse strategies in Calgary implemented over the next 20 years.

In the City of Calgary (similar to most developed cities), expansive collection systems move wastewater by a system of both gravity and pressurized networks and pump stations to large treatment plants, located at different points along the riverside. The City has three wastewater treatment plants that all employ conventional activated sludge processes as shown in Figure 7, with further treatment requirements satisfied by advanced filtration and ultraviolet disinfection technologies. Approximately 90% of water that is treated for municipal use is returned to the river following downstream treatment. The City ensures high-quality effluent and consistently exceeds stringent requirements and environmental regulations. The City of Calgary's Biosolids Management Program is unique: while all solids go through a gravity thickener, fermenter, and digester, there are two solids sub-streams involving separate processes and applications. Stream one supplies the "Calgro" program, where biosolids produced in the spring and summer go to lagoons to settle for six weeks, prior to being transported to agricultural lands and applied using machines. In 2017, the City also opened a composting facility that produces compost from food and yard waste, and from the second biosolids stream. In the fall and winter, most of the biosolids are dewatered and composted for about 60 days, where it is converted to "high quality Category

A" compost and sold as a soil amendment used to enrich agricultural soils. A portion of the finished compost is made available to residents for free. The municipal water system also contains a separated stormwater system that collects precipitation and discharges it directly to the watershed through piping systems and nature-based infrastructure (such as stormwater ponds and engineered wetlands), which discharge directly to the local watershed (i.e. the Bow River).

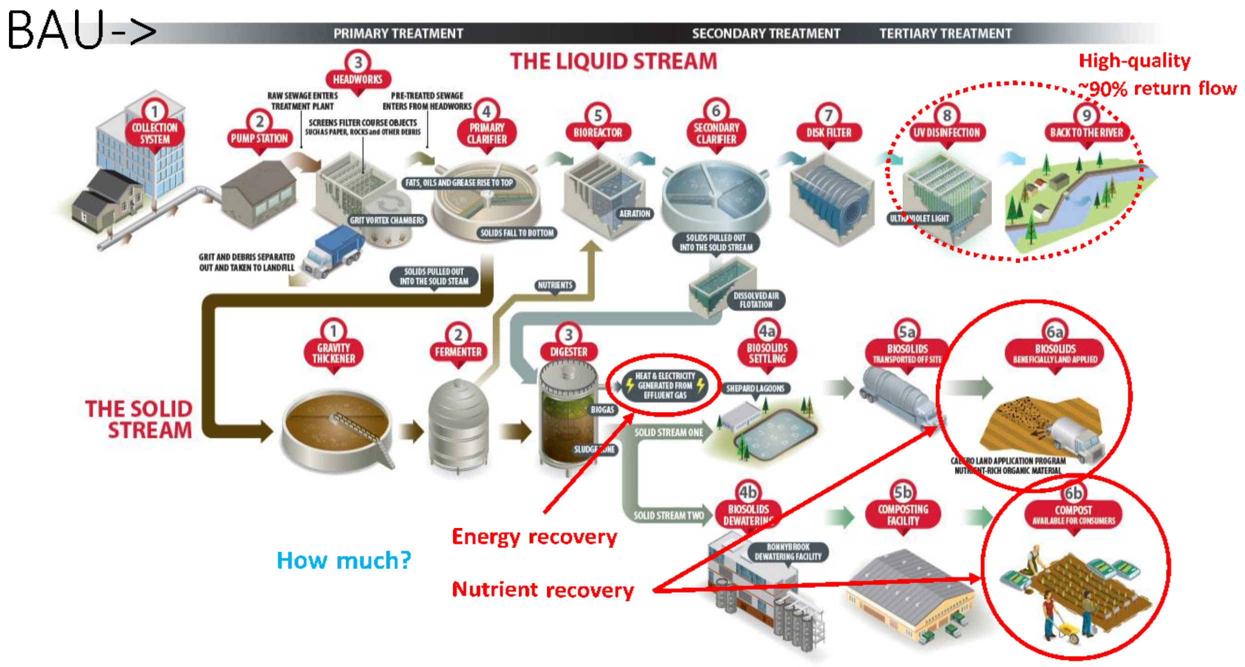


Figure 7 - The "Business as Usual" scenario for Calgary – centralized advanced treatment with high quality return flow (tertiary treatment with UV disinfection), nutrient recovery through biosolids program, and energy recovery through co-generation (City of Calgary, 2023).

The City of Calgary monitors wastewater coming from commercial customers for over-strength wastewater and prohibited materials. In recent years many ICI customers that depend heavily on municipal water utilities have demonstrated the feasibility and benefits of decentralized treatment systems process water effluent volume or pollutant concentration and limit wastewater surcharges. Some businesses have even achieved "zero discharge" by implementing on-site treatment systems and complete cycle reuse of process water. The Sankey diagram in Figure 8 shows the "per capita" potential for greywater reuse in Calgary, assuming 100% residential greywater and ICI water reuse. While this scenario shows the full potential of greywater treatment and reuse, practical implementation would require rapid overhaul of the entire water and wastewater system in the Calgary Economic Region. A more realistic approach involves the gradual implementation of new mixed-development communities designed with source-separated systems.

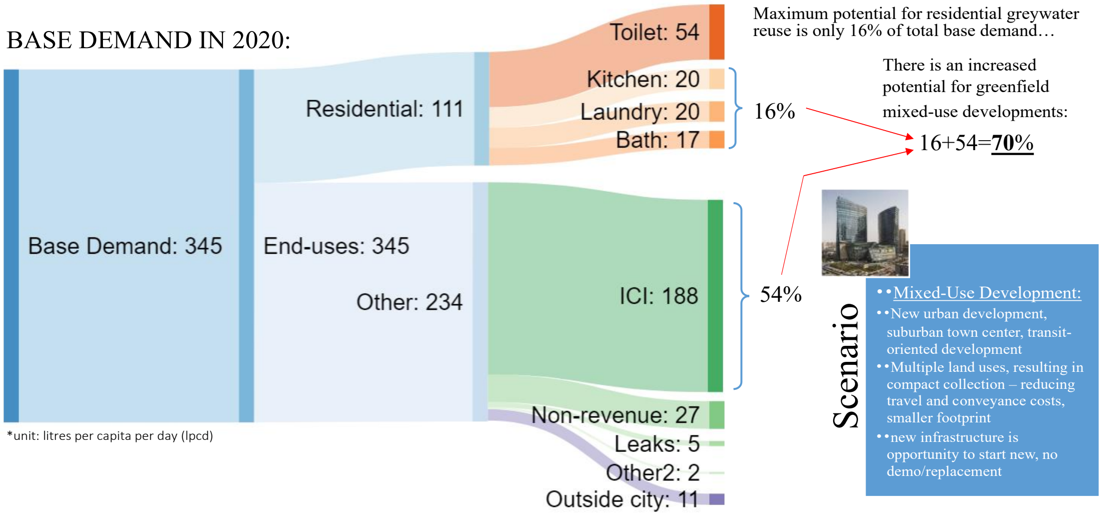


Figure 8 - Source-separated greywater reuse for greenfield mixed developments. There is a much larger weighted impact for combined mixed-use developments with broad-scale greywater reuse strategies.

3.3 Regulation and Governance

The regulations below are taken into consideration for the development of the model to ensure that simulated treatment systems meet or exceed the requirements. The model presented in the next chapter considers relevant regulation and governance regarding wastewater systems effluent and the reuse standards for the selected study areas. This section includes an overview of the applicable regulations and standards that are important to the development and use of the model.

Wastewater effluent affects the natural environment, and environmental compliance has been of paramount concern for both the private and public sector as a result of green initiatives in developed countries gaining traction in recent years. Municipal water planning and management is the responsibility of local governments. The local governments of Canada are formed by a charter or act granted by the province or territory and the actions of a municipality must be within the parameters set in its enabling legislation. Furthermore, since municipal authority is delegated by the legislation of the province, a municipality cannot assert authority over matters that are not within provincial jurisdiction. Both federal and provincial governments have legislative authority relevant to environmental matters, which means that the regulation of wastewater system effluent is a matter of overlapping and concurrent legislative authority (Brenda Heelan Powell, 2018).

The purposes of a municipality, as defined by Section 3 of the Municipal Government Act (Province of Alberta) are to: a) provide good government, a.1) foster the well-being of the environment, b) provide services, facilities or other things that, in the opinion of council, are necessary or desirable for all or a part of the municipality, and c) develop and maintain safe and viable communities, and work collaboratively with neighboring municipalities to plan, deliver and fund intermunicipal services. In 2017, Section 3 was amended by adding the statement regarding the environment after clause (a). The amendment made by the MGA demonstrates the provincial government's recognition of the environment as an important factor in the well-being of a community.

All wastewater systems in Canada must abide by the federal Wastewater Systems Effluent Regulations. Section 6(1) of the regulations specify that the owner or operator of a wastewater system may deposit effluent through the final point of discharge after reporting that effluent sampled in the previous calendar year met the following conditions:

a) the average carbonaceous biochemical oxygen demand due to the quantity of CBOD matter in the effluent did not exceed 25 mg/L;

b) the average concentration of suspended solids in the effluent did not exceed 25 mg/L;

c) the average concentration of total residual chlorine in the effluent did not exceed 0.02 mg/L, if chlorine, or one of its compounds, was used in the treatment of wastewater; and

d) the maximum concentration of un-ionized ammonia in the effluent was less than 1.25 mg/L, expressed as nitrogen (N), at 15°C ± 1°C.

The averages and maximums must be determined monthly, quarterly, or annually depending on the average daily volume of effluent deposited (with different volume thresholds for both intermittent and continuous wastewater systems). The Province of Alberta recognizes that there is growing interest in using reclaimed wastewater for various end-uses and that these strategies pose health and environmental risks. Reclaimed wastewater from any source cannot be used domestically unless it is approved and meets water quality testing and monitoring by the local municipality. The plumbing code allows approved reclaimed wastewater systems to be used for toilet and urinal flushing or underground irrigation. Public Health Guidelines for Water Reuse and Stormwater Use provides information for applicants to consider that will help them create an effective water quality management plan to support their project application (Alberta Health, 2021).

4. Description of the Simulation Model

The decision support tool presented in this chapter is designed to explore the potential realization and value of specific resource recovery products. The model components described in this chapter are used to assess resource recovery options within existing municipal water utilities in the medium to long term (10-30 years), based on simulations that calculate the quantity and quality characteristics of wastewater and stormwater streams. The model quantifies the amount of wastewater produced per person in the City of Calgary, assigns quality characteristics, and simulates the resources (water, energy, nutrients) that can be recovered on a per capita basis depending on the strategy selected. The strategies/scenarios explore resource recovery within a conventional centralized system and also the diffusion of decentralized source-separated systems within an existing municipal water system. The model's input parameters are customized for the City of Calgary, including variables such as population and precipitation to quantify the amount of stormwater produced for potential reuse.

The system dynamics model presented below represents real world processes through nonlinear feedbacks, changing variables, and delays – and is intended to increase the understanding of the connections that exist between resource recovery sub-systems and various "external" systems (such as the relationship between enacting water management policies and the implementation of actual water-related infrastructure investments). The model is not intended to be an optimization tool; therefore it will not suggest the "best" solution to an infinite universe of alternatives. Rather, the system dynamics approach has been applied to assess the implementation of new strategies that are designed based on the principle of resource recovery. Causal loop diagrams and stock and flows represent the structures required to run simulations and explore the relationships of the various system components involved with the implementation of wastewater resource recovery strategies such source separation for advanced per capita water, energy and nutrient recovery.

4.1 Recent Updates: Resource Recovery Systems for Water, Energy, Nutrients

This section describes model components created to represent the simulation of the amount of water, energy, and nutrients that can be recovered from municipal wastewater and stormwater streams. The components of the model in this section represent a tool for simulating the value of resources that can be recovered from different municipal wastewater streams including combined (total wastewater), blackwater, greywater, and stormwater. This section includes equations and figures of the causal diagrams and stock and flow structures for the new model modules (stream selection, wastewater characterization, resource recovery strategy selection, and economic assessment tools). The tools presented below consists of both knowledge mapping and simulation tools that considers municipal water utilities as integrated systems where material flows are considered potential resources. The interconnectedness of the overall system is represented by mathematical relationships between various variables and sub-systems.

The CWMM simulates a variable called "per capita daily municipal water demand by category" which represents the historical and simulated quantitative value of water (in liters per capita daily) used by residents of the City of Calgary (DeOreo, 2016; Wang & Davies, 2018). This variable contains subscripts for numerous water demand end-uses (including toilet, bath, laundry, kitchen, leaks, other, outdoor, ICI, nonrevenue, and outside city), as described in section 2.3.3 and shown below in Figure 9.

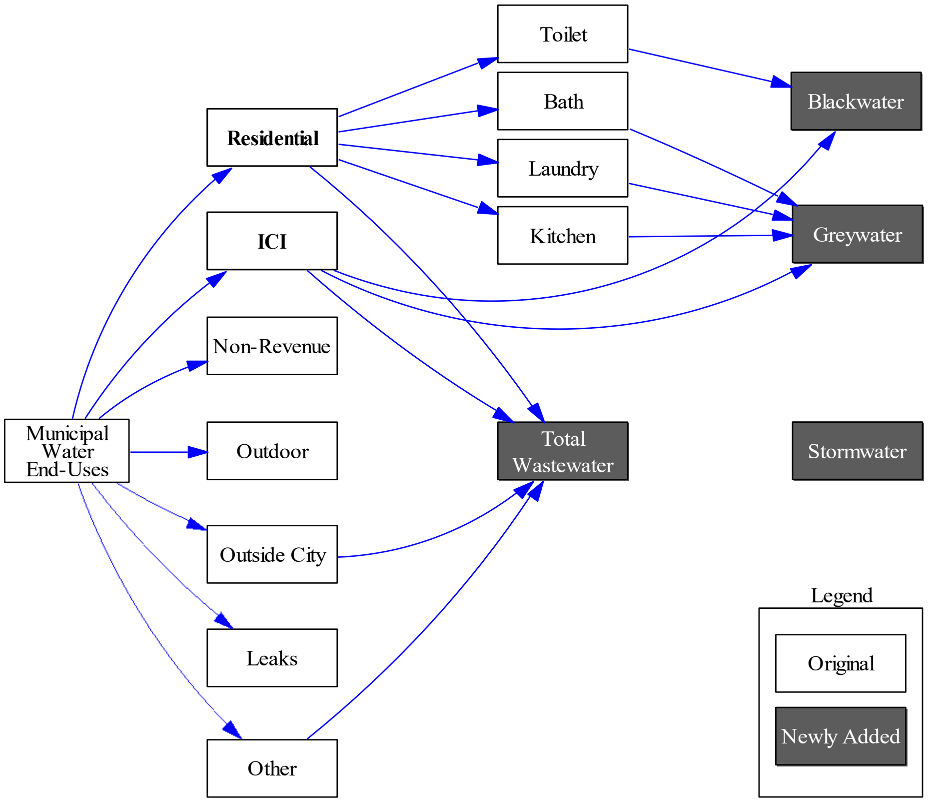


Figure 9 - End-use framework of the modified model to produce new variables for blackwater, greywater, total wastewater, and stormwater

The simplified model structure shown below in Figure 10 illustrates how recent updates fit within the pre-existing structure of the CWMM. The main additions include components for stream selection, wastewater characterization, resource recovery strategies selection, and economic assessment. The stream selection and wastewater characterization section pairs quantitative water demand results with typical wastewater quality parameters. The concentration of various "pollutants" determines the potential for recovery (i.e. highly concentrated wastewater has a higher per capita resource recovery rate). Allowing the user of the model to specify or change input parameters provides decision makers the ability to test a wide range of scenarios with a very fast simulation run time into the future. The model provides the ability to select specific resource recovery strategies such as source-separated sewer systems where greywater is recycled and blackwater is exploited for energy and nutrient recovery. Users can test the economic viability of a strategy using a financial model that projects all of the future revenue inflows and avoided costs associated with an investment, discounted to presented day using a defined interest rate.

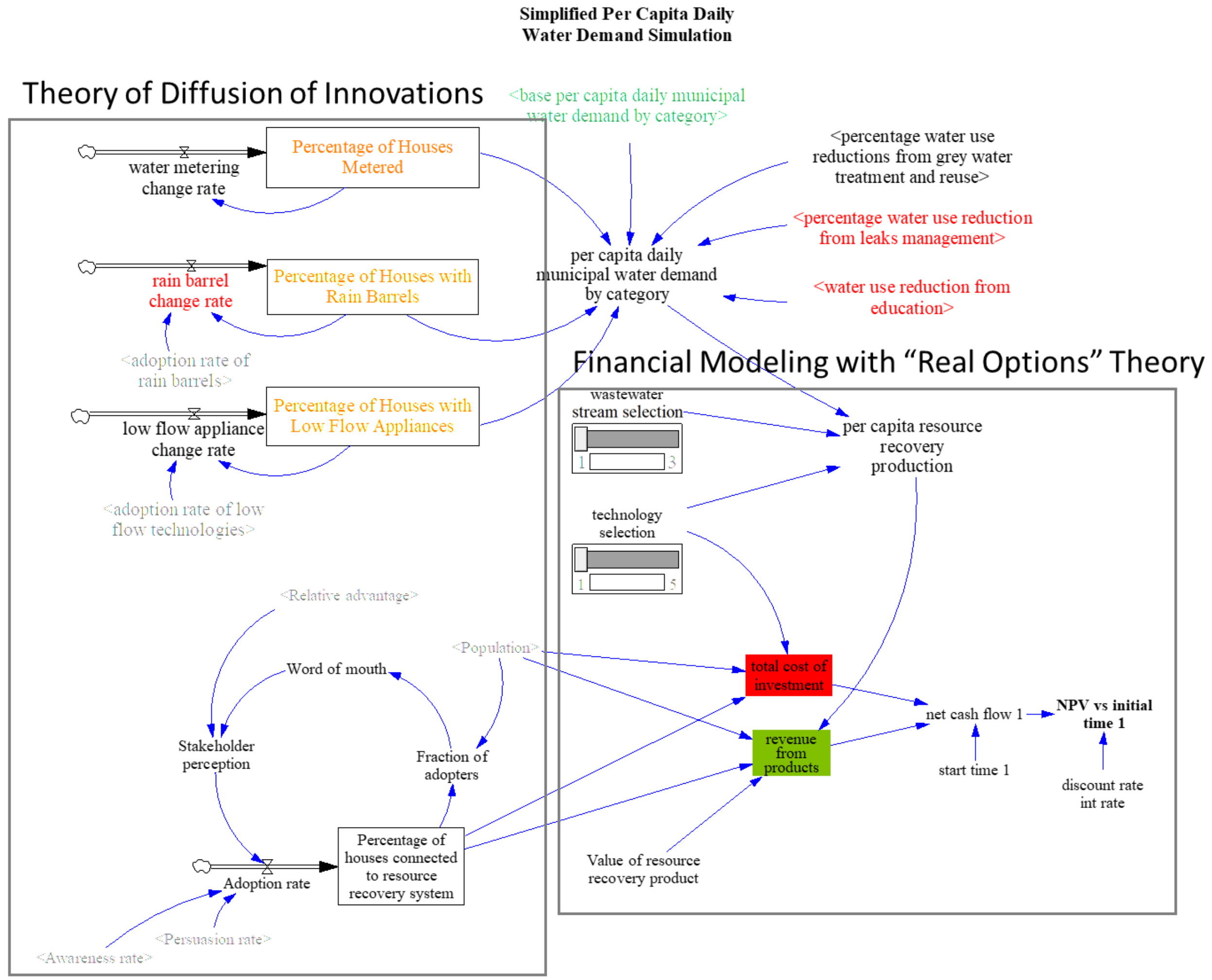


Figure 10 - Basic structure of the system dynamics model depicting how recent updates fit within the existing structure of the CWMM

4.1.1 Stream Selection, Wastewater Characterization and Treatment

The quantity and quality of wastewater produced by municipal utilities are key parameters for the design and operation of new municipal water systems. This sub-section describes the stream selection and wastewater characterization and treatment modules, which exist so the user can specify the type of wastewater being analyzed and explore the potential pathways for resource recovery. The quantity of wastewater simulated depends on derivatives of the "per capita daily municipal water demand by category" variable (PCWD), a pre-existing model variable that quantifies the volume of water used (per capita per day) by summing individual end-uses including toilet, bath, laundry, kitchen, leaks, outdoor, industrial/commercial/institutional (ICI), nonrevenue, outside city, and "other".

The first required user-defined input for the stream selection component of the simulation model is the specification of the "stream selection" variable. This variable is programmed as an "Input Output (IO) Object" within the Vensim software toolkit. The IO Object tool class allows the addition of input sliders that the user can alter to set the value of constants or simulation variables (prior to and throughout the simulation). This flexibility within the model interface allows users to navigate to a specific view (or "tab") of the model and set the water stream that is being analyzed; total wastewater (combined), source-separated streams (greywater or blackwater), or stormwater. The equation below for "per capita daily quantity" calculates the volume of wastewater/stormwater (per capita per day) and is dependent on the user-specified value of the stream selection variable.

$$\begin{aligned} per\ capita\ daily\ quantity = IF\ THEN\ ELSE(&stream\ selection \\ &= 1, total\ wastewater, IF\ THEN\ ELSE(stream\ selection \\ &= 2, greywater, IF\ THEN\ ELSE(stream\ selection \\ &= 3, blackwater, per\ capita\ daily\ stormwater))) \end{aligned}$$

The specific end-uses that make up each of the stream selections are shown below in Figure 11. Combined residential wastewater and "total wastewater" is typically defined by conventional systems including flows collected from the shower, toilet, kitchen, laundry, and "other" end-uses. The greywater stream includes wastewater collected from the shower and laundry, while the blackwater stream represents flows generated by the toilet and potentially the kitchen (especially when kitchen food waste/organics are to be considered as part of the blackwater resource recovery strategy for enhanced energy recovery).

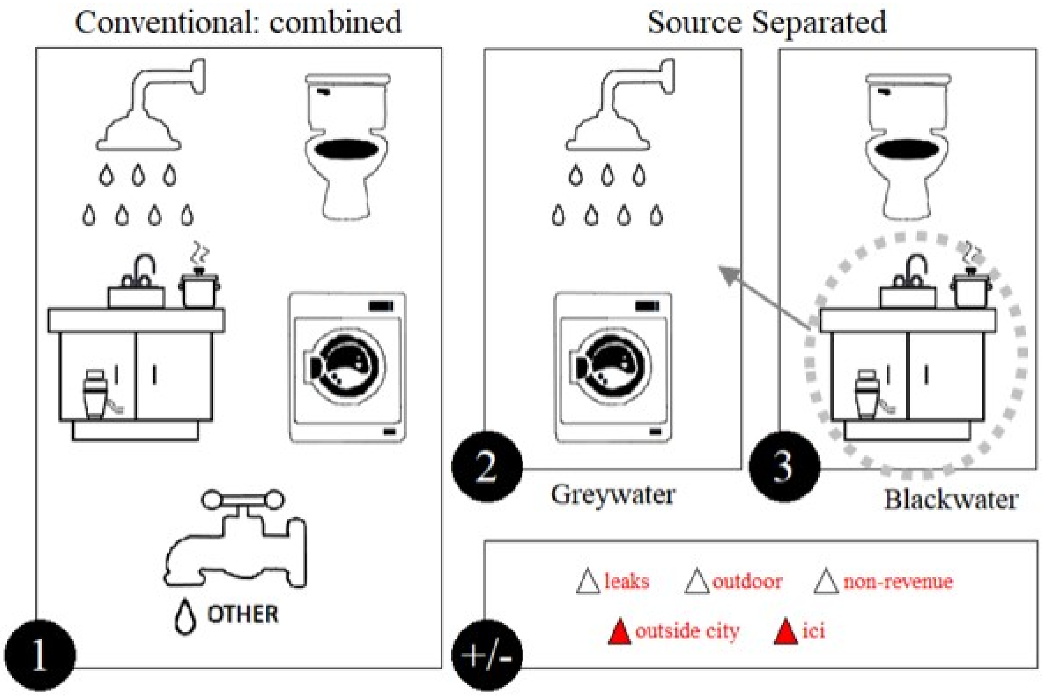


Figure 11 - Depiction of the end-uses included in each of the "stream selection" options

Kitchen wastewater could be treated with the other greywater sources, for example if the resource recovery strategy aimed to generate an extremely low flow and highly concentrated blackwater stream (such as from vacuum toilets that operate with only a 1L or less flush volume). In this case extra care would have to be taken to treat the greywater to a high-quality prior to releasing to the environment or reusing, in order to ensure the removal of pathogens, grease, bacteria, and other contaminants generated from kitchen water uses. The other end-uses are represented as optional additions to either of the streams. While leaks, outdoor, and non-revenue uses are very unlikely to be included in the wastewater stream – "outside city" and "industrial-commercial-institutional (ICI)" are important end-uses for municipal water utilities and most often generate wastewater flows that connect to the municipal sewer conveyance and treatment systems.

Figure 12 below depicts the stream selection and wastewater characterization model interface view, where multiple IO slider tools are used to specify the stream selection and wastewater treatment level for each scenario considered in the next section. The wastewater quality parameters are dependent on the stream selection input that is defined by the model user. The assigned wastewater characterization parameters include total suspended solids (TSS), chemical oxygen demand (COD), biological oxygen demand (BOD), total phosphorous (P), total Kjeldahl nitrogen (TKN), nitrate (NO3-N), and ammonium-nitrogen (NH4-N). The assumptions for the typical quality characteristics of combined, greywater, and blackwater are provided in Table 1 below have been adapted from (Garrido-Baserba et al., 2018). The unit of measurement for all wastewater characterization parameters are represented in mg/L. The equations contained within the wastewater characterization variables utilize nested "IF THEN ELSE" statements that have Boolean expressions testing whether the stream selection variable is set to "1" (for total wastewater), "2" (for greywater only), or "3" (for blackwater only). An example of how the model assigns quality parameters is shown below for the total suspended solids (TSS) wastewater characterization parameter. The function performed by the equation sets the TSS at either 410 mg/L for combined wastewater stream, 175 mg/L for greywater, or 8360 mg/L for blackwater (depending on the user-defined stream selection slider).

$$TSS = IF\ THEN\ ELSE(stream\ selection = 1{,}410, IF\ THEN\ ELSE(stream\ selection = 2{,}175, IF\ THEN\ ELSE(stream\ selection = 3{,}8360{,}410)\ )\ )$$

If the assumed characteristics for the wastewater streams are not accurate for the selected study area, the formulas can be easily adapted to represent local wastewater characterization conditions (such as the specific concentrations of contaminants within the selected water stream). If no entry is made the model assumes "total wastewater" as the default value for stream selection and the simulation of the corresponding "per capita daily quantity" and wastewater characterization values.

Table 1 - Assumed wastewater characteristics for each stream (all numerical values are represented in mg/L)

Parameter	Combined	Greywater	Blackwater
TSS	410.8	175.9	8360.0
COD	701.3	472.2	10560.0
BOD	248.6	175.9	3560.0
TP	13.7	4.6	306.0
TKN	86.1	2.3	2500.0
NH3-N	6.1	2.3	132.4

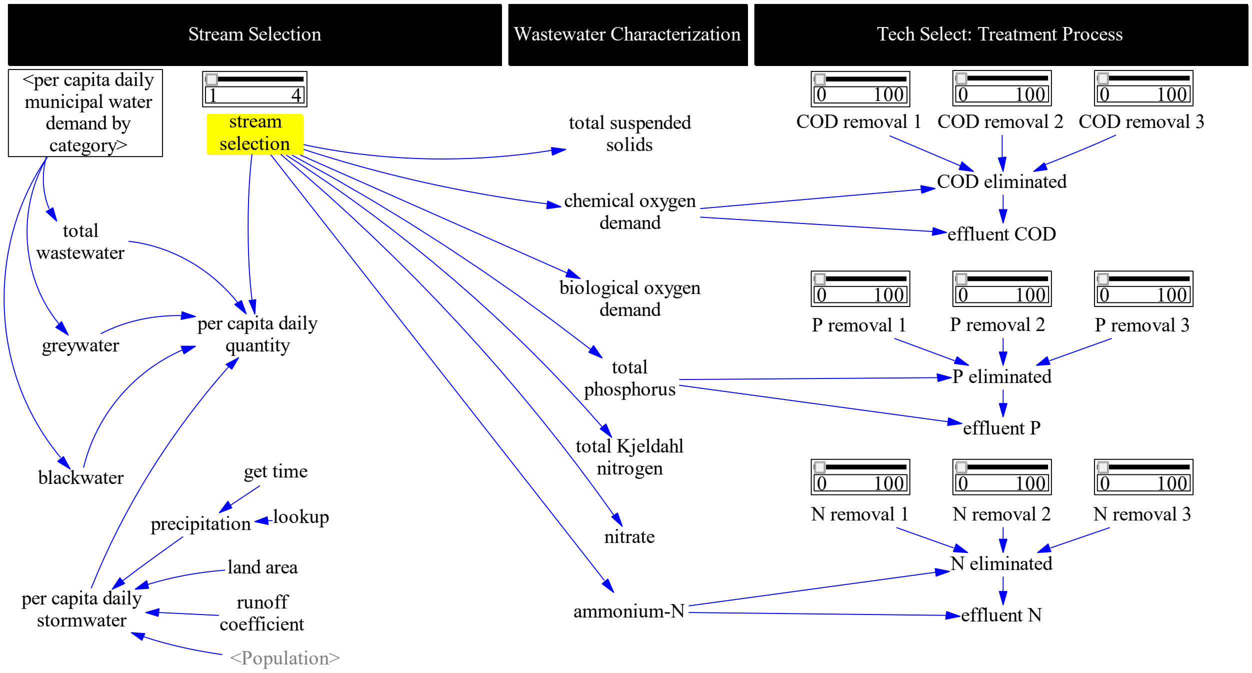
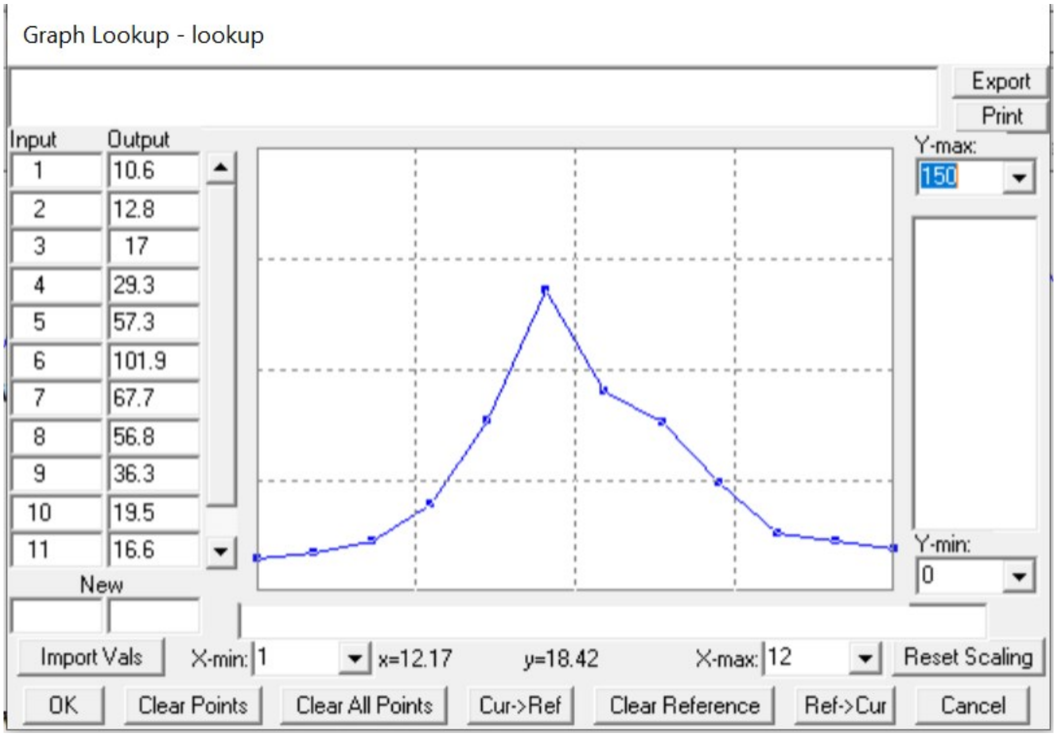


Figure 12 - Model structure for the Stream Selection, Wastewater Characterization, and Tech Select: Treatment Process modules

The "Tech Select: Treatment Process" module allows the user to input specified levels of treatment for COD, P, and N within the gaming mode. Users of the model can specify their current (or desired) treatment system and test the effects of implementing various resource recovery systems into the future. The exact choice of treatment technologies is not important for this analysis, rather the removal efficiency and productivity of the selected overall treatment/resource recovery train is varied under a range of specified conditions based on the desired scenario simulations. Removal efficiency variables represent primary, secondary, and tertiary treatment for the three main water quality characteristics considered (COD, P, and N). Three sliders for each parameter were created so that users can test the effects of implementing new systems and also the effects of infrastructure upgrades (such as expanding primary treatment to secondary, or secondary to tertiary systems). The "COD" and "P" eliminated variables represent the quantity removed from the selected wastewater streams by current or projected treatment systems and are important variables for the following sub-section which describes the implementation of specific source-separated resource recovery strategies.

Stormwater represents another high-potential stream for water capture and reuse for end-uses such as outdoor use (irrigation, car washing, etc.), which is significantly greater in the summer months. This section of the model introduces a "stormwater" variable that is defined by parameters such as precipitation, land area, and a runoff coefficient that are specific to the area of study. The stormwater variable provides a rough estimate of the total quantity of stormwater available at different times throughout the year by multiplying weekly precipitation values by the land area and a runoff coefficient. The value is represented in "liters per capita daily" which is the same unit as the other stream selection variables.

The amount of precipitation is calculated using a "Lookup" function that simply contains a list of numbers represented on an x-axis and a y-axis. The inputs to the lookup are positioned relative to the x-axis, and the output is returned as the corresponding value from the y-axis. This specialized function requires local precipitation data, such as average precipitation values for the City of Calgary. Monthly normalized data from federal government records (Environment and Climate Change Canada) is used as input data for this section. The equation for the "average weekly precipitation" variable makes use of a "GET TIME VALUE" function that returns the specified measure of time (relative to the current, initial, or clock time) offset by a specified amount. Considering the model runs at a weekly time step, any week within the month of January throughout the simulation will return a value of "1". The lookup function shown below in Figure 13 has "x" values ranging from 1-12 for each of the months of the year. When the representative number of the month is used as the input, the function returns the appropriate corresponding y-value (i.e. the average precipitation for the month of January in Calgary). The standard deviation of the normalized averages ranges from ± 47% (± 27.1mm) for the month of May to ± 77% (±9.9mm) for February. The average percent difference between the normalized monthly average values and the standard deviation upper/lower bounds throughout the year is ±62%, indicating significant variability in the stormwater variable. This means that for stormwater resource recovery systems the amount of stormwater available during any given month may be approximately 60% lesser/greater than the water available in any other given year.



Graph Lookup - lookup

Input	Output
1	10.6
2	12.8
3	17
4	29.3
5	57.3
6	101.9
7	67.7
8	56.8
9	36.3
10	19.5
11	16.6

Y-max: 150

Y-min: 0

X-min: 1

x=12.17

y=18.42

X-max: 12

Figure 13 - *Monthly precipitation lookup function for the City of Calgary*

4.1.2 Resource Recovery Strategies: Diffusion of Innovations

Municipalities have great potential to generate numerous resources including water, energy, and nutrients from wastewater and stormwater streams. The purpose of the resource recovery strategies section is to allow the user to simulate how resource production values change depending on the stream of wastewater considered and the efficiency of the technologies assumed to be implemented for water, energy, and nutrient recovery. Figure 14 below shows the interface of the resource recovery strategies view. When the input slider is set to “0”, the model assumes no level of resource recovery. Setting the resource recovery slider to another value (1-5) triggers the assignment of constant values and operation of formulas that adapt according to the scenario being simulated (described in Section 4.2).

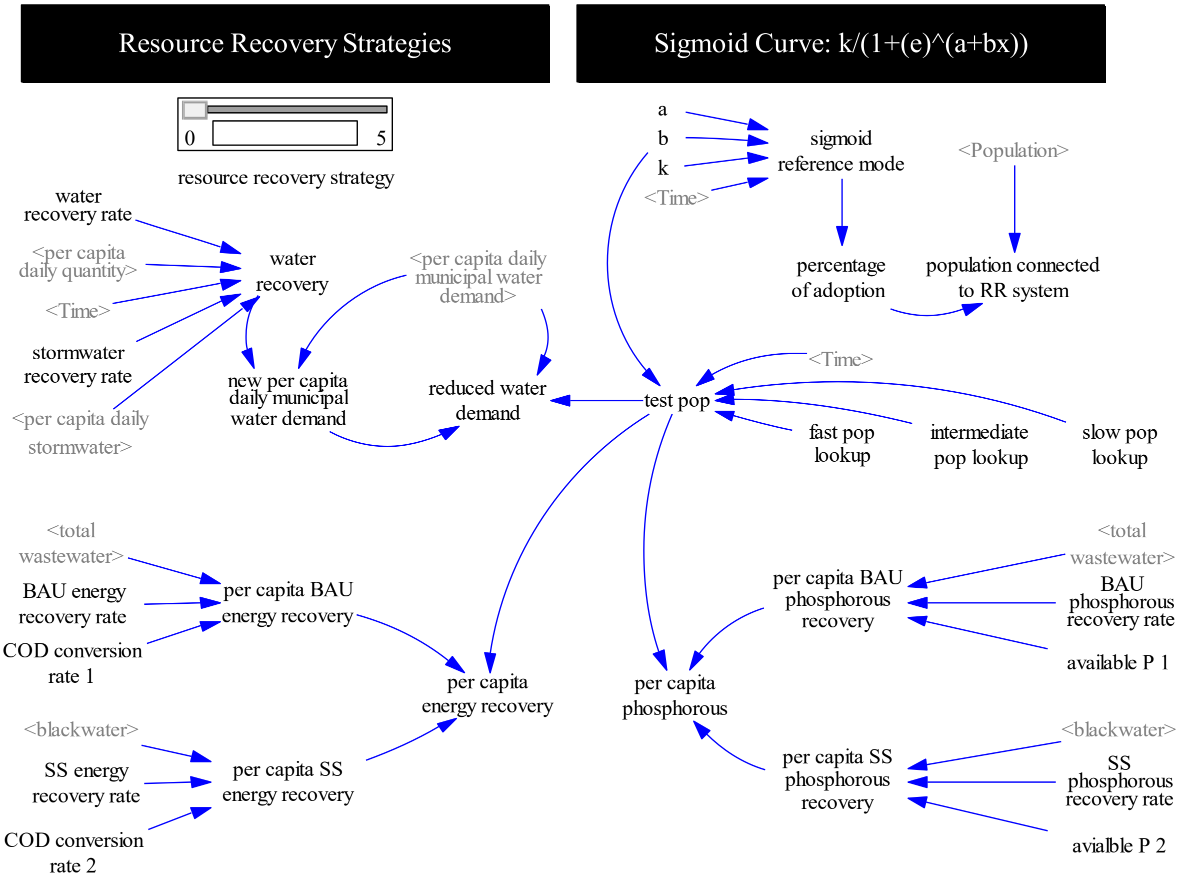


Figure 14 – Resource recovery strategies

The adoption of innovations follows a bell-shaped curve when plotted over time on a frequency basis (rate of adoption), and when the cumulative number of adopters is plotted the result is typically an S-shaped curve (Rogers, 1983). The rate of change and variables that represent this typical behavior within the water industry depend on many factors such as the stakeholder's knowledge of the innovation coupled with a wide range of factors that influence the decision to adopt new systems. The interrelated factors that influence this decision-making process include things like the relative effect of "word of mouth", advertising, the attitude/power of stakeholders, and also the economic and environmental feasibility of implementing new systems (Prouty et al., 2018). These variables are difficult to quantify explicitly and therefore the diffusion of water-based resource recovery systems is represented by an assumed "percentage of adoption" curve that can be altered by the user of the model to represent the most realistic diffusion of resource recovery strategies into the future based on local contexts. The equation of a sigmoid function is used to develop reference modes representing the population affected by various resource recovery strategies. The equation below generates the degrees of implementation reference modes shown in Figure 15, where “k” represents maximum theoretical percentage of adoption of (85%), “x” represents the current “time” value of the simulation, and “a” and “b” are scaling factors that influence the shape of the S-shaped growth. By 2043 (end simulation time), the approximate percentage of adoption by the year 2043 for “fast”, “intermediate”, and “slow” is 80%, 50%, and 20% respectively.

$$percentage\ of\ population = \frac{k}{(1 + e^{(a+bx)})}$$

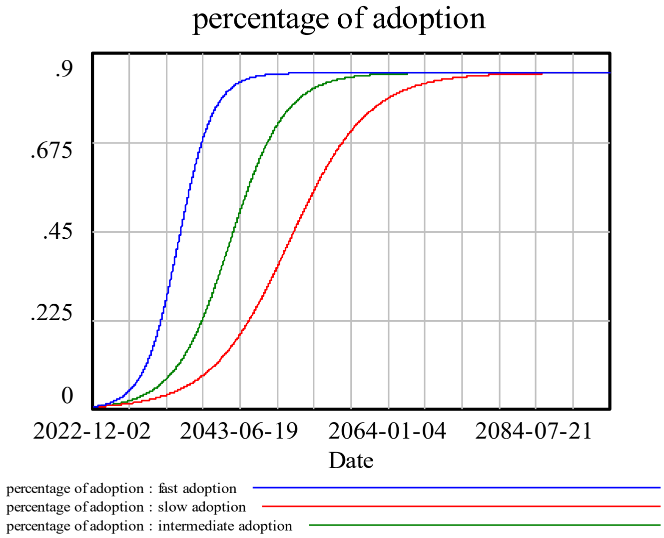


Figure 15 - Percentage of adoption reference modes

The “reduced water demand” variable shown above in Figure 14 is calculated using the following weighted average formula shown below, where the “test pop” represents the percentage of the total population that is serviced by resource recovery systems (for water, energy, and nutrient recovery).

$$reduced\ water\ demand = per\ capita\ daily\ municipal\ water\ demand \times$$

$$(\,(1 - test\ pop) + (test\ pop \times \frac{new\ per\ capita\ daily\ municipal\ water\ demand}{per\ capita\ daily\ municipal\ water\ demand})\,)$$

The “per capita energy recovery” and “per capita phosphorous” variables are also calculated using a weighted arithmetic mean, where the weights of the individual averages are expressed as the percentage of the total population that is serviced by either conventional (existing) and decentralized (source-separated) resource recovery systems.

4.1.3 Economic Assessment Tool

The economic assessment described in this section considers the financial return on investment of specific resource recovery strategies and the projects required to achieve the goals of the municipality. The following figures bring both NPV and Real Options financial analysis methods into consideration. For example, co-digestion is a proven strategy to optimize organic waste management and simultaneously enhance biogas production from sewage sludge. Logistics of the organic material, regional energy prices, changing consumer behaviour, and the efficiency of the technology deployed are only a few factors that are to be considered prior to integrating co-digestion as a resource recovery strategy. The net present value tool shown below in Figure 16 is used to test the economic viability of investing in co-digestion facilities for enhancing biogas production. This model can easily be converted to test other energy recovery strategies.

The externalities associated with non-renewable resources can be complex and unpredictable; therefore in some cases assumptions have been made regarding the future fate of resources (such as the cost per kWh of energy) to further understand the potential variation in the value of the resources being recovered.

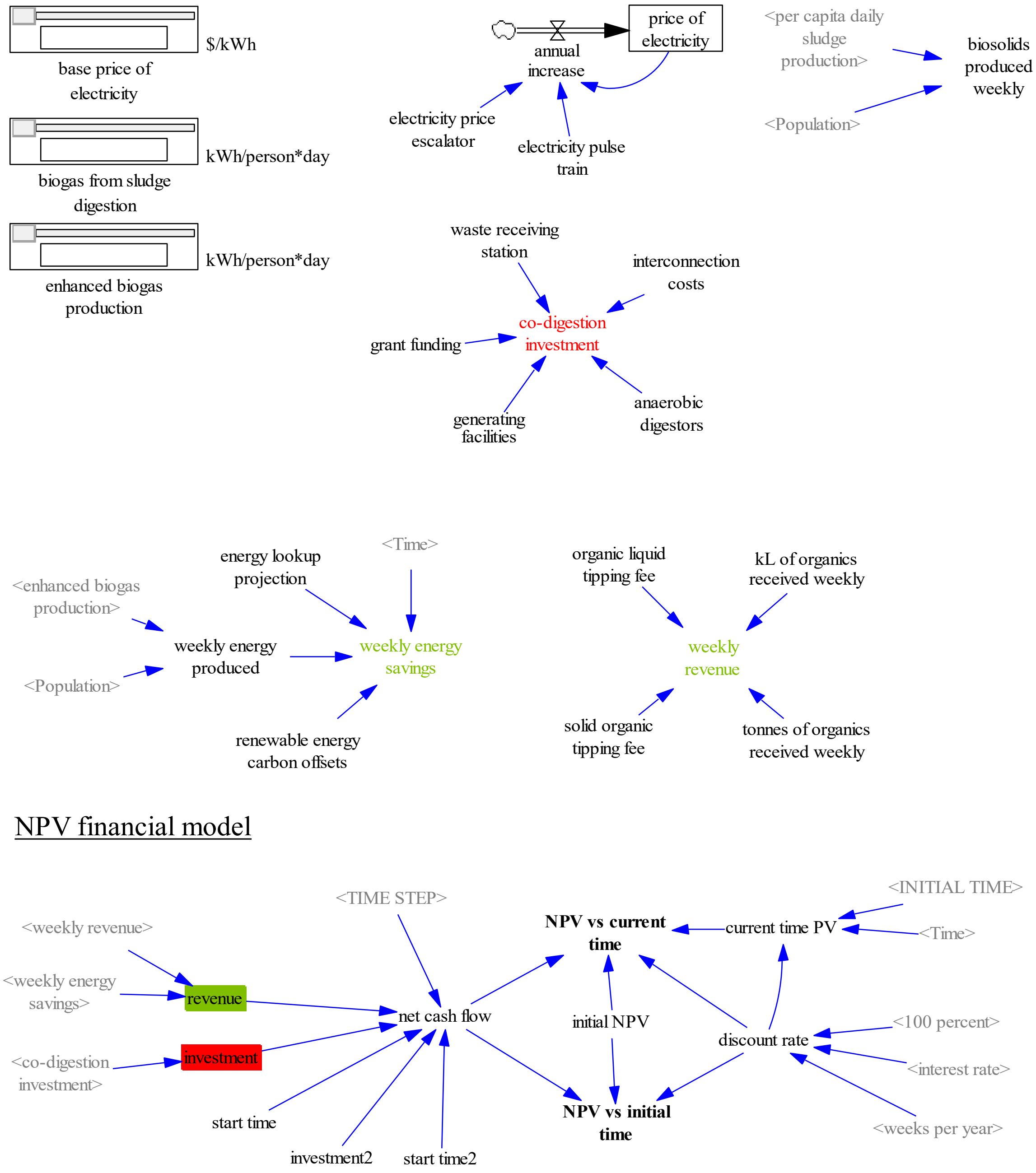


Figure 16 - NPV financial analysis model

4.2 Scenario Descriptions – List of Simulations

The simulation model is designed to test different possible future scenarios, such as the “business as usual” case against various possible alternative future scenarios. The end-use based design of the model provides an opportunity to experiment with different simulation runs and explore how water end-uses change over time based on the implementation of various water efficiency and resource recovery strategies. Table 2 below lists the various simulation groups and the default value of individual input parameters for each of the possible scenarios described in this section. The BAU and source separated (SS) energy and phosphorous recovery variables shown in Figure 14 are assigned the values shown in Table 2, depending on the user-defined slider selection for the specified resource recovery strategy. Selected resource recovery strategies are compared to one another and to the baseline scenario, and important metrics (such as liters of water, kWh of energy, and kg of nutrients) are expressed in terms of resources realized per person ("per capita" values).

Table 2 - List of Scenarios with parameter values

Simulation Group	**Stream Selection**	**Removal Efficiency**	**Resource Recovery**	**Water Recovery**	**Energy Recovery Rate**	**P Recovery Rate**
1. BAU WW	"1"	95%	"0"	N	0%	0%
2. BAU RR	"1"	95%	"1"	Y	35%	10%
3. SS GW	"2"	95%	"2"	Y	0%	0%
4. SS BW	"3"	95%	"3"	N	80%	80%
5. STORM	NA	80%	"4"	Y	0%	0%

Simulation group "1. BAU WW" (business as usual wastewater) is the baseline simulation that produces quantitative wastewater values (from the CWMM BAU water demand scenario) and assigns typical wastewater characteristics for a conventional combined collection and treatment system. When the "stream selection" input object slider is set to the default position of "1" by the model user, the conventional water system for Calgary is simulated, which is comprised of two large centralized water treatment plants, and three wastewater treatment facilities, all serviced by interconnected distribution/collection systems (with all sources of wastewater combined).

Simulation group “2. BAU RR” (business as usual resource recovery) quantifies the per capita energy and nutrient recovery values achieved from the existing conventional wastewater system. This scenario assumes literature-based resource recovery values for both conventional systems that can be easily adapted to represent most cities with centralized water and wastewater utilities. It is assumed that the conventional activated sludge process is employed plus tertiary wastewater treatment where at least 95% of the influent COD is removed and 33% of the total COD is converted to biogas (26% from primary settlement and 7% from secondary settlement, both followed by anaerobic digestion) (Wan et al., 2016). This scenario assumes no level of water recovery, but nutrient recovery is realized through the accumulation of phosphorous in digester sludge, used for agricultural application.

Simulation group “3. SS GW” (source-separated greywater) quantifies the amount of greywater that can be reused by employing decentralized wastewater management strategies. This scenario only quantifies the greywater sources that can be actively recycled from municipal water end-uses. This scenario group contains multiple simulations that were created to explore the wide range of strategies that municipalities can consider within the realm of greywater recycling.

Simulation “4. SS BW” (source-separated blackwater) simulates the energy and nutrient recovery from a concentrated blackwater source. The chemical energy contained in wastewater ranges from 0.0028 – 0.0039 kWh/gCOD (Capodaglio & Olsson, 2020). 80% of the “COD eliminated” variable is assumed to be converted to biogas for this scenario (Pfluger et al., 2020). The blackwater stream is a source of energy and nutrient rich wastewater, but water savings are realized in the greywater (lighter quality) stream that requires less treatment due to the lower concentration levels of pollutants.

Simulation group “5. STORM” tests different stormwater reuse strategies. The City of Calgary has over 200 stormwater ponds. The water contained within stormwater ponds can be reused for specific end-uses (such as “outdoor use” which creates a spike in per capita water use within the summer months/growing season). It is assumed that only the area of 200 storm ponds is readily available for stormwater capture and potential reuse with decentralized treatment technologies (if treatment is required at all). The average stormwater pond was assumed to be 15000 m^2 and the runoff coefficient set to “1” for the scenarios contained within this simulation group. Three stormwater recovery rates are tested representing 20%, 50%, and 80% stormwater recovery rates from new precipitation only within stormwater ponds in the City.

The final simulation group “NPV Co-Digestion” not described in the table above involves the use of the economic assessment tool. The scenario considered for this research represents a co-digestion strategy where a centralized wastewater treatment plant is converted into a co-digestion facility that accepts liquid and solid organic waste as feedstock for enhanced energy production. It is assumed the investment of $35 million is incurred in 2023 and the interest rate for the model was set to be in the range of 3-5%.

5. Results and Discussion

The simulation model described in Chapter 4 is designed to evaluate resource recovery strategies integrated within conventional water systems and explore the socio-economic trade-offs involved with implementing pilot projects and broad-scale strategies based on the principle of resource recovery. The model is capable of displaying the results from multiple scenarios simultaneously to permit comparison among different options. Output objects (such as custom graphs) display or refresh based on the conditions and numerical expressions of the program, following the completion of a set simulation. For every simulation the output objects will reset and be drawn with output appropriate for the current results. These output objects provide an interactive way to review a summary of simulation results that can be exported graphically or as a table of values. The results of the simulated scenarios can be easily exported to figures (such as graphs and tables) that are useful for decision makers of municipal water systems.

5.1 Simulation Results

The model results provide decision aide for implementing strategies focused on increasing the valorization of used water regarding the resources that are available during the wastewater treatment and stormwater management phases of municipal water system. Section 5.1.1 is focused on water recovery while Section 5.1.2 presents the results for specific energy and nutrient recovery scenarios.

5.1.1 End-Use Based Wastewater Production

The first set of results shown below in Figure 17 quantifies the amount of wastewater generated (or the amount of water available) for each individual scenario group, employing the user-defined input objects and model formulas presented in Chapter 4. The model quantifies the historical amount of wastewater and simulates wastewater production 23 years into the future, based on the BAU water demand scenario. The BAU water demand scenario represents a normal population growth rate and continued historical management policies and land use trends, neglecting the effects of climate change (Wang & Davies, 2018) - explaining why the per capita values are relatively stable from the year 2020 to 2043. The amount of stormwater generated is assumed to be fixed, therefore the per capita stormwater available for reuse decreases as population increases into the future.

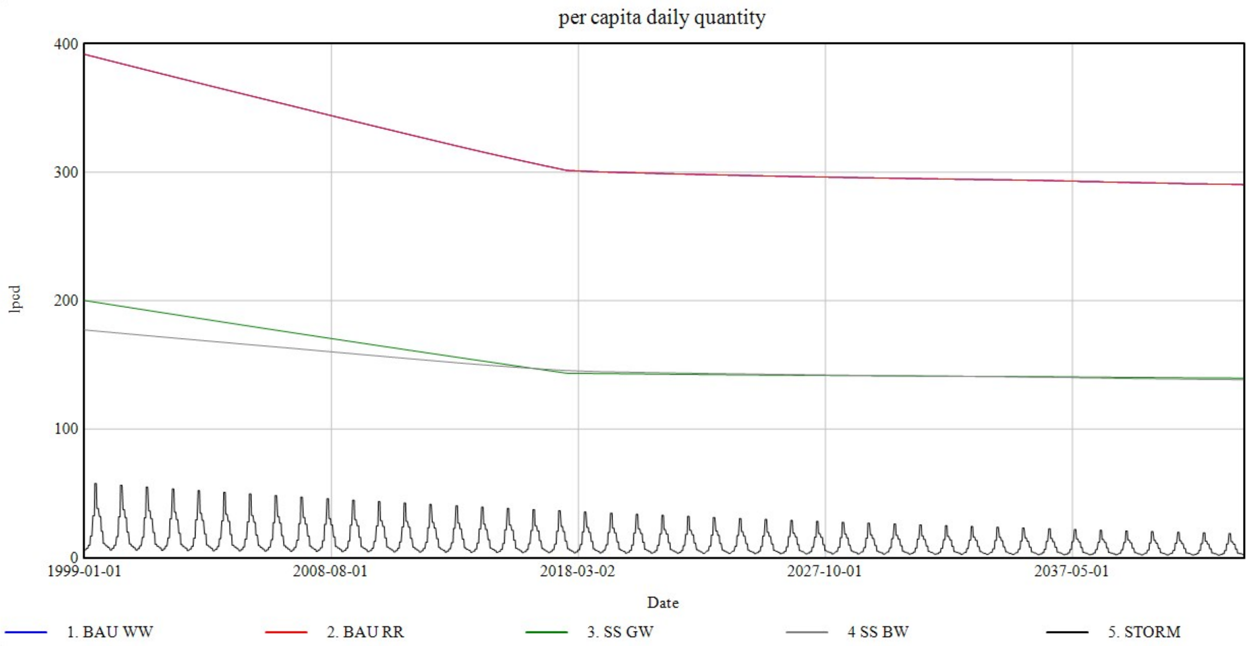


Figure 17 - End-use wastewater and stormwater production

5.1.2 Resource Recovery Experiments

The centralized retrofit scenario is represented by scenario group "3. SS GW", "4. SS BW", and "5. STORM" and compared to the base case per capita daily water demand and centralized resource recovery. The results of the simulations shown in the figures below conceptualizes how a typical utility can transition to a more circular (source-separated) operation. Valuable products will be realized from municipal water sources including blackwater, greywater, and storm/rainwater. The modelled pathways for resource recovery consist of leveraging existing infrastructure coupled with new community-based wastewater treatment plants (resource recovery facilities) and nature-based stormwater systems.

Figure 18 below shows the impact to the City's overall per capita water demand, based on the theory of diffusion of innovations framework and population served by a source-separated resource recovery systems. The BAU simulation run represents the baseline scenario generated by Wang & Davies (2018), where water demand was simulated without factoring in the effects of changes in population growth rate, temperature, streamflow, or rainfall. The "BAU WW" scenario simulates the wastewater produced (per capita daily) in the City that is conveyed to centralized treatment plants through conventional sewer systems. The black line in Figure 18 (b.) below shows the annual average

The relative effect of greywater reuse can be directly observed by comparing the “3. SS GW” simulations (slow, intermediate, and fast rates of adoption) to the BAU simulation. The results show that per capita water use can be reduced significantly by phasing in decentralized systems with source-separated wastewater collection systems and greywater reuse for outdoor use and toilet flushing. The “SS GW fast” simulation produced 376 liters per capita daily (Lpcd) on average by the year 2033. Compared to the BAU rate of 419 Lpcd it is clear that greywater reuse alone at this point is not likely to have been adopted by a large enough percent of the population to achieve the 350 Lpcd by 2033 goal set by the City. This is because even with a “fast” rate of adoption of decentralized systems, only 25% of the population is connected to source-separated systems by the year 2030 (7% and 3% for “intermediate” and “slow”). By the end of the simulation time series the City of Calgary could achieve its goal of reducing per capita water use below 350 liters with either the “intermediate” or “fast” adoption of greywater reuse systems alone. The final result for the average per capita daily municipal water demand at the end of 2043 was 302, 348, and 391 Lpcd for each of the three strategies tested (“fast”, “intermediate”, and “slow”), compared to the average BAU value of 418 Lpcd.

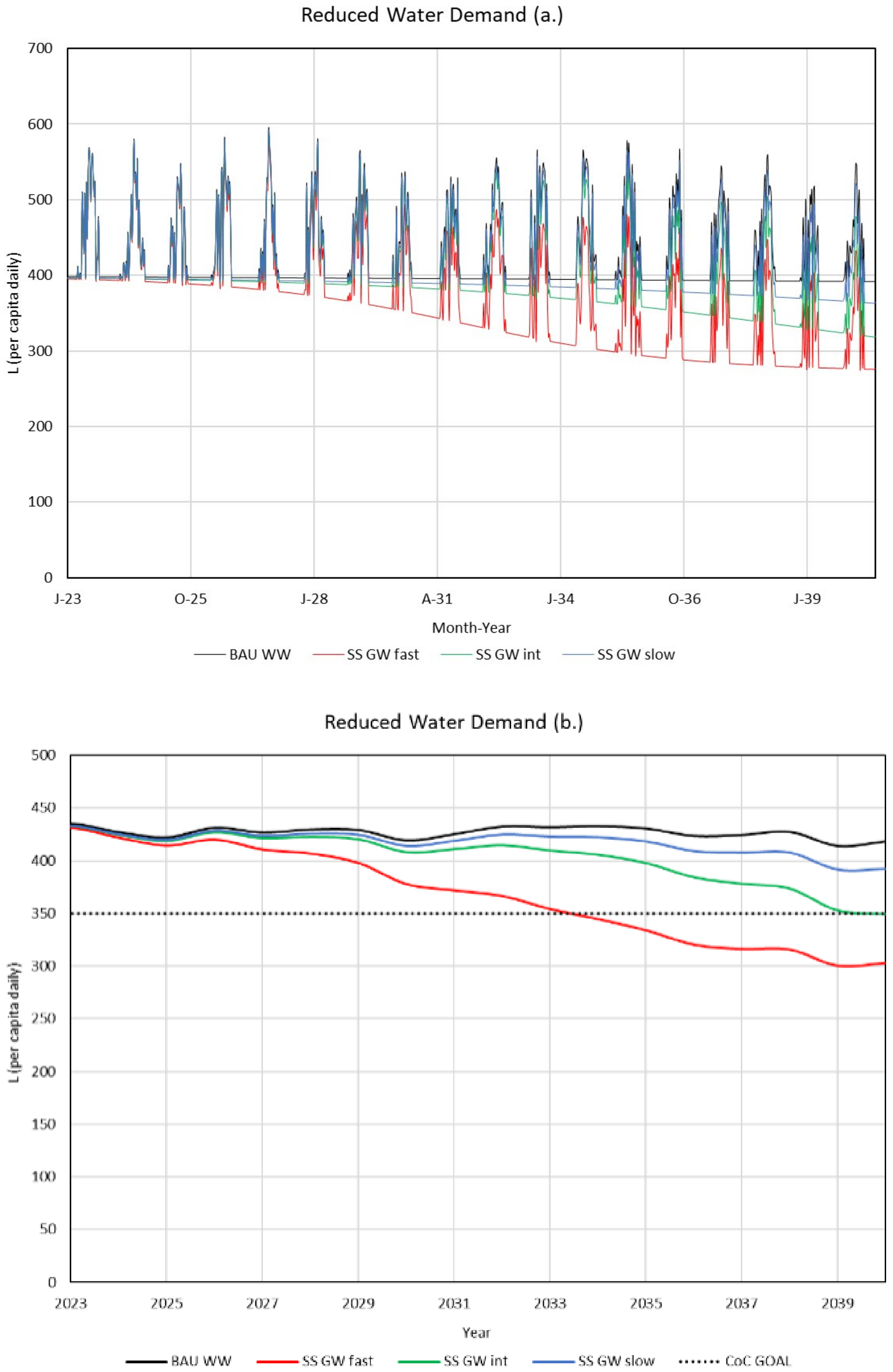


Figure 18 - Reduced water demand from the implementation of source-separated wastewater systems with greywater reuse; shown using a weekly timestep (a.) and annual moving average (b.)

Retrofitted stormwater systems can also offset water production, assuming the stormwater strategies described in Section 4.2. Figure 19 below shows the quantity of water that could be recovered from stormwater ponds if 30%, 50%, and 80% of the precipitation that falls on top of the pond's area was reused. The 80% reuse scenario represents a 25 Lpcd savings, meaning that if this strategy was coupled with a "fast" adoption of source-separated systems with greywater recycling, the water demand could be reduced below 350 Lpcd by the year 2033. In reality, a much larger volume of stormwater reuse could be realized when factoring in the runoff from land area and the large amount of grey infrastructure (with high runoff coefficients). For example, if Calgary has a 620 km^2 land mass and it was assumed to have an average runoff coefficient of 0.5, over 3000 Lpcd would be produced considering the average monthly rain in the month of June.

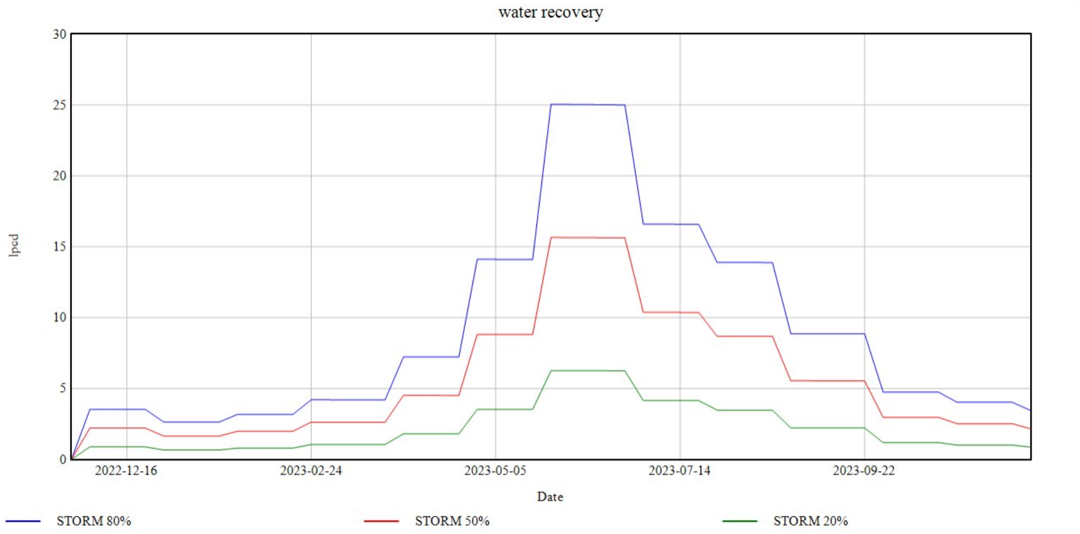


Figure 19 - Potential daily stormwater reuse for different degrees of implementation for an average year

The next set of results compares the "4. SS BW" scenario group to the "2. BAU RR" simulations. The blue line in Figure 20 shows the per capita value of energy in kWh for a typical blackwater system recovering 80% of influent COD as energy. The green line represents BAU system where "total wastewater" is the stream and 30% of the COD was assumed to be captured as energy. The red line represents intermediate adoption of source-separated systems within the current existing system and calculates a weighted average energy recovery value. Similarly, phosphorous recovery is represented below in Figure 21, the units of measurement are grams per capita daily. Significantly more energy and nutrients can be recovered per capita from source-separated resource recovery facilities (represented by the delta between the blue and green lines). The intermediate rate of adoption correlates to an adoption rate of approximately 50% of the population by the end of the simulation timeframe (2043).

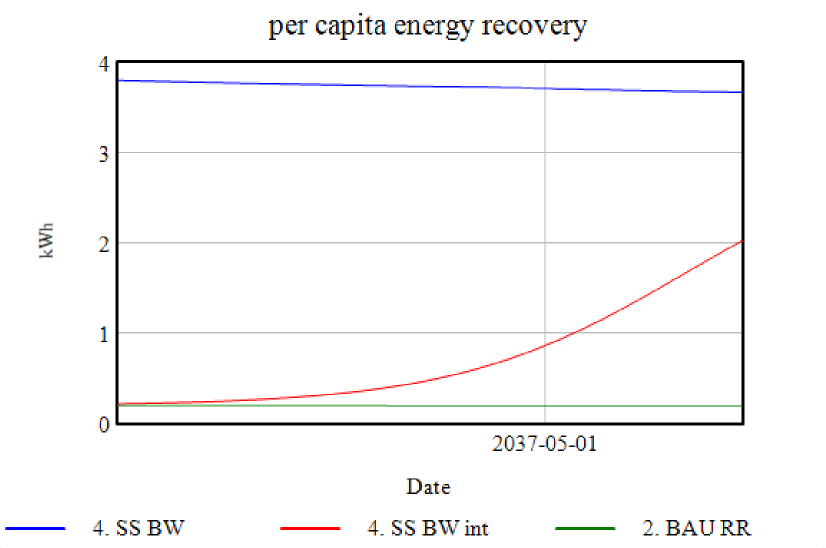


Figure 20 - Per capita energy recovery

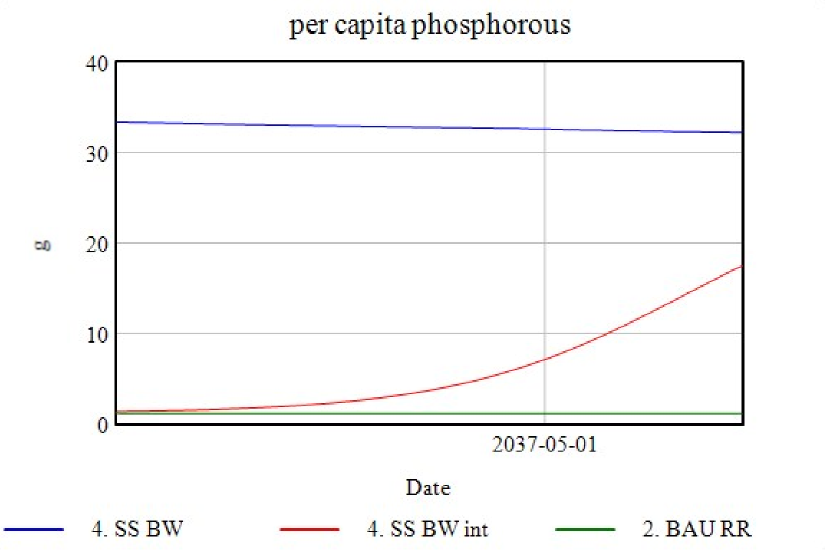


Figure 21 - Per capita phosphorous recovery

The final set of results for this section is the economic assessment of co-digestion as described in 4.1.3. Figure 22 below shows the NPV financial model results for the investment in expanding anerobic digestion facilities to co-digest sludge from conventional facilities with liquid and solid organic waste. The revenue required from tipping fees and also the amount of energy saved from enhanced biogas production quickly offsets the initial investment in approximately 3 years. Sensitivity analysis revealed that the interest rate used to calculate the present value of future cash flows is an extremely important parameter for the economic justification of investments in resource recovery, especially beyond the 20 year mark. All of the assumptions, equations, and rates for the economic assessment tool can easily be adapted to test the economics of other resource recovery strategies, such as the investment in treatment equipment to produce struvite.

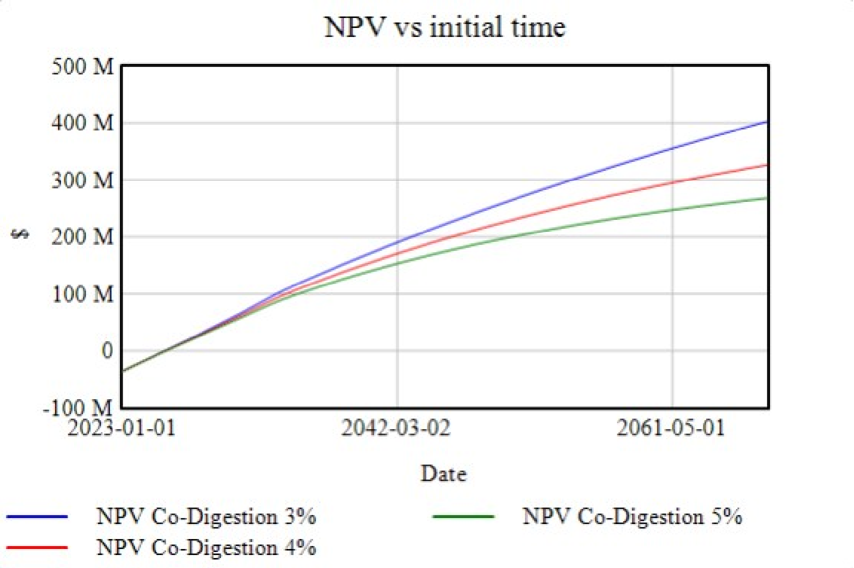


Figure 22 - NPV of co-digestion

5.2 Insights into Municipal Water Planning and Management

Adapting municipal water systems for the reclamation of water and the generation of high-value products can help transition municipal water systems into economically viable resource recovery facilities. Population dynamics, the degree of new system implementation, and resource productivity (efficiency) represent the main variables that were altered to generate resource recovery scenarios for various wastewater streams. The results of this study show that source-separated systems enhance the sustainability of municipal water systems in the following two ways:

1) *Resource recovery*: improving downstream processes for enhanced resource recovery (i.e. source-separated collection systems and anaerobic treatment processes optimized for "less-polluted" greywater and "concentrated" blackwater)
2) *Resource efficiency*: realization of upstream water, energy, and nutrient reduction (i.e the more resource recovery products generated the less resources required upstream to produce these products)

Water reuse represents the first resource recovery pathway analyzed using the simulation model. Reusing treated greywater could dramatically reduce the need for large sewers and drinking water networks, given that greywater accounts for over 50% of total municipal wastewater typically produced. The phasing in of decentralized wastewater treatment systems could save 27-116 Lpcd, representing total municipal water reduction of 7-28%, depending on the implementation rate of source-separated systems. This value is less than the potential reduction typically reported for residential greywater reuse (40-50%) (Marinoski & Ghisi, 2019), because this model considers all municipal end-uses and not just residential end-uses. The inclusion of end-uses such as ICI, non-revenue, outside-city, and leaks increases the total water demand and therefore reduces the relative impact of community based greywater reuse strategies.

The simulated energy recovery from conventional systems was approximately 0.2 kWh per capita daily, which agrees with the chemical energy potential of wastewater reported in the literature (assuming the same COD to biogas conversion rate). Different studies have estimated the chemical energy in wastewater as ranging from 1.7-2.3 kWh/m^3 of wastewater, assuming a diluted COD concentration of 600 mg/L (Capodaglio & Olsson, 2020). Assuming a conventional wastewater production rate of 300 Lpcd and a COD conversion rate of 30%, this reported range can be expressed as 0.15-0.21 kWh per capita daily, which agrees with the simulated value of 0.2 kWh. For energy recovery from blackwater, the simulated value for the intermediate speed of implementation was shown to be approximately 2 kWh per capita daily at the end of the simulation time frame. Verstraete et al. (2009) reported that conventional activated sludge processes consume 25 kWh per person annually, and McCarty et al. (2011) found that with full anaerobic treatment methane production is double to what is typically achieved with conventional aerobic processes, giving anaerobic wastewater treatment processes the potential to be net energy producers. The simulated value agrees with these findings, indeed demonstrating the potential for wastewater treatment processes to be energy positive.

Barriers to the practical implementation of source-separated systems and wastewater reuse in cold-climate regions include the following:

1) The cost of water remains relatively low, therefore there is little incentive to conserve because the total benefits are not widely known
2) The cost of new systems are too high (even the cost of retrofitting may be too high to provide economic benefit, considering the obligation to finance existing infrastructure)
3) Existing building codes and regulations currently prevent more widespread adoption
4) System requirements and design standards are not well established.

The major uncertainty impeding the development of new technologies is the lack of economic viability. Municipalities lack relevant regional information such as capital and operational cost data from similar projects to establish an economic basis for the implementation of new strategies. The decision to implement new systems requires the involvement of multiple parties and the utilization of holistic decision-making tools that weigh both the numerical results of simulation with the interests and concerns of the involved stakeholders. Overcoming these barriers will involve acceptance of innovative technologies motivated by resilient strategy implementation. Struggles with water quality and quantity is the primary bottleneck for fixing the most important environmental and social concerns globally. This research project highlighted the importance of water resources experts, community stakeholders, professional consultants, and the general public all being included within the decision-making process of any major project involving water; as water is the essential requirement for all.

Some systems require a large amount of space and are typically designed to operate year-round. There is an opportunity for communities to leverage the wide availability of ample land to introduce decentralized and nature-based systems at a reduced cost compared to cities with higher population density. One of the main challenges limiting the adoption of water reuse systems in cold climates is the problems with storage and establishing practical reclaimed end-uses. Outside storage becomes impractical in the winter months because irrigation demand is drastically reduced. With regards to indoor storage, energy reclamation can overcome this challenge because there is a necessity, regardless of the time of year. When the water storage level exceeds available capacity, responsible overflow releases are already in place, realized by the inclusivity of the systems thinking theory (minimizing risk due to the availability of safe tie-ins to existing underground infrastructure).

Municipalities have the power to reduce risks through the implementation of environmentally conscious policies outlining a holistic framework for planning, development, and operations. Higher levels of government also play an important role in resource recovery regarding regulatory incentives and barriers. Increasing the regulation of effluent water nutrient contents and disposal of biosolids to land involve increasing costs that are incurred by local governments. Therefore, increasing federal regulation can actually enhance the economic viability of resource recovery implementation through the vehicle of “reduced costs”. As such, regulation of discharges has became another important driver of resource recovery investment opportunities, in addition to other policies enacted by local governments to save water end enhance the resilience of their municipal water systems.

6. Conclusions and Future Work

This research has been carried out to explore the value of resource recovery products from municipal wastewater and stormwater streams. An end-use based water demand system dynamics model was used to simulate and analyze the effects of broader water-related resource recovery strategies focused on downstream reuse. This chapter includes the conclusions and recommendations for future research.

6.1 Conclusions

This research demonstrates the value of system dynamics modelling methods for the economic analysis of resource recovery strategies, by simulating system behaviour that allow utilities to shed light on cause-and-effect relationships. The water demand model described in sub-section 2.3.3 was adapted to simulate source-separated wastewater and stormwater streams quantitatively. Wastewater streams were represented as dynamic variables that can be assigned user-defined quality characteristics and various treatment/recovery levels were applied to individual water streams.

The model was applied to City of Calgary to test whether source-separated systems could be effectively implemented over the next 10 years to achieve the City's goal of reducing per capita water demand to 350 Lpcd. The model results showed that the goal would be achieved with a "fast" rate of adoption of greywater reuse coupled with recycling 80% of the precipitation that falls on the stormwater ponds in Calgary for "fit for purpose" end-uses. The potential for energy recovery is significant, increasing from 0.2 kWh per capita with centralized resource recovery streams (from sludge) to 2 kWh with a fast implementation rate of innovative anaerobic treatment and recovery methods. For an estimated population of 2.4 million people by the year 2043, this calculates to approximately 4800 Mwh per day, from wastewater. In addition, phosphorus and nitrogen can lead to eutrophication, degrading the natural environment. Capturing 2 grams of phosphorus per person per day translates to over 1.7 million kilograms of phosphorus a year being kept out of natural bodies of water in Calgary alone by the year 2043. Phosphorous could also be recovered in the form of struvite and sold as a high-quality fertilizer, providing further economic benefit of nutrient recovery systems.

6.2 Recommendations

Based on the results summarized in the previous sections, it is recommended that the model and presented in this research be used to support the future implementation of decentralized water systems, alleviate concerns regarding long-term sustainability, and generate overall confidence in the concept of resource recovery.

Accuracy of the simulation model could be improved by linking the stream selection and wastewater characterization components of the model so that the quality of wastewater stream is dependent on the mass flow rate of individual contaminants. Rather than using functions that set the quality characteristics of the wastewater as constants depending on the user-defined stream selection input slider, the concentration could be dependent on the mass of contaminants produced per person and the volume of water (which changes over time). In addition, the simulation of stormwater available for reuse could be improved by mapping the study area and obtaining accurate runoff coefficients. The amount of precipitation could also be predicted by integrating other modeling methods (for example artificial neural networks) that would consider several other factors (including climate variables).

Future studies should also include avoided costs in the financial modeling analysis. When the need for water is reduced by reusing greywater or combined wastewater, the costs associated with upstream water production decreases significantly. The associated costs extend to the manufacturing and transportation of chemicals required for treatment and include a reduction in the treatment and pumping costs required to transport water through conventional distribution systems. Similarly, by recovering phosphorous from wastewater streams, conventional production of fertilizer from phosphate rock can be reduced. Future studies should also further explore upstream energy recovery strategies, such as onsite heat recovery systems that process incoming cold water through a heat exchanger where it is pre-warmed by heat from greywater flowing out from end uses requiring hot water. Typical heat exchange systems receiving greywater from a shower can recover up to 60% of the heat that would otherwise go to waste (Alberta WaterSMART, 2011).

Formulation and development of the simulation model for this study was based largely on location-specific data and other prior knowledge about Calgary including population, climate data, and a broad range of existing water management policies. In the future the model could be extended to multiple other cities and used for rural or isolated areas. Future studies should explore how the implementation of decentralized water treatment projects change when dealing with the current struggles of rural/isolated communities. In Canada, a single drinking water advisory can mean thousands of people lack access to safe, clean drinking water; such as Shoal Lake 40 First Nation, where the boil water advisory has been in place since 1995 (5000 population estimate). 73% of First Nations' water systems are at high or medium risk of contamination (*Safe Water for First Nations*, 2021). In the province of Newfoundland and Labrador, there are 144 communities (relying on a total of 184 water supply systems) that are still under boil water advisories (*Newfoundland and Labrador Water Resources Portal*, 2021). In addition to these limiting circumstances, 85% of people from Newfoundland and Labrador do not have access to safe sanitation (*Environment, Climate Change and Municipalities*, 2021). In many cases raw water systems exist without any level of treatment, and wastewater is discharged directly into the most accessible localized body of water (Khan, 2021). In these rural cases the top priority should be first establishing safe water treatment and distribution systems.

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Appendix A: Code for Recent Updates

```
per capita energy recovery=
        (1-test pop)*per capita BAU energy recovery+(test pop)*per capita SS energy recovery

per capita BAU phosphorous recovery=
        (available P 1)*total wastewater*BAU phosphorous recovery rate
        ~
        ~       COD in grams

per capita phosphorous=
        (1-test pop)*per capita BAU phosphorous recovery+(test pop)*per capita SS phosphorous
        recovery
        ~
        ~       (1-test pop)*per capita BAU phosphorous recovery+(test pop)*per capita SS \
                phosphorous recovery

per capita daily quantity=
        IF THEN ELSE(stream selection=1,total wastewater,IF THEN ELSE(stream
        selection=2,greywater\,IF THEN ELSE(stream selection=3, blackwater, per capita daily
        stormwater)))
        ~       lpcd
        ~

water recovery=
        IF THEN ELSE(Time>1247,(0*per capita daily quantity*water recovery rate+per capita
        daily stormwater\*stormwater recovery rate),0)
        ~       lpcd
        ~

SS phosphorous recovery rate=
        0.8

per capita SS phosphorous recovery=
        (avialble P 2)*blackwater*SS phosphorous recovery rate

available P 1=
        (14/1000)*0.95*1
        ~
        ~       concentration * removal efficiency

BAU phosphorous recovery rate=
        0.3

avialble P 2=
        (306/1000)*0.95*1
```

```
stormwater recovery rate=
        0.8

test pop=
        IF THEN ELSE(b=-0.008,fast pop lookup(Time),(IF THEN ELSE(b=-0.005,intermediate
        pop lookup\(Time),slow pop lookup(Time))))

slow pop lookup(
intermediate pop lookup(
fast pop lookup(
        lookup function data included in model file

per capita phosphorous recovery=
        phosphorous recovery rate*per capita daily quantity*P eliminated

COD conversion rate 1=
        701/1000*0.95*1*0.0033
        ~
        ~       concentration * removal efficiency * g COD to kwh (FIX)

COD conversion rate 2=
        (10560/1000)*0.95*1*0.0033

per capita SS energy recovery=
        (COD conversion rate 2)*blackwater*SS energy recovery rate

per capita BAU energy recovery=
        (COD conversion rate 1)*total wastewater*BAU energy recovery rate
        ~
        ~       COD in grams
                0.0028 – 0.0039 kWh/gCOD

phosphorous recovery rate=
        0.85

BAU energy recovery rate=
        0.3

per capita daily stormwater=
        (precipitation*land area*1000*runoff coefficient)/(7*Population)
        ~       lpcd
        ~       CHECK FOR 0

SS energy recovery rate=
        0.8
```

```
reduced water demand=
        per capita daily municipal water demand*((1-(test pop))+((test pop)*(new per capita daily
        municipal water demand/per capita daily municipal water demand)))
        ~       lpcd
        ~

new per capita daily municipal water demand=
        per capita daily municipal water demand-water recovery

new housing starts=
        (22000/52)*Time

water recovery rate=
        1

slider=
        Population

Inflow 01=
        growth rate*STOCK 01*(1-STOCK 01/slider)*Time

a=
        5
        ~
        ~       1: 5

loss fraction 0=
        effect of stock 0(STOCK 0/normal stock 0)*normal loss fraction 0

sigmoid reference mode=
        GAME ((k/(1+exp(a+b*(Time)))))

growth rate=
        0.0001

population connected to RR system=
        (percentage of adoption)*Population

percentage of adoption=
        DELAY FIXED (sigmoid reference mode/100,1248,0)

STOCK 01=
        INTEG (Inflow 01*turn on,1)

normal loss fraction 0=
```

```
        0.025

precipitation=
        lookup(get time)/1000
        ~       m
        ~

normal stock 0=
        100

lookup(
        [(1,0)-
        (12,200)],(1,10.6),(2,12.8),(3,17),(4,29.3),(5,57.3),(6,101.9),(7,67.7),(8,56.8\),(9,36.3),(1
        0,19.5),(11,16.6),(12,14.2))

get time=
        GET TIME VALUE(0,1,3)

b=
        GAME (-0.005)
        ~
        ~       slow: -0.0035
                int: -0.005
                fast: -0.008

k=
        85

Outflow 0=
        loss fraction 0*STOCK 0

effect of stock 0(
        [(0,0)-(1,5)],(0,1),(1,2))

STOCK 0=
        INTEG (Inflow 0-Outflow 0,1)

resource recovery strategy=
        GAME (1)

Inflow 0=
        STOCK 0*gain fraction 0

turn on=
        GAME (1)
```

```
gain fraction 0=
        0.05

effluent P=
        total phosphorus-P eliminated

balance=
        INTEG (earned interest*TIME STEP,1e+06)

daily service charge=
        0.5+0.93+0.52
        ~       $
        ~       For the city of Calgary: \
                https://www.calgary.ca/water/customer-service/residential-water-rates-and-b\
                illing.html

P eliminated=
        (total phosphorus*P removal 1/100)+(total phosphorus-total phosphorus*P removal
        1/100)*P removal 2/100+(total phosphorus-total phosphorus*P removal 1/100-((total
        phosphorus-total phosphorus\*P removal 1/100)*P removal 2/100))*P removal 3/100

COD removal 2=
        GAME (0)
        ~       percentage
        ~

potential daily water savings=
        0.5*total wastewater*water treatment and supply usage rate

earned interest=
        balance*0.0015

runoff coefficient=
        0.5
        ~
        ~       Assume 1 if you use stormpond assumption

land area=
        6.2172e+08
        ~       m*m
        ~       Make assumptions for 200 storm ponds (125m x 125m)
                Assume 15,000m^s per pond
                200*15000

blackwater=
```

```
        per capita daily municipal water demand by category[toilet]+0.5*(0.9*per capita daily
        municipal water demand by category[ici])

current week per capita daily leak demand=
        DELAY FIXED (per capita daily municipal water demand by category[leaks],1,0)
        ~       lpcd
        ~

Calgary daily water demand by category[municipal subsectors]=
        Population*per capita daily municipal water demand by category[municipal
        subsectors]\/1e+09
        ~       MCM
        ~

total wastewater=
        per capita daily municipal water demand by category[toilet]+per capita daily municipal
        water demand by category\[bath]+per capita daily municipal water demand by category
        [laundry]+per capita daily municipal water demand by category[kitchen]+per capita daily
        municipal water demand by category[other]+0.9*per capita daily municipal water demand
        by category[ici]+0.9*per capita daily municipal water demand by category[outside city]

water treatment and supply usage rate=
        (1.45+1.57)/1000
        ~       $
        ~

per capita daily residential water demand=
        per capita daily municipal water demand by category[toilet]+
        per capita daily municipal water demand by category[bath]+
        per capita daily municipal water demand by category[laundry]+
        per capita daily municipal water demand by category[kitchen]+
        per capita daily municipal water demand by category[leaks]+
        per capita daily municipal water demand by category[other]+
        per capita daily municipal water demand by category[outdoor]
        ~       lpcd
        ~

per capita daily ICI water demand=
        per capita daily municipal water demand by category[ici]
        ~       lpcd
        ~

greywater=
        per capita daily municipal water demand by category[bath]+per capita daily municipal
        water demand by category\[laundry]+per capita daily municipal water demand by
        category[kitchen]+0.5*(0.9*per capita daily municipal water demand by category
```

```
        [ici])

per capita daily outside city water demand=
        per capita daily municipal water demand by category[outside city]
        ~       lpcd
        ~

residential indoor water demand=
        per capita daily municipal water demand by category[toilet]+
        per capita daily municipal water demand by category[bath]+
        per capita daily municipal water demand by category[laundry]+
        per capita daily municipal water demand by category[kitchen]+
        per capita daily municipal water demand by category[leaks]+
        per capita daily municipal water demand by category[other]
        ~       lpcd
        ~

per capita daily nonrevenue water demand=
        per capita daily municipal water demand by category[nonrevenue]
        ~       lpcd
        ~

revenue=
        weekly energy savings+weekly revenue
        ~       $/Week
        ~

greywater treatment application 0=
        weekly new homes with greywater application 0
        ~       Dmnl
        ~

"current week # of homes with greywater requirement 0"=
        Population/4*percentage of homes with greywater treatment 0*greywater treatment 0

percentage of homes with greywater treatment 0= GAME (
        0)
        ~       Dmnl
        ~

last week percentage of homes with greywater requirement 0= DELAY FIXED (
        percentage of homes with greywater treatment 0*greywater treatment 0,1,0)
        ~       Dmnl
        ~

new homes with greywater treatment requirement 0=
```

```
        IF THEN ELSE("current week # of homes with greywater requirement 0">="last week #
        of homes with greywater requirement 0","current week # of homes with greywater
        requirement 0"-"last week # of homes with greywater requirement 0"\, 0 )
        ~       Dmnl
        ~

percentage water use reductions from grey water treatment and reuse 0[municipal subsectors\]=
        current week percentage of homes with greywater treatment 0*constant grey water and
        reuse multipliers\[municipal subsectors]
        ~       fraction
        ~

current week percentage of homes with greywater treatment 0=
        homes with greywater treatment 0/(Population/4)
        ~       fraction
        ~

homes with greywater treatment 0=
        INTEG (greywater treatment application 0,0)
        ~       Dmnl
        ~

"last week # of homes with greywater requirement 0"=
        last week Calgary Population/4*last week percentage of homes with greywater
        requirement 0
        ~       Dmnl
        ~

homes with greywater treatment application 0=
        DELAY FIXED (new homes with greywater treatment requirement 0,delay of greywater
        application 0,0)
        ~       Dmnl
        ~

cumulative new homes with greywater treatment requirement 0=
        INTEG (new homes with greywater treatment requirement 0-homes with greywater
        treatment application 0\,0)
        ~       Dmnl
        ~

delay of greywater application 0=
        156
        ~       Dmnl
        ~

greywater treatment 0=
```

GAME (0)

weekly new homes with greywater application 0=
cumulative new homes with greywater treatment requirement 0/delay of greywater application 0
~ Dmnl
~

Fraction of adopters=
Decided to adopt resource recovery systems/Population
~
~ AdF = DA/ 〖Pop〗 _TOTAL
The fraction of the total population (〖Pop〗 _TOTAL) that has decided to \
adopt a RR systems (DA).

Word of mouth=
0.5*Fraction of adopters
~
~ WOM=CC× 〖WOM〗 _EFF×AdF
The rate by which community members come into contact with one another to share \information (community connectivity – CC), the effectivness of the \information being shared (〖WOM〗 _EFF), and the fraction of people who \have already adopted an RR system (AdF).
NB: use 0.5 for CC and WOMeffectiveness

Site demonstrations=
0.1
~
~ SiteDemo=f(〖Demo〗 _FREQ, 〖Demo〗 _EFF, 〖Demo〗 _INTERVAL)
A composite factor based on surveys, interviews, and participatory \observations that incorporates a demonstration frequency \(〖Demo〗 _FREQ), non-uniform interval between demonstrations \(〖Demo〗 _INTERVAL), and the demonstration's effectiveness \(〖Demo〗 _EFF).

Persuaded about adopting resource recovery system=
INTEG (Persuasion rate,0)
~
~ PerA=∫(〖Per〗 _RATE- 〖Adpt〗 _RATE)dt
The population of individuals that are positively persuaded about adopting \a RR system.

Persuasion rate=
Behavioural intention*(1-Fraction becoming persuaded)
~
~ 〖Per〗 _RATE=BI×(1-PerF)

This is the rate function by which the aware population (〖Pop〗 _AW) \becomes persuaded about adopting RR systems. The rate is relative to their \behavioral intentions (BI) and the fraction of the total population that \has already become persuaded (PerF).

Adoption rate=
Stakeholder learning

Fraction becoming persuaded=
Persuaded about adopting resource recovery system/Population
~
~ PerF = 〖Per〗 _A/ 〖Pop〗 _TOTAL
The fraction of the total population (〖Pop〗 _TOTAL) that has become \persuaded to adopt a RR system.

Stakeholder learning=
Persuaded about adopting resource recovery system*(Relative advantage+Site demonstrations\+Word of mouth)/1000
~
~ SL=PerA ×(SiteDemo+RA+WOM)
The combined effect on individuals who are persuaded to adopt (PerA) from \
onsite learning (SiteDemo) about RR sytems, implicit perception of the \
systems' relative advantage (RA) over an alternative option, and their \
conversations with system adopters (WOM) .

Relative advantage=
0.1
~
~ RA=(w_1 Env+ w_2 Econ+w_3 Health)/TIMESTEP
Survey data was used to develop site-specific weights (w_(1-3)) applied to \
stakeholders' values for the environmental (Env), economic(Econ), and \
health (Health) benefits associated with the RR system. The economic \
benefits are reflected by the payback period (PP).

Decided to adopt resource recovery systems=
INTEG (Adoption rate,0)

Behavioural intention=
(Aware of resource recovery systems*Stakeholder power*Stakeholder attitudes)/52
~
~ A yearly amount of the aware population (〖Pop〗 _AW) that believes RR systems are \able to achieve a particular goal (i.e. reducing the impacts of nutrients \to the environment or reducing wastewater's impact to human health).
NB: A weekly amount? May need to change drastically to get reasonable \results for weekly time step

```
Aware of resource recovery systems=
        INTEG (Awareness rate,0)
        ~
        ~       The stock of households that become aware of RR systems each year.
                NB: of "population" not households. Can likely convert to households with \
                pop/household factor

Awareness rate=
        Advertising*(1-Fraction becoming aware)
        ~
        ~       A rate function that is driven by advertising (Adv) and the fraction of \
                the population becoming aware of RR systems (AwF).

Fraction becoming aware=
        Aware of resource recovery systems/Population
        ~
        ~       The fraction of the total population (〖Pop〗_TOTAL) that is aware of \
                the RR systems.

Advertising=
        2500
        ~
        ~       Adv=〖Ad〗_EFF×〖Ad〗_FREQ
                The rate product of advertising effectiveness (〖Ad〗_EFF) and frequency \
                (〖Ad〗_FREQ) derived from interviews and participatory observations.

Stakeholder attitudes=
        1
        ~
        ~       SA=PE+PR
                A value derived from interviews and survey data that combines stakeholders’
                \previous experiences (PE) with wastewater systems and previous research \(PR)
                about RR technologies.


Stakeholder power=
        0.48
        ~
        ~       SP=0.48
                A value derived from interviews representing the stakeholder's assurance of \
                possessing the necessary resources (i.e. information and power in \decision-
                making) to achieve a desired outcome (i.e. adopting a wastewater \technology). A
                percentage represented as a decimal value between zero and \one.
                NB: Ok
```

k2=
85

b2=
-0.05

a2=
-2

a3=
2.6

a4=
2.6

k4=
85

k3=
85

shower sigmoid=
GAME (k2/(1+exp(a2+b2*(Time/52))))

b4=
-0.16

clothes washer sigmoid=
GAME (k3/(1+exp(a3+b3*(Time/52))))

b3=
-0.16

greywater reuse=
GAME (k4/(1+exp(a4+b4*(Time/52))))

Inflow=
STOCK*gain fraction

gain fraction=
0.05

STOCK=
INTEG (Inflow-Outflow,1)

```
normal loss fraction=
        0.025

normal stock=
        100

Outflow=
        loss fraction*STOCK

loss fraction=
        effect of stock(STOCK/normal stock)*normal loss fraction

effect of stock(
        [(0,0)-(1,5)],(0,1),(1,2))

current time PV 2=
        exp(discount rate 2*(Time-INITIAL TIME))
        ~       Dmnl
        ~       Relative present value factor for the current time period

"co-digestion investment 2"=
        anaerobic digestors 2+generating facilities 2+interconnection costs 2+waste receiving
        station 2\+grant funding 2

net cash flow 2=
        -investment 2/TIME STEP*PULSE(start time 2,TIME STEP)-investment2 2/TIME
        STEP*PULSE(\start time2 2,TIME STEP)+STEP(revenue 2,start time 2)
        ~       $/Week
        ~

investment 2=
        "co-digestion investment 2"
        ~       $
        ~

initial NPV 2=
        500
        ~       $
        ~

investment2 2=
        0

anaerobic digestors 2=
        0
```

```
NPV vs current time 2=
        NPV(net cash flow 2,discount rate 2,initial NPV 2,current time PV 2)
        ~       $
        ~       returns the net present value at Time for the cash flow to Time.

start time2 2=
        0

interconnection costs 2=
        0

organic liquid tipping fee 2=
        0.11
        ~       $/l
        ~

generating facilities 2=
        3.6e+07
        ~       $
        ~

solid organic tipping fee 2=
        60
        ~       $/tonne
        ~

renewable energy carbon offsets 2(
        [(0,0)-(2080,50)],(0,40),(520,40),(521,0),(2000,0))
        ~       cents/kWh
        ~       zeroed out

kL of organics received weekly 2=
        1.37897e+06

weekly energy produced 2=
        Phosphorous*7*Population

energy lookup projection 2(
        [(0,6)-(624,20)],(0,0.075),(26,0.071),(52,0.072),(78,0.07),(104,0.073),(130,0.072),(\
        156,0.076),(182,0.08),(208,0.08),(234,0.081),(260,0.089),(286,0.092),(312,0.1),(338\
        ,0.099),(364,0.104),(390,0.109),(416,0.112),(442,0.114),(468,0.122),(494,0.128),(520\
        ,0.132),(546,0.132),(572,0.113),(598,0.095),(624,0.094))
        ~       cents/kWh
        ~

weekly energy savings 2=
```

```
	weekly energy produced 2*energy lookup projection 2(Time)+0*renewable energy carbon
	offsets 2\(Time)

revenue 2=
	weekly energy savings 2+weekly organics revenue 2-weekly sludge management costs 2
	~	$/Week
	~

discount rate 2=
	interest rate/weeks per year/"100 percent"
	~	fraction/Week
	~

Phosphorous=
	GAME (0.23)
	~	kWh/person
	~

NPV vs initial time 2=
	NPV(net cash flow 2,discount rate 2,initial NPV 2,1)
	~	$
	~	returns the net present value relative to the initial time for the cash \
		flow to Time.

grant funding 2=
	0

cost of disposal per tonne 2=
	0

percent of biosolids use 2=
	0

tonnes of organics received weekly 2=
	36

biosolids produced 2=
	0*kL of organics received weekly 2*tonnes of organics received weekly 2+per capita daily
	sludge production\*7*Population
	~
	~	change so that organics are not 0d out

start time 2=
	0
	~	Month
	~
```

```
waste receiving station 2=
        0

weekly sludge management costs 2=
        biosolids produced 2*(1-percent of biosolids use 2)*cost of disposal per tonne 2

weekly organics revenue 2=
        kL of organics received weekly 2*organic liquid tipping fee 2+tonnes of organics received
        weekly 2\*solid organic tipping fee 2

renewable energy carbon offsets(
        [(0,0)-(2080,50)],(0,40),(520,40),(521,0),(2000,0))
        ~       cents/kWh
        ~       zeroed out

weekly energy savings=
        weekly energy produced*energy lookup projection(Time)+0*renewable energy carbon
        offsets\(Time)

weekly energy produced=
        enhanced biogas production*7*Population

interconnection costs=
        0

waste receiving station=
        0

anaerobic digestors=
        0

electricity price escalator=
        1.5/100

electricity pulse train=
        PULSE TRAIN(52, 1, 52 , 2500 )

annual increase=
        price of electricity*(1+electricity price escalator)*electricity pulse train-(price of
        electricity\*electricity pulse train)

generating facilities=
        3.6e+07
        ~       $
        ~
```

```
price of electricity=
	INTEG (annual increase,base price of electricity)

investment=
	"co-digestion investment"
	~	$
	~

solid organic tipping fee=
	60
	~	$/tonne
	~

kL of organics received weekly=
	1.37897e+06

grant funding=
	0

tonnes of organics received weekly=
	36

biosolids produced weekly=
	per capita daily sludge production*7*Population
	~
	~	change so that organics are not 0d out

"co-digestion investment"=
	anaerobic digestors+generating facilities+interconnection costs+waste receiving
	station\+grant funding

weekly revenue=
	kL of organics received weekly*organic liquid tipping fee+tonnes of organics received
	weekly\*solid organic tipping fee

organic liquid tipping fee=
	0.11
	~	$/l
	~

energy lookup projection(
	[(0,0.07)-(624,0.2)],(0,0.075),(26,0.071),(52,0.072),(78,0.07),(104,0.073),(130,0.072\
	),(156,0.076),(182,0.08),(208,0.08),(234,0.081),(260,0.089),(286,0.092),(312,0.1),(\
	338,0.099),(364,0.104),(390,0.109),(416,0.112),(442,0.114),(468,0.122),(494,0.128),\
	(520,0.132),(546,0.132),(572,0.113),(598,0.095),(624,0.094))
```

```
          ~          cents/kWh
          ~

base price of electricity=
          GAME (0.1)
          ~          $/kWh
          ~

enhanced biogas production=
          GAME (0.23)
          ~          kWh/person
          ~

start time2=
          0

investment2=
          0

population increase=
          (Population*(birth rate+average net migration))*(1+future to historical increase rate ratio\)

Population=
          INTEG (population increase-population decrease,initial Calgary population)

population decrease=
          Population/(average life*52)

"current week # of homes with xeriscaping requirement"=
          Population/4*percentage of homes with xeriscaping*xeriscaping
          ~          Dmnl
          ~

"current week # of homes with greywater requirement"=
          Population/4*percentage of homes with greywater treatment*greywater treatment

current week percentage of homes with greywater treatment=
          homes with greywater treatment/(Population/4)
          ~          fraction
          ~

current week percentage of homes with xeriscaping=
          homes with xeriscaping/(Population/4)
          ~          fraction
          ~
```

```
"application # of low-flow toilet due to incentive"=
	IF THEN ELSE(Percentage of Houses with Low Flow Appliances[toilet]<=0.45,increase
	rate of low flow appliance adoption with incentive[toilet]*Population/4, (max low flow
	appliances rate[toilet]-Percentage of Houses with Low Flow Appliances\[toilet])*2.5*
	increase rate of low flow appliance adoption with incentive[toilet]*Population/4)
	~	toilet
	~

last week Calgary Population=
	DELAY FIXED (Population,1,0)
	~	Dmnl
	~

weekly wate saving from education by category[municipal subsectors]=
	water use reduction from education[municipal subsectors]*Population*7
	~	liter
	~

biogas from sludge digestion=
	GAME (0.04)
	~	kWh/person
	~

"100 percent"=
	100
	~	percent
	~

initial NPV=
	0
	~	$
	~

current time PV=
	exp(discount rate*(Time-INITIAL TIME))
	~	Dmnl
	~	Relative present value factor for the current time period

start time=
	0
	~	Month
	~

interest rate=
	5
	~	percent/Year
```

```
	~

net cash flow=
	-investment/TIME STEP*PULSE(start time,TIME STEP)-investment2/TIME
	STEP*PULSE(start time2\,TIME STEP)+STEP(revenue,start time)
	~	$/Week
	~

weeks per year=
	52
	~	weeks/Year
	~

NPV vs initial time=
	NPV(net cash flow,discount rate,initial NPV,1)
	~	$
	~	returns the net present value relative to the initial time for the cash \
		flow to Time.

discount rate=
	interest rate/weeks per year/"100 percent"
	~	fraction/Week
	~

NPV vs current time=
	NPV(net cash flow,discount rate,initial NPV,current time PV)
	~	$
	~	returns the net present value at Time for the cash flow to Time.

thermochemical conversion=
	GAME (0)

aerobic treatment=
	GAME (0)

liming=
	GAME (0)

direct land application=
	GAME (0)

no strategy=
	GAME (0)

per capita daily sludge production=
	GAME (0)
```

```
        ~       g
        ~       Needs to be lpcd*COD(mg/L)*sludge conversion coefficient...consider an \
                improvement of efficiency between BAU and decentralized...

pcd toilet 0=
        (base per capita daily municipal water demand by category[toilet])*((1-Percentage of
        Houses with Low Flow Appliances[toilet])*1+Percentage of Houses with Low Flow
        Appliances\[toilet]*(1-water use reduction from low flow appliances[toilet]))

energy lookup(
        [(1,0)-
        (1000,20)],(1,7.366),(5.3333,7.446),(9.6666,7.622),(13.9999,8.407),(18.3332,8.084\),(22.
        6665,8.675),(26.9998,8.933),(31.3331,8.449),(35.6664,8.124),(39.9997,8.16),(44.333\,7.
        787),(48.6663,8.061),(52.9996,9.613),(57.3329,10.99),(61.6662,11.101),(65.9995,9.939\)
        ,(70.3328,9.925),(74.6661,10.104),(78.9994,9.291),(83.3327,8.944),(87.666,8.777),(\91.9
        993,9.714),(96.3326,9.875),(100.666,9.675),(104.999,11.919),(109.333,11.647),(113.666
        \,9.976),(117.999,10.108),(122.332,10.726),(126.666,11.881),(130.999,9.954),(135.332\,
        10.953),(139.666,9.036),(143.999,7.213),(148.332,7.38),(152.665,6.821),(156.999,8.475\
        ),(161.332,8.353),(165.665,6.786),(169.999,5.377),(174.332,6.789),(178.665,7.784),(\18
        2.999,6.576),(187.332,6.261),(191.665,5.691),(195.999,5.471),(200.332,6.338),(204.665\
        ,7.367),(208.998,8.718),(213.332,8.303),(217.665,6.687),(221.998,5.418),(226.332,5.565
        \),(230.665,6.732),(234.998,7.581),(239.332,8.976),(243.665,7.093),(247.998,11.763),\(2
        52.331,6.299),(256.665,6.92),(260.998,9.989),(265.331,12.953),(269.665,8.256),(273.99
        8\,12.426),(278.331,9.12),(282.665,13.302),(286.998,15.114),(291.331,13.952),(295.664\
        ,7.983),(299.998,7.3),(304.331,6.356),(308.664,7.841),(312.998,9.03),(317.331,11.547\),
        (321.664,10.36),(325.997,10.287),(330.331,7.568),(334.664,8.561),(338.997,8.876),\(343
        .331,7.523),(347.664,7.288),(351.997,8.206),(356.331,7.1),(360.664,7.074),(364.997\,10.
        76),(369.331,11.406),(373.664,10.522),(377.997,8.232),(382.33,8.244),(386.664,8.146\),
        (390.997,8.689),(395.33,7.471),(399.664,6.991),(403.997,6.986),(408.33,8.922),(412.664
        \,5.995),(416.997,7.198),(421.33,8.021),(425.663,7.954),(429.997,8.737),(434.33,7.127\),
        (438.663,7.545),(442.997,7.302),(447.33,6.583),(451.663,5.431),(455.997,5.832),(460.33
        \,4.337),(464.663,4.089),(468.996,6.14),(473.33,5.813),(477.663,5.387),(481.996,5.498\),
        (486.33,5.212),(490.663,5.489),(494.996,5.304),(499.329,4.753),(503.663,4.521),(507.99
        6\,3.65),(512.329,3.346),(516.663,3.611),(520.996,4.975),(525.329,4.754),(529.663,3.97
        1\),(533.996,4.456),(538.329,3.736),(542.663,3.982),(546.996,4.111),(551.329,3.873),(\5
        55.662,3.32),(559.996,3.032),(564.329,2.782),(568.662,2.823),(572.996,3.469),(577.329\
        ,3.715),(581.662,3.365),(1000,19.8246))
        ~       cents/kWh
        ~               |

total suspended solids=
        IF THEN ELSE(stream selection=1,410,IF THEN ELSE(stream selection=2,175,IF THEN
        ELSE\(stream selection=3,8360,410) ) )
        ~       mg/l
        ~       TSS
```

```
          source: The Economics of Wastewater Treatment Decentralization: A Techno-
          economic \
          Evaluation - TABLE 1
          can be constant

total phosphorus=
     IF THEN ELSE(stream selection=1,14,IF THEN ELSE(stream selection=2,5,IF THEN
     ELSE(stream selection\=3,306,14) ) )
     ~    mg/l
     ~    TP

"ammonium-N"=
     IF THEN ELSE(stream selection=1,6,IF THEN ELSE(stream selection=2,2,IF THEN
     ELSE(stream selection\=3,132,6) ) )
     ~    mg/l
     ~    NH4+ N

N eliminated=
     ("ammonium-N"*N removal 1/100)+("ammonium-N"-"ammonium-N"*N removal
     1/100)*N removal 2/100+("ammonium-N"-"ammonium-N"*N removal 1/100-
     (("ammonium-N"-"ammonium-N"*N removal 1/\100)*N removal 2/100))*N removal
     3/100

effluent N=
     "ammonium-N"-N eliminated

total Kjeldahl nitrogen=
     IF THEN ELSE(stream selection=1,86,IF THEN ELSE(stream selection=2,2,IF THEN
     ELSE(stream selection\=3,2500,86) ) )
     ~    mg/l
     ~    TKN

biological oxygen demand=
     IF THEN ELSE(stream selection=1,249,IF THEN ELSE(stream selection=2,176,IF THEN
     ELSE\(stream selection=3,3560,249) ) )
     ~    mg/l
     ~    BOD

nitrate=
     IF THEN ELSE(stream selection=1,4,IF THEN ELSE(stream selection=2,6,IF THEN
     ELSE(stream selection\=3,0,0) ) )
     ~    mg/l
     ~    N NO3-
          No value reported in Table 1 for concentration of nitrate in BW stream

chemical oxygen demand=
```

```
	IF THEN ELSE(stream selection=1,701,IF THEN ELSE(stream selection=2,472,IF THEN
	ELSE\(stream selection=3,10560,701) ) )
	~	mg/l
	~	COD

effluent COD=
	chemical oxygen demand-COD eliminated

N removal 1=
	GAME (0)
	~	percentage
	~

N removal 2=
	GAME (0)
	~	percentage
	~

N removal 3=
	GAME (0)
	~	percentage
	~

COD removal 1=
	GAME (0)
	~	percentage
	~

stream selection=
	GAME (1)

P removal 1=
	GAME (0)
	~	percentage
	~

P removal 2=
	GAME (0)
	~	percentage
	~

P removal 3=
	GAME (0)
	~	percentage
	~
```

COD removal 3=

GAME (95)

~ percentage

~

COD eliminated=

(chemical oxygen demand*COD removal 1/100)+(chemical oxygen demand-chemical oxygen demand*COD removal 1/100)*COD removal 2/100+(chemical oxygen demand-chemical oxygen demand*COD removal 1/100-((chemical oxygen demand\-chemical oxygen demand*COD removal 1/100)*COD removal 2/100))*COD removal 3/100

~ mg/person

~ +(chemical oxygen demand-(chemical oxygen demand-chemical oxygen \
demand*COD removal 1)*COD removal 2)*COD removal 3

pcd toilet=

(base per capita daily municipal water demand by category[toilet])*((1-Percentage of Houses Metered[toilet])*1+Percentage of Houses Metered[toilet]*(1\-water use reduction from water metering[toilet]))

pcd toilet2=

(base per capita daily municipal water demand by category[toilet])*((1-Percentage of Houses Metered[toilet])+Percentage of Houses Metered[toilet]*(1-water use reduction from water metering[toilet]))*((1-Percentage of Houses with Low Flow Appliances[toilet])+Percentage of Houses with Low Flow Appliances[toilet]*(1-water use reduction from low flow appliances[toilet]))