Integrated Water Resources Management and Modelling for Decision-making at the River Basin Scale

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
in
Water Resources Engineering

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University of Alberta

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Abstract

As an essential resource for nature and socio-economic development, water is under increasing pressure due to population and economic growth, uneven resource distribution, and climate change uncertainties. Therefore, with increasing concern over environmental impacts, ecosystem damage, and economic cost, water resources management is shifting from a “hard path”, which relies on hydraulic infrastructure, to a “soft path” – the focus of this research – that considers efficient water management and conservation. In this context, the United Nations proposed Integrated Water Resources Management (IWRM) as an approach to managing water from a holistic perspective, both in its natural state and in balancing the competing demands – agricultural, municipal, industrial, and environmental – to achieve long-term water sustainability.

The central theme of this research is to understand and quantify IWRM ideas at the river basin scale. Following a systems approach which contains main water uses under the IWRM context – agricultural, municipal, industrial, and environmental sectors – three water management models with different sectoral focuses are discussed in this research. Chapter 1 introduces a drought management model focusing on the agricultural water simulation with five representative rain-fed and irrigated crops, four livestock types, two tree crops, and vineyards. An integrated water resources model for scarcity management, which is discussed in Chapter 2, has a detailed representation of the industrial water sector including power generation, conventional oil and gas extraction, mining, and manufacturing. Chapter 3 introduces a municipal water management model that includes ten specific end-uses with seven residential end-uses (six indoor and one outdoor use), and three non-residential uses. Results from all three models reveal the broad impacts of drought and water scarcity on farmers, municipalities, industries, and the environment, and the effectiveness of available water, land, financial, and technological policies, especially their trade-offs in the context of IWRM.

These models could be used for water demand projection, water balance analysis, water shortage impacts estimation, and water management policy impacts and trade-off simulation with social, economic, and environmental considerations under future uncertainties. The models are intended as decision-support tools for water resource managers and planners, policy-makers, researchers, students, and the public. Further, using some of these models in a simulation gaming format makes them suitable decision support tools to provide management strategy feedback, promote collaborative decision-making, and contribute to the understanding and practice of IWRM.

Preface

This thesis is an original work by Kai Wang, and is organized in a journal-article format. Each chapter (excluding Chapters 1 and 5) is a standalone article for journal submission, and detailed publication and submission information is provided for each. Therefore, each chapter contains its own introduction and conclusion. The models referred to in Chapters 2, 3, and 4, as well as literature reviews, are my original work with the assistance of Dr. Evan Davies. Chapter 1 provides a general introduction to the thesis, and Chapter 5 summarizes conclusions of this research as a whole. An integrated reference list has been provided at the end of the thesis because of overlapping references.

Acknowledgments

First, I wish to acknowledge the help and support of my supervisor Dr. Evan Davies, who motivated my research insights, guided my research directions, and shaped my scientific thinking and academic writing. I would also like to thank my co-supervisor Dr. Thian Yew Gan for his invaluable input and help. Without them I could not be where I am today.

Second, I thank the China Scholarship Council (CSC), Agriculture and Agri-Food Canada, the Albert Land Institute, the University of Alberta, the Graduate Students' Association, and International Student Services for providing funding support, as well as my parents, wife (Xinying Dai), and friends (especially Vincent McFarlane) for their endless love, help, and encouragement.

Finally, many thanks for the contributions of the committees for my PhD candidacy and final exams (Dr. Aminah Robinson Fayek, Dr. Mark Loewen, Dr. Patricia Gober, Dr. Scott Jeffery, and Dr. Yuntong She), and thanks as well to the people who provided valuable research suggestions and support (Dr. Graham Strickert, Dr. Harvey Hill, Mr. Aaron Boulton-Chaykowski, and Mr. Richard Phillips).

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Chapter 1 General Introduction

1.1 Integrated Water Resources Management (IWRM)

Water scarcity is becoming an increasing concern worldwide, especially in the context of population and economic growth, uneven resource distribution, and climate change uncertainties (UN-Water, 2015; Rijsberman 2006; Wagener et al. 2010; United Nations, 2014). Integrated Water Resources Management (or IWRM, Cardwell et al, 2006; Global Water Partnership (GWP), 2000) provides a comprehensive approach for water scarcity management through balancing various human demands, including the environmental requirement for long-term sustainability (Bakker, 2012).

IWRM is defined by GWP (2000: 22) as a process that "promotes the coordinated development and management of water, land and related resources in order to maximise economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems and the environment". As a central theme of this research, IWRM aims to manage water from a holistic perspective, both in its natural state and in balancing competing demands – agricultural, municipal, industrial and environmental – to use and protect water in a more efficient way and achieve long-term sustainability (UNESCO and IHP, 2009; GWP and Technical Advisory Committee (TAC), 2011).

At a global scale, agriculture is the largest water use and accounts for 70% of total water withdrawal and more than 90% of the total water consumption (FAO, 2016). In Canada, agriculture is a significant water use in most basins of the Canadian Prairies for irrigation (the most significant use), feedlots, and stock watering (AMEC, 2007). Industry is the second largest use, at 19% of total global water withdrawal (FAO, 2016). Industries such as power generation, oil extraction, mining, and steel production require water for cooling, processing, cleaning, fabricating, diluting, or transporting purposes (USGS, 2015; EUROSTAT, 2015). In Canada, the thermal power generation industry withdraws the most water for cooling and the production of steam (Environment Canada, 2017). Municipal use represents the smallest percentage (11%) of water withdrawal at the global scale (FAO, 2016). In Canada, municipal water systems serve residential, industrial, commercial, institutional and public clients, and residential use accounts for the greatest fraction of the water withdrawal (Mayer and DeOreo, 1999; DeOreo et al., 2016). Environmental water demand, or the instream flow requirement, represents the amount of water needed to maintain a healthy ecosystem, and usually varies at both spatial and temporal scales (Dyson 2003). In most water-scarce regions, the risk of not meeting the environmental demand is high, especially as water demands of other sectors grow (Mekonnen and Hoekstra, 2016).

To manage these demands in an IWRM context requires the integration of ecosystem sustainability, economic efficiency, and social equity considerations (GWP and TAC, 2011). To achieve this, water policies and assessment models are important management instruments in converting the qualitative ideas of IWRM into quantitative plans for both operational (short-term) and planning (long-term) purposes (UNESCO, 2009; Prodanovic and Simonovic, 2010). Further, IWRM treats river basins as fundamental management units since they are the fundamental unit of hydrology, and thus represent the available water supply (Jury & Vaux, 2007; Mitchell et al., 2014). Therefore, this research focuses primarily on river-basin scale IWRM, with the exception of the municipal water management model, and uses simulation models to evaluate various management policies in addressing water scarcities under uncertainty.

1.2 Water Resources Management Policies and Models

With considerations of environmental impact, ecosystem damage, and economic cost, water resources management is shifting from a “hard path”, which relies on hydraulic infrastructure, to a “soft path” that considers efficient management and water conservation, including policies and technologies, open decision making, and water markets (Gleick, 2003). Water policy – which refers to not only the legal and regulatory framework but also to planning around resource collection, allocation, use, and disposal – is critical for this soft path management, as it is the basis for legislation, strategic planning, and operational management, and it often affects water management in the long run (UNESCO, 2009; Percy, 2005). Various studies (Jury & Vaux, 2007; Cosgrove and Loucks, 2015) have investigated management policies from both supply (e.g. infrastructure expansion and new sources such as desalination) and demand (e.g. water saving and conservation using technological development and economic methods) sides. Policies have also been discussed and tested for the agricultural (Iglesias and Garrote, 2015; Iglesias et al., 2009; de Fraiture and Wichelns, 2010), municipal (Cohen and Neale, 2006; Escriva-Bou et al., 2015), industrial (Harto and Yan, 2011; Davies et al., 2013), and environmental (Chatterjee et al., 2008; US-EPA, 2013a) water sectors to manage the related water demands and to plan for the future. In the regional and river basin scales, management policies related to more than one water use sector are usually tested using mathematical models to address different concerns such as economic analysis (Harou et al., 2009; Wilkie, 2005), climate change adaptation (Girard et al., 2015; Iglesias et al., 2011), and drought mitigation (Wang and Davies, 2015).

Water management models that provide analytical support to decision making under uncertainty are important instruments for the implementation of IWRM (Prodanovic and

Simonovic, 2010). These models have wide ranges of both spatial (e.g. municipal, watershed and global scales) and temporal scales (e.g. hourly, weekly, and annual time steps). The typical purpose of these models is to manage the gaps between water supply and demand, or "water scarcity". Used to simulate the water supply, hydrological models are simplified characterizations of the hydrological cycle and are used to understand and project water availability by simulating variables including stream-flow, reservoir storage, and groundwater level (Singh and Woolhiser, 2002; Moradkhani and Sorooshian, 2009). Compared to the prediction of the available supply, water demand management highlights the need to make better use of water supplies. Thus, demand management models focus on investigating the behaviour of water users, and include the application of water policies and technologies, and the projection and evaluation of their water requirements (Raes et al., 2009; House-Peters and Chang, 2011; Davies et al., 2013; Dyson et al., 2003). However, the increasing complexity of water systems and the integrated approach of IWRM require management of both the demand and supply sides – a systems view, since supply management aims to satisfy water demand maximally while demand management tries to use water supply sustainably. The models based on this view aim to investigate the relationship between physical water supply and socio-economic water demand and manage the imbalance between them (Tidwell et al., 2004; Langsdale et al., 2007). The system dynamics methodology is typically adopted for these models and is introduced as follows.

1.3 System Dynamics Methodology

System dynamics (SD, Forrester, 1961; Sterman, 2000) – the modelling methodology used for this research – has been employed widely to model complex systems such as global climate, ecosystems, natural resources, and business (Davies and Simonovic, 2011). It focuses on the role of system structure, especially interactions/feedback among disparate but interconnected subsystems in determining the larger system's behaviour, to identify and understand its root causes (Barlas, 1996; Mirchi et al., 2012). This makes it a good method to integrate the water supply (the physical component) and various water demand sectors (socio-economic components) through water diversions, allocations, uses, and returns, and to capture the big picture of the water system to support IWRM applications.

Further, SD models can be developed quickly, are typically easy to modify and understand, run fast, and can present simulation results clearly to a wide audience of users and decision makers (Prodanovic and Simonovic, 2010). This means SD models are often used for educational purposes, participatory planning and modelling, and public engagement (Williams et al., 2009; Tidwell et al., 2004). Further, SD models can be used to assess policy options easily and inexpensively through alternative scenario building, sensitivity analysis, and a recently emerging gaming approach (Winz et al., 2009; Savic et al. 2016). Therefore, SD models are powerful tools to analyse water management policies under future uncertainties such as population growth and climate change.

Detailed literature reviews of system dynamics and its applications in water resources management, as well as alternative modelling approaches, are discussed in the following chapters. Specifically, SD models are used in this research for standard water management simulation and to support decision making in simulation games.

1.4 Simulation and Simulation Gaming Approach

Simulation imitates real-world processes or systems over time (Banks et al., 2001: 3). A model is developed to represent the characteristics and dynamics of the specific process or system, and simulation then represents the operation of the modelled system. Computer simulation – the focus of this research – models real-world systems on a digital computer and simulates their operation by changing variable values (Sokolowski and Banks, 2009: 6). Therefore, simulation is used to answer “what if” questions, rather than questions related to “the best” operation, which are answered instead by optimization methods. Simulation has been used widely in physics, chemical, economics, and engineering to improve the understanding of the specific systems.

At the river-basin scale, which includes many conflicting water uses, the prioritization of water sectors under scarcity is not straightforward, since not all sectors can be easily evaluated through economic values, such as environmental flows, which are also required by IWRM. Further, the water demands of a single sector are also affected by various water management policies as well as uncertainties (e.g. population growth, climate change). Therefore, simulation models can be useful tools to test various water allocations and conservation policies in addressing basin or sectoral scale water scarcity through different scenarios’ simulations and analyses.

Simulation gaming is a modification of the standard simulation approach that began in the military and spread to non-military applications during the mid-1950s. It has since been adopted by disciplines such as education, policy analysis, economics, and engineering with an increasing recognition of its effectiveness as a tool for the management of limited resources (Mayer and Veeneman, 2002; Mayer, 2009). Simulation games are “experimental, rule-based, interactive environments, where players learn by taking actions and by experiencing their effects through feedback mechanisms that are deliberately built into and around the game” (Mayer, 2009: 825). In a game, individuals assume roles, interact with other actors and experience their choices’ results. Although gaming approaches include board games, role playing, online debates, scenario building, and computer simulation models (Hoekstra, 2012), this research focuses specifically on computer simulation models, which are used to represent physical and socio-economic systems and respond to players' actions to enhance exchanges between them beyond the game itself.

Simulation gaming provides an effective and collaborative environment for water policy analysis and integration of stakeholders from different disciplines to promote practices of IWRM. Competition and cooperation – the nature of a game – help stakeholders to discuss options, negotiate priorities, and reach a cross-sectoral consensus under a multi-disciplinary context (Rusca et al., 2012). In practical terms, simulation gaming models can support decision-making by illustrating the comprehensive results of management decisions, and thus promoting participants' understanding of complex water resources systems, management trade-offs, and other stakeholders' positions (Wang and Davies, 2015).

1.5 Research Objective and Novelty

The goal of this research is to investigate an integrated approach for water resources management and modelling to understand and quantify IWRM ideas at the river basin scale. To achieve this, the goal can be divided into the following specific and interconnected objectives:

1 To provide decision-support tools that reveal the broad impacts of water scarcity and assess water management policy effectiveness and trade-offs under future uncertainties in the context of IWRM,

2 To improve the understanding of complex water resources systems and their dynamic mechanisms in both river basin and sectoral scales, especially under water scarcity

conditions including drought, to improve both short and long-term water sustainability, and,

3 To promote stakeholder engagement and consensus building, student and public education, and proactive management for water hazard mitigation.

The novel aspects of this research include,

1 Adoption of an integrated approach for water resources modelling that combines the following aspects systematically: the main water sectors relevant to IWRM, regional and basin modelling scales, fictitious and real-world study areas, as well as annual and weekly modelling time steps to develop a comprehensive understanding of the water system.
2 Assessment of management policy trade-offs for decision support by providing comprehensive policy analysis, including water allocation, social and environmental impacts, water conservation effectiveness, and economic cost.
3 Investigation of simulation and simulation gaming applications in promoting education and engagement of various stakeholders, and motivating insights in basin-scale IWRM practices.

1.6 Chapter Overview

This thesis is formatted based on three contributions to water resources management and modelling in the IWRM context. Each contribution has been published in the academic literature, or has been prepared for publication, and is discussed in a separate chapter that focuses on specific water use sectors, and temporal and spatial scales (see Table 1-1) to achieve the three objectives discussed above. Specifically, Chapter 2 has been published as: Wang, K., Davies, E.G.R., 2015. A water resources simulation gaming model for the

Invitational Drought Tournament. Journal of Environmental Management 160, 167-183. The content of Chapter 3 is currently being prepared as a journal manuscript: Wang, K., Davies, E.G.R., 2017. River Basin Simulation Modelling for Integrated Water Resources Management. Advances in Water Resources. The content of Chapter 4 has been submitted for publication. The reference is as follows: Wang, K., Davies, E.G.R., 2017. Municipal water planning and management with an end-use based simulation model. Environmental Modelling & Software (submitted, May 2017). Chapter 5 discusses the overall findings, recommendations, and conclusions of the research, and presents plans for future research.

Table 1-1: Chapter information

Chapter	Theme	Objectives	Sectors	Spatial Scale	Time
2	Basin drought management	1, 2, 3	A*, M, I, E	Fictitious basin	Annual
3	Integrated water management	1,2, 3	A, M, I*, E	Bow River Basin	Annual
4	Municipal water management	1, 2	M	City of Calgary	Weekly

*A=agriculture sector, M=municipal sector, I=industrial sector, E=environmental sector, * focuses particularly on this sector*

Chapter 2 Agriculture Water Management

2.1 Introduction

Drought results from a prolonged period of abnormally dry weather that reduces water availability for human and environmental needs (Bonsal et al., 2011). It occurs in nearly every climatic zone (Mishra and Singh, 2010) and is hard to predict in terms of onset, potential duration and severity (Wilhite and Glantz, 1985). It is also challenging to manage its negative social and environmental effects that can spread over large geographical areas (Giacomelli et al., 2008; Iglesias, 2003; Mishra and Singh, 2010). These negative effects are significant: for example, Mishra and Singh (2010) detail drought damages in the United States of $40 billion in 1988, with total damages of $144 billion (or 41.2% of the total weather-related disasters) from 1980-2003. More recent droughts of 2009, 2011 and 2012 are estimated to have caused $5.0 billion, $12.0 and $30.0 billion, respectively, in damage to crops (NCDC, 2014). In Canada too, prolonged, large-area droughts are among the costliest natural disasters, with "major impacts on sectors such as forestry, industry, recreation, human health and society, and aquatic environments" (Bonsal et al., 2013: 501). Both drought frequency and severity are projected to increase throughout the world in the 21st century with climate change (Prudhomme et al., 2013).

Although drought has no standard definition, droughts are typically classified as meteorological, agricultural, hydrological or socio-economic (Wilhite and Glantz, 1985); further, a key characteristic is their "temporary aberration" in climate with a potential persistence of months or even years (Mishra and Singh, 2010). According to the World Meteorological Organization (WMO), "drought means a sustained, extended deficiency of

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The content of this chapter has been published as: Wang, K., Davies, E.G.R., 2015. A water resources simulation gaming model for the Invitational Drought Tournament. Journal of Environmental Management 160, 167 -183.

precipitation"; when this deficiency occurs over an extended period, a meteorological drought can result (Wilhite and Glantz, 1985). Agricultural and hydrological droughts follow from meteorological drought and are characterized by decreased soil moisture and eventual deficiency in surface and subsurface water systems (streams, rivers, reservoirs and ground water) respectively. These three types of drought are physical phenomena. Socio-economic drought – the fourth category and the focus of this paper – incorporates aspects of meteorological, agricultural and hydrological drought, but is also associated with the supply and demand of economic goods and the effects of water scarcity on human activities (Wilhite and Glantz, 1985). According to Mishra and Singh (2010: 206), "socio-economic drought occurs when the demand for an economic good exceeds supply as a result of a weather-related shortfall in water supply". Focusing specifically on its economic, social and environmental impacts, the U.S. National Drought Mitigation Centre (2013) places socio-economic drought on their scheme of drought types as the final outcome of first meteorological, then agricultural, and then hydrological drought.

Given drought's broad impacts, drought management aims to (1) guarantee sufficient water for human needs, (2) minimise negative impacts on the condition of a river, stream, lake, aquifer or other water body and (3) minimise negative impacts on economic activities (European Commission, 2007). Traditionally, drought management activities have been initiated as a drought intensifies, abandoned after a weakening of drought conditions, and then activated again with the next drought (Abraham, 2006). This crisis-management approach, termed the "Hydro-Illogical Cycle" by Wilhite (2011), has proven ineffective because of an often-slow, expensive and poorly-coordinated response (Abraham, 2006; Wilhite et al., 2000). Therefore, drought management has begun to move from a reactive, crisis-management approach, such as response and recovery, to proactive risk management, involving early warning systems, risk and impacts assessments and drought mitigation (Sivakumar and Wilhite, 2002). Wilhite (1997) discussed many management actions which are grouped to nine categories: monitoring and assessment, legislation, supply augmentation and planning, public education, technical assistance on water conservation, demand reduction, emergency response, water use conflict resolution and drought contingency planning. However, these approaches require a better understanding of the broader impacts of drought and drought mitigation strategies, as well as public support (Stoutenborough and Vedlitz, 2014). Therefore, stakeholders from drought-affected sectors should be engaged in drought management, and successful experiences in adopting a comprehensive and active approach to drought management should be widely shared (AAFC, 2011; European Commission, 2007).

To encourage proactive, participatory planning and adaptation for future droughts in Canada, Agriculture and Agri-food Canada (AAFC) has recently developed a new tool, called the Invitational Drought Tournament (IDT), to support institutional drought preparedness by (1) enhancing discussions between stakeholders from different disciplines about proactive drought management, (2) improving the understanding of drought impacts on socio-economic and environmental subsystems by linking physical science (the hydrological cycle and agricultural science) with socio-economic effects and (3) assessing the effectiveness of drought mitigation strategies in reducing ecological, economic and social drought risk (Hill et al., 2014).

This paper describes a new, simulation gaming-based decision support tool that communicates both direct and indirect effects of drought management decisions to IDT participants. Section 2 introduces the Invitational Drought Tournament. Section 3 provides background on simulation models for drought and water resources management. Section 4 introduces and describes a new IDT Model, beginning with simulation games and gaming models, then overview of IDT Model and introducing system dynamics modelling methodology (Section 4.1), and finally explaining the main IDT Model structures (Section 4.2) and model performance (Section 4.3). Section 5 demonstrates model application with results from past IDTs. Finally, the paper closes with conclusions and next steps for future research.

2.2 The Context: The Invitational Drought Tournament (IDT)

The Invitational Drought Tournament combines a workshop with features of a game such as competition, cooperation, rules, strategies, players and referees. Essentially a "workshop with a winner", the IDT involves multi-disciplinary teams of typically five players each, who compete over the course of a day for the best score, which is determined based on the ability of their drought mitigation plan to reduce social, economic and environmental drought risks in both the short- and longer-term. The gaming format of the IDT provides a safe "experimental environment", based on reality, in which participants can better understand and manage the complex interactions of drought conditions, gaming decisions, and natural and socio-economic results both within teams (collaboration) and against others (competition) (Mayer and Veeneman, 2002). Further, the mixture of collaboration and competition make the IDT an enjoyable experience for the participants (Hill et al., 2014).

A number of IDT events have been held in several Canadian provinces with participants from a variety of sectors. A Calgary, Alberta, IDT in 2011 included 46 interprovincial water managers, while two Prairie IDTs in Saskatoon, Saskatchewan, in 2012 and 2013 involved graduate students from four Canadian Prairies universities. Finally, an Okanagan IDT in 2012 included a variety of water resources stakeholders, and was held in Kelowna, British

Columbia (Hill et al., 2014). Each IDT occurred in a semi-fictitious basin developed by Agriculture and Agri-food Canada (AAFC): the Oxbow Basin was based on a Canadian Prairie river basin, and used in the Calgary and Saskatoon IDTs, while the Seco Creek Basin was based on the Okanagan Basin of British Columbia and used in the Okanagan IDT. Using a fictitious river basin based on real data allows the IDT to (1) involve broader groups of participants from various river basins, (2) encourage creative decision-making, (3) reduce geopolitical sensitivities between stakeholders and (4) ensure a proper balance between realism and simplicity (Hill et al., 2014).

At the start of each IDT, participants are told that drought has begun to create an imbalance between water supply and sectoral (municipal, industrial, recreational and agricultural) water demands; teams are not told how long the drought will last. Detailed descriptions of the basin water supply, including precipitation and reservoir storage, and anticipated sectoral water demands are then provided to the teams – and similar descriptions are provided at the beginning of each subsequent game year, with each year corresponding to a round of the game. Teams use the information provided to judge current drought conditions, assess the risks of a continued drought, and plan their actions to deal with the drought in the current game year. Teams are also given a drought mitigation budget at the start of each year – which, for realism, can vary unpredictably from one year to the next – which they allocate to a set of drought management options. These management options can focus on either a short- or long-term reduction of drought impacts, and are organized into four main categories: water management, financial management, land management and technological improvements (Table 2-1). At the end of each round, referees score each team based on its success in drought management, as judged by the effectiveness of the chosen adaptation options in reducing ecological, economic and social drought risk. Figure 2-1 shows the IDT process.

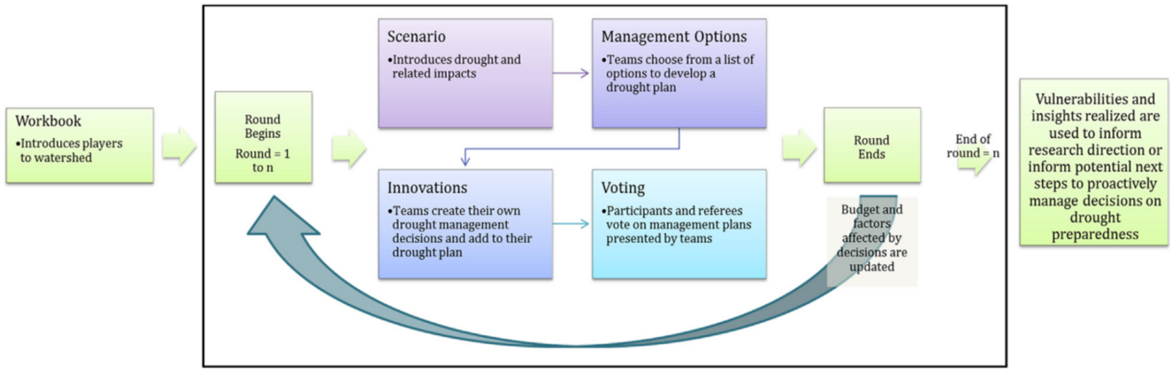


Figure 2-1: IDT process (Hill et al., 2014)

The scoring system has evolved through the IDT events from expert-derived to participatory press conferences, and then to a hybrid approach (Hill et al., 2014). In the longer term, however, the results of a new simulation gaming model, “the IDT Model” – the subject of this paper – will be incorporated into team scoring and communicate to the teams the effectiveness of their policy choices.

Table 2-1: Drought management policies in the IDT (AAFC, 2011)

Adaptation option	Adaptation type	Details
Water Management		
Enhance irrigation water diversion/application efficiency by 25%	Long-term technology- and infrastructure-focused strategy that takes 5 years to implement	Convert 120,000 ha to high efficiency irrigation and line 1000 km of canal with concrete to reduce seepage
Divert water from another basin to the Oxbow	Long-term infrastructure strategy that takes 10 years to implement	Inter-basin water transfer of 250 million cubic meters (MCM) every year
Build a dam and reservoir	Long-term infrastructure strategy that takes 10 years to implement	Increase water storage capacity in the Oxbow basin by 500 MCM
Ration water	Short-term responsive strategy aimed at reducing consumption	Reduce water demands by cutting allocations. Teams to choose which sector(s) is (are) cut and by how much

Utilize reservoir draw down (storage)	Short-term responsive operational strategy to help satisfy local water demands	Initially there is 450 MCM of storage capacity. If teams choose this option, they have to keep track of how much water remains in storage
Financial Management		
Relief payout to producers	Short-term emergency response strategy aimed at reducing immediate economic and social stress in the agricultural sector	Provide an emergency payout of $85 per hectare to producers affected by drought
Land Management		
Promote green cover	Long-term operation management strategy aimed at changing land use in the basin	Provide producers with $210 per hectare over 10 years to cover 60,000 ha of marginal annual cropped land at-risk of soil degradation to perennial cover
Promote winter cropping	Annual cropping management strategy that facilitates flexible seeding	Promote seeding in fall instead of spring to take advantage of fall soil moisture
Promote stocking rate Reductions	Short-term strategy to reduce ecological stress and pasture degradation	Promote a 15% reduction in stocking rates. Reduce number of head by 2,500,000 head. Compensate at $50/head
Promote diversification of pasture species composition	Long-term strategy to diversify species composition of pastures	Promote seeding of a variety of species in pastures. include early and late season and cool and warm shrubs and plants
Technology		
Expand irrigation	Long-term strategy to convert rain-fed to irrigated farming	Add 200,000 ha of high efficiency irrigation to the basin
Invest in water-related research and development	Long-term strategy to investigate alternative drought adaptation strategies	Develop new and innovative ways to adapt to dry conditions
Invest in agriculture-related research and Development	Long-term strategy to investigate alternative drought adaptation strategies	Develop new and innovative ways to adapt to dry conditions
Invest in grey water Treatment	Long-term water conservation strategy to recycle and reuse water	Subsidize grey water treatment technology for toilet and laundry for 50,000 homes in the basin

2.3 Drought Management and Water Resources Models

A variety of models and methods are available as decision support tools for meteorological, agricultural and hydrological drought management. Fewer models are available for socio-economic drought management, although a range of “systems models” have been developed for other water resources management applications. This section reviews models and methods available for the first three drought classifications briefly before focusing on socio-economic drought management tools.

Meteorological drought is a physical phenomenon since it is caused by a reduction of physical precipitation (Wilhite et al., 2000), and monitoring and early warning systems, which integrate climate and hydrologic models, are used for management with outputs such as time (onset), intensity and duration of drought. Examples of drought monitoring and early warning systems include the Drought Monitor in the United States (NIDIS, 2013) and Drought Watch in Canada (Agriculture and Agri-Food Canada, 2013); see also Wilhite et al. (2000) and Mishra and Singh (2010) for further examples.

Agricultural drought links water stress from precipitation shortages to impacts in the form of yield reductions (Ray and Gul, 1999; Siebert and Doell, 2010). A variety of agricultural models can simulate crop development processes based on physical states such as climate and soil conditions and management actions such as irrigation. For example, the FAO's well-known CROPWAT (Smith, 1992) and AquaCrop (Raes et al., 2009; Steduto et al., 2009) models simulate crop water- and irrigation requirements, irrigation depths and schedules and attainable crop biomass and harvestable yields based on water availability (Steduto et al., 2009). DSSAT combines crop, soil and climate data to simulate multi-year outcomes of crop management strategies, and is widely used for yield forecasting, irrigation management and precision agriculture (Jones et al., 2003). CropSyst simulates both yearly and multi-year crops and crop rotations, and can generate not only soil water budget, crop yield, but also soil nitrogen and erosion (Stöckle et al., 2003). For agricultural models used in Canada, examples are the Irrigation Water Demand model (Fretwell, 2009) and the Irrigation District Model

(Irrigation Water Management Study Committee, 2002), which simulate irrigation requirement and management in the Okanagan and South Saskatchewan River Basins, and the Alberta Irrigation Management Model (Alberta Agriculture and Rural Development, 2014a) which assists irrigators in the timing and amounts of their irrigation water applications in the Province of Alberta.

For agricultural drought management, these models can express drought impacts on crop yields explicitly and can reveal effects of mitigation actions. Scott et al. (2004) used CropSyst to analyze the negative effects of drought on crop yields in the Yakima Basin, USA. Iglesias et al. (2009) used DSSAT to quantify impacts of climate change, including dry conditions, on crop yields in Europe, and tested the effects of adaptations such as water and fertilizer management to mitigate the impacts. Deficit irrigation can be an effective water-saving practice for coping with drought (Rossi et al., 2007), since it offers a means of reducing water use while maintaining yields near their optimal values, as described by Geerts et al. (2010) and Marsal and Stöckle (2012) who used AquaCrop and CropSyst to derive deficit irrigation schedules to maximise water productivity and avoid water stress in Central Bolivia and Spain, respectively. Economic factors also affect agricultural water use under water stress. For example, Iglesias and Blanco (2008) and Elmahdi et al. (2007) developed models to simulate effects of water tariffs and total water cost on agricultural water use in Spain and two hypothetical irrigation areas in Australia, respectively. Finally, the irrigated area must also be considered in agricultural drought management efforts. As described by Fernández and Selma (2004), management of the interaction between the irrigated area and available water could help to address water deficits and also have environmental benefits.

Hydrologic drought results from a shortfall in precipitation that reduces the surface and subsurface water supply available for human activities (U.S. National Drought Mitigation Centre, 2013; Wilhite and Glantz, 1985). Consequently, as simplified characterizations of hydrologic cycle components, hydrologic models can be used as support tools for drought management and can help to improve understanding and prediction of hydrologic processes by simulating stream-flow, reservoir storage, groundwater level and so on (Singh and Woolhiser, 2002; Sorooshian et al., 2009). Specifically, for hydrologic drought forecasting, Trambauer et al. (2013) evaluated the suitability of sixteen well-known hydrologic models, including VIC, MATSIRO, WaterGAP and Macro-PDM, based on the representation of different hydrologic processes and fluxes, applicability to the research area, data requirements and capabilities for downscaling and forecasting. For the investigation of the effective management of a limited supply, Sechi and Siulis (2010) compared water supply management and planning models such as AQUATOOL, MODSIM, RIBSIM, WARGI, WEAP and MIKE-BASIN, which can be used as decision support tools to simulate various water supply management strategies under different hydrologic conditions, including low flows.

The integration of natural and socio-economic factors in socio-economic drought increases the potential both for social conflict and for environmental, social and economic impacts (Pérez and Hurlé, 2009). Further, in many historically water-scarce regions of North America, the demands for drinking and domestic water, crop production, industrial water supply, environmental flows and water-based recreational activities are increasing with population growth and economic expansion (Environment Canada, 2004; Jury and Vaux, 2007; Rijsberman, 2006). Therefore, a greater understanding of drought management options and preferences could help society in preparing for, adapting to and recovering from socio-economic drought. Such an understanding should focus on identifying which water-use sectors are affected and which is the most affected, the causes of the impacts, how stakeholders act in response and most importantly how to mitigate their effects in a dynamic and interactive context (Abraham, 2006).

Although models that can provide an integrated and comprehensive view of socio-economic drought are rare, systems models for water resources management offer a useful foundation. Such models aim to manage imbalances between the physical water supply and socio-economic water demands (Mirchi et al., 2012; Winz et al., 2009), and are typically modelled with System Dynamics, a "systems modelling methodology" discussed in Section 4.1. Some of these water resources management models focus primarily on water demands. For example, Qaiser et al. (2011) and Ahmad and Prashar (2010) used dynamic simulation models to evaluate alternative water conservation policies for Las Vegas and South Florida, USA, respectively. Qi and Chang (2011) modelled the effects of population growth and regional economics on municipal water demand for Manatee County, Florida. Other models investigate inter-relationships between water supply and demand. Langsdale et al. (2007) and Xu et al. (2002) developed simulation models to explore future water supply and demand under different water conservation policies and climate change scenarios in the Okanagan Basin, Canada and the Yellow River Basin, China, respectively. WaterSim (Gober et al., 2011), an urban water planning model, was developed to investigate effects of climate change, population growth and protection policies on future water supply and demand in Phoenix, Arizona. Madani and Mariño (2009) analyzed the effectiveness of water supply (trans-basin diversions) and demand (population control) policies in addressing water scarcity in the Zayandeh-Rud River Basin, Iran. Tidwell et al. (2004) developed a water planning model to balance the regional supply and demand with alternative water management strategies for residential/non-residential, bosque, agriculture, reservoirs and desalination in the Middle Rio Grande Basin, New Mexico.

The models described above focus on the effects of climate change, population growth and water conservation policies on regional water scarcity, as represented by the difference between physical water supply and socio-economic water demand. However, the broad impacts of water shortage on the socio-economic system are not investigated. In contrast, Williams et al. (2009) developed a dynamic simulation model to improve understanding of the complexity and conflicts in water resources systems. The model can not only simulate the available water supply (stream flow, groundwater, reservoir, imported water and treated water) and sectoral (agricultural, industrial, residential and non-residential) water demands, but also reveal the effects of water scarcity on agriculture yield, farming incomes, per capita water use, supply cost and environmental economic valuation, based on the current water balance, and their connections to population growth, land management and water conservation policies. The model is used as an education tool for undergraduate students in the University of Arizona to improve their understanding of both the complexity of, and potential conflicts related to, water resources systems in the socio-economic context.

Finally, a small subset of water resources models couples the water supply and demand components described above with a simulation gaming approach. The complexity and unpredictability of water resources systems make management of the impacts of water scarcity on conflicting uses difficult. Furthermore, competition between water users is likely to be more intense and the effects of management actions to be more unpredictable under drought conditions, because of uncertainty about future conditions and the lack of reliable statistics on historical droughts (World Meteorological Organization and Global Water Partnership, 2011). For these reasons, simplification of real river basins, a safe environment for testing potential outcomes of policy selections and a fast learning process can contribute to understanding of complex water resources systems, collaborative decision-making and consensus-building under water stress (Hill et al., 2014; Mayer, 2009).

Along these lines, Rusca et al. (2012) introduced a systems model for their "Ravilla Simulation Game" that was designed to provide participants with hands-on experience of Integrated Water Resources Management (IWRM) in an experimental, safe-gaming environment. The Ravilla model provides a "big picture view" of a complex, basin-scale water resources system – in the fictitious Ra Basin, the Netherlands – and includes simulation of economic production and income, water quality and quantity, and water shortages and losses based on team strategies for water use and allocation. Compared to this game, "Irrigania" (Seibert and Vis, 2012) is a web-based simulation game, which focuses on the irrigation water conflicts between farmers. Irrigania can show both current and cumulative economic performance as well as current hydrologic conditions, including depth to groundwater and cost for groundwater irrigation, based on player-selected combinations of irrigation sources (rain-fed, groundwater and river) for the farmland. The turn-based decision-support and gaming approach of the Ravilla, Irrigania and IDT Models fit into a larger simulation gaming context, described below.

2.4 The IDT Simulation Gaming Model

Simulation games are "experimental, rule-based, interactive environments, where players learn by taking actions and by experiencing their effects through feedback mechanisms that are deliberately built into and around the game" (Mayer, 2009: 825). An effective simulation game can respond to players by offering immediate, contextualized and sometimes surprising feedback results; it also allows players to explore possible solutions, without real consequences, to improve their understanding of a complex system and trigger their curiosity and imagination (Barreteau et al., 2007; Crookall, 2009; Oblinger, 2004). In practice, simulation games require individuals to assume roles, interact with multiple actors and experience the results of their choices, and can therefore provide an excellent environment for entertainment, training, motivation, assessment, education and learning, research and decision support (Mayer and Veeneman, 2002; Oblinger, 2004). Overall, simulation games help to (1) determine how the system of interest works and how it can be influenced by players' choices, (2) understand the positions of other players, and interactions between their differing interests and (3) explore new institutional and organizational arrangements (Rusca et al., 2012).

Simulation gaming approaches include board games, role playing, online debates, scenario building and computer simulation models (Hoekstra, 2012). The focus here is on computer simulation models, which are used to represent the natural and socio-economic system under consideration, "respond to the influence of the players… to trigger imagination and exploration from the participants" of a set of 'potential realities', and enhance exchanges between participants and decision-makers beyond the game itself (Barreteau et al., 2007: 187). As its name suggests, simulation gaming brings together simulation – which simplifies the real world, making it "as simple as possible, but no simpler" (Holling, 2001: 391), for a better understanding of complex systems – with games, which include rules, players, cooperation and competition (Rusca et al., 2012). See Figure 2-2, below.

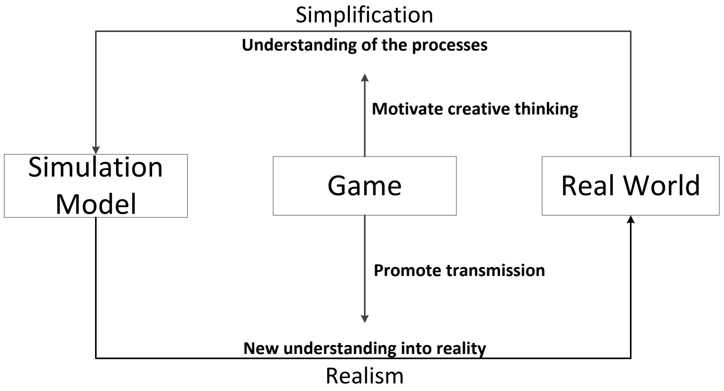


Figure 2-2: Interaction between real world, simulation model, and gaming format

Of all organizations, the military may have the greatest depth of experience in simulation gaming, according to Oblinger (2004). During the mid-1950s, simulation games began to spread from military to non-military applications, and in the 1970s and 1980s – with increasing recognition as an effective tool for the management of limited resources – gaming was adopted by social science disciplines, including education, biology, land management, policy analysis and economics (Mayer, 2009; Mayer and Veeneman, 2002). There are many gaming approaches to water resources management as well, including irrigation management-focused games like the River Basin Game (Hoekstra, 2012) and Irrigania (Seibert and Vis, 2012), flooding and river management games such as the River Waas Game (Valkering et al., 2013), and basin-scale water management and education games such as the Ravilla simulation game (Rusca et al., 2012) and the LASY game (Valkering, 2009).

With its focus on reconciling high water demands with a limited supply, socio-economic drought management requires decisions among interacting and often competing socio-economic and environmental alternatives, and must contend with stakeholders with different viewpoints and objectives (Stoutenborough and Vedlitz, 2014). In their roles as decision-support and learning tools, simulation gaming models aid exploration and comparison of both direct- and feedback-based socio-economic effects of alternative drought mitigation strategies. The next section describes a new simulation gaming model for socio-economic drought management: the IDT Model.

2.4.1 An Overview of the IDT Model and System Dynamics

The IDT Model was developed to address IDT team requests for more feedback on both the short-term and cumulative effects of their gaming decisions (Hill et al., 2014). It focuses on providing a comprehensive and integrated basin-scale overview of drought conditions and management in a simulation gaming context, and on helping teams to evaluate the effectiveness of their selected adaptation options – and those of opposing teams – in mitigating social, economic and ecological stress at an annual scale during a multi-year drought. Therefore, the IDT model (1) has a user-friendly interface, (2) illustrates through figures and tables the results of teams' policy choices on key water resources, land use, economic, and agricultural variables, (3) permits comparison of results among the IDT teams and (4) generates simulation results quickly for display to individual teams and the larger IDT group. Further, because the overall IDT framework is designed for portability (Hill et al., 2014), the IDT Model is likewise relatively easily configured for IDT events in different river basins.

System dynamics (Forrester, 1961; Sterman, 2000), the methodology used for the IDT Model, has been employed widely to model complex systems, and focuses on the role of system structure – stock and flow dynamics, material and informational delays and nonlinear feedbacks – in determining behaviour (Simonovic and Fahmy, 1999; Winz et al., 2009). Its "causal-descriptive" mathematical models aim to reproduce and then predict real-world behaviours, and aid assessment of the effectiveness of alternative policies (Barlas, 1996).

Further, because complex systems can give rise to problems that resist solution, system dynamics aims to "facilitate recognition of interactions among disparate but interconnected subsystems" that drive the larger system's dynamic behaviour, and to identify and understand their root causes (Mirchi et al., 2012: 2423). System dynamics is often used for educational purposes and to promote public participation (Tidwell et al., 2004; Williams et al., 2009), and to assess policy options easily and inexpensively through comparison of alternative "what if" simulations (Winz et al., 2009). Its models can be developed easily and quickly, are typically easy to modify and understand and can present simulation results clearly to a wide audience of users and decision makers (Prodanovic and Simonovic, 2010). System dynamics applications are frequently interdisciplinary and include water resources management, energy policy analysis, climate change assessment, urban planning and business (Davies and Simonovic, 2011). Further information on system dynamics is available in Sterman (2000), Winz et al. (2009), Martinez-Moyano and Richardson (2013) and Mirchi et al. (2012).

2.4.2 Model Structures

The IDT Model is a system dynamics-based simulation gaming tool that represents drought management decisions at an annual time step in the fictitious Oxbow Basin of the Canadian Prairies, which is the most drought-prone region in Canada (Khandekar, 2004). In the Prairies, agriculture is the largest water user and accounts for 50% of water withdrawal, followed by industrial (thermal power, 34%, manufacturing, 5%, and mining, 1%) and municipal (10%) use, according to the Manitoba Sustainability Initiatives Directory (2013). To represent these water uses, the model is organized into six interconnected parts, or "sectors" – population, water supply, municipal water use, agricultural water and land use, industrial water use and recreation – that are connected through water allocations and other water, land and financial management and technology policies. The sectors themselves contain variables related to water supply, sectoral water demands, land use, population, economics and the IDT policies. The model simulates both short-term (annual) and long-term (cumulative) effects of various policy combinations, including infrastructure improvements, water allocation strategies, land-use decisions and technological investments, on the basin water balance and land use. Model outputs include the variables above as well as agricultural production and profit for five representative field crops on both rain-fed and irrigated land, four livestock types, two tree crops and vineyards; mining production and profit for three representative mine types; thermal and hydro power generation; and representative recreational expenditures in a reservoir-based park at an annual scale.

The population sector calculates municipal, rural and livestock populations in each game year, with growing populations driving increased water demands, and municipal water conservation policies and livestock "stocking rate reductions" reducing demands (see Table 2-1).

In the context of system dynamics, stocks and flows, delays and feedback loops are used to represent key real-world structures and processes. Any variable that accumulates material or information over time is represented as a 'stock' (integral), with values that can only be changed by flows (rates). Stocks, flows and variables are connected by arrows which represent visually the mathematical equations used to change stock, flow and variable values over time. For example, municipal and livestock populations are represented in the model as stocks, with initial values of 3 million and 44.76 million (3.5 million beef cattle, 1.2 million pigs, 40 million chickens, and 60,000 dairy cattle) respectively, based on AAFC (2011) and Alberta Agriculture and Rural Development (2014b). Human and animal population changes are determined by "flows" that represent birth rates and average lifespans for the basin, based on data from Statistics Canada (2013a, 2012a) and AAFC (2011). Equation (2-1) calculates the municipal population as,

$$P_t = P_0 + \int_0^t (MI(t) - MD(t))dt \tag{2-1}$$

where P_t is the municipal population (people) at time t, P_0 is the initial population (people), MI and MD are the population increase and decrease (people/year) during time t, as determined by the birth rate (fraction/year), average lifespan (year) and net immigration rate (fraction/year). Table 2-2 compares model parameters with 2012-2013 data from Statistics Canada (2013b). The farming population, which is used to calculate the income for each farmer in the model, was calibrated based on the initial total farmland area (ha) in the IDT Model and the average farm size (ha/producer) in the Canadian Prairies (Statistics Canada, 2006a, 2006b).

Table 2-2: Population and growth rate comparison between IDT Model and Canadian Prairies

	IDT	Canadian Prairie Provinces		
		Alberta	Saskatchewan	Manitoba
Population (million)	3.0	4.0	1.1	1.3
Growth rate (%)	3.0	3.4	1.9	1.2

Livestock water – which accounts for approximately 3% (for feedlots and stock watering) of the total agricultural water use in Alberta (AMEC, 2007) – and feed requirements are also included in the model. Since animals at each growth-stage have different water and feed requirements, the model represents animal fractions in baby, juvenile and adult categories, with annual water and feed requirements then calculated for each animal type and growth stage. Equation (2-2) calculates the annual stock water requirements (L/year), WR, as,

$$WR = \sum_{i=1}^{3} (GSF(i) \ * GSWR(i) \ * AP * 365) \tag{2-2}$$

where *GSF* means the fraction of animals in each growth stage (growth stage fraction; dimensionless), *GSWR* means growth stage water requirements (L/animal/day), *AP* means animal population (number of animals), and *i* is an index with 1=baby, 2=juvenile and 3=adult. The annual feed requirement calculations, for tons of grain and roughage per year, are similar to equation 2-2. Daily water requirement values for baby, juvenile and adult animals are taken from Ward and Mckague (2007), while animal grain and roughage requirements are from Statistics Canada (2003).

The Oxbow Basin water supply has three components: the base renewable flow, reservoir storage and inter-basin water diversions (a pre-game policy option), which are the main sources in the Prairie Provinces. Groundwater is omitted since its use in the Prairies is limited; for example, only 3% of the licensed water use in Alberta is from groundwater sources (Alberta Environment, 2011). All three sources have annual values to match the timescale of the game, and can be adjusted easily for different basins. Figure 2-3 illustrates the model structure for this section, with the positive signs indicating that an increase in one variable causes an increase in the next variable.

The base renewable flow and basin precipitation are set to represent different drought levels for each year of the game, with unique values for each IDT (cf. Hill et al., 2014). Reservoir storage is a stock, with current and maximum storage values affected by IDT policies that "draw down storage" or "increase the storage volume" (Table 2-1). Water diversion is an IDT policy typically available for implementation only during a pre-game session, because in reality significant time would be required in advance of a drought to build the necessary diversion infrastructure.

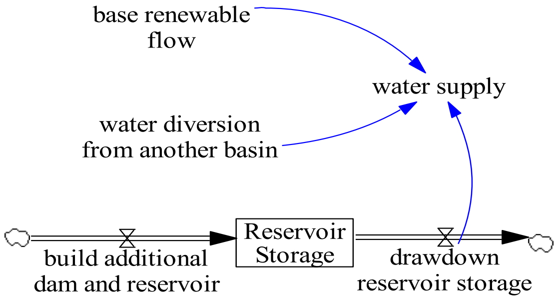


Figure 2-3: Water supply structure

The municipal water sector includes interactions between increases in municipal water demands with population growth (Statistics Canada, 2013b), the available water supply and the effects of water conservation policies, to simulate the annual municipal water use – which may be less than the water demand in drought years. A variety of water conservation methods are available for municipal water management, such as low-flow fixtures and appliances (toilets, showers and washers), grey-water reuse, xeriscaping, drip irrigation and rainwater harvesting systems for outdoor water use, as well as water pricing, while water research and development has the potential to reduce both indoor and outdoor water demand in the longer term (Ahmad and Prashar, 2010; Coomes et al., 2010; Tidwell et al., 2004; Williams et al., 2009). The IDT Model represents a sub-set of the conservation methods, including adoption of low-flow appliances, grey-water treatment and reuse, investment in water-related research and development and water rationing (Table 2-1). Under normal conditions, a rising population drives a gradual increase in municipal water demand, while the steady adoption of water conservation approaches gradually reduces water demand. Under drought conditions, the difference between the municipal water demand and the (falling) supply triggers an imbalance represented as a “municipal water deficit”, which accelerates the adoption of low-flow technologies to decrease municipal water demands in subsequent years. Figure 2-4 presents an overview of the structure of this sector.

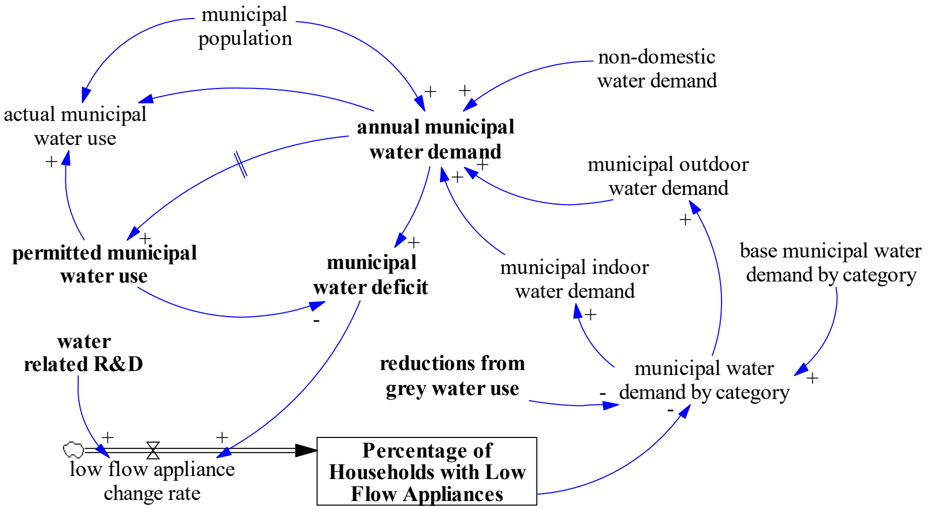


Figure 2-4: Basic structure of the municipal water use sector

The municipal water sector subdivides water demand into six components (Ahmad and Prashar, 2010): indoor use, in the four categories of kitchen, toilet, bathing and laundry uses; outdoor use; and non-domestic water use (Figure 2-5). The indoor water use categories are represented separately because water conservation efforts target specific domestic water uses – toilet flushing, showering and bathing, washing and appliance uses – with explicit simulation of water use in each category.

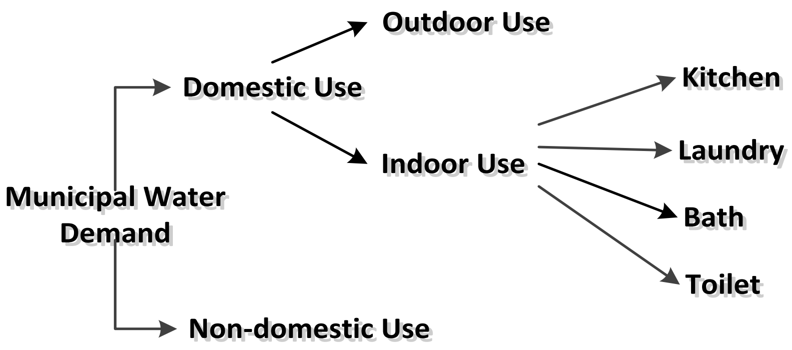


Figure 2-5: Municipal water demand categories (adapted from Ahmad and Prashar, 2010)

Water use reductions with low-flow appliance adoption for each category are represented as changes in the "stocks" of households equipped with each type of low-flow fixture or appliance (Figure 2-4). The "municipal water deficit" as well as water conservation policies increase the adoption of low-flow fixtures and appliances such as toilets, showerheads and front-load washers, for example. Equation (2-3) represents the municipal water demand, MWD, in million cubic meters (MCM) per year as,

$$MWD = [p_l * (1 - f_l) * k + (1 - p_l) * k - R + W_{non}] * P * 365/10^9 \tag{2-3}$$

where p_l is the percentage of households with each type of low-flow fixture or appliance (%), f_l is the corresponding fractional reduction in water use (dimensionless), k is the base domestic water use per capita for the specific water use category (L/capita/day), R is the water reduction from the (optional) grey water treatment policy (L/capita/day), W_{non} is the non-domestic (commercial, industrial, and public) water demand (L/capita/day) supplied by the municipal system and P is the municipal population (people).

The licensed municipal water withdrawal, called the "permitted municipal water use", is set at the beginning of the IDT; players can also reduce the available municipal supply through rationing (Table 2-1). To represent drought effects on the municipal sector, the model allocates the available supply to each the six water use categories based on their relative importance, or "priority", if water demands exceed the licensed or rationed value. High priority uses – like kitchen water use – receive water in preference to lower-priority categories, such as outdoor water use; the priority values selected ensure that kitchen water demands are met, while other, lower-priority, indoor water demands are met before outdoor demands. Table 2-3 gives typical municipal water use values and assigned water-use priorities, based on

North American water survey data (Coomes et al., 2010; Mayer and DeOreo, 1999). Outdoor water use is typically significant and tends to fluctuate, with high uses in summer (Nouri et al., 2013). Therefore, the 33L/capita/day annual outdoor water use of Edmonton, Alberta, of the drought year 2002 (EPCOR, 2010) was revised to produce a peak daily water demand for June-August of 134 L/capita/day. This number is much lower than the average 381.6L/capita/day outdoor water use value provided by Mayer and DeOreo (1999), because Canadian Prairie households have fewer residential pools and outdoor hot tubs (Eaton, 2012) than regions farther south. Further, the Prairies' cooler and shorter summers than the Mayer and DeOreo (1999) study sites also result in lower outdoor water use.

Table 2-3: Municipal water use data

Categories	Laundry	Bath	Toilet	Kitchen	Outdoor
Base per capita daily demand by category (L/use)	165	55	14	50	134
Base times per capita per day (Dmnl)	0.37	0.75	5.05	1	1
Water use reduction for low flow appliances (%)	11.7	9	10	7	30
Municipal water use priority (Dmnl)	5	5	3	10	1

Inadequate rainfall during a drought can seriously affect agricultural yields (Ray and Gul, 1999). To represent the effects of differences in agricultural water supply, the IDT Model includes both irrigated and rain-fed agriculture, and simulates the soil-water balance, agricultural land use and management and crop yields for both land types, as well as water allocations and applications for irrigated crops. Of particular importance are outputs related to the cropping areas, water requirements and yields of five generic field-crop types – forages, cereals, oilseeds, vegetables and grass – on irrigated and rain-fed land, with parameters based on the widely-grown crops of alfalfa, barley, canola, potatoes and grass (Statistics Canada, 2012b). The Okanagan IDT model version also includes two tree crops, apples and cherries, and grapevines on irrigated land, which account for 52% of the irrigated area in the Okanagan (van der Gulik et al., 2010). Four land use types in the model include irrigated, rain-fed, fallow and non-producing land under “green cover”.

Teams can choose among a variety of agricultural policies to mitigate drought effects on agriculture (Table 2-1): land management policies that convert land from one use to another, or that alter management (for example, promote green cover, promote winter cropping, promote stocking rate reductions and promote diversification of pasture species composition); water management policies, including water rationing, reservoir releases and enhancement of irrigation efficiency; economic policies, such as relief payouts to farmers; and technological policies like irrigation expansion, investment in agricultural research and development and investment in water-related research and development. Figure 2-6 shows the simplified model structure for this sector.

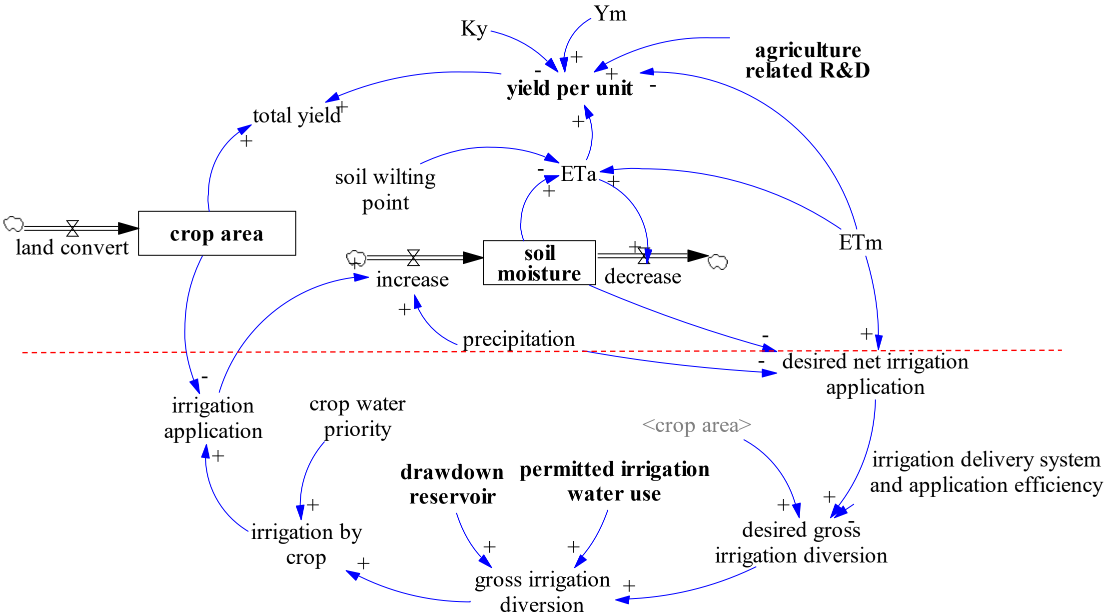


Figure 2-6: Basic structure of the irrigated-agriculture water use sector

For both irrigated and rain-fed agriculture, the IDT Model simulates changes in the soil-water content and land use, both represented as stocks, over the course of the drought. Each crop type uses water available in its associated soil moisture stock, with the soil-water content used to determine both net crop-water requirement and crop yield. Increases to soil moisture come from irrigation (for irrigated agriculture) and precipitation (for both irrigated and rain-fed crops), while decreases occur through evapotranspiration (ET). The model uses linear ET-yield relationships developed for the Canadian Prairies by Bennett and Harms (2011). In addition to soil moisture, yields can also be affected by IDT policies, including investment in "agriculture-related research and development" (Table 2-1), which gradually increases yields through improvements to crop drought resistance (Keogh et al., 2011; Quarrie, 1999). The model can be applied to other regions by adjusting the ET-yield equation parameters to match local figures.

For irrigated agriculture, crop water demands (ET) are supplied by precipitation, initial soil moisture and irrigation applications (see the bottom half of Figure 2-6). Each year, the model automatically allocates the available water, called the "permitted irrigation water use", to irrigated crops based on their water-allocation priority; note that IDT policies, such as "reservoir drawdown" and "water rationing" can affect this available supply. Irrigators are assumed to irrigate to the initial soil moisture conditions for the next year after satisfying the maximum evapotranspiration (ET_m, mm) water demands in the current year, with the desired net irrigation application ($DNIA_t$, mm) for year t calculated as shown in equation (2-4),

$$DNIA_t = \begin{cases} ET_{m_0} - P_0 - ISM_0 & t = 0 \\ ET_{m_t} - P_t - SMB_t & t > 0 \end{cases} \tag{2-4}$$

where P_t is precipitation (mm) in year t, ISM_0 is the initial soil moisture (mm) at the start of the game and SMB_t is soil moisture at the beginning of year t (mm). Incorporation of irrigation losses related to evaporation from canals and crops, canal seepage, root-zone deeppercolation and application efficiency (Howell, 2001) produces the desired gross irrigation diversion.

In normal years, when water is plentiful, crops typically receive the desired irrigation application and achieve near-maximum yields; however, in a drought year, the gross irrigation application may be less than the desired value. In this case, the IDT Model automatically allocates the available irrigation water to the crops with higher priorities based on their "crop water value" (CWV, \$/m^3), as calculated in equation (2-5),

$$CWV = CP * CWP \tag{2-5}$$

where *CP* is the crop price (\$/kg), and CWP is crop water productivity (kg/m^3). For tree crops and vines, the first priority is to the bearing over the non-bearing area (young trees), and then among the different crops based on crop water values.

Precipitation and land area values are taken from IDT workbooks (Hill et al., 2014), maximum ET (ET_m), yield response factors (K_y) and maximum yields (Y_m) are from Bennett and Harms (2011), and crop coefficients, crop water productivity and prices are from Allen et al. (1998), Siebert and Doell (2010), and USDA (2014), respectively. Tree crop and vine water use data and prices are based on the British Columbia (BC) Ministry of Agriculture, Food and Fisheries (2013) – see Table 2-4, below.

Table 2-4: Agricultural water use data

Categories	Alfalfa	Barley	Canola	Potato	Grass	Apple	Cherry	Grape
ET_m (mm)	747	447	476	599	539	901	901	589
K_y (–)	1.05	1.15	1.15	1.1	1.05	1	1	0.85
Y_m (Mg/ha)	18	7.3	3.9	67.2	13.4	38	16.6	17.3
CWP (kg/m^3)	5.9	0.85	1.03	4.16	0.64	3	0.64	1.82
Crop price (\$/kg)	0.16	0.25	0.42	0.18	0.15	0.7	4.19	1.74

Industrial water use faces reductions during drought because of decreased water supply, the ability to import power from unaffected regions, and a relatively low water-use priority (Harto et al., 2011; Hightower and Pierce, 2008). Based on Statistics Canada (2007), industrial water use in the IDT Model is divided into the mining of metals, non-metals and coal, and thermoelectric and hydroelectric power generation, with key variables related to water demands, water allocation, and production and profits for each of the five components.

Industrial water demands are based on simulated annual mining production and power generation, and may not be satisfied under drought conditions if teams choose to decrease industrial water use through water rationing. In terms of model behaviour, the five components of the industrial water demand increase over time with economic growth, as represented by the "industrial expansion rate". Mining water-demand was determined from the annual production (tons) and mining water-use efficiency (m^3/ton), using data from three large mining companies in the Canadian Prairies: PotashCorp (2010) for non-metal (potash) mining, HudBay (2011) for metal (gold, silver, copper and zinc) mining and Grande Cache Coal Corporation (2011) for coal mining – see Table 2-5. Water demand for electricity generation is based on total thermoelectric and hydroelectric generation and plant water-use efficiencies (m^3/MWh), with data from SaskPower (2007) and the United States Department of Energy (2006). Note that water use efficiencies can be improved with selection of the "water related R&D" policy (Table 2-1). Figure 2-7 shows the main structure of the industrial water use sector.

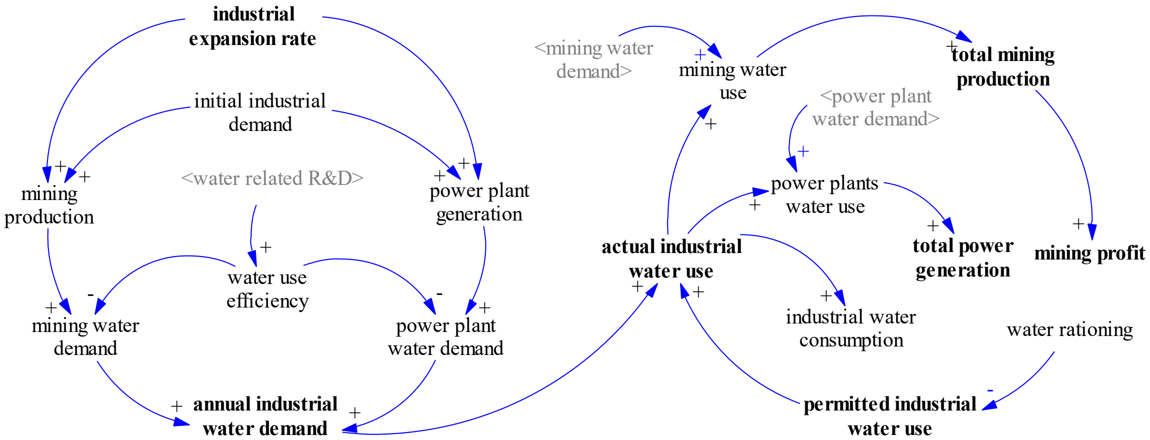


Figure 2-7: Basic structure of the industrial water use sector

The actual industrial water use each year is the minimum of the current water demand and the "permitted industrial water use". Further, if the permitted use is less than the demand, the available water is allocated to mining and power generation based on their relative priorities and water demands, and mining water use is assumed to have higher priority. Power generation and mining production are calculated from the amount of water available for each use (m^3) and its water use efficiency: cubic meters per ton (m^3/t) for mining, and cubic meters per megawatt-hour (m^3/MWh) for power generation, with mining profit the multiplication of mining production by the unit mining-profit values ($/t). All minerals produced in a year are assumed to be sold in that year.

Table 2-5: Industrial water use data

Categories	Mineral extraction (m^3/ton)			Power generation (m^3/MWh)	
	Metal	Non-metal	Coal	Thermoelectric	Hydroelectric
Water withdrawal efficiency	91	1	0.2	15	-
Water consumption efficiency	3.8	0.04	0.01	1.6	6.4
Profit ($/ton)	1.3 M	300	45	-	-

Drought can affect recreational activities, particularly those around reservoirs (Ward et al., 1996). The IDT Model represents the trade-off between high reservoir water-levels for recreational activities and reservoir drawdown for other water uses in two parts: 1) the relationship between water level and storage in the reservoir, which is expressed as a reservoir storage curve; and 2) the connection between reservoir levels and recreational expenditures.

To represent generic reservoir characteristics for the IDT, the storage curves of seven large reservoirs in Alberta – Lake Abraham, Brazeau, Blood Indian Creek, Chain Lakes, Crawling Valley, Glenmore and Little Bow Lake – were averaged based on figures from the University of Alberta & Alberta Environment (1990), with the resulting relationship between reservoir water storage and level shown in Figure 2-8.

Reservoir visitor numbers and expenditures can be affected by many factors, such as pool volume and elevation, availability of parking, visitor income and travel costs (Eiswerth et al., 2000; Ledwaba, 2011; Santiago et al., 2008). The IDT Model focuses on the relationship between the reservoir water level and annual visitor expenditures, with their relationship based on Hanson et al. (2002), who estimated the impacts of six reservoirs' water storage levels on lakefront property values, recreational expenditures, and preservation values in Alabama, using contingent valuation questions collected through on-site, telephone and mail surveys. The maximum recreational expenditure is adopted from Bewer (2012), who investigated recreational expenditures at Chestermere Lake, in Alberta. Figure 2-9 characterizes the effects of water level on recreational expenditures at the Oxbow Reservoir as an expenditure-level curve; note that a decrease in the water level of more than 1.6 m causes recreational expenditures to drop to zero.

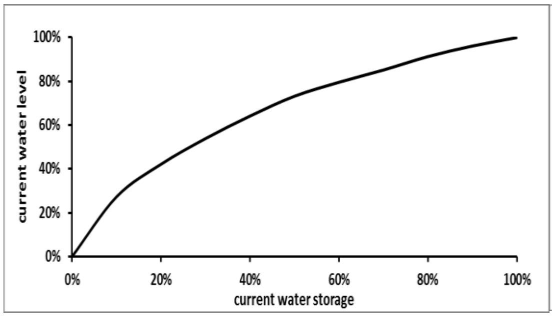


Figure 2-8: Reservoir volume-level curve

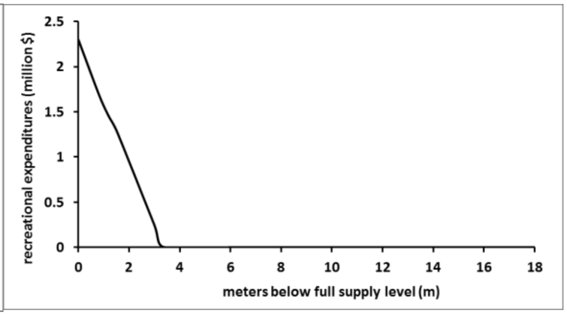
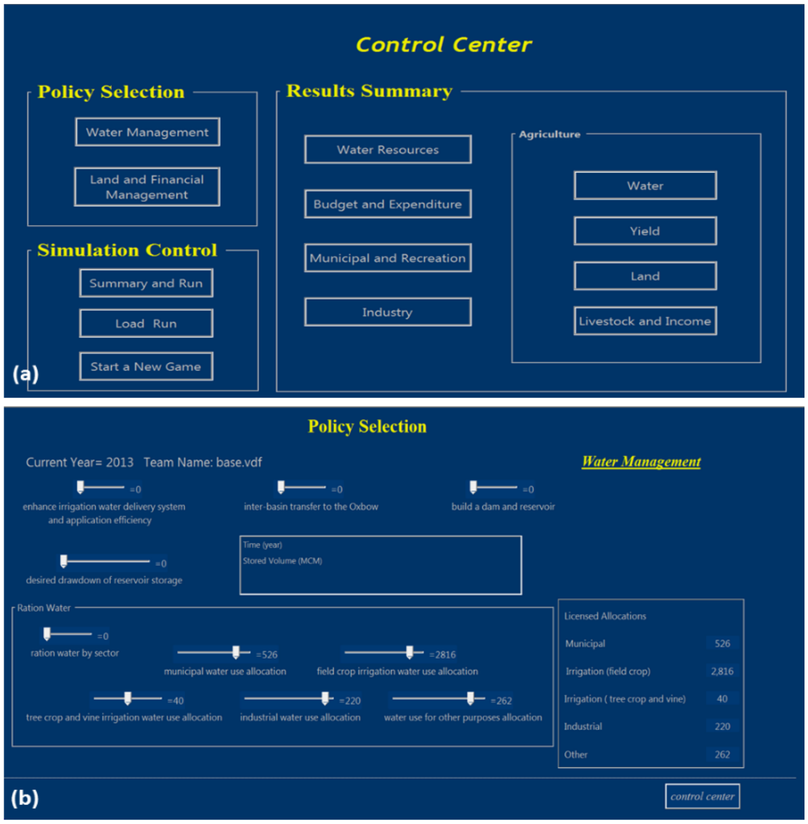


Figure 2-9: Reservoir park expenditure-level curve

The IDT model has a user-friendly interface that allows teams to select easily among the available drought mitigation options, run the model and view summary results. Figure 2-10a shows the main menu, or "control center", for the model. Each of the boxes on the panel represents a button users can select to go to a different screen, while a "control center" button on each subsequent screen links back to the control center.



Current Year= 2013 Team Name: base.vdf

enhance irrigation water delivery system and application efficiency =0

inter-basin transfer to the Oxbow =0

build a dam and reservoir =0

desired drawdown of reservoir storage =0

ration water by sector =0

municipal water use allocation =526

field crop irrigation water use allocation =2816

tree crop and vine irrigation water use allocation =40

industrial water use allocation =220

water use for other purposes allocation =262

Licensed Allocations	
Municipal	526
Irrigation (field crop)	2,816
Irrigation (tree crop and vine)	40
Industrial	220
Other	262

Figure 2-10: Model interface screens

Figure 2-10b shows the “policy selection” screen, which offers three kinds of management policies: water, land and financial. IDT participants move “sliders” and tick checkboxes in the interface to indicate their policy choices. Once teams are satisfied with their policy selections, they can run the model forward from the current year to the next game year. Previously-saved simulations can also be viewed through the “Load Run” button (see Figure 2-10a) and compared with the current simulation. The “results summary” screen (not shown) displays tables and graphs of model results related to water use for different sectors, agricultural yields and land areas, economic values and reservoir water storage. Representative pictures are also used to demonstrate policy effects on socio-economic and environmental conditions, such as dried lawns and falling reservoir water levels – these images can be customized for different locations. The pictures are intended to provide a quick, clear indication of the current water balance, and to motivate participants to investigate the causes of differences between teams. Sample model results from past IDTs are shown in Section 5.

2.4.3 Model Performance

The following standard tests for system dynamics models were applied to validate model behaviour: (1) model structure and parameter validation tests to ensure that the model describes real-world systems, (2) extreme condition tests to confirm that the model generates reasonable results given extreme inputs and (3) behaviour reproduction tests to ensure that the model replicates historical trends under similar initial conditions (Barlas, 1994; Forrester and Senge, 1980; Mirchi et al., 2012; Sterman, 2000).

The structure and parameter validation tests were satisfied by using existing knowledge of the real world and modifying existing models, and by using published data to set model parameter values, as described in section 4.2. Extreme condition tests for twenty-eight of the model's key variables were run. These tests involved the assignment of extreme values to selected model parameters that affect water and land allocations, such as crop price and production, mineral price, water use priority values and water supply, to determine model responses to significant changes in input values. Two examples follow. In the first extreme condition test, the oilseed crop price was set to a value of \$100/kg – a large increase, given that March 2014 canola prices were \$0.41/kg (Government of Saskatchewan, 2014) – and the "irrigation expansion" policy was then selected to test land and water allocations to oilseed production. As expected, the model simulated the allocation of oilseed rain-fed land to irrigated land; further, all irrigation water demands for oilseed production were satisfied, with any remaining irrigation supply allocated to other crops. A second test with specialty crop prices set to \$0/kg resulted in water allocation to all other crops first, while specialty crops received irrigation water only once other crop demands were satisfied.

IDT Model behaviour has been validated through comparison with historical data and trends for the Canadian Prairie provinces of Alberta, Saskatchewan and Manitoba. For agricultural yields, the reference scenario values were compared with Canadian and U.S. yields, which are based on a combination of rain-fed and irrigated production averages in normal years (Table 2-6). The IDT Model results are slightly higher than the observed values in some cases, because the model bases its yields on optimal irrigation values for Southern Alberta (Bennett and Harms, 2011). Further, the annual time step and spatially-averaged representations of the

IDT Model omits significant variations in natural conditions (soil and climatic) and agricultural management in each region.

Table 2-6: Yield comparison between the IDT Model and observations in non-drought years

Crop yields (tons/ha)	Alfalfa	Barley	Canola	Potato	Grass	Sources
IDT Model (irrigated)	7.7	4.6	2.6	50	6.6	IDT reference
IDT Model (rain-fed)	5.6	4.0	2.1	32	5.8	IDT reference
Alberta	-	4.2	2.2	42	-	Government of Alberta (2006)
Saskatchewan	4.7	5.4-5.7	0.2-4.7	33.3	-	Sask. Agriculture and Food (2007)
Manitoba	-	2.5-4.0	1.5-2.2	-	-	Honey (2011)
Canadian Prairies	-	4.0	2.2	39.5	-	Statistics Canada (2013c)
U.S.	8.4	4.0	1.7	52.3	6.2	USDA (2013)

Crop yields in the IDT Model decrease in drought years as shown in Table 2-7. The calculated yields are based on the average precipitation for Southern Alberta in 2002 (Environment Canada, 2014), a drought year that affected almost all of Southern Canada from central British Columbia to the Atlantic Provinces (Wheaton et al., 2008). Observed yields for the Canadian Prairies are also presented for comparison, with the results from the IDT model slightly higher than real yields under drought conditions. Note that although precipitation in the model was set to equal observations, its annual time-scale omits any monthly precipitation deficits under drought conditions that would reduce yields. Further, crop yields in the model are only affected by water availability in the IDT model, while other effects such as pests, crop diseases, non-optimal management and decreases in soil fertility, which can all reduce yields, are omitted. Despite these shortcomings, Tables 3-6 and 3-7 demonstrate that the IDT model simulates representative crop yields in both normal and drought years.

Table 2-7: Yield comparison between the IDT Model and observations in drought years

Crop yields (tons/ha)	IDT Model (irrigated)	IDT Model (rain-fed)	Alberta	Saskatchewan	Manitoba
Barley (cereal)	2.7	2.2	2.3	1.8	2.9
Canola (oilseed)	1.8	1.3	1.2	1.0	1.7

Potato (specialty)	50	18.6	35.1	35.8	27.7
Sources	IDT drought year		Statistics Canada (2013c)		

Municipal indoor water demand values were based on the average residential water demands of fourteen North America cities (Mayer and DeOreo, 1999). To assess model behaviour, the model was run from 1999 to 2023 to permit a comparison with historical values (1999-2013) and to illustrate future trends (2013-2023). Figure 2-11 shows simulation results for per capita residential indoor water demand in comparison to data from Western Canadian cities (Edmonton and Calgary) and two American cities (Louisville and Denver). Values for the historical period are in the range of observations, and decreased 4.3% from 1999-2013, which is close to the actual reduction in North American residential water demand from 1978 to 2008 of 4.4% per ten years (Coomes et al., 2010). Further, the simulated water demand trends into the future (2013-2023) follow the historical (1999-2013) trend.

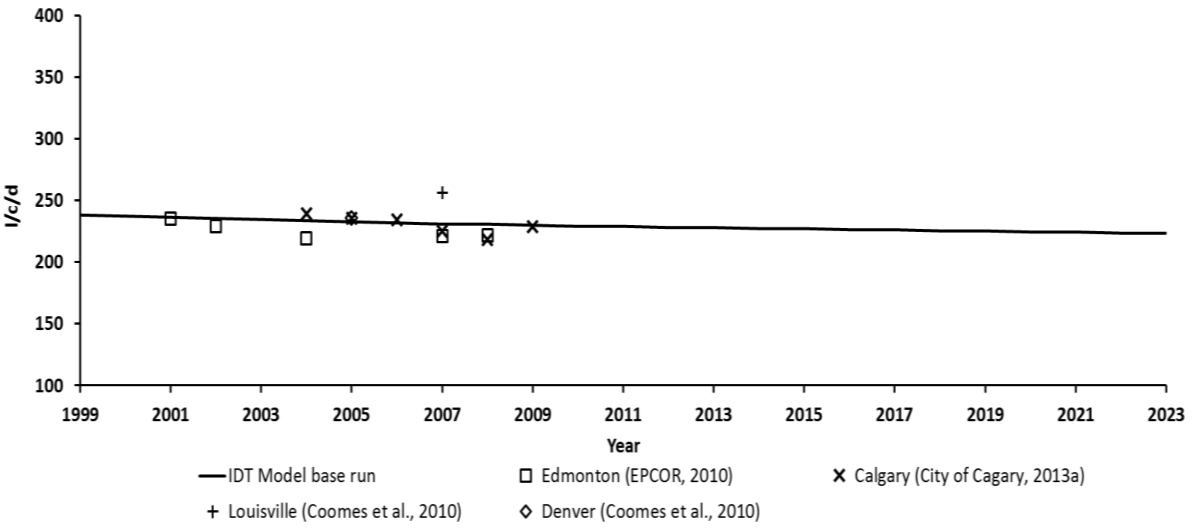


Figure 2-11: Per capita municipal indoor water demand

2.5 Results from Past IDTs

This section presents simulation results from three IDT events held in Saskatoon (2011 and 2013) and Kelowna (2012), with examples based on the effects of team drought-policy decisions on total basin water use, irrigation diversions and water allocations for each sector and agricultural production. Further, because the IDT Model permanently records game results, the IDT organizers, the research team and the participants can return to the model to reassess the effects of their policy choices long after a game is complete. Comments are therefore also provided on preferred drought management strategies based on the lists of teams' policy selections from three IDT events, and on the value of simulation gaming approaches to socio-economic drought management.

The introduction of the IDT Model in Saskatoon, Saskatchewan, in 2011 allowed the research team to evaluate model performance and demonstrated the effects to five IDT teams of their chosen drought mitigation options on social, economic and ecological stresses during a simulated drought of 2014-2017. Figure 2-12 shows total basin water use over the course of the game for all five teams; clearly, the model exposed significant differences in the effects of each team's short- and longer-term policy selections.

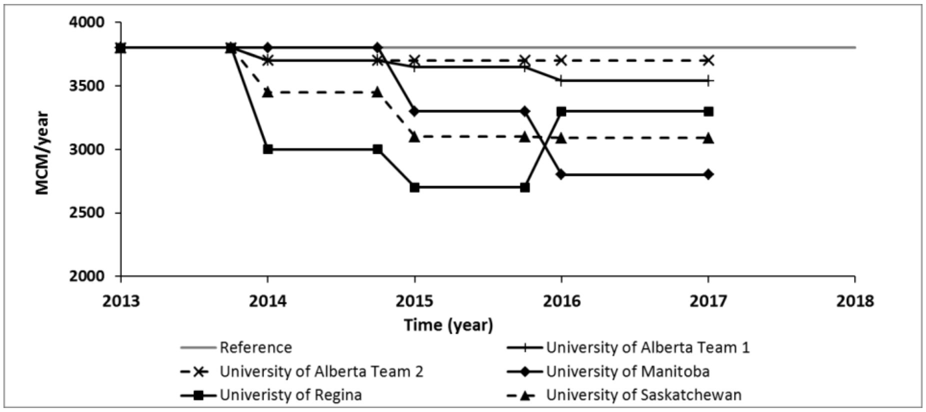


Figure 2-12: Total basin water use in the Prairies IDT, Saskatoon 2011

Further, the drought resulted in a significant irrigation shortfall. Because of reduced rainfall, gross irrigation demands for the three drought years were 5760, 6280 and 6310 MCM – much higher than under normal conditions (3480 MCM) – while only 2820 MCM was available for irrigation use in the reference case. Figure 2-13 shows gross irrigation diversions for the reference case and for each team. Diversions above the reference case show that the teams drew down the storage reservoir for additional irrigation supply, while applications below the reference case indicate that teams rationed agricultural water use or also drew down the reservoir but drew down volume was less than the rationed water. For example, the University of Manitoba drew down its reservoir for irrigation purposes in each year from 2014-2016 and used more water for irrigation than the reference case from 2014-2015, but then rationed irrigation water use in 2015 and 2016 (see also Table 2-8), which brought down its irrigation diversion. See real cases of irrigation water allocation in California during 2007-2009 and 2012-2014 droughts (California Department of Water Resources, 2012; Nature News, 2015).

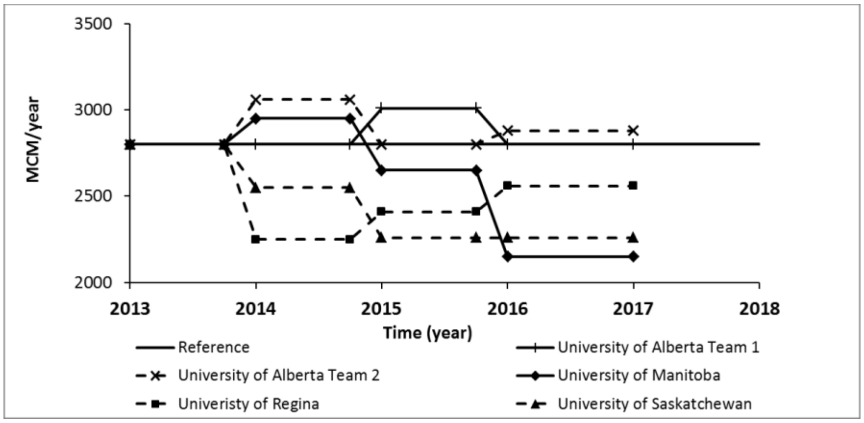


Figure 2-13: Gross irrigation diversions in the Prairies IDT, Saskatoon 2011

Table 2-8: University of Manitoba water management policy selections

Adaptation option	2014	2015	2016
Enhance irrigation system	1	0	0
Build dam and reservoir	1	0	0
Ration water	0	1	1
Municipal allocation (MCM)	526	360	360
Irrigation allocation (MCM)	2856	2565	2072
Industrial allocation (MCM)	200	144	144
Environmental allocation (MCM)	262	252	252
Reservoir draw-down (MCM)	150	150	150

Water rationing was a popular strategy for all eight teams that played the Prairies IDT (the two Saskatoon tournaments in 2011 and 2013); however, each team rationed water uses differently, with their choices representing different drought management priorities among the teams. Specifically, the average water allocations for municipal, irrigation, industry and environment were 77%, 90%, 81% and 96% respectively, with standard deviations of 9.0%, 10.0%, 19.8% and 9.6% for each sector. Figure 2-14 provides eight water allocation strategies for game year 2015 – note that 2015 has quite similar drought conditions in both IDTs in terms of precipitation (336 mm and 334 mm) and base river flow (3.41 million dam^3 and 3.4 million dam^3). Results present similar findings of Stoutenborough and Vedlitz (2014) about priority of water rationing under water stress.

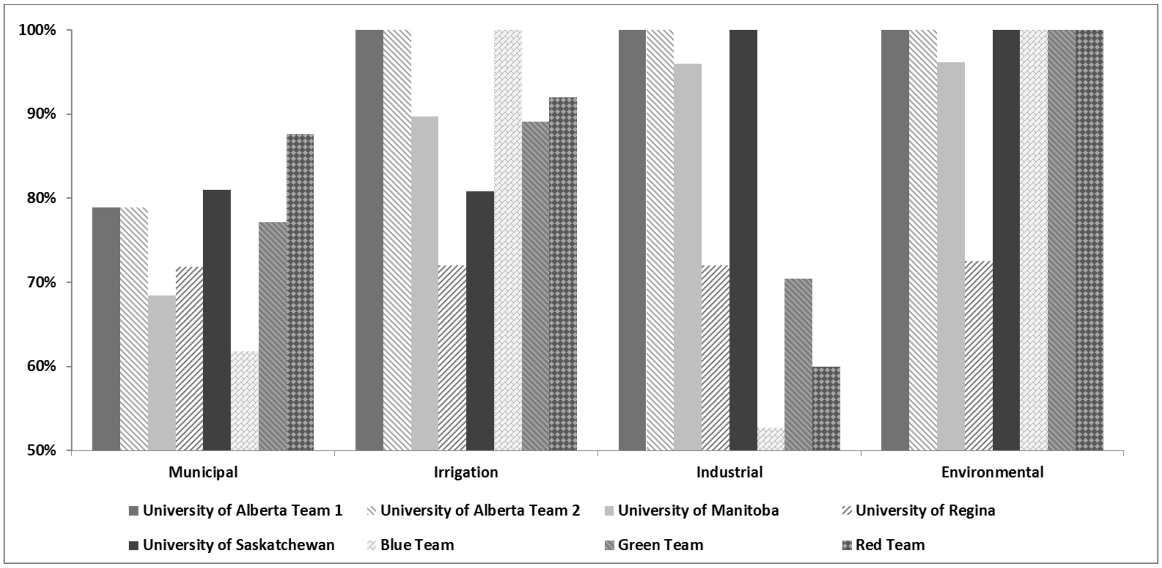


Figure 2-14: Team water rationing as a percentage of the reference case water allocation for the eight Prairies IDT teams, where the University teams played in the 2011 IDT, and the color teams played in the 2013 IDT

The new IDT Model version introduced in 2012 at the Okanagan Invitational Drought Tournament in Kelowna, BC, included the improved graphical user interface (see section 4.2.7), which is the source of the next set of figures. Figure 2-15 highlights differences in domestic water use, including both indoor and outdoor uses, based on the policy selections of the “yellow” and “red” teams over the course of a hypothetical 2021-2024 drought. Because the model prioritizes available domestic water for indoor uses, municipal water-rationing first reduced outdoor water use (see recent California drought as an example, California Water Boards, 2015) and resulted in the browning of the yellow team’s lawns (see Figure 2-15a). In contrast, although the red team also rationed water from 2021 to 2022, its outdoor water use did not decrease while indoor water use did (see Figure 2-15b), because the red team reduced its indoor water use by investing in grey water treatment and reuse; the model reallocated this conserved water to outdoor uses. The red team therefore conserved water and obeyed the rationing policy, but maintained green lawns throughout the drought. In terms of presentation of results, the combination of pictures (Figure 2-15, left side) with water use trends (Figure 2-15, right side), as well as the juxtaposition of team results, helped each team to visualize and compare the effects of different policy combinations – useful information as they developed plans for the next game year.

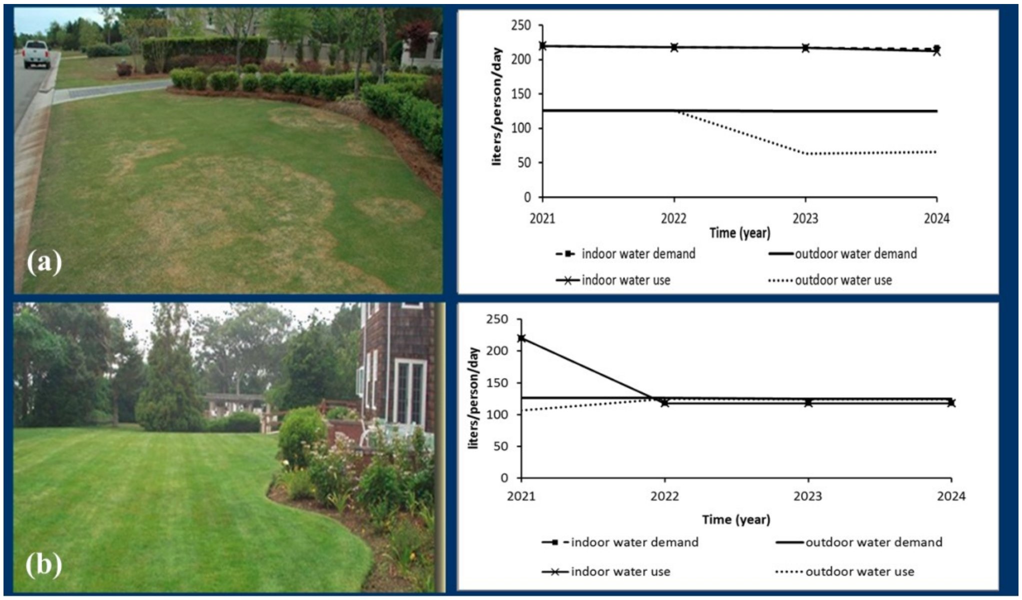
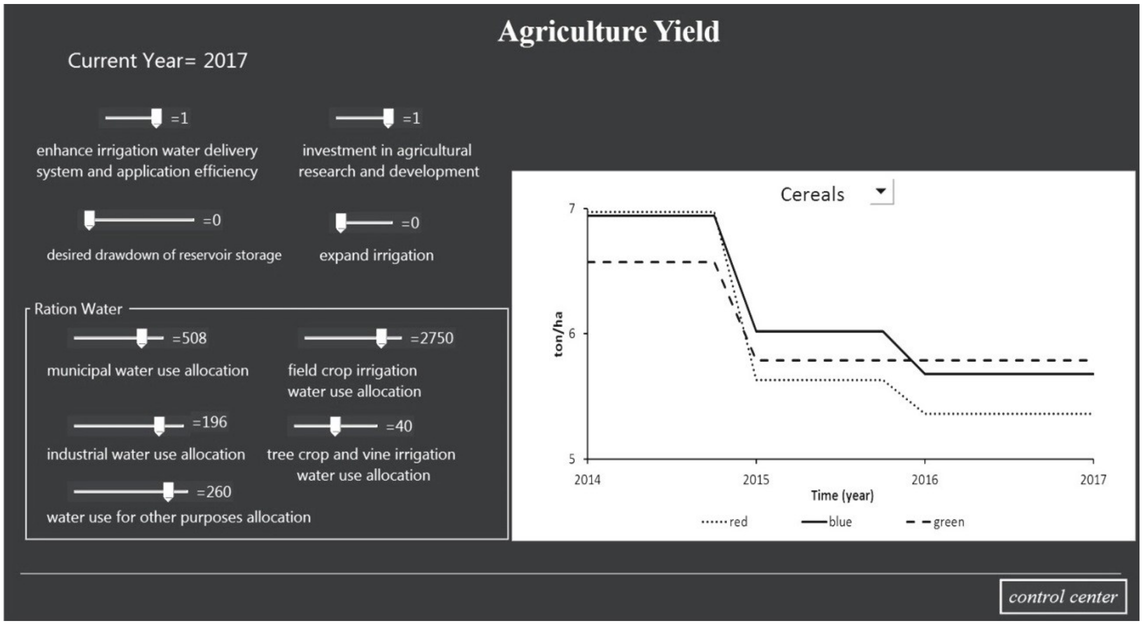


Figure 2-15: Domestic water use comparison between the (a) yellow and (b) red teams

The third Invitational Drought Tournament, held in Saskatoon in 2013, aimed to expose a class of graduate students to group decision-making under uncertainty. Figure 2-16 shows the simulated cereal yields – the selected crop type can be changed through the model interface – of three teams (red, blue and green) based on their adaptation strategies during the game. Clearly, the cereals yield per hectare decreased for all three teams over the course of the drought, from 2014 to 2017. Further, all other crop types also experienced yield reductions because of insufficient water availability to the agricultural sector – with the exception of specialty crops, which have the highest crop water value, causing almost 100% of their water demand to be satisfied for all three teams, since high-value crops usually get more water than the lower ones under drought condition (Howitt et al., 2014).

More importantly, the yield reductions for each team differed according to the drought policies they adopted. Water availability is a critical factor that affects yield (Bennett and Harms, 2011), and it is the only concern in the IDT Model in yield simulation. For example, the green team diverted less water for irrigation purposes from 2014-2015 (2030 MCM) than the red and blue teams did (3260 and 3150 MCM, respectively), and so produced the smallest yields of all crop types that year – including cereals, as shown in Figure 2-15. In contrast, the green team allocated more water for irrigation (2430 MCM) from 2016-2017 than the other teams (2120 MCM for both), and so had the highest yields over that period. However, technological policies and land-use policies also affect crop yields (Keogh et al., 2011; Fernández and Selma, 2004). In 2016, for example, the red and blue teams diverted the same water volume, but the blue team had higher yields for cereals (5.68 ton/ha *versus* 5.36 ton/ha, Figure 2-16) and other crops because of an investment in 2014 in “agriculture-related research and development” that gradually increased crops’ drought tolerance. Further, an expansion in the irrigation area should maintain or increase the total crop yield relative to dryland production, but it uses more of the mitigation budget, leaving less for alternative policies, and spreads the available irrigation supply more thinly, so that yields per hectare decrease – all examples of drought management trade-offs. Therefore, not only yields per hectare, but also total crop yields differed by team. For example, the blue team adopted the irrigation expansion policy in 2015, and despite its lower yields per hectare than the green and red teams, produced a greater oilseed yield of 1.9 million tons, as compared with 1.6 million and 1.5 million tons for the green and red teams.


Current Year= 2017

enhance irrigation water delivery system and application efficiency =1
investment in agricultural research and development =1
desired drawdown of reservoir storage =0
expand irrigation =0

Ration Water
municipal water use allocation =508
field crop irrigation water use allocation =2750
industrial water use allocation =196
tree crop and vine irrigation water use allocation =40
water use for other purposes allocation =260

Figure 2-16: Crop yield comparison between IDT teams

IDT results also provide an indication of the attractiveness of drought mitigation options. Tables 3-9 and 3-10 summarize the policy selections from three IDT events with a total of thirteen teams, comprised of both graduate students (Prairie IDTs) and stakeholders in water-related sectors (Okanagan IDT). Numbers in the two tables represent the drought years in which each policy was used – for example, “13” means the policy was used in the first and third years of a three-year drought. The two Prairie IDT events, which used the same drought mitigation policies and had very similar drought conditions, are summarized in Table 2-9. In terms of pre-game adaptation options, all teams chose to "enhance irrigation efficiency" as a long-term policy, while no team chose to "divert water from another basin", a more costly and environmentally-contentious policy ($840 million vs. $193 million). Water rationing was the most popular drought mitigation option overall, which is also found by Stoutenborough and Vedlitz (2014), and was chosen by all teams in all three drought years except for two teams in year 1, followed by relief payouts to producers, the promotion of winter cropping and the promotion of green cover. Other policies, including investment in water-related R&D, expansion in irrigation and promotion of diversification of pasture species composition were not popular, and were chosen only four to six times each during the three drought years. Note that the maximum number of times a policy could be selected as a pre-game adaptation option is eight, while the maximum during a game is twenty-four – selection by eight teams in each of three drought years.

Table 2-9: Policy selections of the Prairies IDTs teams

Adaptation option[1]	Event	2011 Prairie IDT[2]															2013 Prairie IDT[2]									Total Selections
	Team	UA1			UA2			UM			UR			US			Blue			Green			Red			
	Round	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	
Water Management																										
Ration water		■	■	■	■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	22
Release reservoir			■		■		■	■	■	■		■	■				■					■	■			11
Financial Management																										
Relief payout to producers		■	■	■			■		■	■	■	■	■		■	■		■	■	■			■	■	■	17
Land Management																										
Promote green cover		■	■	■	■	■		■	■	■	■	■		■		■	■	■				■				15
Promote winter cropping		■	■	■	■	■		■	■		■	■			■			■			■	■	■	■	■	16
Reduce stocking rate			■	■			■		■	■		■			■			■			■			■		10
Diversify pasture species		■			■	■											■			■			■			6
Technology Management																										
Expand irrigation					■									■	■			■				■				5
Invest in agriculture-related R&D		■	■	■	■	■	■										■	■		■						9
Invest in water-related R&D			■												■						■		■			4
Invest in grey water treatment		■								■				■		■	■	■		■			■			8

[1] Pre-game drought adaptation option selections: Build a dam (UA1, UM, UR); Divert water from another basin (None); Enhance irrigation efficiency (All)

[2] The following abbreviations are used in the table: UA1 is the University of Alberta Team 1, UA2 is the University of Alberta Team 2, UM is the University of Manitoba, UR is the University of Regina, and US is the University of Saskatchewan

Table 2-10 summarizes the policy selections of five teams during the three-year drought of the Okanagan IDT. All teams chose four policies: no lawn watering, xeriscaping, producer payouts for not irrigating and collaborative meetings with all levels of stakeholders. Further, drought education was also a popular policy, chosen by four teams (all teams except for orange), and was implemented by these four teams during all three drought years (except for the yellow team). Note that, all those policies were adopted for dealing with historical Canadian droughts (Bonsal et al., 2011). However, commercial and industrial rationing, agricultural demand first after residential and the development of a basin drought plan were unpopular, chosen only once each during the game.

Table 2-10: Policy selections of the Okanagan IDT teams

Adaptation options[1]	Team	Blue			Green			Orange			Red			Yellow			Total Selections
	Round	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	
New Bylaw																	
Commercial & Industrial rationing		■															1
No lawn watering		■	■		■	■	■		■		■	■	■		■		10
No outdoor pools					■	■	■		■								4
Residential outdoor rationing								■			■				■		3
Xeriscaping		■	■		■	■		■			■			■	■		8
New Regulation																	
Reuse indoor water					■	■		■	■	■	■						6
Regulate Water Use																	
Agricultural first, after residential								■									1
Environmental first, after residential		■									■				■		3
New Tax Policy																	
Producer payout for not irrigating		■	■		■	■	■		■		■	■	■	■			10
Program/Activity																	
Collaborative meetings		■	■	■	■	■	■	■	■			■	■	■	■		12
Develop basin drought plan		■															1
Develop local drought plan					■		■	■	■		■			■	■		7
Drought education		■	■	■	■	■	■				■	■	■	■	■		11
Health services		■	■		■	■					■			■			6

[1] Pre-game drought adaptation option selections: Increase system storage capacity (Red, Yellow); Enhance irrigation efficiency (Blue, Green, Orange, Red)

Finally, the IDT Model also incorporates drought effects on livestock, mining production and profitability, electric power generation and recreational expenditures in reservoir parks. Therefore, the model represents socio-economic drought impacts on a wide cross-section of water users in a river basin, as well as the general effects of drought mitigation strategies. By investigating the effects of their own strategies and comparing their results with those of other teams – which clearly differed as a result of differing game strategies and policy choices, despite teams being subject to the same drought conditions – participants learned about the effects of urban water conservation policies such as "grey water treatment" and "low flow appliances", mitigation policies such as water rationing, investments in infrastructure and land-use conversions and more importantly about the effects of policy combinations and trade-offs. Participant feedback indicated that the effects of changes were sometimes surprising, with unanticipated results that improved their understanding of the complexities and feedbacks within the river basin (Hill et al., 2014).

2.6 Conclusions and Next Steps

Each drought is unique in terms of severity, duration and impact, but conflicts among water use sectors exist in each drought and necessitate trade-offs. The Invitational Drought Tournament (IDT) developed by Agriculture and Agri-Food Canada provides a new tool to encourage proactive, participatory planning and adaptation for future droughts in Canada and other drought-prone regions (Hill et al., 2014). It combines a workshop with features of a game in which multidisciplinary teams compete for the best score based on their policy selections – among short- and long-term water management, land management, financial management and technology policies – designed to reduce impacts of a hypothetical drought, and subject to information about the current water balance and the available mitigation budget.

Since 2011, IDT events have been held in Canada and the United States with participants from variety of sectors with the aims of improving their understanding of drought management, sharing their experiences in dealing with drought, and improving collaborative decision-making and consensus-building approaches.

Simulation gaming offers a useful and effective tool for collaborative water resources policy development and analysis under drought conditions. The simulation gaming model developed for the Invitational Drought Tournament (Hill et al., 2014) and introduced here provides a comprehensive, "big picture view" of socio-economic drought at the basin scale that incorporates physical and socio-economic components as well as their interactions. It clearly illustrates the effects of team policy choices, based on different policy combinations and their cumulative effects, with results that sometimes surprise participants and contribute to learning. Results of team policy choices relate to basin-scale water and land uses, and agricultural and industrial production, and help participants to understand better 1) how complex water resources systems work and 2) the kinds of trade-offs that result from policy choices. The model also helps to elicit and record stakeholder preferences for drought management options, such as water and land allocations, economic and infrastructural priorities and mitigation policy combinations.

Additionally, the IDT Model can be used experimentally to explore various policy combinations and motivate creative thinking about drought management – indeed, the model is intended to support learning, a key objective of both simulation gaming and System Dynamics, about both drought and drought management. By showing both physical and socio-economic outputs for different water use sectors, participants can improve their understanding of other stakeholders' positions, interact with one another, prioritize management options and potentially build consensus. Finally, as an educational tool, the model may aid regional and local levels of government in developing and assessing plans and soliciting public support for drought management, and contribute to proactive drought management efforts. Taken together, these features make the IDT Model an effective simulation gaming model for drought management.

The IDT Model was developed for a simulation game based on a fictitious basin; however, the model structure and initial data were based on the Canadian Prairies and the Okanagan Basin. Therefore, the model structure and modelling framework may be applicable to other basins facing similar challenges. More broadly, a modified model could be used as the basis of (1) drought impact assessments, (2) drought preparedness and mitigation, (3) long-term water resources planning and management for water-stressed basins and (4) public and student drought education and engagement. Further, the integration of social, economic and environmental aspects in the IDT and its focus on efficient, sustainable and proactive solutions, all of which are important components of Integrated Water Resources Management (or IWRM; Cardwell et al., 2006; GWP, 2000), suggests that the IDT workshop and gaming-model framework may provide a useful approach to translate IWRM principles into practical applications at the river basin scale.

Chapter 3 Industrial Water Management

3.1 Introduction

An essential resource both for the environment and for socio-economic development, water is under increasing pressure due to population and economic growth, uneven resource distribution, and climate change (UN-Water, 2015; Rijsberman, 2006; Wagener et al., 2010). Currently, approximately 1.2 billion people live in physically water-scarce areas, and this number is projected to increase to 1.8 billion by 2025 (United Nations, 2014). Water scarcity management has the central theme of balancing various human demands, including environmental requirements, for long-term sustainability (Bakker, 2012). One proposed approach to achieve this is the implementation of Integrated Water Resources Management (or IWRM; Global Water Partnership (GWP), 2000; Ait-Kadi, 2014).

The core principle of IWRM is the management of water from a holistic perspective – with the river basin as the fundamental management unit – both in its natural state and in balancing competing agricultural, municipal, industrial and environmental demands, for more efficient, sustainable use. The GWP (2011) defines IWRM as a process that "promotes the coordinated development and management of water, land and related resources in order to maximise economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems and the environment". In general terms, IWRM aims to move from a "sectoral" to an "integrated" approach, from vertical "planning" to horizontal "stakeholder interaction and participation", and from "command and control" to "collaborative decision-making and consensus-building" (Kenabatho and Montshiwa, 2006; World Meteorological Organization (WMO) and GWP, 2011; see Figure 3-1a). To apply IWRM principles requires

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The content of this chapter has been submitted for publication. The reference is as follows: Wang, K., Davies, E.G.R., 2017. River Basin Simulation Modelling for Integrated Water Resources Management. Journal of Hydrology (submitted, August 2017).

the integration of ecosystem sustainability, economic efficiency, and social equity and the involvement of stakeholders at all levels in planning and decision-making processes (GWP and Technical Advisory Committee (TAC), 2011; see Figure 3-1b).

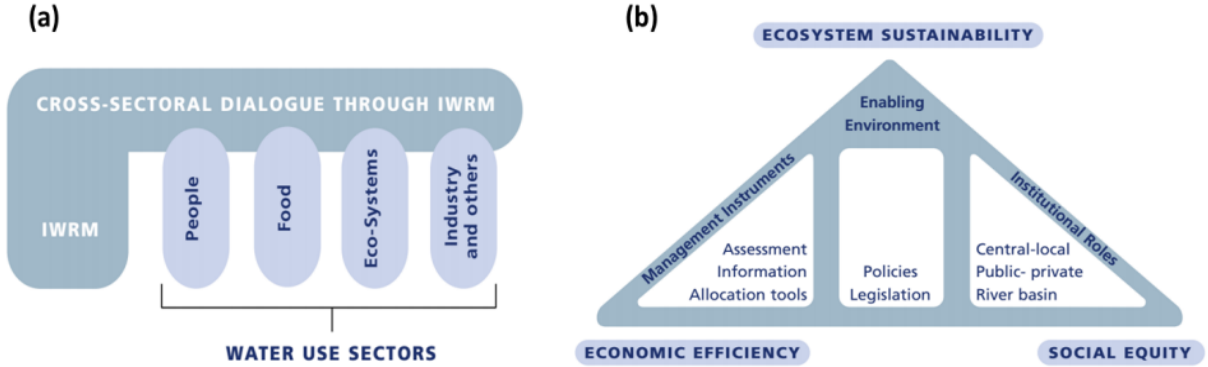


Figure 3-1: (a) IWRM and its related subsectors and (b) IWRM considerations in basin scale (GWP and TAC, 2011)

Significant challenges to IWRM include the division of river basins into multiple jurisdictions that are not managed based on hydrological characteristics, and a lack of experience in integrated management, since it is rarely practiced (Jury and Vaux, 2007; Mitchell et al., 2014). Additional difficulties include, (1) providing a comprehensive and integrated view of whole-basin conditions, such as the basin water balance and potential trade-offs inherent in water management decisions, (2) promoting multi-sectoral stakeholders' dialogue and cooperation, and (3) turning conceptual ideas into action (UNESCO et al., 2009). To overcome the first difficulty, it is important to evaluate the water system conditions quantitatively; therefore, many indices have been developed at the regional and river basin scale (Rijsberman, 2006; Damkjaer and Taylor, 2017). For example, the water stress index, often called the Falkenmark Indicator (Falkenmark et al., 1989), proposed 1000 m^3 per person per year as the threshold of water scarcity. The sustainability index (SI, Xu et al., 2002) divides the water deficit by the water supply in a given region, and ranges in value from zero, which is unsustainable, to values greater than 0.2, which are no-stress conditions. Finally, the withdrawal to availability ratio (WTA, Raskin et al., 1997) is defined as annual basin-scale withdrawals divided by the renewable resources, with values higher than 0.4 representing high water-stress conditions. These indices omit water quality considerations. Further, in the context of IWRM, a combination of indicators may help to guide more comprehensive and efficient management, and permit a comparison of policy effects where there are trade-offs among different performance criteria. For example, UNESCO et al. (2009) provided an index that integrated four aspects: cost recovery, environmental and river flows, water quality, and water safety for domestic, industrial, and irrigation purposes. In addition, Habiba and Takeuchi (2011) and Acosta-Michlik et al. (2008) integrated both social aspects, including education, employment, water sufficiency, water conflict, and health and economic aspects, involving income, GDP, and power generation, into national drought risk and water susceptibility assessment.

Simulation gaming may help to address IWRM challenges by bringing multiple stakeholders together for collaborative management and consensus building (Wang and Davies, 2015; Bassi et al., 2015; Crookall, 2009). Common simulation gaming approaches include board games, role playing, online debates, scenario building, and computer simulation models (Hoekstra, 2012). This paper focuses on computer simulation models, which can be used as decision support tools for gaming, and have proved useful in the past by providing information that shows the results, and trade-offs, of water management decisions, improves stakeholder communication, motivates creativity, promotes their understanding and provides hands-on management experience (Van der Wal et al., 2016; Bassi et al., 2015). Recently, the use of gaming in combination with simulation modelling for water system planning and management has received more attention (Savic et al., 2016), with examples including CauxOperation (Souchère et al., 2010), the Invitational Drought Tournament (Hill et al., 2014; Wang and Davies, 2015), Irrigania (Seibert and Vis, 2012), Ravilla (Rusca et al., 2012), River Waas Game (Valkering et al., 2013), SeGWADE (Savic et al., 2016), SimCity (D'artista and Hellweger, 2007), Sustainable Delta (Van der Wal et al., 2016), and WATERSTORY (Bassi et al., 2015). Most models used for water resources games adopt a river-basin scale, while a few focus on urban (e.g. SimCity and WATERSTORY) and agricultural (e.g. Irrigania) water management. Further, most of the basin scale models address flooding, drought, and transboundary issues; to date, only the Ravilla Game and the model introduced here have focused on IWRM.

This paper presents the Bow River Integrated Model (BRIM), which simulates basin-scale water allocations and uses, and key socio-economic and environmental factors, in support of IWRM-focused gaming. The model expands on the earlier Invitational Drought Tournament (IDT) Model (Wang and Davies, 2015), with a detailed representation of the industrial water sector, calibration to the Bow River Basin in Alberta, Canada, and a novel integrated basin water sustainability index that provides a comprehensive overview of basin-scale sustainability. The BRIM provides a decision support tool that (1) permits a rapid, comprehensive simulation of IWRM-based policy and technical alternatives for management and conservation in the Bow River basin, (2) improves understanding of basin-scale conditions and management policy trade-offs, and (3) illustrates the possible evolution of the river-basin water system under future uncertainties of both demand and supply. The BRIM can be used for both standard simulation – the focus in this paper – and simulation gaming, which permits multiple, user-defined adjustments in model inputs as a simulation progresses.

The model also can be adapted for IWRM-based management in other river basins through modifications in a spreadsheet program.

The following sections introduce the research area, the Bow River Basin (Section 2), and then describe the BRIM (Section 3), in terms of modelling methodology (Section 3.1), and model structure and data sources (Section 3.2). Section 4 provides the model validation, and Section 5 demonstrates and discusses possible model applications. Finally, Section 6 provides conclusions.

3.2 Study Area

The Bow River Basin, in Southern Alberta, Canada (Figure 3-2a), has a semi-arid climate with 400-500 mm of precipitation and approximately 400 mm of evapotranspiration annually (BRBC, 2010; Alberta Government, 2013). The main water source of the Bow River is snowmelt (80%) from the Rocky Mountains, with the remainder from rain, groundwater, and glacial melt (BRPRC, 2010). The river experiences peak flows during spring and summer, and low flows during late summer, fall and winter, and is highly regulated by hydraulic infrastructure. Approximately 46% of its natural annual flow is allocated to agricultural, municipal, and industrial uses (Figure 3-2b); further, the 1969 Master Agreement on Apportionment (Prairie Provinces Water Board, 2015) requires Alberta to pass on 50% of this flow to the downstream provinces of Saskatchewan and Manitoba. In 2006, the South Saskatchewan River basin, of which the Bow River is a part, was closed to new water allocations (Province of Alberta, 2007). Finally, recent studies of potential climate change impacts on the Bow River Basin project increased temperature, uncertain precipitation, and decreased streamflow, which all result in a greater probability of lower water availability into the future (Dibike et al., 2016; Jiang et al., 2015; Tanzeeba and Gan, 2012).

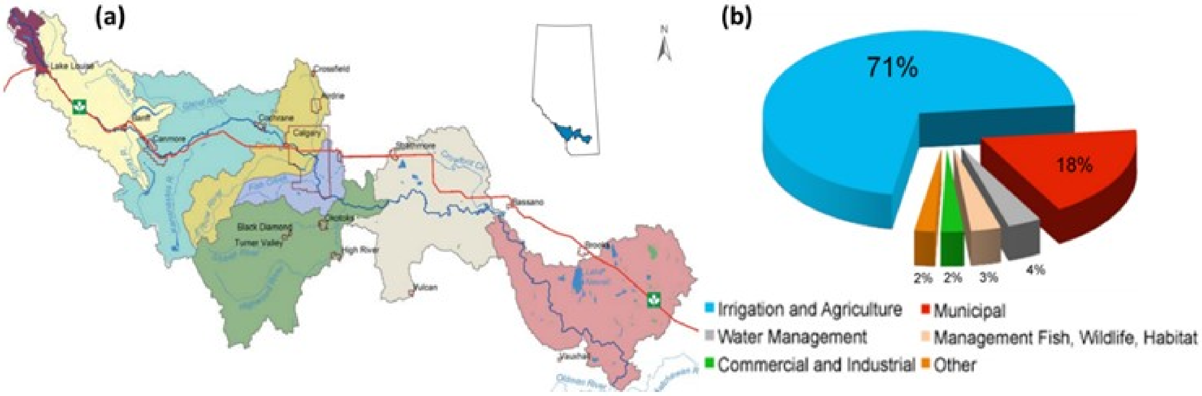


Figure 3-2: (a) Bow River Basin map (BRBC, 2005) and (b) basin water allocations (BRBC, 2016)

Thus, the Bow River Basin is facing growing challenges in balancing future growing water demand with a limited and uncertain water supply. In the dry years of 2000 and 2001, with averages of 2600 million m^3 annual flow, the total irrigation diversions were more than 90% of the basin irrigation license of 1689 million m^3 (AAF, 2016). In the largest city in the basin, Calgary, the municipal consumption has averaged 72% of the peak-day production capacity over the past decade (Boulton-Chaykowski, water management analyst at the City of Calgary, personal communication in April 2017) primarily because of high population growth (Statistics Canada, 2016). Poor water quality and low river-flows that do not meet environmental water demands are more frequent, especially in dry years and close to the basin mouth (BRPRC, 2010). Further, in addition to its effects on basin water availability, climate change may increase irrigation and municipal water demands, reduce hydro-power generation, and result in poorer water quality (AI-EES and WaterSMART, 2013a; AMEC, 2009; Natural Resources Canada, 2007).

Water management of the Bow Basin is shared among jurisdictions that focus on different water use sectors (BRBC, 2005; Ali and Klein, 2014). They have taken various actions to manage the risk of water scarcity, including on-farm water efficiency improvement (Ammar et al., 2014), municipal water conservation (City of Calgary, 2010), environmental water protection (Alberta Environment, 2006), and climate change planning (AI-EES and WaterSMART, 2013b). However, there is a lack of management approaches to integrate all concerns of these jurisdictions, such as a holistic analysis of management policy impacts and their trade-offs, and communication and collaboration among different stakeholder groups to ensure basin-scale water sustainability in the context of IWRM. To address this gap, the Bow River Integrated Model (BRIM) can be used in the fashion of a "serious water management game" (Savic et al., 2016) to gain hands-on integrated water resources management experience.

3.3 The Bow River Integrated Model (BRIM)

The BRIM is a system dynamics-based model that can quantify and communicate the effects of water management strategies at an annual scale in the Bow River Basin. Covering the time period from 1996 to 2040, the BRIM includes the main water use sectors in the Bow River Basin: agricultural, municipal, industrial, environmental, and recreational water uses, as well as the water supply (see the names in bold type in Figure 3-3). These sectors are connected through water allocations and other water, land, technical, and financial management policies. Based on selections of these policies, the model simulates changes in variable values – many of which are also indicators of basin-scale sustainability – such as crop yields, municipal water use, power generation, conventional oil and gas production, mining production, manufacturing value-added, recreational values of water, and environmental water use. The model results then represent basin-scale social, economic, and environmental conditions related to the main water sectors both in the short- (1 or 2 year) and longer terms (>10 years). Finally, the BRIM can operate as a game, with a pause after each annual time-step that allows players to change their management strategies based on current model variable and indicator values; this policy adjustment process is represented in Figure 3-3 as a "feedback", which is intended to improve player understanding of management effects and their potential trade-offs. Results presented in this paper are generated through standard simulation, with variable values specified at the beginning of the simulated period.

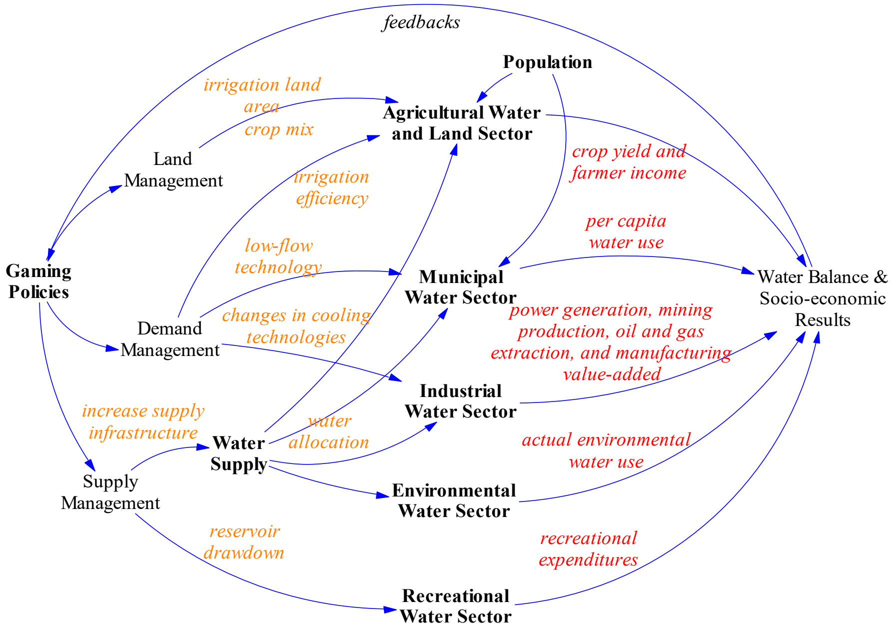


Figure 3-3: General structure of BRIM (yellow: sample management policies, red: sample model outputs)

3.3.1 Modelling Methodology: System Dynamics

System dynamics (SD; Forrester, 1961; Sterman, 2000) has been used widely to model complex systems for decision-support purposes. It produces "causal-descriptive" models that can be used to project future conditions, based on a representation of system structure in terms of stock and flow dynamics, material and informational delays and nonlinear feedbacks. Winz et al. (2009) and Mirchi et al. (2012) provide further details and examples of system dynamics applications to water resources management.

System dynamics can “facilitate recognition of interactions among disparate but interconnected subsystems” that drive the larger system's dynamic behaviour, and can identify and improve understanding of their root causes (Mirchi et al., 2012: 2423). Its ability to capture interactions among subsystems that can lead to complex dynamics in the whole system (Davies and Simonovic, 2011; Yang et al., 2014) make it useful for integrating physical processes, socio-economic, and environmental systems to support IWRM at the river-basin scale (Rusca et al., 2012).

Finally, SD models can be developed quickly, run fast, are typically straightforward to modify and understand, and provide clear and accessible simulation results (Winz et al., 2009). Thus, SD is often used to improve understanding and learning, to promote public education and participation, and to assess the effectiveness of alternative policies comprehensively and inexpensively through alternative scenario building, sensitivity analysis, and gaming approaches (Mirchi et al., 2012; Savic et al., 2016; Alessi and Kopainsky, 2015).

3.3.2 Model Structures and Data Sources

Several model structures in the BRIM – the water supply, population, municipal, agricultural, environmental, and recreational sectors – are adapted from the IDT Model (Wang and Davies, 2015) and modified for the Bow River Basin. In terms of adjustments, (1) water supply scenarios were based on data from S. Tanzeeba (hydrologist at Government of Alberta, personal communication in September 2015), and Environment Canada (2015, 2016); (2) population data were from City of Calgary (2013b), and AMEC (2007, 2009); and (3) agricultural crop types and municipal water uses were modified to correspond to Bow River Basin conditions and initialised based on AAF (2016), DeOreo et al. (2016), and City of Calgary (2010).

The BRIM includes a new, detailed industrial water sector based on twenty-one of the NAICS industry categories (Statistics Canada, 2012c), which were developed to provide a consistent framework for the collection, analysis, and dissemination of industrial statistics, and are widely-used by policy analysts, researchers, business, and the public. Further, a novel integrated basin water sustainability index (IBWSI) that combines social, economic, and environmental considerations into a single index for IWRM purposes reveals management trade-offs, estimates basin-scale water sustainability, and aims to support decision-making. These changes to the model make it more useful for basin-scale water management, allow it to provide clearer evaluations of water resources conditions, and demonstrate its potential value for adaptation to other river basins.

3.3.2.1 Industrial Sector

The industrial water sector in the BRIM simulates industrial water demand, allocation, and use for the power generation, mining, oil and gas extraction, and manufacturing industries of the Bow River Basin (Martz et al., 2007) shown in Table 3-1. The manufacturing sub-categories are further classified into three groups based on their value-added ratios ($\$/m^3$ water intake, Statistics Canada, 2014a; Statistics Canada, 2014b; Martz et al., 2007). In the following discussion, each sector is described with a general model structure including outputs, key variables, policies, and their dynamics, as well as data sources for model initialization.

Table 3-1: Industrial sector categories (Statistics Canada, 2012c)

Industry categories	Sub-categories of Bow River Basin	NAICS Digits
Power generation	Thermal-power generation Hydro-power generation	221
Mining	Limestone mining and quarrying	212
Oil and gas extraction	Oil extraction Gas extraction	211

Manufacturing	High value-added group	Printing and publishing	323
		Furniture and fixtures	337
		Electrical and electronic	335
		Transportation equipment	336
		Machinery	333
		Plastics	326
		Fabricated metal product	332
		Wood product	321
		Computers	334
		Textiles, clothing and leather	313-316
		Miscellaneous	339
	Medium value-added group	Food manufacturing	311
		Beverage manufacturing	312
		Non-metallic minerals	327
	Low value-added group	Chemical manufacturing	325
		Primary metal manufacturing	331
		Paper manufacturing	322
		Petroleum and coal	324

The thermal power generation sector simulates power plant water demands for cooling purposes, which vary with the electricity generation technology and cooling system types and their shares (Davies et al., 2013). In the Bow River Basin, natural gas fired power plants are cooled by once-through, cooling tower, and cooling pond systems – see Table 3-2 for the water withdrawal and consumption rates and system shares of each cooling system. Water demand for thermal power generation is simulated based on the annual electricity demand and basin-averaged plant water use efficiency (Figure 3-4). The electricity demand increases over time with population and economic growth (represented by “thermal power generation change rate”) and, if not satisfied under water-stress conditions, can result in a “thermal power generation deficit”, which represents one effect of water shortages on basin water sustainability. Further, the water use efficiency is averaged based on cooling system shares, which are affected by a policy called “cooling system changes” that is available in the gaming mode. Finally, the required water withdrawal is calculated from the minimum of the current water demand and water allocation. Basin-scale electricity demands are estimated based on Enmax (2012, 2014), TransCanada (2004-2014), and AESO (2014), while water use efficiencies are based on Enmax (2008-2012), Innovation Steam Technologies (2015), and Davies et al. (2013).

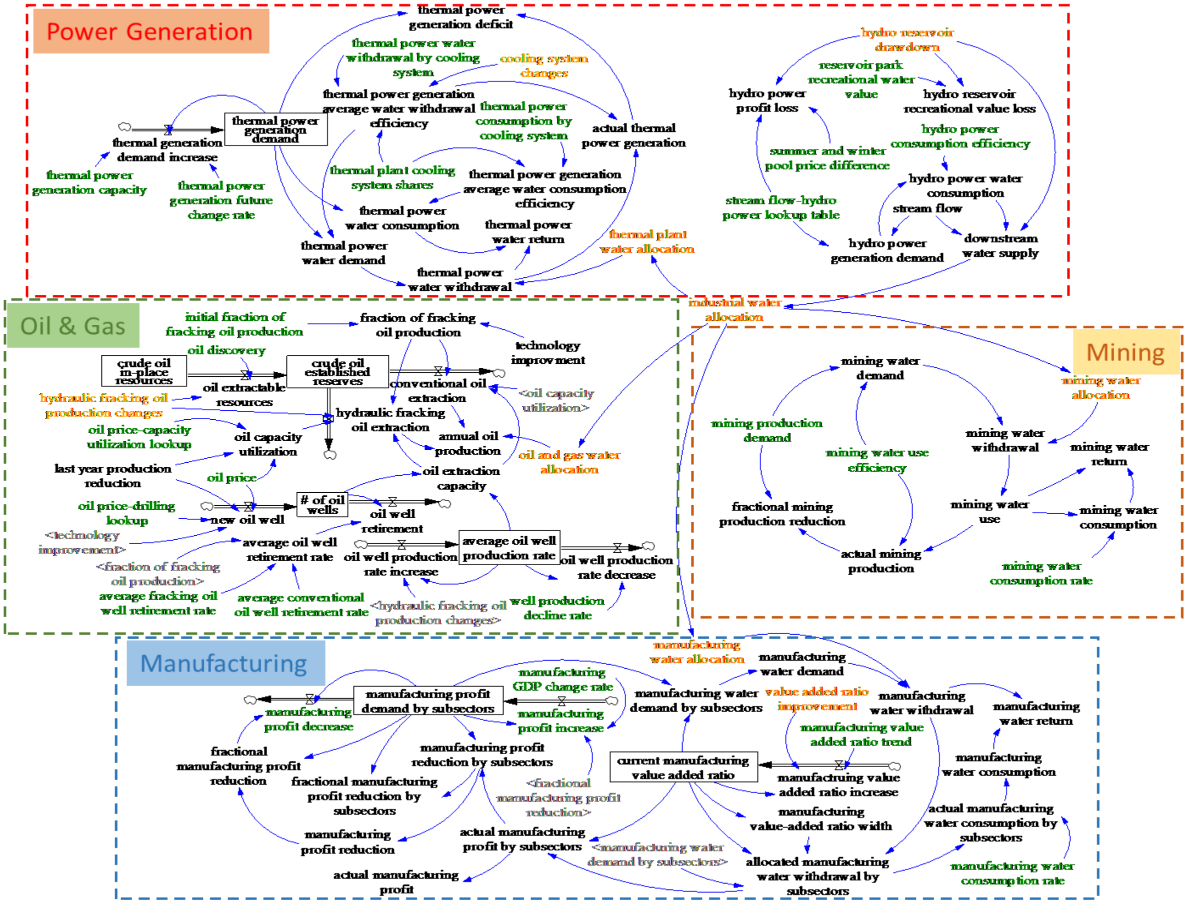


Figure 3-4: Basic structures of industrial water sector (green: inputs; yellow: policies; < >: shadow variables as copies of existing variables)

The hydropower sector simulates annual electricity generation, water consumption, and the relative profitability of production (Figure 3-4), based on a simplified annual streamflow to annual hydropower generation relationship derived from data provided by TransAlta (2014) and S. Tanzeeba (personal communication in September 2015). The volume of water consumed by evaporative losses, which are affected by climate and reservoir characteristics such as the surface area, depends on the water consumption rate (m^3/MWh). Losses in profit result from a management policy used in the gaming mode of the model, “hydro reservoir drawdown”, to mitigate downstream water stress (usually during summer seasons and typically used to maintain environmental flow requirements). Although such summer reservoir releases do not necessarily affect total annual hydropower generation, these variables are intended to represent their possible effects on profitability that result from a lower power pool price in Alberta in summer than in winter (TransAlta, 2014). Reservoir releases also reduce the recreational value of reservoir parks (Ledwaba, 2011). In terms of data, annual hydropower generation values were estimated according to TransAlta (2014), and summer and winter power price differences ($/MWh) and hydropower water consumption values were obtained from AESO (2016) and Davies et al. (2013), respectively.

Table 3-2: Thermal plant and mining water use data

Cooling system types	Once-through	Cooling pond	Cooling tower
Withdrawal efficiency, m^3/MWh	107	2	0.9
Consumption efficiency, m^3/MWh	0.86	1.8	0.73
Shares	11%	8%	81%
Limestone-derived products	Cement	Hydrated lime	Pulverised
Production capacity, tons	1300000	85000	470000
Limestone weight percentage	60%	80%	90%

The mining water sector simulates annual water demand, use, and mining production (Figure 3-4). Mining in the Bow River Basin is of primarily non-metallic minerals – limestone that is used to produce cement, hydrated lime, and pulverised limestone (Natural Resources Canada, 2014). These three products, which are produced at the mining site in the Bow River Basin, are used here to estimate the limestone production based on its weight percentage. Mining water demand is simulated based on annual limestone production and water use efficiency, with the annual production demand assumed to be the plant production capacity, and water efficiency assumed to be constant. The mining sector water withdrawal is set as the minimum of the demand and allocation, and is then used to calculate the mining production. In normal years, the water demand is satisfied; however, in water-scarce years, production may be reduced, as represented by the "fractional mining production reduction". Mineral production data for the Bow River Basin come from Lafarge Inc. (2013) and Graymont (2014), water use efficiency and limestone weight percentage data are estimated based on Lafarge Inc. (2011, 2014), National Lime Association (2015), Semi-Bulk System (2011), The Since of Concreate (2017), and Business Valuation Resources (2013) – see Table 3-2.

The oil and gas extraction sector simulates annual oil and gas production using parallel model structures, one for oil and one for natural gas, as well as the associated water demand and use. The oil extraction subsector, described here as an example, was developed based on the Hubbert peak theory (Hubbert, 1956) and the Fossil2 model developed by Naill (1992) – see Figure 3-4. Production is determined from (1) established reserves, (2) extraction capacity, and (3) capacity utilization, and is subdivided into conventional and hydraulic fracking production based on an adjustable "fraction of fracking production" ratio and an adjustable "hydraulic fracking production changes" policy for the gaming mode. The established reserve is modelled as a stock with discovery increasing and extraction decreasing its value, while the extraction capacity depends on the number of wells and average well production, also modelled as stocks. Well production can increase through technological improvements, such as hydraulic fracking, and otherwise decreases over time. The number of wells increases with drilling activity, which depends on oil price, while well numbers decrease with well retirements. Technological progress also increases the number of wells – for example, horizontal well drilling for hydraulic fracking – and water stress, modelled as “last year’s production reduction”, decreases drilling activity. Finally, capacity utilization is variable, and is determined by price (modelled as a lookup function) and water stress values.

Water demands for oil and natural gas are simulated based on the production of each resource and its corresponding water use efficiency, which is affected by the extraction method. For example, fracking can extract tight oil, but requires relatively more water than the enhanced oil recovery (EOR) method. The water withdrawal is the minimum of the demand and the available supply, which is determined by the water allocation and can be adjusted over time by a policy that permits “alternative water sources utilization”, which includes saline water and municipal/industrial effluents. Under water-scarce conditions, the withdrawn water may not satisfy demands due to limited water allocation; the available supply is then allocated to oil and gas extractions by their relative value ($\$/m^3$ water withdrawal), as determined from the resource market price, production cost, and water use efficiency. Initial oil reserves, resource discoveries, and average well production including both vertical and horizontal wells in Alberta are all estimated based on AER (2014). The price-to-drilling lookup is developed according to the oil price and data on annual numbers of producing wells (CAPP, 2014), and is shown in Figure 3-5a. The average well retirement rate is determined from the average conventional and fracking well-retirement rates and their relative fractions, according to Encana (2011). The oil price and capacity utilization look-up is developed based on a crude oil supply curve from Energy Matters (2014), and is shown in Figure 3-5b. Historical price and cost data are from CAPP (2014), AER (2014), and CERI (2013), while water use efficiencies for both conventional (EOR) and hydraulic fracking methods are estimated from CAPP and OSDG (2011), CSUG (2014), USGS (2016), and Gallegos et al. (2015).

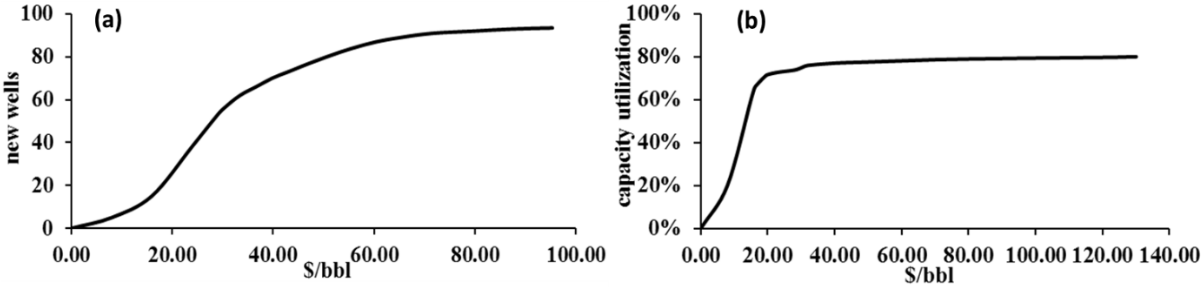


Figure 3-5: Lookup functions for (a) price-drilling activity and (b) price-capacity utilization

Finally, the manufacturing sector calculates the profit for three manufacturing categories (high, medium, and low) based on their water value-added ratios ($\$/m^3$ water intake), and the corresponding water demand and use values. These three categories represent profit losses for a reduction in water access (Martz et al., 2007) for the specific industry types in each category, which are grouped as shown in Table 3-1. The maximum profit for the manufacturing categories (modelled as stocks) is driven by the GDP from the corresponding manufacturing categories in Calgary. The annual manufacturing water demand is calculated from the combination of maximum profit ($) with the value-added ratio ($/m3 water intake), which can change over time through improvements in the manufacturing value-added ratio trend and adoption of the "value-added ratio improvement". Then manufacturing water withdrawal is the minimum of water demand and the available supply, and the withdrawn water is then allocated to each of the three manufacturing categories according to their value-added ratios, with the allocated volume used to calculate the profit. Under water stress conditions – when the actual profit may be lower than the maximum profit, represented as a fractional profit reduction – the resulting decrease in profitability drives a slow conversion from lower to higher value-added ratio groups. The GDP values for all manufacturing categories were provided by C. Osuji (senior corporate economist at City of Calgary, personal communication in 2015) and City of Calgary (2012), and the value-added ratios were estimated from Statistics Canada (2014a, 2014b) and Martz et al. (2007).

3.3.2.2 The Integrated Basin Water Sustainability Index (IBWSI)

The BRIM introduces a new basin-scale water sustainability index that incorporates key aspects of IWRM, and follows recommendations on indicators for water management such as the inclusion of environmental flows and safety for domestic and irrigation purposes (Acosta-Michlik et al., 2008; UNESCO et al., 2009; Habiba and Takeuchi, 2011). This index, called the Integrated Basin Water Sustainability Index (IBWSI), includes key variables from each water-use sector in the Bow River Basin, and is intended to support the multi-dimensional assessment of basin-scale water sustainability (Figure 3-6). Therefore, IBWSI is intended to reveal water stress through the water balance (supply and demand), as the other indicators do, but also to provide greater detail on the social, economic, and environmental aspects of the water demands. This focus on water demand differentiates IBWSI from the other common indices such as WTA, SI, and Falkenmark Indicator, whose values are compared with IBWSI below.

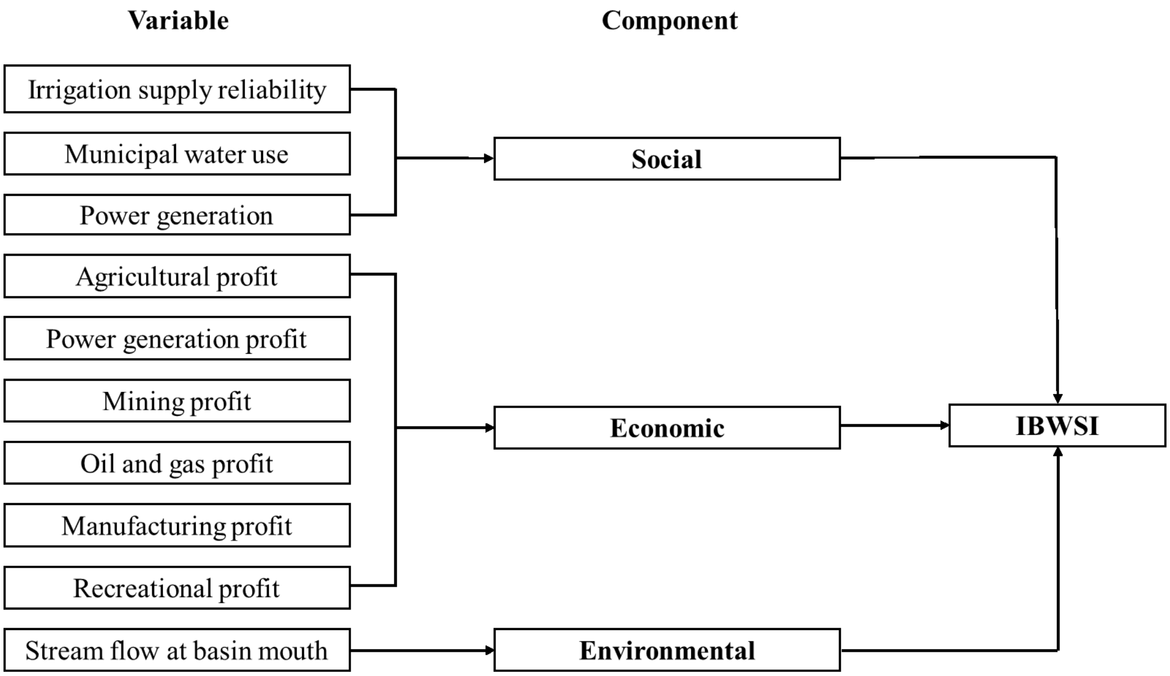


Figure 3-6: Framework of IBWSI

The ratio of each variable's current value to either its maximum value or to the demand (under no water stress) is calculated first, and then the component value is calculated as the average of its related variable ratios. Finally, the IBWSI is calculated by the composite index approach based on the component values (*C*) and their weighted values (*w*), as in Equation (3-1). The components are weighted equally by default, but weightings can also be set based on stakeholders' or model users' preferences. IBWSI values of 1 correspond to sustainable conditions, values between 0.8 and 1 represent low water stress, and values lower than 0.8 indicate unsustainable conditions, where 20% or more of the water demands are unmet.

$$IBWSI = \frac{\sum_{i=1}^{3} C_i * w_i}{\sum_{i=1}^{3} w_i} \tag{3-1}$$

3.4 Model Validation

BRIM model structures were developed and parameters were set based on existing models and published data to ensure that mathematical equations and variable values represented corresponding real-world systems adequately. The model was also subjected to several extreme-condition tests to ensure that it generated reasonable results even for significant changes in input. Figure 3-7 shows the results of model calibration and validation, comparing model behaviour with historical data and trends for the Bow River Basin in terms of social, economic, and environmental variables at an annual scale (Figure 3-7). In general, the model outputs matched the historical data trends quite closely.

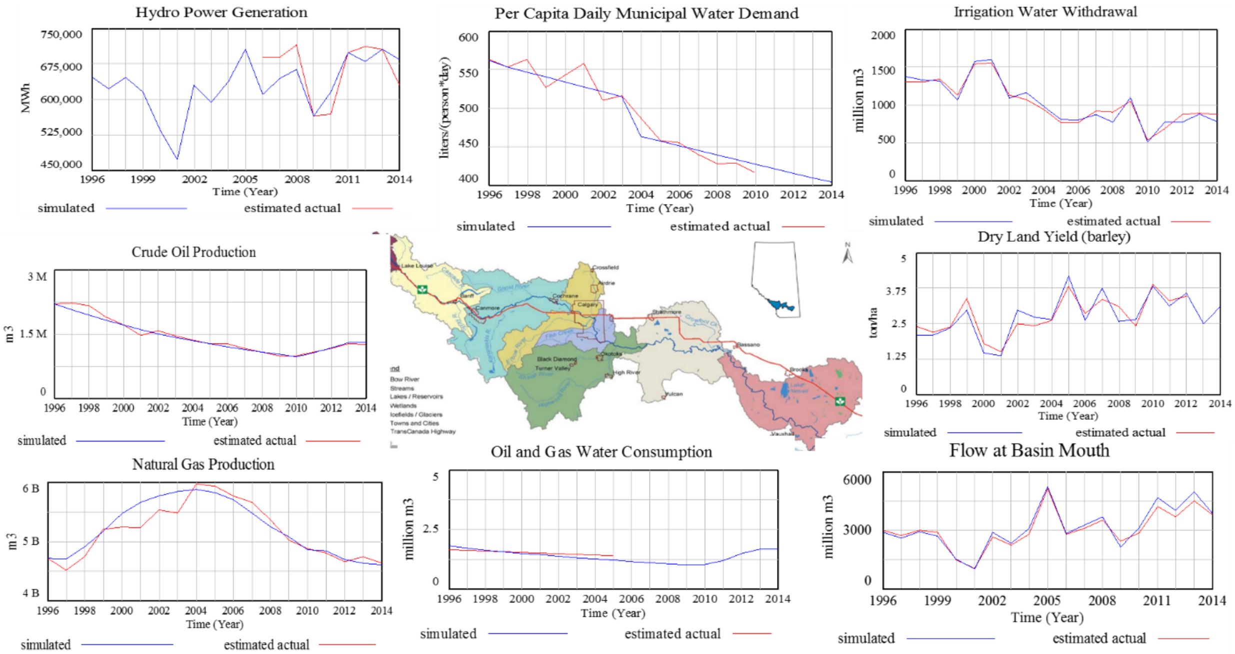


Figure 3-7: Model simulated results and estimated actual data

Further, Monte Carlo simulations were used to test the sensitivity of the IBWSI to the three component weights. Their base values were all set to 0.33, and each weight was tested for a range of 0 to 1 with the other two weights each set equal to half of the remainder. See Figure 3-8a for an example of a test of the economic weighting for four confidence ranges from 50% to 100%. The IBWSI was found to be more sensitive to the economic weight, with a range of indicator values from 0.75 to 1 (Figure 3-8b), than to the social and environmental weights (both with a range from 0.88 to 1; not shown). The greater sensitivity to economic weight resulted from increases in the industrial water stress after 2035, which then affects most of the variables in the economic component (Figure 3-6).

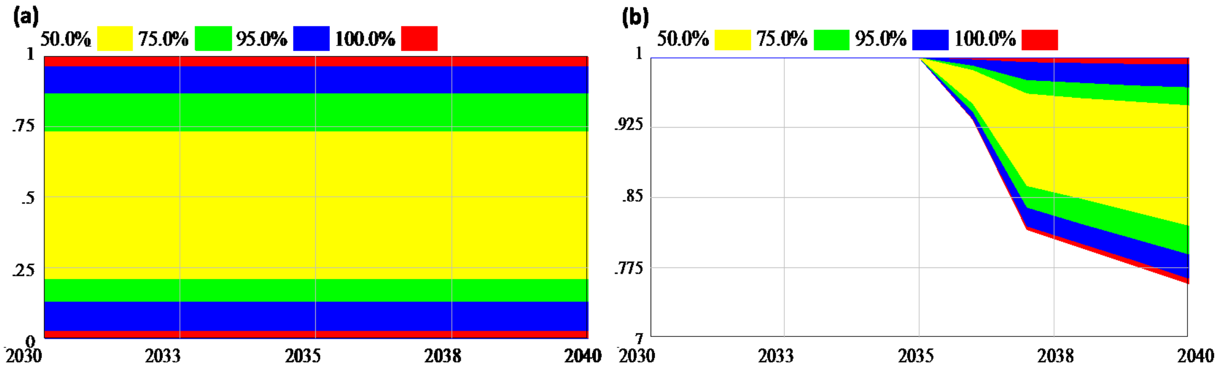


Figure 3-8: Sensitivity analysis of (a) economic weight on (b) IBWSI

3.5 Model Investigations

This section provides model results for five sample simulations based on three possible water demand scenarios, which are intended to represent plausible future conditions in the Bow River Basin. These scenarios are developed to illustrate a wide range of plausible socio-economic, climate, and management conditions into the future; they also provide an indication of the capabilities of the BRIM as a gaming decision-support tool, and could form the basis of comparisons against gaming scenarios.

3.5.1 Water Demand Scenarios

Three water demand scenarios – high water demand (HWD), business as usual (BAU), and low water demand (LWD) – were prepared with different population growth rates, climate change and economic conditions, and water management policy adoptions, as shown in Table 3-3. Changes in the population growth rate were set to values from -10% to 20% relative to the historical average growth rate of 2.6% per year (Government of Alberta, 2015); the low growth rate was observed in 2010, while the high growth rate matches a population projection from the Government of Alberta (2015). Representative climate scenarios were developed based on recent studies (Jiang et al., 2015; Rood et al., 2016; Tanzeeba and Gan, 2012) that have projected 10%-20% increases in temperature, uncertain precipitation, and decreases in streamflow corresponding to higher evapotranspiration during spring and summer seasons in Alberta. The overall impact of uncertain precipitation and increased evapotranspiration was projected to increase the irrigation requirement (AMEC, 2009), simulated by reducing precipitation values in the BRIM. Economic conditions were established according to AAF (2016), AESO (2016), Calgary Economic Development (2015), and CAPP (2014). Management policy selections depended on historical management actions and projected future water demand scenarios.

Table 3-3: Simulation scenarios' configurations

Scenarios and their configurations		HWD	BAU	LWD
Population	Change in population growth rate	20%	0	-10%
Climate	Temperature change rate	20%	0	0
	Streamflow change rate	-20%	0	0
	Precipitation change rate	-20%	0	0
Economy	Annual irrigation expansion rate	0.6%	0.25%	0.25%
	Annual power generation increase rate	4%	2%	2%
	Annual mining production increase rate	1%	0	0
	Chang in mfg. GDP increase rate	10%	0	0
	2040 oil and gas price, \$/bbl, \$/m^3	92, 0.4	66, 0.23	66, 0.23
Agricultural policy	Annual irrigation efficiency increase rate	0	0.45%	0.5%
	Crop mix changes (e.g. forage area change)	10%	0	-10%
	Irrigation reservoir drawdown, million m^3	0	0	0
	Livestock rate reduction (beef, pigs), million	0	0	0.17, 0.03
	Relief payout, \$/ha	0	0	0
Municipal policy	Conservation programs (outdoor), lpcd	0	2	6
	Leak management for conservation	0	50%	60%
	Economic incentive (annual increase of low-	0	0.3%	0.5%
	Greywater reuse (except for kitchen uses)	0	0	30%
	Xeriscaping (outdoor water conservation)	0	0	30%
Industrial policy	Cooling system changes [a]	0	0	10%
	Hydraulic fracturing utilization rate change [b]	20%	0	-10%
	Saline water usage rate [c]	0	0	10%
	Mfg. value-added ratio improvement rate [d]	0	0	10%
Environmental	Hydro reservoir drawdown, million m^3	0	0	0

[a] Changing cooling tower share rates of thermal power plant in 2018 balanced by a corresponding reduction of once-through and cooling pond shares respectively; [b] Changing percentage of oil and gas production using fracturing method each year; [c] Using given percentage of demand as saline water each year; [d] Improving manufacturing water use efficiency (measured by value-added ratio, $\$/m^3$ water intake) by given percentage each year.

Five aspects of model behaviour, termed model investigations, are discussed below for the time period of 2018-2040, based on these three scenarios:

- Investigation 1 determines basin-scale and sectoral water withdrawal demands, and compares them against licensed water allocations in the Bow River basin; environmental flow and downstream requirements are omitted from this investigation since they do not withdrawal water from the river;
- Investigation 2 explores the effects of four industrial water management policies on industrial demands through five scenarios (one scenario combines the four policies), and compares them against the base case HWD scenario; note that policy details are provided below;
- Investigation 3 demonstrates model behaviour under low water-supply conditions, where the actual available water supply is unable to meet water demands; adherence to environmental flow and Master Agreement on Apportionment requirements is included in this investigation;
- Investigation 4 illustrates the effects of three scenarios of water management policies – the combined industrial policies (the fifth scenario of Investigation 2), municipal rationing, and hydro reservoir drawdown – and the base case HWD scenario on the IBWSI value, where component weights are set equal; and,
- Investigation 5 compares the IBWSI against the WTA, SI, and Falkenmark Indicator for the HWD scenario.

3.5.2 Results and Discussion

In Investigation 1, the basin-scale water withdrawals in all three scenarios were within the existing water license for the entire simulation period (Figure 3-9a) – note that the annual fluctuations came from variations in irrigation demands (approximately 80% of the total demand), which were caused by the prescribed future precipitation patterns. In 2035, the demand reached a maximum of 85% of the license in the HWD scenario (Figure 3-9a), and the irrigation demand was lower than the licensed volume (Figure 3-9b) even as climate change increased it by 20%-30%. In the same scenario, municipal water demand approached 95% of its license in 2040 (Figure 3-9c). Finally, industrial demands exceeded the water license in 2028 and then 2036 in the HWD and BAU scenarios, respectively (Figure 3-9d); the increasing demand resulted mainly from the growth of power generation and manufacturing GDP.

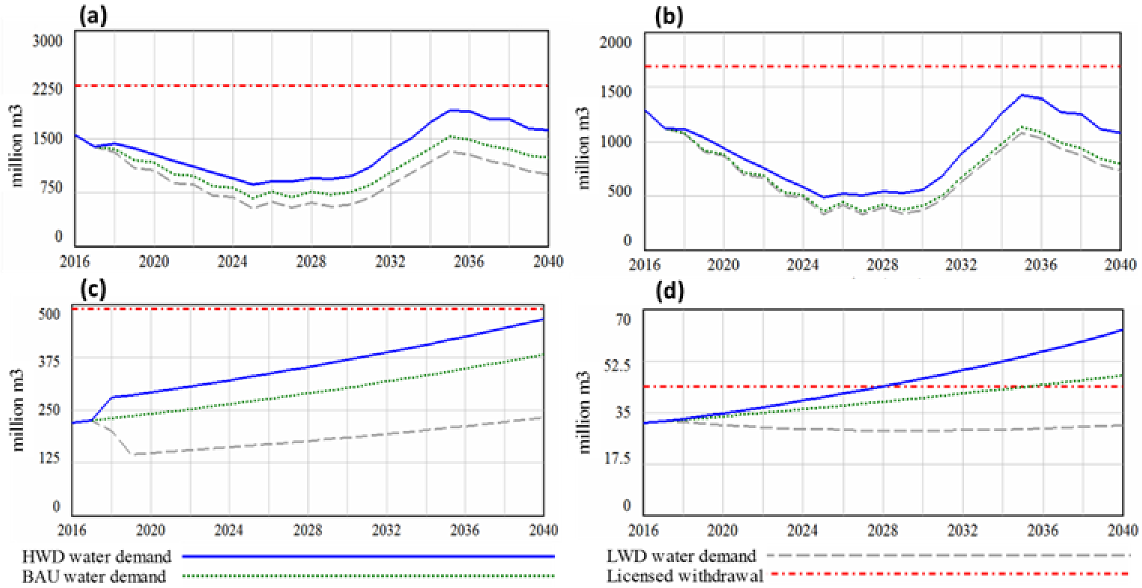


Figure 3-9: Water withdrawal demand and license of (a) basin scale, (b) irrigation, (c) municipal, and (d) industrial sectors

Industrial demands for the five management scenarios of Investigation 2 – i) 10% decrease in the hydraulic fracking utilization rate, ii) 10% use of saline groundwater, iii) 10% increase in manufacturing water efficiency, iv) 10% increase in cooling tower share, v) combined industrial policies including i), ii), iii), and iv) – are shown in Figure 3-10, along with the base case scenario (HWD) from Table 3-3. Policies 2i and 2ii had a very limited impact on the demand compared to the base case scenario, with less than a 1% reduction in demand. The reason is simple: these two policies only reduce the water requirements for oil and gas extraction, which represent only 4% of the industrial demand in 2018. Note, however, that reductions in water demands for oil and gas production may result in better surface water quality (Jensen 2008), which is an effect not simulated in the BRIM. Policy 2iii decreased the total industrial demand by 3% through reducing the manufacturing water demand by 9%. Suitable water conservation policies and technologies for the manufacturing sector could include, for example, dry cleaning processes for food and beverage manufacturing and water reuse for chemical and machinery manufacturing (Fabricators and Manufacturers Association 2013). Finally, policy 2iv decreased the total industrial demand by 25% through reducing power plant water demands by 42%. However, to increase cooling tower shares from 80% to 90% through decreasing the once-through and cooling pond shares by 5% respectively, is expensive and time-consuming (Davies et al., 2013), which is the main trade-off of this policy. Finally, the combined policy 2v was clearly the most effective in reducing total industrial demand, and was the only scenario that kept demand within the current water license (44 million m^3) over the course of the simulation. However, again, its constituent policies, such as “cooling system changes” and “saline water usage”, may be costly and time-consuming, and such considerations are not currently included in the BRIM.

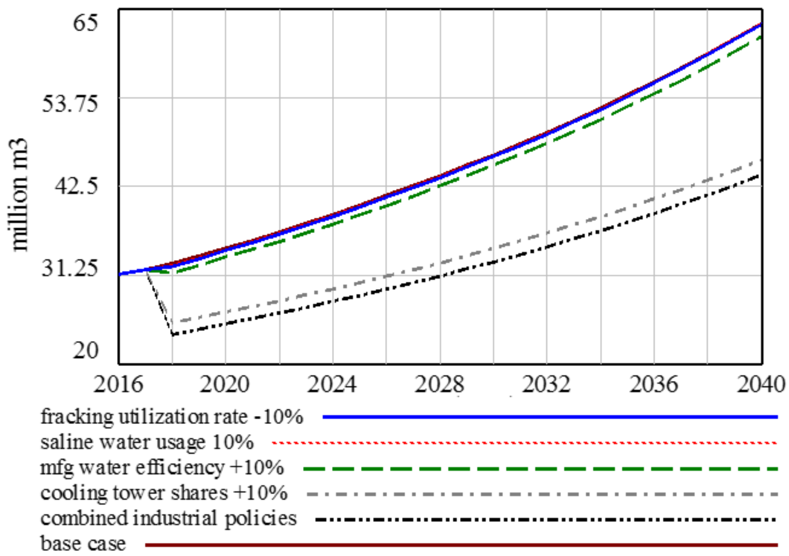


Figure 3-10: Industrial water withdrawal demand

Investigation 3 revealed that the basin water supply can satisfy all sectoral demands of the BAU and LWD scenarios in all years. However, the HWD scenario produces two years under water-stress conditions, with a maximum 5% deficit in these years (Figure 3-11a), because of population and economic growth as well as climate change. This deficit resulted in low-flow conditions at the basin mouth that would not satisfy environmental flow requirements and downstream water demands, especially in 2039.

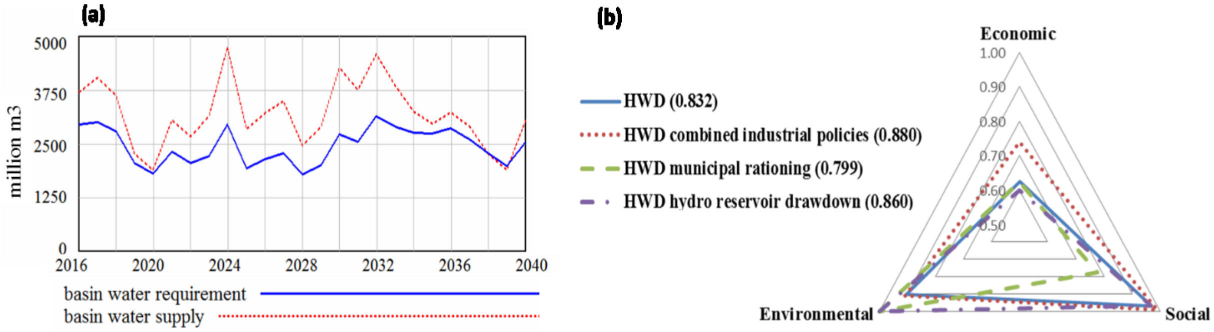


Figure 3-11: For the HWD scenario, basin scale (a) water requirement and supply and (b) IBWSI and its subcomponent values for 2039

The HWD scenario was used as the base case for Investigation 4, and its policy settings for several model parameters were adjusted to create three scenarios, including policy 2v (described above); municipal rationing, to 70% of the municipal water license; and hydro reservoir drawdown, to eliminate environmental flow deficits. Sample IBWSI subcomponent values for the year 2039, in which demands were greater than supply, revealed clear differences among the corresponding policies and demonstrated the effects of policy trade-offs in IWRM (Figure 3-11b). Clearly, all scenarios had relatively low economic index values, since the industrial withdrawal began to exceed its license annually in 2028 in the HWD scenario (Figure 3-9d), and the resulting water deficit reduced industrial profits in subsequent years. However, of the three policies, the "combined industrial policies" scenario (policy 2v) had the highest economic and social index values (0.74 and 0.91) since the water conservation policies it implemented reduced the industrial water demands relative to the HWD base case, which then mitigated the potential losses in industrial profits and reductions in power generation. The base case HWD scenario had the lowest environmental index (0.91) because of the combination of high water demands and zero conservation policy adoptions. The other two policies increased the environmental index to "1", but reduced values for different non-environmental sectors: the "municipal rationing" scenario had the lowest social index (0.78) because of its rationing to 70% of the municipal water license to satisfy environmental and downstream flow requirements, and the "hydro reservoir drawdown" had the lowest economic index (0.60) because of its reduction in both hydropower generation and recreational profits. Comparison of the composite IBWSI values for all four scenarios shows that the combined industrial policies (policy 2v) scenario had the highest overall index (0.88).

Finally, results of the four indices – IBWSI, WTA, SI, and the Falkenmark Indicator – for Investigation 5 are shown in Figure 3-12. Only the WTA index showed significant water stress in 2019 and 2020, primarily because the WTA does not count return flows as available water (Rijsberman, 2006). Further, the WTA, Falkenmark Indicator, and SI revealed water stress and unsustainability from 2033 to 2040, from 2037 to 2040, and from 2038 to 2039, respectively, because of a climate-change-induced supply reduction and an increase in demand with population growth and economic development. The SI uses a value of zero to represent unsustainable conditions, but it does not classify the seriousness of the condition; thus, while the other three indicators showed differences between the 2038 and 2039 index values, SI had values of zero for both years. Finally, the Falkenmark Indicator reflects water availability but does not include water demands. In contrast, the IBWSI showed unsustainable conditions from 2028 onward, because of the water stress in the industrial sector that began in this year. Therefore, the IBWSI is more useful in detecting unsustainable conditions from the social, economic, and environmental (IWRM) aspects at both river basin and sectoral scales. Further, the WTA, SI, and Falkenmark indicators are easy to understand and produce aggregate values for the whole river basin, while the new IBWSI reflects both a river-basin total value as well as sectoral water stresses; however, its calculation requires more information and is not as volatile as other indicators due to the integration and averaging of multiple factors in the calculation.

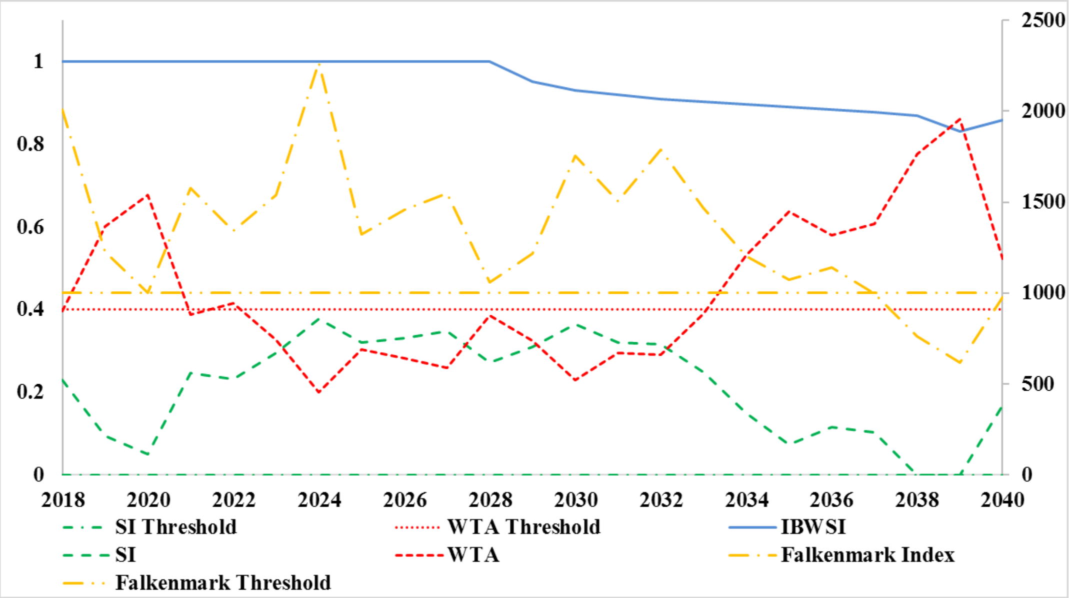


Figure 3-12: Basin water indicators and thresholds under HWD scenario

3.6 Conclusions

This paper introduced a simulation gaming model, called the Bow River Integrated Model (BRIM), to promote understanding and quantify IWRM principles at the river-basin scale. Model structures were modified from the IDT Model (Wang and Davies, 2015) with calibration to the Bow River Basin, Canada; further, a new industrial sector including twenty-one NAICS categories classified into four groups, and an integrated basin water sustainability index (IBWSI) were introduced.

The BRIM simulates water balance and socio-economic factors of the main water uses based on various population, economic, climate, and management policy scenarios. The modelling process and simulation results improve the understanding of complex water systems, especially management policy trade-offs, under water stress conditions to aid basin-scale IWRM. Further, simulation gaming may provide a useful approach to promote IWRM practices by bringing multiple stakeholders together in a safe management-practice environment to achieve consensus building at the river basin scale.

Water system indicators permit a quantitative evaluation of river basin conditions to guide more comprehensive and efficient management, and permit a comparison of different policy performance criteria. The IBWSI provides a comprehensive and clear illustration of basin-scale and water-demand sector sustainability in the context of IWRM. Compared with most existing indicators, IBWSI is more suitable to reveal unsustainable water system condition from social, economic, and environmental aspects and sectoral sub-systems to aid the IWRM. However, it requires more information for calculation, and is less volatile than other indicators.

Further, BRIM runs fast and is easily modified to produce a variety of scenarios. Although the Bow River Basin was the focus of this research, the BRIM can also be applied to other basins that face similar water management issues with limited modifications, and has the potential to support basin water management and planning, drought and scarcity management, water policy assessing and development, public and student education and engagement, as well as serious water management games in the context of IWRM.

Chapter 4 Municipal Water Management

4.1 Introduction

Population growth and climate change present challenges for water resources planners and managers (McDonald et al., 2011), and water security is increasingly of concern to urban authorities (Grafton et al., 2011, Yigzaw and Hossain, 2016). On the water supply side, a variety of studies have investigated effects of changing precipitation patterns, glacial retreat, and sea level rise on hydrological variables (cf. Dibike et al., 2016; Eshtawi et al., 2016; Scalzitti et al., 2016) as well as urban hydraulic infrastructure expansions and management (Padowski and Jawitz, 2012; Mays, 2002). Water authorities also recognize the value of managing water demand – the focus of this research – which is less time-intensive and more cost-effective and environmentally-friendly than supply-side management (House-Peters and Chang, 2011; Gleick, 2003).

Municipal water systems serve residential, industrial, commercial, institutional and public clients (Mayer and DeOreo, 1999), whose demands are affected by both long-term impact factors – population change, economic conditions, and water conservation activities – and short-term impact factors, including seasonal weather patterns and the associated summer peak demands (Corbella and Pujol, 2009). In most urban systems of North America, the total water demand increases with population growth, while per capita water use decreases with water conservation efforts such as adoptions of "low-flow" fixtures and appliances, educational campaigns, leak detection programs, economic incentives, xeriscaping, and water treatment and reuse (Billings and Jones, 2008; DeOreo et al., 2016).

The content of this chapter has been submitted for publication. The reference is as follows: Wang, K., Davies, E.G.R., 2017. Municipal water planning and management with an end-use based simulation model. Environmental Modelling & Software (under revision).

Reliable water demand modelling and forecasting provides the basis for both the short-term (operational) and long-term (planning) aspects of urban water management, in terms of capital investment, infrastructure expansion, conflict mitigation, policy analysis, and system optimization, and it can improve understanding of the underlying factors and dynamics that affect water demand and use (Billings and Jones, 2008). However, accurate demand forecasting and analysis are challenging because of, (1) the limited quantity and quality of data (Brown, 2002), (2) the numerous variables and drivers that affect demand (Corbella and Pujol, 2009), (3) the high uncertainties associated with climate change, economic conditions, population growth, and conservation activities (Gober et al., 2011), (4) the complexity of a quantitative analysis of water conservation options and their implementation costs (Billings and Jones, 2008), and (5) the different model horizons required for short-term and long-term purposes, both of which affect water security (Donkor et al., 2014).

This paper presents a novel end-use-based model as a decision-support tool for municipal water management that addresses many of the challenges above. The model simulates short- (weekly) and long-term (>10 years) municipal water demand and use patterns under various climate change, population growth, and water conservation scenarios, and reveals management trade-offs such as the potential water savings and economic costs of alternative water management policies. It includes ten specific end-uses with seven residential end-uses (six indoor and one outdoor use), and three non-residential uses, 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. Called the Calgary Water Management Model, or CWMM, the model is easy to use, requires relatively few input data, and matches the historical municipal demands in Calgary, Alberta, accurately (R^2 =0.99), while also permitting exploration of various plausible water scenarios into the future. A system dynamics model, the CWMM can be adapted to other municipalities by changing model inputs stored in a MS Excel file, and refined from a whole-city scale to represent individual neighborhoods or city regions.

The paper is structured as follows. First, municipal water modelling methodologies and models are reviewed. Then the research area and data availability are presented in terms of water supply, demand, and management conditions. The model is next described and validated using data for Calgary, and sample results such as per capita water demand, management policy conservation effectiveness, and policy cost are presented. Finally, the paper closes with conclusions, a discussion of modelling limitations and potential next steps for the research.

4.2 Municipal Water Management and Modelling

A wide range of methods can be used for municipal water management and modelling, with the selection depending on modeler skill, available resources and data, and accuracy requirements. Methods such as time-series analysis, regression analysis, artificial intelligence (AI), and system dynamics (SD) are discussed in this section, as well as modelling concerns related to water customer disaggregation, modelling time step, and economic considerations.

4.2.1 Available Modelling Methods

Water demand projections rely on estimated population growth and per capita water demands, and modelling methods differ primarily in their treatment of the latter. Time-series models predict per capita demand based on historical trends, using moving averages, exponential smoothing, or autoregressive integrated moving-average methods (Billings and Jones, 2008).

This approach assumes that the future will be like the past and does not account for system changes such as water conservation and water price; therefore, it is usually used to predict short-term demands (usually less than a year) for small utilities. See Qi and Chang (2011) and Donkor et al. (2014) for examples.

Regression models use social and economic factors, called explanatory variables, such as water price, house and lot size, water-saving technologies, family income, education, and gender to estimate per capita or family water consumption through linear, log-linear, or exponential models (Billings and Jones, 2008). These drivers are analyzed in terms of temporal and spatial scales (House-Peters and Chang, 2011), direct and indirect impacts on water demand (Jorgensen et al., 2009), and economic and non-economic factors (Corbella and Pujol, 2009). Similarly, artificial intelligence models use computational procedures (e.g. learning algorithms) to investigate relationships (usually non-linear) between water demand/consumption and explanatory variables (Qi and Chang, 2011), and then to project future demands. The relationships between explanatory variables and water demand – represented as coefficients in the regression equations – are time-invariant, and are therefore less appropriate for long-term planning (Donkor et al., 2014). Such models also have limited ability to assess alternative management strategies since the explanatory variables are not usually tied to specific water end-uses or conservation policies.

In contrast with regression and time-series models, which apply statistical methods to reproduce historical trends and extrapolate them into the future, system dynamics (SD) models attempt to replicate real-world physical structures and processes – in this case, to simulate the water end-use processes that together produce the total municipal demand.

System dynamics has been used widely for policy assessment and decision making through alternative scenario building, sensitivity analysis, and gaming (Winz et al. 2009; Mirchi et al., 2012; Alessi & Kopainsky, 2015; Savic et al., 2016). Its “causal-descriptive” mathematical models (Barlas, 1994) use stock and flow dynamics, material and informational delays, and nonlinear feedbacks to represent the key structures and processes of the real world that determine system behaviour (Simonovic and Fahmy, 1999). The connection of stocks and/or variables into loops by arrows creates feedbacks, which represent circular cause-and-effect processes and can provide insight into unintended consequences of management actions (Mirchi et al., 2012). Finally, SD models are easy to modify and understand, and provide comprehensive and clear results to users and decision makers (Wang and Davies, 2015).

Municipal water systems have well-established “end-uses” such as toilet flushing, kitchen uses, showering, lawn watering, commercial uses, and so on, that are focuses of different demand management programs (DeOreo et al., 2016). System dynamics can model these individual end-uses through a structural approach, and its simulated end-use water demands, and their summation to total residential and commercial demands, for example, can then help managers to plan municipal systems for capacity expansions for specific water users; analyze policy, environmental, and economic trade-offs; explain root causes of system behaviour; show consequences of alternative actions clearly; and potentially mitigate conflict among various end-users (Stave, 2003). Municipal water managers usually implement several policies simultaneously, making estimation of the effectiveness of individual options difficult, especially under population growth and climate change uncertainties (Tanaka et al., 2006). SD models can be used to reveal individual and combined effects of policies through scenario investigations, and sensitivity analyses can be used to test policy effects over a wide range of plausible futures (Gober et al., 2011).

Municipal water systems also have important "cause-and-effect" interactions. For example, a water shortage in one year, with associated water rationing, could also increase water conservation efforts and thereby mitigate the impact of future shortages (Pacific Institute and NRDC, 2014). Such interactions can be investigated through the incorporation of feedback mechanisms – in which the initial "cause" produces action that ultimately reduces the effects of future "causes" – to support management and planning at the strategic level (Mirchi et al., 2012). Thus, SD models allow decision makers to investigate both changes in human behaviour and technological changes in fixtures and appliances, by assembling various changes in policy and model parameters into scenarios and then comparing their results. Examples of SD applications to municipal water management include Qi and Chang (2011), Gober et al. (2011), Qaiser et al. (2011), Ahmad and Prashar (2010), and Stave (2003).

4.2.2 Model Characteristics and Capabilities

The level of model disaggregation significantly affects the abilities and accuracy of municipal water management models (Billings and Jones, 2008). Models with more customer categories provide greater insight into sources of demands and effects of management programs, and can also help to improve model accuracy. However, the level of aggregation depends on utility size, modelling methods, and water metering characteristics – small utilities may not be able to categorize customers because of potentially excessive volatility within customer categories or inadequate data (Billings and Jones, 2008). While time-series and regression models usually focus on general customer categories, SD models usually include a variety of different groups, such as residential, industrial, commercial, and institutional customers. For example, Gober et al. (2011) simulated both residential and commercial uses, and Qaiser et al. (2011) and Stave (2003) included indoor and outdoor residential water uses. The most detailed municipal SD model, developed by Ahmad and Prashar (2010), includes residential end-uses such as kitchen, toilet, bath, laundry, and outdoor uses, as well as public, commercial, and industrial uses.

The simulation time-step also affects model characteristics and capabilities. In general, small time-steps (from hourly to seasonal) are used for short- (less than a year) and medium-term (from one to ten years) models. These models are developed for system operations and assessment of pumping requirements, with focuses on demand changes under a fixed or slowly-changing customer base, and seasonal variations in demands, for example (Billings and Jones, 2008). Time-series, regression analysis, and artificial neural network model are common methods here; see examples provided by Donkor et al. (2014). In contrast, longer time-steps up to the annual scale are usually used for long-term (often a decade or more) planning and management to address questions related to infrastructure sizing (Billings and Jones, 2008), uncertainties associated with changing socio-economic conditions, and climate change. See, for example, Donkor et al. (2014), Qi and Chang (2011), Gober et al. (2011) and Qaiser et al. (2011).

Models often incorporate economic factors as water-use drivers, and include their effects on the viability of management options. Water price and family income are widely included in time-series and regression models through estimation of price and income elasticities – see examples discussed by Corbella and Pujol (2009). Several studies have analyzed municipal management policies in terms of trade-offs between water supply expansion and demand reduction. For example, Chung et al. (2009) developed an optimization model that incorporated system reliability and the economic feasibility/cost of municipal supply design. Scott et al. (2012) coupled infrastructure cost optimization with scenario modelling to support urban water-wastewater infrastructure planning under both demand and supply uncertainties. On the demand side, White and Fane (2007) and Levin et al. (2006) used least-cost planning methods to evaluate costs of several conservation strategies, while Rehan et al. (2011) analyzed the effects of rehabilitation strategies on the financial sustainability of water and wastewater services. Stavins and Olmstead (2009) compared price and non-price measures such as water restrictions on water conservation. Further, Barton and Argue (2009) investigated cost implications of water reuse in a residential water planning model, while the National Research Council (2012) investigated costs of potable and non-potable reuse facilities, and other water source alternatives such as desalination and water transfers.

4.3 Study Area and Data Availability

Calgary is the largest city in Alberta, and had a population of 1.2 million people (about 37% of the provincial population) in 2014 (City of Calgary, 2014a). Further, the city has had the highest annual growth rate among all Canadian cities over the last five years, with a 3.8% growth rate from 2012 to 2013 (Statistics Canada, 2016), and is projected to reach a population of 2.4 million by 2041 (Government of Alberta, 2015).

The city is concerned about water-use sustainability (City of Calgary, 2011), since the supply is limited by both its water license and the water treatment plant capacity. In terms of the water license, future water availability for Calgary is limited by the closure of the South

Saskatchewan River basin to new water allocations in 2006 (Province of Alberta, 2007), while municipal consumption has averaged 72% of the peak-day production capacity over the past decade (Boulton-Chaykowski, 2016). At a regional scale, water is shared by diverse upstream and downstream users including farmers and irrigation districts, industrial users, and recreational activities (Ali and Klein, 2014; Percy, 2005), and their water demands are also increasing with population growth.

Adding to the challenges of population growth and limited allocations are potential impacts of climate change. Calgary depends heavily on consistent river flows primarily from the annual snowpack and glacial meltwater. The city has experienced increased temperatures, which can significantly increase outdoor demands, and decreased river flow over the last 100 years (Natural Resources Canada, 2007), and such trends are expected to continue (Rood et al., 2016). However, climate change impacts on temperature and precipitation are unclear. Recent studies project changes in seasonal precipitation of -15% to 25%, while seasonal temperatures may increase by up to 4.2 °C in Alberta by the 2050s (Jiang et al., 2015). For the Bow River Basin, changes of monthly mean precipitation could range from -1% to 8%, and monthly mean temperature is projected to increase by 2 °C to 4.5 °C by the 2050s (Tanzeeba and Gan, 2012).

4.3.1 Water Supply and Demand

Calgary is located in one of the driest regions in Canada with average annual precipitation and evapotranspiration of 413 mm and 405 mm respectively (Alberta Government, 2013). Calgary relies on two surface water sources, the Bow and Elbow rivers, which originate in the Rocky Mountains west of Calgary and flow eastward through the Canadian Prairies (Figure 4-1).

From these two water sources, the city has an annual licensed withdrawal of 460 million m^3 (AEP, 2015). Two water treatment plants, Bearspaw and Glenmore plants, located along the Bow and Elbow Rivers, respectively, are capable of providing up to 1 million m^3 of drinking water to the city each day (City of Calgary, 2015).

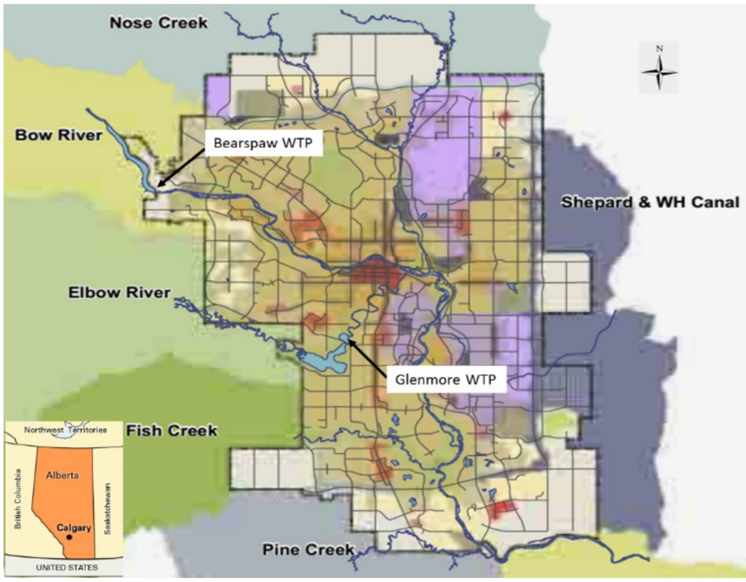


Figure 4-1: City of Calgary location and water sources (City of Calgary, 2011)

In 2013, the average residential water use in Calgary was 231 liters per capita per day (lpcd; City of Calgary, 2013c), which is 64% of the North American residential average of 360 lpcd (DeOreo et al., 2016). Calgary has reduced its per capita daily demand from an average total per capita demand of 500 lpcd in 2003 to 406 lpcd in 2010 (City of Calgary, 2011) through implementation of water conservation policies and low-flow technologies. Specific data are not available for Calgary, but Table 4-1 shows the average indoor fixture and appliance usage in 1999 and 2016 for North American cities (DeOreo et al., 2016). Despite these per capita decreases in water use, Calgary's total water demand continues to increase. Total water demand has almost doubled from 1972 (98 million m^3; Headwater Communication, 2007) to 2015 (170 million m^3; Boulton-Chaykowski, 2016) as the population has grown from approximately 400 000 in 1971 (Statistics Canada, 1977) to 1.4 million in 2015 (Statistics Canada, 2016).

Table 4-1: Sample changes in North American municipal water use from 1999 to 2016 (DeOreo et al., 2016)

Category	Toilet	Shower	Faucet	Dishwasher	Laundry
Fixture uses per capita per day in 1999 (number)	5.05	0.66	15	0.09	0.81
Fixture uses per capita per day in 2016 (number)	5.00	0.69	20	0.10	0.78
Average per capita daily use in 1999 (lpcd)	70	44	41	3.8	57
Average per capita daily use in 2016 (lpcd)	53.8	42	42	2.6	36

Major water uses in Calgary (Figure 4-2a) include residential; industrial, commercial, and institutional (ICI); non-revenue (street cleaning, firefighting, and losses); and wholesale supply to nearby communities. Residential indoor uses are typical for a North American city (DeOreo et al., 2016), as shown in Figure 4-2b. Outdoor water use accounted for about 12% of total annual use in 2007 (Headwater Communications, 2007), a value much lower than the North American average of 50% (DeOreo et al., 2016), mainly because of the short growing season in Alberta. Calgary’s outdoor use is known to increase dramatically when weekly mean temperatures are higher than 10˚C (Chen et al., 2006) and is also affected by weekly rainfall (Akuoko-Asibey et al., 1993). In normal years, summer demand can be 170% of winter demand, and up to 250% of winter demand in hot and dry years (Natural Resources Canada, 2007).

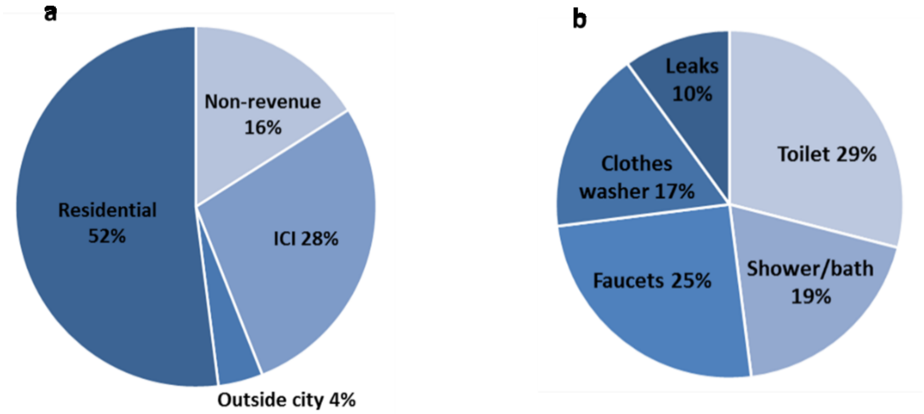


Figure 4-2: Water use categories with percentages for the City of Calgary (a) and residential indoor uses (b) (City of Calgary, 2010)

4.3.2 Water Management and Conservation

Calgary uses the following evaluation criteria to assess its water management options: water conservation effectiveness, such as per capita demand reduction and peak daily demand reduction; cost-effectiveness (\$ per m^3 of water conserved); and social impacts of water shortage, such as unmet water demand (City of Calgary, 2010). For the past decade, Calgary has adhered to a "30-in-30" plan (Headwater Communication 2007), which targets the same volume of water withdrawal in 2033 as in 2003 by reducing per capita water demand by 30 percent (from 500 lpcd to 350 lpcd) over those 30 years. A 2015 assessment found that the city was on track to its goal (City of Calgary, 2016a). Calgary has implemented water metering and pricing, encouraged adoption of water-efficient appliances such as low-flow toilets, offered economic incentives, improved leak detection efforts, and educated citizens about water use and conservation. For example, Calgary's water metering rate increased from 44.5% in 1996 to 97% in 2014, and the low-flow toilet incentive program awarded 75 000 rebates from 2003 to 2014 (Boulton-Chaykowski, 2016). The prevalence and water conservation effectiveness of a variety of water management policies are discussed in the Appendix (Table 4-3).

4.4 Calgary Water Management Model (CWMM)

The Calgary Water Management Model (CWMM) is a system dynamics model that simulates municipal water demand and use, and treatment plant water withdrawals, at a weekly timescale, beginning in 1996 and ending in 2040, to aid both near-term evaluation of water-use characteristics and long-term planning and management of regional water resources. The CWMM includes interactions between increases in municipal water demands with population growth, the available water supply, and the effects on demand of climate change and water conservation policies, including those described in Table 4-3: water metering, low-flow appliances, rain barrels, leak management, educational programs, economic incentives, water rationing, greywater reuse, and xeriscaping. The model is described briefly below; a detailed description is provided in the Supplemental Material.

4.4.1 Model Structures and Interface

In each simulation run, the CWMM first simulates the water demands of various end-uses in liters per capita per day, and then sums them to generate total per capita water demands. The model subdivides municipal water demand into ten end-use categories, based on Mayer and DeOreo (1999) and Coomes et al. (2010): toilet, shower and bath, laundry, kitchen, leaks, other, outdoor, ICI (industrial, commercial, and institutional), non-revenue (for street-cleaning and firefighting, for example), and extra-municipal (water wholesale) uses, see Figure 4-3. The per capita daily water demand of each residential indoor end-use is calculated according to a combination of the base per-use demand, number of daily uses, and fraction of households equipped with water conserving fixtures and appliances (Table 4-1). Per capita outdoor demands are based on local weekly temperature and rainfall, using a set of climate-based relationships developed for Calgary (Chen et al., 2006; Akuoko-Asibey et al., 1993).

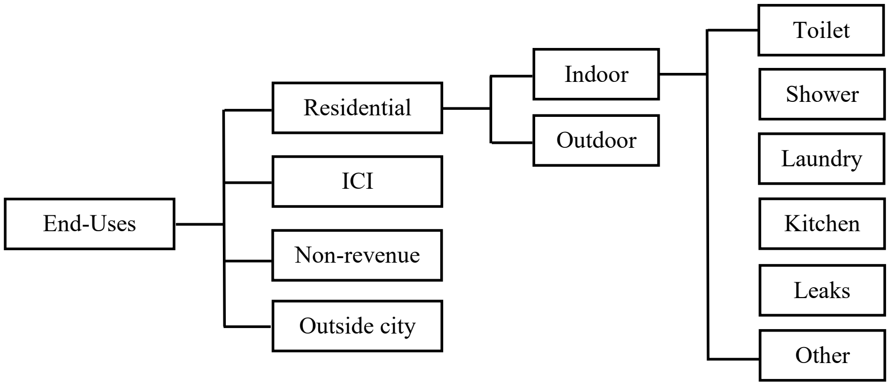
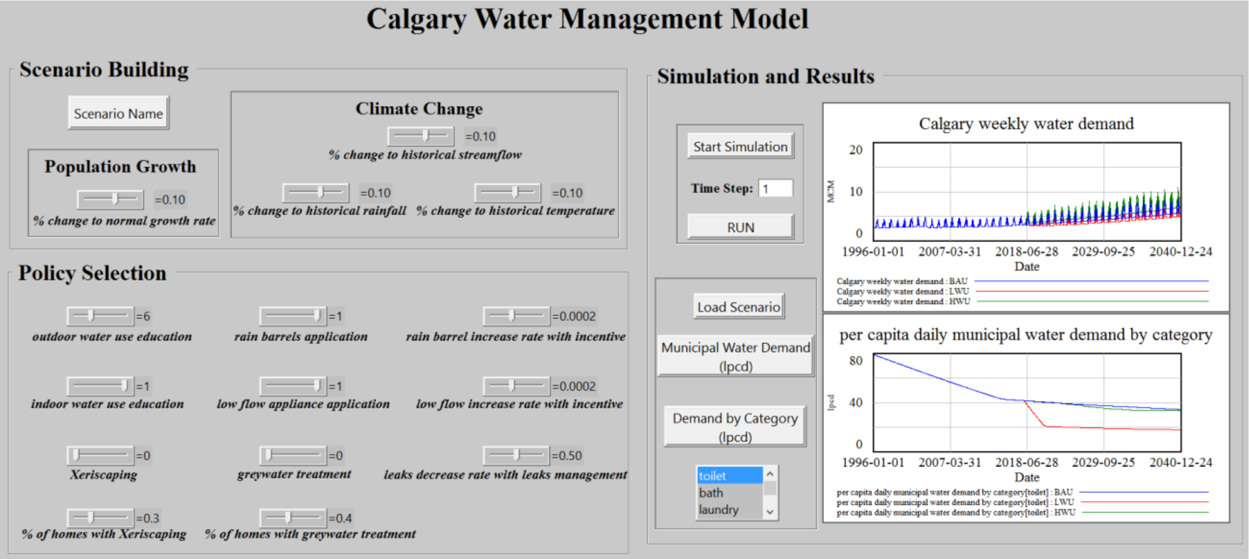


Figure 4-3: Municipal water end-uses (adapted from Coomes et al., 2010)

To calculate the total municipal demand, the model multiplies the per capita demands with the municipal population and adds ICI, non-revenue, and wholesale demands. This total demand is compared with the available water supply to determine the weekly water withdrawal. Finally, the withdrawn water is used to satisfy water demands, and if demands cannot be fully satisfied, a water shortage is generated and represented as an "unmet water demand", as explained in Wang and Davies (2015). This unmet demand can drive more rapid adoption of low-flow fixtures and appliances, and the implementation of conservation policies such as rationing. The effects of water conservation policies are simulated either by increasing the adoption rates of low-flow fixtures and appliances or by decreasing specific end-use demands directly. Policy application costs are modelled using a conservation cost per unit ($\$/m^3$) multiplied by the amount of water conserved, the adoption cost of each low-flow appliance or xeriscaping of each property multiplied by the number of appliances adopted or the number of properties converted from turf to xeriscaping.

The model has a user-friendly interface (Figure 4-4) that facilitates the construction of various population and climate change scenarios, as well as policy selection among the available management policies. Sliders are used to select among policies – for example, "0" means off and “1” means on – or to set policy application intensities to specific values. The model interface also displays results such as weekly and per capita water demands for specific water end-uses, or can display results from multiple scenarios simultaneously to permit comparison among different options. Finally, the CWMM supports both a “scenario mode”, where pre-set values are used for a single, continuous simulation run from 1996 through 2040, and a “gaming mode”, which allows users to refine policy selections at a week-by-week (to longer) time step over the 1996-2040 time period.



=0.10 *% change to normal growth rate*

=0.10 *% change to historical streamflow*

=0.10 *% change to historical rainfall*

=0.10 *% change to historical temperature*

=6 *outdoor water use education*

=1 *rain barrels application*

=0.0002 *rain barrel increase rate with incentive*

=1 *indoor water use education*

=1 *low flow appliance application*

=0.0002 *low flow increase rate with incentive*

=0 *Xeriscaping*

=0 *greywater treatment*

=0.50 *leaks decrease rate with leaks management*

=0.3 *% of homes with Xeriscaping*

=0.4 *% of homes with greywater treatment*

Time Step: 1

Figure 4-4: The model’s user-friendly interface

4.4.2 Model Validation

The following tests were used to validate the model (Barlas, 1994; Sterman, 2000): 1) model structure and parameter tests confirmed that mathematical equations and interrelationships adequately represent the corresponding system in the real-world; 2) extreme conditions tests ensured that the model generated reasonable results even with extreme values assigned to model parameters; 3) sensitivity analyses permitted investigation of the model responsiveness to important uncertainties such as model equations and parameters; and 4) key model outputs such as per capita water demand, weekly water demand, and total water withdrawal were compared with historical values to ensure that the model could replicate historical behaviour. The first three tests are discussed in the Supplemental Material. Further the simulated municipal water use at weekly scale closely matched ($R^2 = 0.99$) historical values from 2005 to 2015, as shown in Figure 4-5. Note that the simulated and observed patterns differed in several important ways: 1) during winter seasons, the simulated water use fluctuated less than the observed values since specific events such as water-main breaks, street cleaning, or car washing were not modelled; and 2) during summer seasons, simulated weekly water use varied both upwards and downwards from observed values, because of model simplifications and the unpredictability of outdoor water use behaviour.

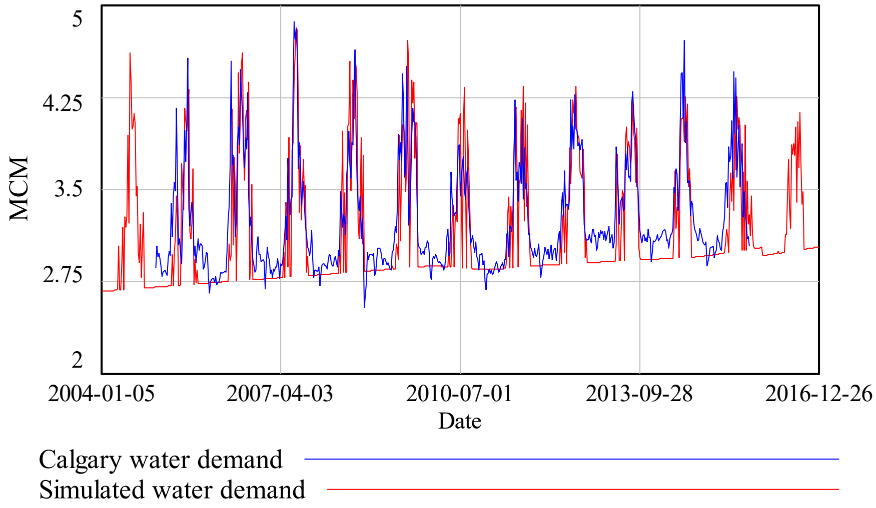


Figure 4-5: Comparison of observed and simulated municipal water demands

4.5 Results and Discussion

4.5.1 Model Forecasting and Water Demand Scenarios

Four scenario groups, with a total of seventeen scenarios, were developed for an investigation of Calgary's potential future water demands under various degrees of population growth, climate change, and water conservation policy implementations – see Table 4-2 for the scenario details. Water use, which can be lower than water demand under water stress conditions, is discussed in some scenarios, where appropriate. Conservation policies are applied from 2018 onwards, and scenario comparisons are shown for the period of 2015 to 2040.

Scenario group 1 focuses on climate change and population growth effects – these are the most commonly assessed variables in water demand studies and provide comparison points for other scenarios. First, climate change scenarios that included increased temperature, decreased streamflow, and increased precipitation were simulated, while population growth rates were held fixed. Several recent studies have projected 10%-20% increases in temperature and precipitation and decreases in streamflow due to higher evapotranspiration (Jiang et al., 2015, Rood et al., 2016, Tanzeeba and Gan, 2012) during spring and summer seasons in Alberta, while another recent study revealed a rate of global warming from 2000-2015 as fast as, or even exceeding, that of the last half of the 20th century (NOAA, 2016). Therefore, the scenarios here included 10%, 20%, and 30% changes in climate variables under normal population growth conditions. Second, three different population growth rates relative to the normal growth rate were tested under constant climate conditions. The normal population growth rate was adapted from historical and projected population values provided by the Government of Alberta (2015) with an average of 2.6% each year, while the low-growth scenario applied a 10% reduction in the growth rate (a value that actually occurred in 2010), and the higher-growth scenarios applied 10% and 20% increases to the normal growth rate. Under these three scenarios, the population of Calgary reaches 2.1, 2.5, and 2.7 million people by 2040, respectively.

In scenario group 2, three scenarios with different population growth rates, climate change conditions, and water management policy adoptions were tested against Calgary's "30-in-30" water management goals; they were called the high water-demand (HWD), business-as-usual (BAU), and low water-demand (LWD) scenarios – see Table 4-2. These scenarios were intended to represent a realistic range of future water demand conditions, where HWD had a high population growth rate, moderate climate change, and minimal effort to conserve water (using only low-flow appliances and rain barrels), BAU had a normal population growth rate without climate change and continued historical management policies and land use trends, such as economic incentives and a fixed percentage of households with xeriscaping, and LWD also used normal population growth rates, without climate change, and implemented xeriscaping, and greywater reuse policies more broadly.

Scenario group 3 focused on policy trade-offs, with four policies – economic incentives, greywater reuse, xeriscaping, and water rationing – adopted separately in 2018. Their water use, social impacts (represented by unmet water demands), and application costs were simulated under high population growth and climate change conditions. Note that the costs of economic incentives programs were based on the City of Calgary's toilet rebate program (Headwater Communications, 2007), the municipal share of greywater system and water rationing costs were Australian values taken from Alberta WaterSMART (2011) and Turner et al. (2007), and xeriscaping costs were estimated from a xeriscaping program in Southern Nevada, USA (Sovocool, 2005). Although all costs were adjusted to the same base year (2016 Canadian dollars), the simulated policy costs may not be representative of the situation in Calgary.

Scenario group 4 focused on greywater reuse in terms of conservation impact and policy cost, where the individual scenarios applied various greywater reuse intensities under high population growth and climate change conditions. Four greywater reuse scenarios represented percentages (20%, 50%, 80%, and 100%) of homes and ICI users with greywater reuse. Further, based on assumptions in Alberta WaterSMART (2011), the first three scenarios also imposed water demand reductions of 50% for toilets, 20% for outdoor use, and 10% for ICI purposes, while the fourth scenario (100% greywater reuse) reduced all end-use demands by 50% except kitchen water uses. Note that the greywater reuse policy is phased-in over three years for all scenarios of this group.

Table 4-2: CWMM set-up for the four scenario groups

Simulation groups and scenarios[a]		Detail set up									
		Population and climate set up			Policy selection[b]						
		Change in pop growth rate	Temp. change rate	Streamflow and rainfall change rate	Edu	EI	LM	GR	% of GR	% of Xer	WR
1	NG_CC_10%	0	10%	-10%, 10%	X	X	X				
	NG_CC_20%		20%	-20%, 20%	X	X	X				
	NG_CC_30%		30%	-30%, 30%	X	X	X				
	PG_-10%_NC	-10%	0	0, 0	X	X	X				
	PG_10%_NC	10%			X	X	X				
	PG_20%_NC	20%			X	X	X				
2	HWD	10%	10%	-10%, 10%							
	BAU[c]	0	0	0, 0	X	X	X	N	5	30	
	LWD	0	0	0, 0	X	X	X	N	50	80	
3	HG_CC_EI	10%	10%	-10%, 10%		X					
	HG_CC_GR							N	100		
	HG_CC_Xer									100	
	HG_CC_WR										X
4	HG_CC_GR_20%	10%	10%	-10%, 10%				N	20		
	HG_CC_GR_50%							N	50		
	HG_CC_GR_80%							N	80		
	HG_CC_GR_100%							F	100		

[a] Scenario name abbreviations: NG=normal population growth, HG=high population growth, PG=population growth, CC=climate change, NC=non-climate change, HWD=high water demand, BAU=business as usual, LWD=low water demand

[b] Policy abbreviations: Edu=education, EI=economic incentive, LM=leak management, GR=greywater reuse, Xer=xeriscaping, WR=water rationing, N=normal reuse (toilet, outdoor, and ICI), F=full reuse (all end-uses except kitchen), X=policy is turned on

[c] A greywater reuse percentage of 5% is debatable; however, recent news and industry reports (CBC News, 2013; Lowes, 2017) indicate that greywater systems are increasingly common in new houses in Calgary. “Xeriscaping” in the business-as-usual case is intended to represent land use change as well as behavioural changes (primarily turf watering) believed to have reduced residential water use in the past decade or so.

4.5.2 Model Forecasting and Scenario Results

Model outputs for the six scenarios of group 1 are shown in Figure 4-6. The applied climate change conditions clearly increased maximum weekly water demands during summer seasons (Figure 4-6a) by increasing outdoor water demand; they also produced longer outdoor watering seasons. Specifically, the changes in climate increased maximum seasonal demands in all three scenarios, with a range from a minimum of 4.9 million m^3 in summer 2018 to a maximum of 9.3 million m^3 in summer 2040 for the NG_CC_10% and NG_CC_30% scenarios, respectively. Further, maximum demand for NG_CC_30% was 1% and 9% higher than the NG_CC_10% in 2018 and 2040, respectively. Interestingly, during lower water-demand seasons, NG_CC_30% had relatively lower demand than the other scenarios because of a model feedback that altered model behaviour in response to repeated water shortages: higher unmet summer demands drove relatively greater adoption of water conserving fixtures and appliances, such as low-flow toilets and washing machines, which then resulted in greater conservation indoors during the winter. After 2038, all three scenarios were close to their maximum low-flow fixture adoption levels and therefore had similar winter demands (Figure 4-6a). Finally, at an annual scale, outdoor water demand represented only about 10% of the total, and water use patterns were assumed not to change under climate change; therefore, climate change did not change Calgary’s annual water demand significantly. However, CWMM does not simulate changes in water supply, and at a weekly scale, the potential for significant increases in maximum water demands during warmer summers of the future may require further study.

Compared to the climate change scenarios, weekly water demand was significantly more sensitive to population growth (Figure 4-6b). Specifically, the population growth scenarios significantly increased water demand in all seasons over the simulation period. For example, the maximum demand of PG_20%_NC was greater than PG_-10%_NC by less than 1% in 2018, and by more than 20% in 2040.

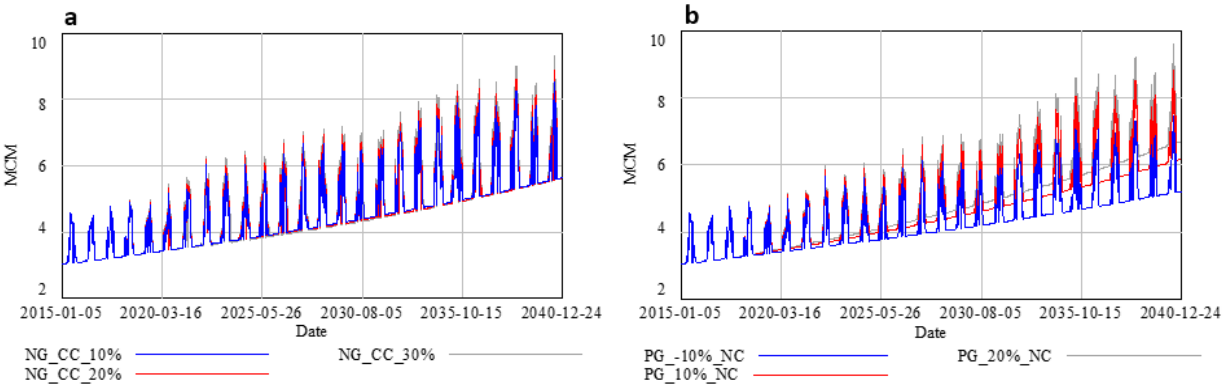


Figure 4-6: Calgary weekly water demand under climate change (a) and population growth (b) scenarios

For the three scenarios of group 2, the model produced significantly different values for annually-averaged per capita daily water demands (Figure 4-7). From 2015 onward, the decreasing trends of all three scenarios slowed – as compared with the historical period – since water-metering was already 97% in 2014 and low-flow shower head and toilet adoption percentages approached their theoretical maxima (85%, according to Rogers, 1995). Therefore, HWD and BAU had annually-averaged per capita daily demand values of 426 lpcd and 372 lpcd, respectively, from 2020 to 2040. To continue to decrease water demands, a broader implementation of greywater reuse and xeriscaping policies simulated by LWD reduced the per capita daily demand to 340 lpcd in 2020, below the management goal of 350 lpcd.

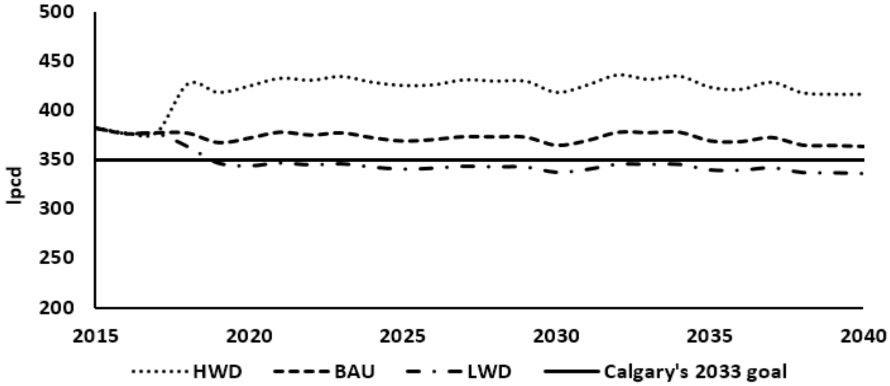


Figure 4-7: Annual average per capita daily water demand

In addition to total municipal demand, the model also simulated the water demands of each end-use. Comparing these end-uses across scenarios clarifies the impacts of population growth, climate change, and management policies on the total demands shown in Figure 4-7 – see Figure 4-8, which shows the components of the annual peak-daily per capita demand for the three scenarios. Compared to BAU, HWD had higher leakage losses (50% higher) and outdoor water demand (about 16% higher) because of reduced leak management efforts and gradually increasing temperatures after 2018 with climate change. In the LWD scenario, toilet, outdoor, and ICI water demands decreased from BAU levels by 20%, 35%, and 4%, respectively, as a result of broader implementation of greywater and xeriscaping policies after 2018.

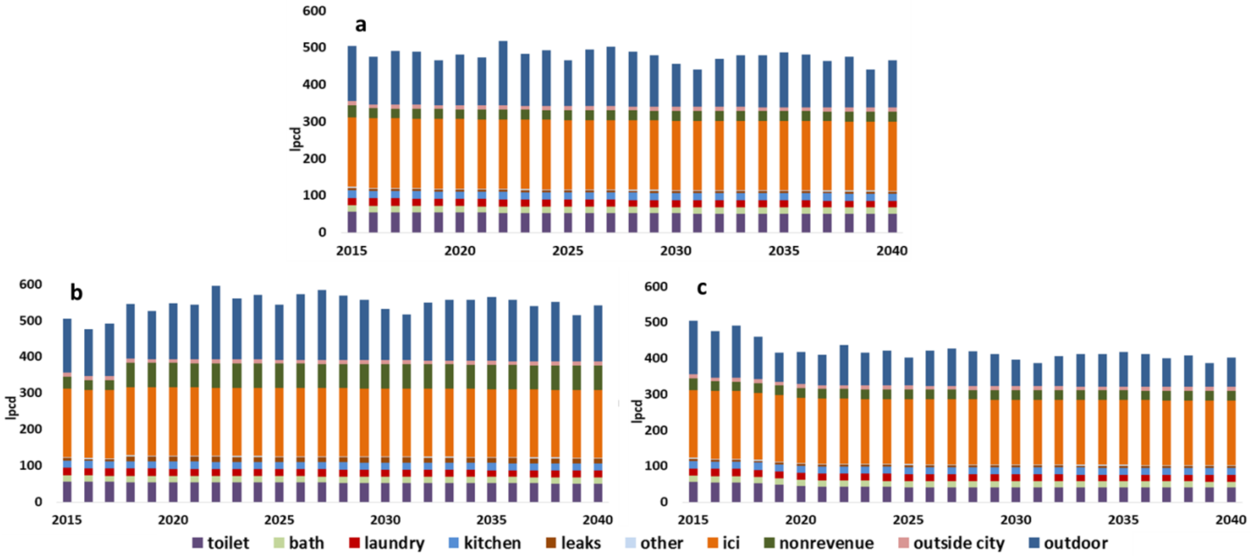


Figure 4-8: Components of peak per capita daily water demand of the BAU (a), HWD (b), and LWD (c) scenarios

Scenario group 3 illustrates weekly water use and unmet demand values for four different conservation options under high population growth and climate change conditions from 2018 to 2040 – see Figure 4-9. To compare these policies, adoption of each conservation option was simulated individually. CWMM simulated similar water-use levels for the economic incentives and xeriscaping scenarios, but xeriscaping reduced summer-season weekly water use by a maximum of 10% (a difference of 540 000 m^3 in the peak-demand week) and increased non-summer season water use by 0.5%, compared with economic incentives. The reason for the difference was that xeriscaping only reduced outdoor use during the summer season while economic incentives affected indoor, outdoor, and ICI uses in all seasons by increasing the adoption rate of low-flow fixtures and appliances, which reduced non-summer uses relative to the xeriscaping scenario (see Figure 4-9a). Under water stress conditions after 2022, both scenarios used the maximum water supply during the summer. Water rationing, the third scenario of group 3, had very similar water use (0.2% higher) to economic incentives in all seasons; however, compared to xeriscaping, its summer use was 10% higher – because water rationing used all the available water during the high-demand summer season – while use in other seasons was 1% lower, as a result of a 2% greater low-flow fixture and appliance adoption rate (Figure 4-9a). This high adoption rate resulted from the high level of unmet demand during summer (Figure 4-9b), which drove a greater low-flow appliance adoption rate through model feedbacks. Finally, greywater reuse, the fourth policy of the group, was the most effective policy in reducing weekly water use in all seasons: it produced a 14% reduction in water use and a low unmet demand under both stress and no-stress conditions (Figure 4-9b).

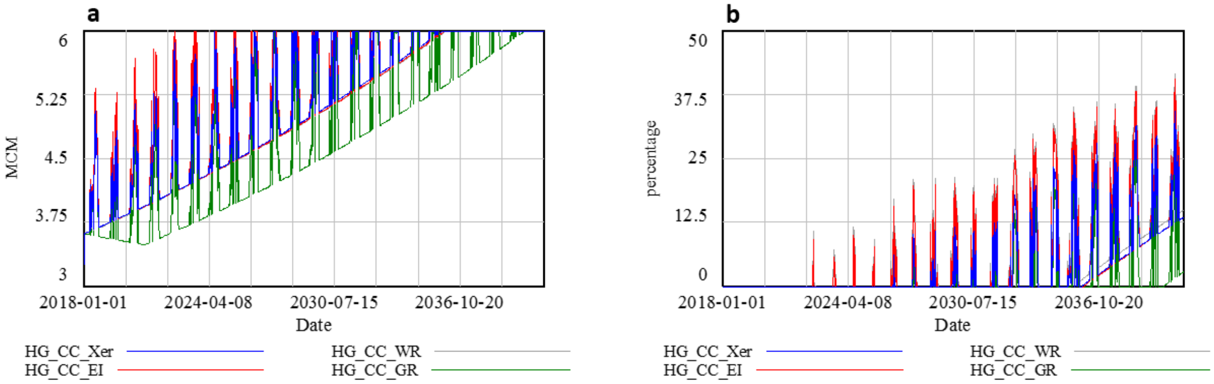


Figure 4-9: Weekly municipal water use (a) and unmet water demand (b)

Group 3 scenario costs were also simulated, based on details provided in the Supplemental Material. Their order, ranked from lowest to highest cost, was rationing, economic incentives, xeriscaping, and greywater reuse. Figure 4-10a compares economic incentives with water rationing costs, and shows economic incentive costs decreasing from about $1200 to nearly $0 per week from 2018 to 2040. This decreasing trend resulted from the saturation of households with low-flow fixtures and appliances. For example, low-flow toilets were installed in close to 70% and 80% of homes in 2018 and 2040, respectively; therefore, there was little uptake of the economic subsidy later in the simulation period. In contrast, water rationing had a relatively low cost when applied during water shortages (Figure 4-10a), but caused high unmet water demand (Figure 4-9b). Xeriscaping had the highest cost of all four scenarios in the first application year (Figure 4-10b) – approximately \$1450 million per year for a 100% application rate – for the conversion of all lawns in the city to xeriscaping; however, costs were relatively lower in the following years (approximately \$60 million per year) to provide 100% of new homes with xeriscaping (Figure 4-10b). Finally, greywater reuse had the highest total cost, at \$570 million per year over three years for a 100% application rate of the normal reuse scenario, as well as the longest implementation time (Figure 4-10b). Note that all implementation costs are approximate, and that implementation times for the xeriscaping and greywater reuse policies are modelled with delays that can be changed to simulate different conditions in other cities. The CWMM can also calculate the unit water saving cost (\$/m^3 saved; not shown here) for further comparison of policies.

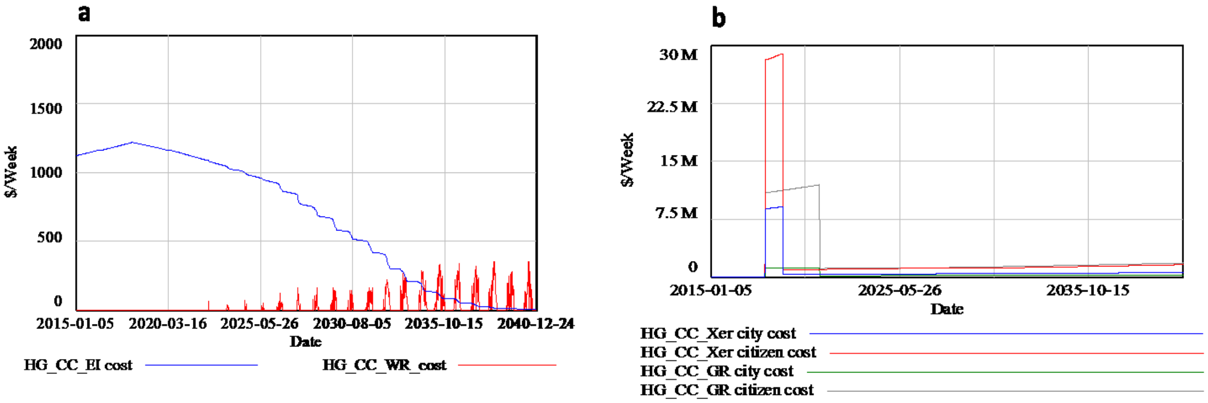


Figure 4-10: Weekly costs for economic incentive and rationing (a) and xeriscaping and greywater reuse (b) policies

Finally, scenario group 4 tested several application intensities of the greywater reuse policy under high population growth and climate change conditions. Differences among the weekly water demands of the HG_CC_GR_20%, 50%, and 80% scenarios were not large, with a maximum 8% difference (Figure 4-11a) between them. The reasons are that their major effect is on toilet water demand (reduced by 50%), which represents 14% of the total municipal water demand, and outdoor and ICI uses, which represent about 10% and 28% of the total municipal demand, are reduced by 20% and 10%, respectively. In contrast, full application of the greywater reuse policy (HG_CC_GR_100%) dramatically reduced total weekly water demand – by 44%, compared with the HG_CC_GR_20% scenario, for example (Figure 4-11a). In reality, of course, the efficacy of the greywater reuse policy would depend heavily on the quality of treated water and its suitability for different water end-uses, as well as the implementation cost (Figure 4-11b). Here, the municipal share of the application cost for the 100% policy was approximately three times higher (at $120 million per year, or $80 million per year above the next highest scenario) than in the other three scenarios.

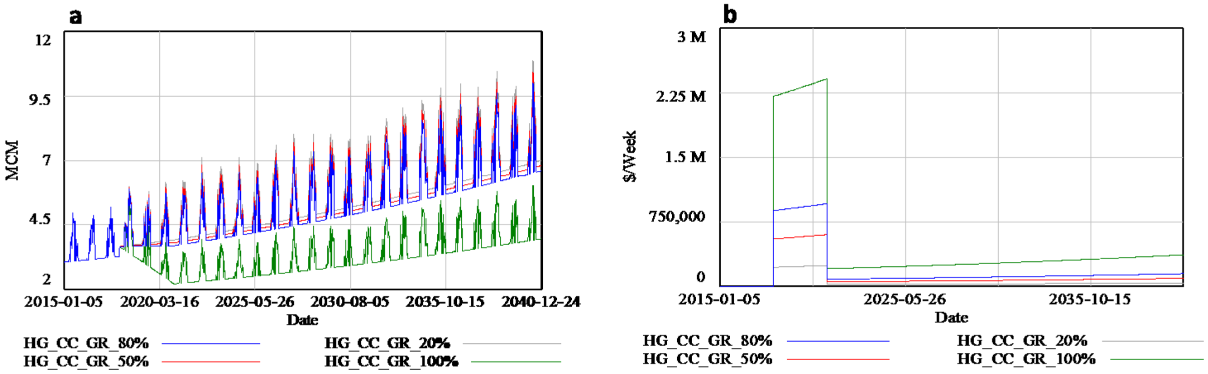


Figure 4-11: Weekly municipal water demand (a) and municipal share of the cost (b) of greywater reuse

4.5.3 Discussion

Application of the CWMM to Calgary revealed that adoption of several water conservation policies will ensure water availability under future population growth, a limited water license, and uncertainties from climate change. The model showed that weekly water demand was more sensitive to population growth than to climate change. Further, City of Calgary is on its way to achieving its “30-in-30” goal, and may achieve further demand reductions through a wider application of xeriscaping and greywater treatment and reuse programs. At an annual scale, these policies could reduce water demand per person per day by 10% relative to the BAU scenario. In particular, xeriscaping reduced the maximum municipal water use during the summer season by an average of 10%, while adoption of low-flow appliances and greywater reuse affected end-uses in all seasons. Water rationing resulted in high unmet water demands (here, a maximum of 40% of the total demand); however, it is a relatively inexpensive conservation approach. Indeed, implementation costs represent the main trade-off of conservation policies for both the city and its citizens. For example, greywater reuse in CWMM reduced water use by 14% during hot and dry conditions, as compared with water rationing, but required approximately $60 million per year for three years from the city government in one scenario (100% application with normal reuse) to implement the required infrastructure. Note that such economic figures are uncertain and require further research.

4.6 Conclusions

This paper introduced a system dynamics model for Calgary, Alberta, as an alternative to commonly-used time-series analysis, regression analysis, and artificial intelligence (AI) approaches. The Calgary Water Management Model (CWMM) supports water resources management and planning under various population growth and climate change conditions, and the implementation of alternative water conservation policies. Intended for use as a seasonal- to decadal-scale decision-support tool, the CWMM adopts, (1) a process-based, end-use oriented structure with ten individual water end-uses, (2) a weekly calculation time-step, and (3) a user-friendly data-entry system and graphical user interface. The end-use based structure permits simulation of the impacts of nine water management policies, including conservation education, leak management, economic incentives, water rationing, low-flow appliances, rain barrels, water metering and pricing, xeriscaping, and greywater reuse, on specific municipal end-uses. Further, the weekly time-step reveals seasonal water demand patterns and their responses to various management policies, and facilitates investigation of system capacity in high water-demand seasons as well as alternative climate change scenarios.

Several model limitations will be addressed through future research. Although adoption of low-flow fixtures and appliances is, at least partially, an economic decision, the current version of the CWMM does not incorporate water price. The addition of water pricing would permit simulation of policy payback times to support water management decision-making for policies such as xeriscaping and greywater reuse. Disaggregation of residential uses to detached- and multi-unit housing, and to regions of the city, would permit (1) a more detailed analysis of infrastructure needs, and (2) more sophisticated model validation approaches. Such an approach would also allow a more detailed representation of turf and landscape irrigation, and potential effects of changing land use over time. Disaggregation of industrial, commercial and institutional (ICI) water end-use would allow investigation of alternative industrial and commercial development pathways, as well as sector-specific policies. Finally, daily or even hourly time-steps could be simulated, if data at these levels were available.

The City of Calgary was the focus of the model development, but the resulting CWMM framework is suitable for other cities facing similar water resources management and planning challenges. The CWMM is intended to provide comprehensive decision-support for municipal water managers, planners, researchers, and modelers. A modified model may also assist with city water resources management and assessment, drought preparedness and mitigation, long-term water resources planning, and public engagement and education.

4.7 Appendix

4.7.1 Simulation of the Per Capita Municipal Water Demand

The Calgary Water Management Model (CWMM) divides municipal water demands into ten end-uses – toilet, shower and bath, laundry, kitchen, leaks, other, outdoor, ICI (industrial, commercial, and institutional), non-revenue (for street-cleaning and firefighting, for example), and outside city (water wholesale) uses – based on Mayer et al. (1999) and Coomes et al. (2010). In particular, indoor demand is divided into specific end-uses because many water conservation technologies target specific plumbing fixtures or appliances. The per capita daily water demand of each residential indoor end-use is calculated according to a combination of the base per-use demand, number of daily uses, and fraction of households equipped with water conserving fixtures and appliances, as shown in Figure 4-12. Values for indoor demand per use and number of uses per day are taken from DeOreo et al. (2016). The base outdoor demand differs from indoor demands, since temperature and precipitation increase and decrease outdoor demands, respectively (Zapata, 2015). Factors such as the irrigated area, plant type, and water price also affect outdoor water requirements (DeOreo et al., 2016), but are not included in the current version of the model. The CWMM therefore calculates per capita outdoor demands based on local weekly temperature and rainfall, using a set of climate-based relationships developed for Calgary (Chen et al., 2006; Akuoko-Asibey et al., 1993). Climate change can be incorporated by developing scenarios with a range of percentage changes in temperature and precipitation relative to historical records.

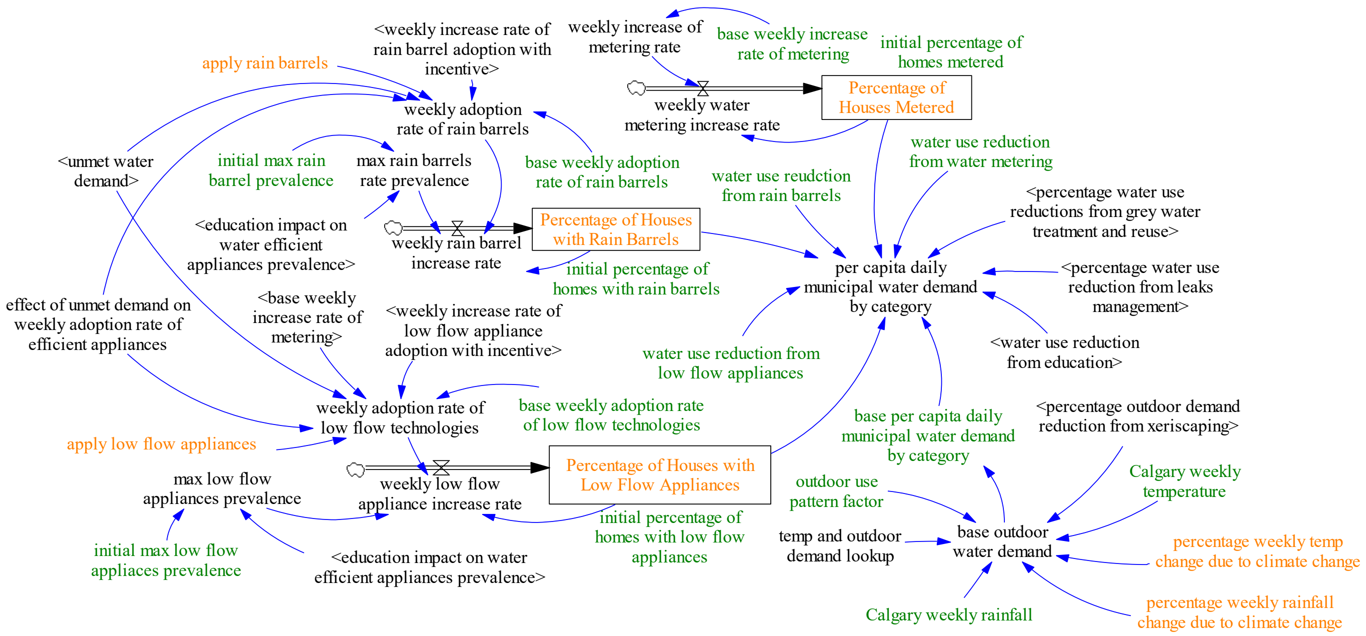


Figure 4-12: Stock and flow representation of per capita daily water demand simulation (black: model variables, green: model inputs, orange: model policies, < >: "shadow variables", or duplicates of existing variables used for clarity)

The adoption of new water conservation technologies changes municipal per capita water demands over time. Using the system dynamics (SD) methodology, the CWMM represents many of these effects by tracking the percentage of households equipped with each type of fixture or appliance through "stock" (accumulation) variables, represented as boxes in Figure 4-12; such technology adoptions are assumed to be permanent over the simulation period. Stocks are variables that accumulate material or information over time (integrals), and whose values can only be adjusted by changing flows (rates). For example, a reservoir can be modelled as a stock, with its stored volume changed by inflows from upstream and outflows to its downstream. Arrows connect stocks, flows and variables in an SD model to represent visually the mathematical equations used to change their values over time. Other conservation policies can either increase the adoption of efficient appliances or decrease end-use demands directly. For example, economic incentives increase the adoption of low-flow toilets in the

CWMM, while xeriscaping directly reduces outdoor water demands. In addition, water shortages – modelled as the “unmet water demand” and shown as a shadow variable in Figure 4-12 – can also increase the adoption rate of water-efficient appliances. Equation (4-1) calculates the per capita daily municipal water demand by category, *PMWD*, in liters per capita per day as,

$$\begin{aligned} PMWD = \sum\nolimits_i \{ & [(p_{li}(1-f_{li}) + (1-p_{li})) \\ & * (p_{mi}(1-f_{mi}) + (1-p_{mi})) \\ & * (p_{ri}(1-f_{ri}) + (1-p_{ri}))] * k_i - R_{ei} - R_{li} - R_{gi} \\ & - R_{xi}\} + W_{ICI}[(q_l(1-g_l) + (1-q_l)]) + W_{NR} + W_{OC} \end{aligned} \tag{4-1}$$

where i is the residential water end-use category, p_l, p_m, p_r are the percentages of households with each category of low-flow appliance (toilet, shower, laundry, and so on), water metering and pricing, and rain barrels (%), q_l is the percentage of ICI with low-flow appliances, f_l, f_m, f_r are the corresponding fractional reductions in residential water demand (dimensionless), g_l is the corresponding fractional reduction in ICI water demand, k is the base residential water demand per capita for the specific water demand category (L/capita/day), R_e is the water reduction from the (optional) education policy (L/capita/day), R_l is the water reduction from the (optional) leak management policy (L/capita/day), R_g is the water reduction from the (optional) grey water treatment policy (L/capita/day), R_x is the water reduction from the (optional) xeriscaping policy (L/capita/day), W_{ICI} is the industrial, commercial, and institutional water demand (L/capita/day), W_{NR} is the non-revenue water demand (L/capita/day), and W_{OC} is the outside-city (for regional water supply) water demand (L/capita/day). Note that conservation policies do not affect all residential end-use demands.

For example, xeriscaping only reduces the outdoor water demand, and thus the only index i for which its value would be non-zero is the one for outdoor water demand.

4.7.2 Simulation of Total Water Demand, Withdrawal, and Use

After the per capita municipal demand is calculated, the CWMM determines the water withdrawal from a comparison of the available supply and the municipal demand – see Figure 4-13. The municipal demand is calculated from the multiplication of the per capita municipal water demand (*PMWD*) with the city population, which can increase over the simulation period according to scenario assumptions. Next, water withdrawal is calculated based on water demand, the water treatment plant (WTP) efficiency, which is used to convert the water demand to the necessary withdrawal, and the licensed supply. Specifically, the demand is converted to a desired withdrawal by adding the additional water volume required to backwash WTP filters every 60 hours (City of Calgary, 2016b), and the actual withdrawal is then the minimum of this desired withdrawal and the water license; both the WTP capacity and license are exogenous variables. Note that climate change could reduce the natural water supply (stream flows) and make the full licensed volume unavailable. However, for simplicity, the impact of climate change on the water supply is simulated by decreasing the water license by specified percentages to investigate future climate change uncertainties.

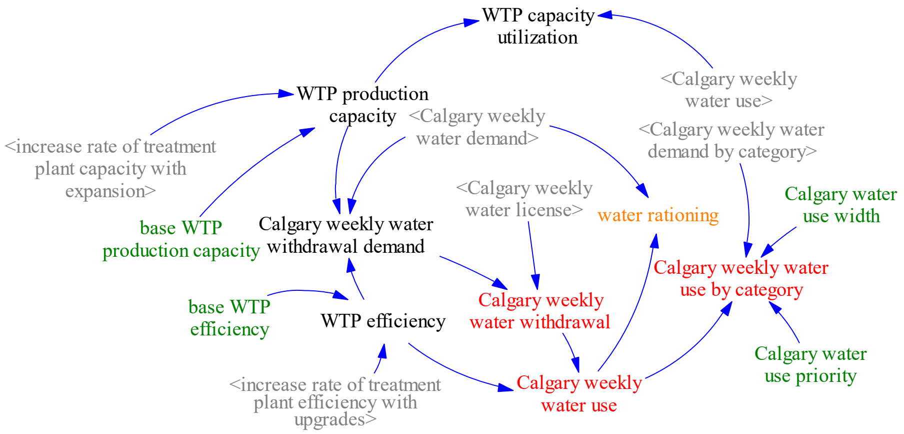


Figure 4-13: Municipal water use simulation

Finally, the withdrawn water is used to satisfy water demands, and if demands cannot be fully satisfied, water shortage is generated and represented as “unmet water demands”, using the difference between water use and demand divided by demands. Impacts of water shortages are modelled as feedbacks in the model; specifically, under water shortage conditions, water rationing is triggered and the model allocates all available supply to each of the ten end-uses based on their relative importance, or “priority”. High priority uses – particularly kitchen water use – then receive water in preference to lower-priority categories, such as outdoor water use; the priority values for the ten end-uses are provided in Wang and Davies (2015). Additionally, unmet water demands increase the adoption rate of water-efficient appliances (shown in Figure 4-12) to mitigate the effects of future water shortages.

4.7.3 Simulation of Water Management Policies

The prevalence and water conservation effectiveness of a variety of water management policies are shown in Table 4-3 and discussed in this section. Note that policies that are frequently investigated in other studies, but not currently used by the City of Calgary, are also listed.

Table 4-3: Water management policies in Calgary

Low-flow appliances	Toilet	Shower	Laundry	Kitchen	ICI	Sources
Prevalence in 1996	4%	74%	0%	0%	0%	DeOreo et al. (2011 and 2016); U.S. EPA (2013b); Inman and Jeffrey (2006)
Prevalence in 2016	37%	80%	46%	20%	20%	
Annual adoption rate	1.6%	0.3%	2.3%	1%	1%	
Reduction in end-use	40%	3%	26%	6%	2%	
Other household conservation measures	Prevalence in 1996	Annual increase		Water savings		
Rain barrels	0%	1%		9 lpcd		Green Calgary (2015)
Water metering and pricing	44.5%	3%		40%-60%		Headwater Communications (2007); City of Calgary (2010); Environment Canada (2011)
Conservation Policies	Effect of policy or technology adoption					
Leak management	Reduce leaks and system losses by 50%					Headwater Communications (2007); Inman and Jeffrey (2006)
Education (outdoor use)	Reduce outdoor demand by 6 lpcd					
Education (indoor use)	Increase maximum prevalence of low-flow appliances by 5%					
Economic incentives	Increase low-flow appliance and rain barrel adoption rate by 0.3% per year					
Greywater reuse	Toilet		Outdoor	ICI		Greywater Action (2016); Alberta WaterSmart (2011); City of San Francisco (2012)
	50% reduction		20% reduction	10% reduction		
Xeriscaping	Reduce outdoor demand by 30%-50%					U.S. EPA (2013c); Sovocool (2005); Boot and Parchomchuk (2009)

Low-flow and water-efficient appliances can reduce municipal – particularly residential – water demand significantly, and the percentage of North American households equipped with them has increased from 1999 to 2016 (DeOreo et al., 2016), as shown in Table 4-3. Notice in particular the increases in the prevalence of front-load washers and low-flow toilets; in contrast, low-flow shower head adoption only increased by 5% over that period, most likely because their installation is approaching the maximum theoretical value for efficient appliances in an innovation adoption lifecycle of 85% (Rogers, 1995). DeOreo et al. (2011) compared average daily household end-uses in North American cities with and without low-flow appliances – Table 4-3 shows percentage reductions for the low-flow fixtures of each end-use. Low-flow fixtures can also affect ICI water use. For example, the U.S. EPA (2013b) found that low-flow spray valves for restaurants and hotels may reduce water use by 20%. Rain barrels can reduce outdoor water use, normally capturing about 3.4 m^3 of water per house per year (Green Calgary, 2015) – a value that amounts to approximately 9 lpcd for outdoor water use during the summer season, assuming an average of 3 people per household (Statistics Canada, 2013d).

Water metering and pricing has also significantly reduced per capita demands in Calgary, with an increase in the water metering rate from 44.5% in 1996 to 97% in 2014 (Headwater Communications, 2007; Boulton-Chaykowski, 2016), for an annual increase rate of 3%. Effects of metering and pricing in Canada include average residential water use reductions of about 40% (Environment Canada, 2011) to 60% (City of Calgary, 2010) through reducing shower frequency and duration, operating washing machines and dishwashers only with full loads, fixing dripping taps, adopting low-flow toilets, and so on. Leak detection programs can also reduce water losses considerably; Calgary estimates a 50% reduction in leakage losses since 1980. In 2003, leak management conserved an estimated 39.5 million liters of water per day (Headwater Communications, 2007), and leak detection and proactive water main replacements conserved over 16 million liters of water in 2014 (City of Calgary, 2015).

Educational programs have focused mainly on reducing summer-season peak outdoor demand through water-efficient landscaping and watering practices. Such programs have been estimated to reduce water use by 2 lpcd (Headwater Communications, 2007) annually, or by about 6 lpcd during the summer. Further, education can affect indoor water use by increasing the adoption rate or ultimate prevalence of water-efficient appliances (Rogers, 1995). Finally, economic incentives can increase low-flow appliance and rain barrel adoption (Coomes et al., 2010). For example, Calgary offered a low-flow toilet incentive in 2003 that awarded 900 rebates (representing about 0.3% of families) of $50 each (Headwater Communications, 2007).

Additional policies in Table 4-3 are frequently discussed in other studies and provide options for the City of Calgary to consider. For example, treated greywater – or wastewater from residential activities involving sinks, showers, tubs, and washing machines (Greywater Action, 2016) – can be used for various residential purposes such as irrigation, toilet flushing, and even potentially laundry and shower uses (Capital Regional District, 2004), increasing water availability without the need for additional fresh water and without affecting consumption patterns. In Alberta, toilet flushing, garden irrigation, and heat reclamation in residential and ICI sectors are the most likely potential uses of greywater (Alberta WaterSmart, 2011). Alberta WaterSmart (2011) estimated a 25% reduction in residential water consumption for greywater use in toilet-flushing. Further, Troy et al. (2005) stated that a maximum of 80% laundry water can be recycled; its use for irrigation could decrease outdoor water demand by about 20% (City of San Francisco, 2012). A second water conservation option, xeriscaping uses native and drought-tolerant plants and appropriate irrigation practices to reduce water requirements of landscaping (City of Bend, 2005). A multi-year study in Southern Nevada, USA, found that xeriscaping reduced water consumption by 30% (Sovocool, 2005), and Boot and Parchomchuk (2009) state that it has the potential to reduce irrigation demands by more than 50%.

Finally, water management policy trade-offs should be assessed in terms of implementation costs versus conservation benefits. Such values depend on location and context, and are not widely published; however, for illustrative purposes, implementation costs of four representative policies are described here (in 2016 Canadian Dollars). Water rationing costs based on residential control plans in Canberra, Australia (Turner et al., 2007) could include all capital and operating costs associated with management and evaluation, estimated together as \$0.1 per m^3 water rationed. A rebate program for low-flow toilets has offered \$50 for each unit installed residentially in Calgary since 2003 (City of Calgary, 2016c). The conversion of traditional turf-grass to a xeric landscape and the installation of new xeric landscaping accounts for the majority of xeriscaping costs. In Southern Nevada, a xeriscaping study of more than 500 households reported average household costs of approximately \$4600 and average municipal incentives of approximately \$1400 per household for the conversion (Sovocool, 2005). Finally, greywater reuse costs stem from construction and installation, and range from \$300 for a filtering sink for toilet flushing, to \$10 000 for a more complex treatment processes that incorporates sedimentation tanks, bioreactors, filters, pumps, and disinfection (Alberta WaterSmart, 2011). As incentive for greywater system installation, the Government of Australia provides residential rebates of \$500 to \$1000 (Alberta WaterSmart, 2011).

Water management policies simulated in CWMM include educational programs on water conservation (indoor and outdoor), leak management, economic incentives, water rationing, low-flow appliances, rain barrels, water metering and pricing, xeriscaping, and greywater reuse. The effects of these water conservation policies are simulated in two different ways: 1) some policies, including educational programs and economic incentives, conserve water by increasing the adoption rates of low-flow fixtures and appliances, and 2) other policies decrease specific end-use demand directly, such as leak management and xeriscaping. Initial settings for these policy conservation impacts are based on data provided in Table 4-3.

The simulation of policy application costs is another important feature of the model. Such costs are modelled in one of two ways, by a conservation cost per unit or by a policy-adoption cost. In the first approach, a per-unit water conservation cost is multiplied by the total water conserved to simulate the approximate policy application cost. For example, the cost of water rationing depends on the per-unit cost of water rationing multiplied by the volume of water rationed. Alternatively, policy costs can be calculated based on the cost of each adoption of a low-flow appliance or fixture, or landscaping change multiplied by the number of appliances adopted or landscapes changed. For example, the policy cost of xeriscaping is calculated from the xeriscaping cost for an average household multiplied by the number of households that adopt xeriscaping. Further, the model simulates the overall cost per unit of water conserved ($\$/m^3$) for a basket of conservation policies, which can then be used to compare alternative scenarios. For historical simulations (from 1996 to 2016), note that policies are adopted according to initial settings based on historical water management in Calgary, while the policies used in model projections (for 2018 to 2040) can be adopted or abandoned at user-specified times, and their application intensities can also be varied. Furthermore, the model currently assumes one and three years of delay, respectively, to fully implement xeriscaping and greywater reuse policies, and these policy delays can be changed to simulate different policy adoption lags.

4.7.4 Model Validation

The following tests were used to improve confidence in model performance (Barlas, 1994; Sterman, 2000): 1) model structure and parameter tests confirmed that mathematical equations and interrelationships adequately represent the corresponding system in the real-world; 2) extreme conditions tests ensured that the model generated reasonable results even with extreme values for model parameters; 3) sensitivity analyses investigated model responsiveness to important uncertainties; and 4) key model outputs such as per capita water demand, weekly water demand, and total water withdrawal were compared with historical values to ensure that the model could replicate historical behaviour.

Specifically, the model structure and parameters were based on well-established and accepted knowledge, modification of existing models, and published data. Extreme-conditions tests evaluated model response to significant input changes, such as weekly water allocations of only 50% of their initial values, which caused no outdoor water allocation due to a low outdoor water use priority (see Wang and Davies, 2015) and sharp reductions of toilet, shower, and laundry water uses. As a second example, leak management programs were disabled in another extreme condition test. As expected, leakage losses increased as older pipes were no longer maintained and outdoor water use decreased over time because of its low allocation priority under water shortage conditions, which were caused by population growth and a fixed water license. However, other end-uses were not affected since leaks only represent about 10% of the total residential demand.

Sensitivity analyses evaluated a variety of uncertainties in model equations and parameters; two Monte Carlo simulations described here explored uncertainties related to the effectiveness and implementation rates of residential indoor conservation policies. The first analysis varied the effects of an economic incentive for the adoption rate of low-flow toilets and high-efficiency washing machines (both within a range of 0% to 2.6% annual increase rates, from a base value of 0.5%) as well as their maximum household uptake (evaluated for a range of 70% to 100% adoption, from a base value of 85%). Note that approximately 40% and 50% of households were equipped with low-flow toilets and high-efficiency washing machines at the beginning of the simulation period. The second analysis varied the adoption of greywater treatment (from an initial value of 0% uptake to a maximum of 30% uptake) and types of grey water end-uses (from toilet-only to all residential indoor uses, excluding kitchen uses). These test ranges resulted in significant ranges of low-flow appliance prevalence (here, low-flow toilets) and greywater system implementations of approximately 30% by 2040, as shown in Figure 4-14 for four confidence ranges from 50% to 100%.

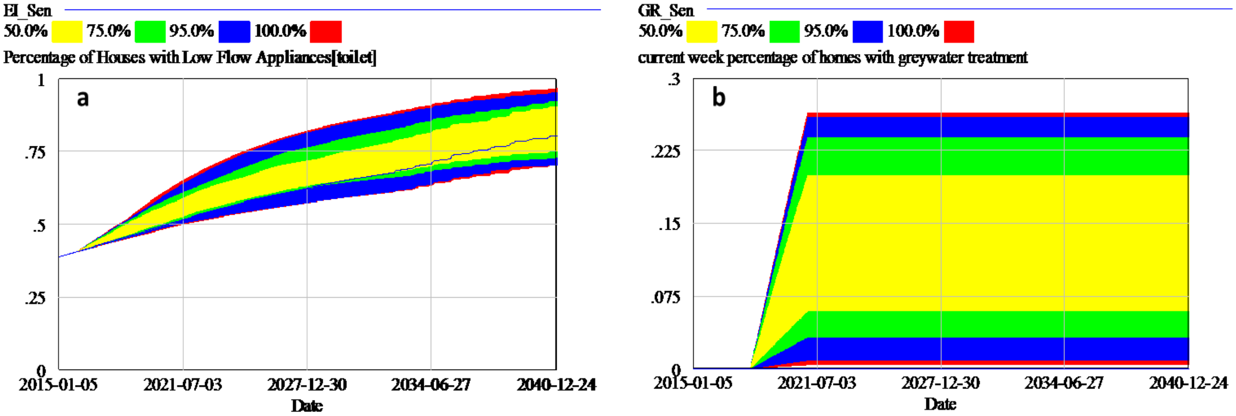


Figure 4-14: Household adoptions of low-flow toilet (a) and greywater reuse (b)

Figure 4-15 shows the effects of these conservation options, and reveals that residential indoor water use is more sensitive to greywater treatment and reuse than to the increased adoption of low-flow appliances with economic incentive programs. The reasons for greater sensitivity to greywater reuse policies include, (1) the focus of economic incentive programs, which usually increase the prevalence of low-flow toilets and high-efficiency washers – the focus of most rebate programs in North America (City of Guelph, 2016) – while treated greywater can be used for a variety of indoor and outdoor purposes, (2) the greater water volume conserved by greywater reuse (U.S. EPA, 2012; Alberta WaterSmart, 2011), and (3) the effect of rebate levels on low-flow appliance adoption, as well as the already significant prevalence of these fixtures, which is currently close to the maximum adoption rate in many cases (DeOreo et al., 2016; Rogers, 1995).

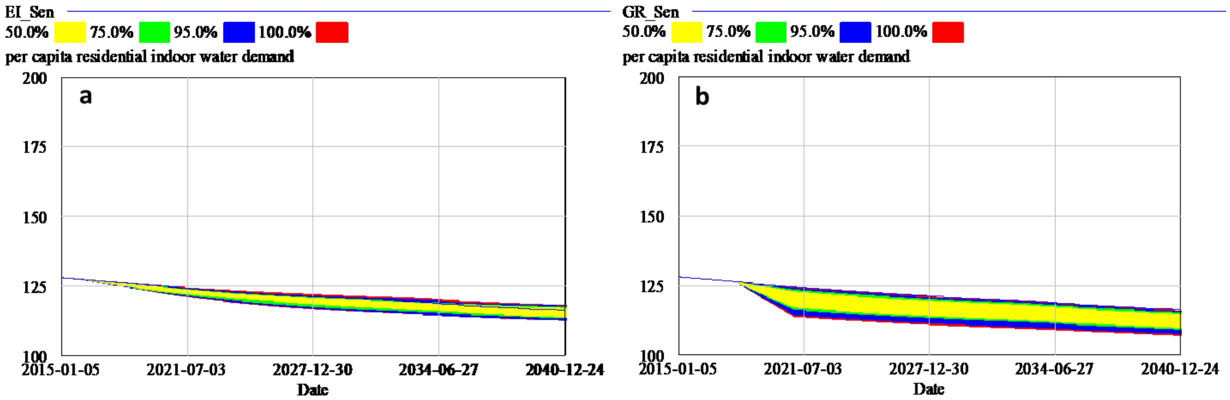


Figure 4-15: Sensitivity analysis for per capita residential indoor water demand to prevalence of low-flow toilets (a) and greywater treatment and reuse (b)

Finally, model behaviour was validated through reproduction of historical trends. At an annual scale, simulated per capita daily water demand, total municipal water demand and total surface water withdrawal from 1996 to 2014 are shown below in comparison with the available data from the City of Calgary. These Figures averaged the model-generated results from a weekly time step into annual values, which were then compared against available data from Calgary. Specifically, per capita daily municipal demands from 1996 to 2010 were provided by Headwater Communications (2007) and City of Calgary (2011), and are shown with model simulated results in Figure 4-16a. Further, total municipal demands (1996-2006) and surface water withdrawals (2003-2014b) from Headwater Communications (2007) and

City of Calgary (2013d and 2014) are shown with corresponding model results in Figure 4-16b in black (total municipal water demand) and grey (water withdrawal) respectively.

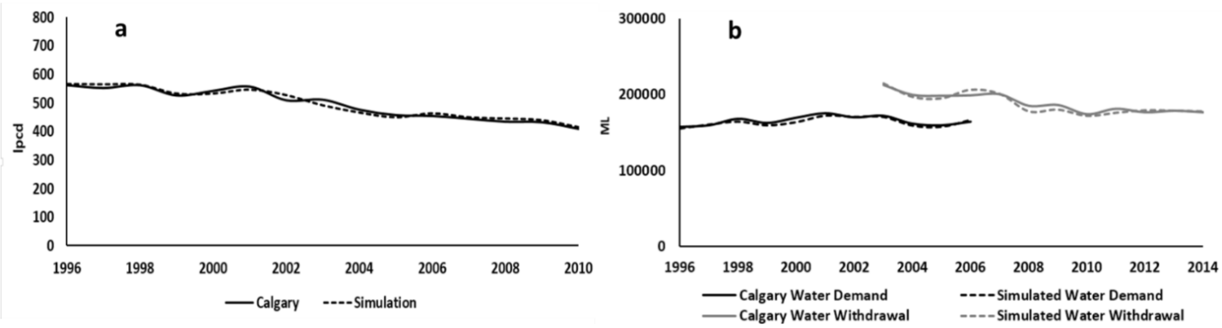


Figure 4-16: Comparison of observed and simulated daily per capita water demands (a) and total municipal demand and withdrawal (b)

Chapter 5 Conclusions

Water scarcity is an increasing concern in many regions of the world, and is becoming an important issue for many water authorities due to population growth, economic development, and uncertain climate change impacts. One option to address this issue is to implement integrated water resources management (IWRM) to help in achieving water security for all water use sectors in the long-term. This research adopts an integrated, systems approach for water resources management and modelling of major water use sectors, differing regional modelling scales, fictitious and real river basins, as well as annual and weekly modelling time steps to quantify and promote greater understanding of IWRM principles at the river basin scale. The three research goals were achieved, with explanations as follows.

In terms of the first research goal of providing water management decision-support tools, Chapters 2, 3, and 4 introduced three simulation models (the IDT Model, BRIM, and CWMM) as decision support tools for water resources management in an IWRM context. These models can be used to reveal the broad impacts of drought and water scarcity on farmers, municipalities, industries, and the environment, and to assess the effectiveness of available water, land, financial, and technological policies, especially their trade-offs in social, economic, and environmental contexts.

The second research goal of improving the understanding of complex water resources system was achieved through the modelling processes as well as the models' outputs, which helped to improve the understanding of the system's dynamic mechanisms, especially in considering ecosystem sustainability, economic efficiency, and social equity under water scarcity conditions. However, these considerations are more difficult to address than representation of the water balance, because they need water to be treated not only as a physical resource but also as a socio-economic good. To demonstrate the socio-economic values of water explicitly, including the impacts of water shortages and the effectiveness of management policies, the author faced the following difficulties: (1) human actions are not uniform under water stress conditions such as indoor and outdoor municipal water use pattern changes, agricultural irrigation schedule development, and crop choices; (2) the economic value of water is hard to estimate for the industrial sector since water is used in many different production processes which require vastly different quantities of water, even for different plants in the same industry, and the available water use data are limited; (3) management policy costs and effectiveness are difficult to evaluate since more than one policy is usually applied simultaneously, and both costs and efficacy vary across regions and over time; and (4) environmental demands vary both spatially (within different river sections) and temporally (in different seasons), and are affected by both water quantity and quality. Although the IDT Model, BRIM, and CWMM adopt relatively simple processes to evaluate policy costs and environmental water requirements, they still provide a comprehensive view of the basin condition to support the IWRM and can be a benefit to other similar research.

Finally, in terms of the third research goal, which aims to promote stakeholder engagement and education, the three models introduced in this research were developed as decision-support and educational tools for water resources management. Model outputs can improve the understanding of other stakeholder’s conditions, provide a big-picture view of basin-scale water sustainability, and promote stakeholder engagement and consensus building. Specifically, the IDT Model was used to support the Invitational Drought Tournament, which includes stakeholders, water managers, and planners, for proactive drought management, and to investigate group decision-making under uncertainty. The BRIM and CWMM have been used to support water management gaming in several events on the University of Alberta campus. Their aims are to promote public participation and water conservation, and to improve the understanding of water systems and the IWRM concept.

5.1 Recommendations

To apply IWRM at the river-basin scale, (1) multi-disciplinary studies are required such as research on soil water balance and crop yield, household water end-uses, and power plant cooling system water usage to evaluate the water values for all users in the basin; (2) an integrated index is useful to provide comprehensive and clear basin water conditions and aid decision making and policy development; (3) climate change, population and economic growth, and management policy adoptions are the main uncertainties that should be considered in scenario analysis to generate reasonable ranges of future water demand for infrastructure expansion, system optimization, and capital investment; (4) monthly or weekly time steps are appropriate to reveal the seasonal water use patterns of sectors such as irrigation and municipal uses to support short-term and operational water management such as water rationing and education; (5) management policy application costs should be considered and compared with water conservation to provide a reliable analysis on trade-offs for decision makers; (6) duration of policy impacts should be considered in long-term policy analysis to provide reasonable water conservation and demand projections – for example, educational impacts on water conservation efforts are relatively short compared with the longer-term effects of new conservation technologies; (7) water conservation technologies such as grey water treatment and reuse are critical for water scarcity management in the future and thus should be the focus of researchers, stakeholders, and policy makers; (8) water rationing is not recommended to water managers except in urgent water shortage conditions and applied with other conservation policies such as education to avoid high unmet demands; (9) management of water hazards such as drought should move from a reactive, crisis-management approach to a proactive, risk management approach to reduce economic losses and water conflicts as early as possible; and (10) simulation gaming is a useful approach for bringing stakeholders from different jurisdictions together to promote the practise of IWRM and gain management experience for institutional adaptation.

5.2 Next steps

Future research should add more detail to the water supply sector, such as stream flow simulation and reservoir management, to integrate the whole water system (i.e. from source to sink) and provide broader-based results to support IWRM. In addition, more variables such as water price and price elasticity should be considered to generate a more reasonable analysis of water management policies such as payback times to support decision-making and policy development. The agricultural model in BRIM could be modified with a weekly or seasonal time step to interact with the weekly municipal model, CWMM, and provide the basin sale seasonal water demand patterns. Disaggregation of industrial, commercial and institutional (ICI) water end-use would also aid investigation of alternative industrial and commercial development pathways, as well as sector-specific policies. If data are available, water quality, such as total nitrogen and total dissolved solids which are affected by runoff and return flows from agricultural, municipal, and industrial sectors, could be simulated to provide more useful results for the environmental water sector, especially during high water demand seasons; while daily or even hourly time-steps could be simulated as well. Finally, the models discussed in this research could also be used as simulation-gaming decision support tools for IWRM with focuses on water scarcity management.

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Appendix A. Invitational Drought Tournament (IDT) Model Code

IDT Model structures are provided to show how the variables are connected, and model code required to reproduce the model is provided below. Model inputs are shown in green, policies are shown in red, variables to eliminate in the game are shown in orange, and shadow variables (duplicates of existing variables used for clarity) are shown in grey.

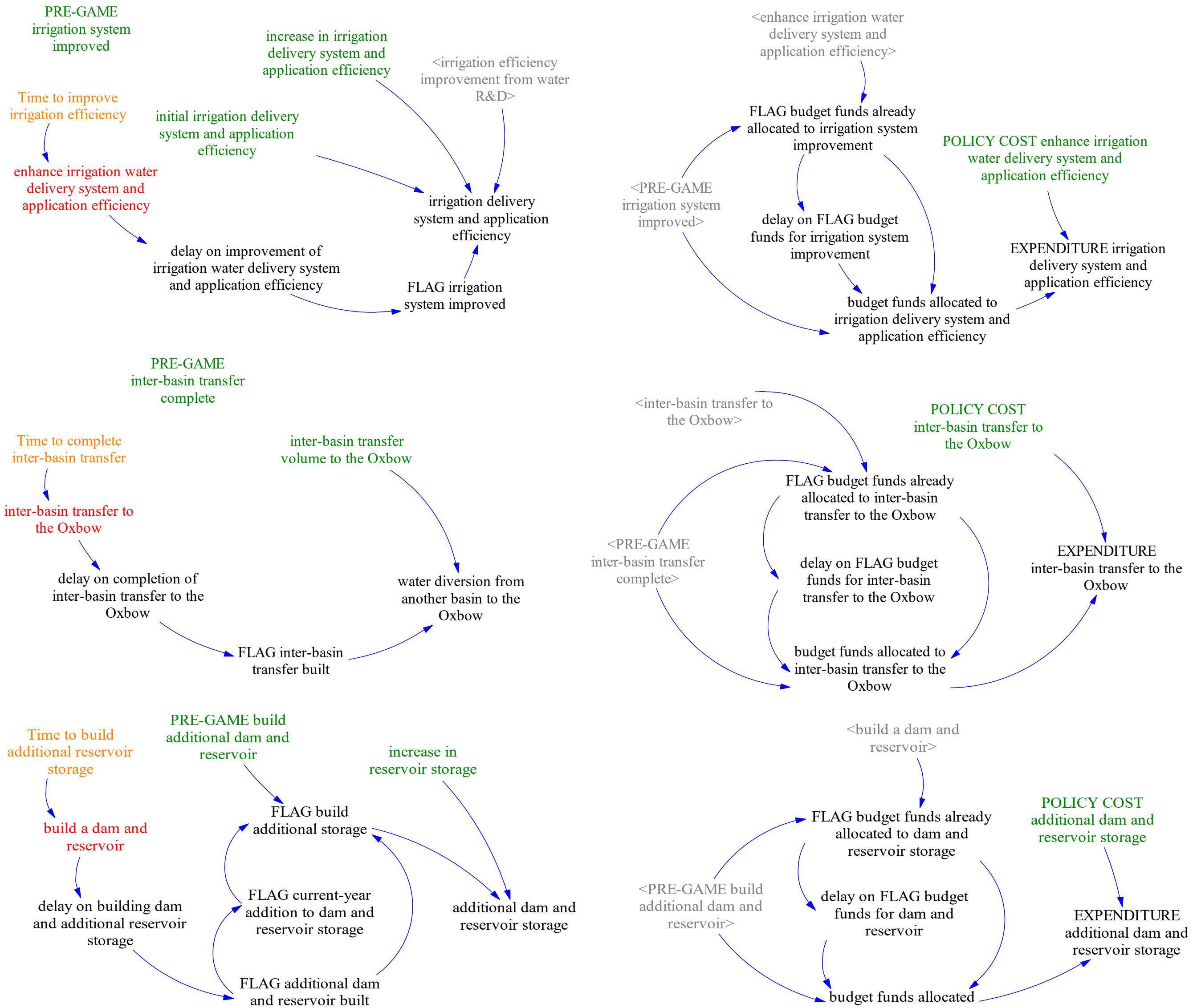

Figure A-1: Management policy simulation

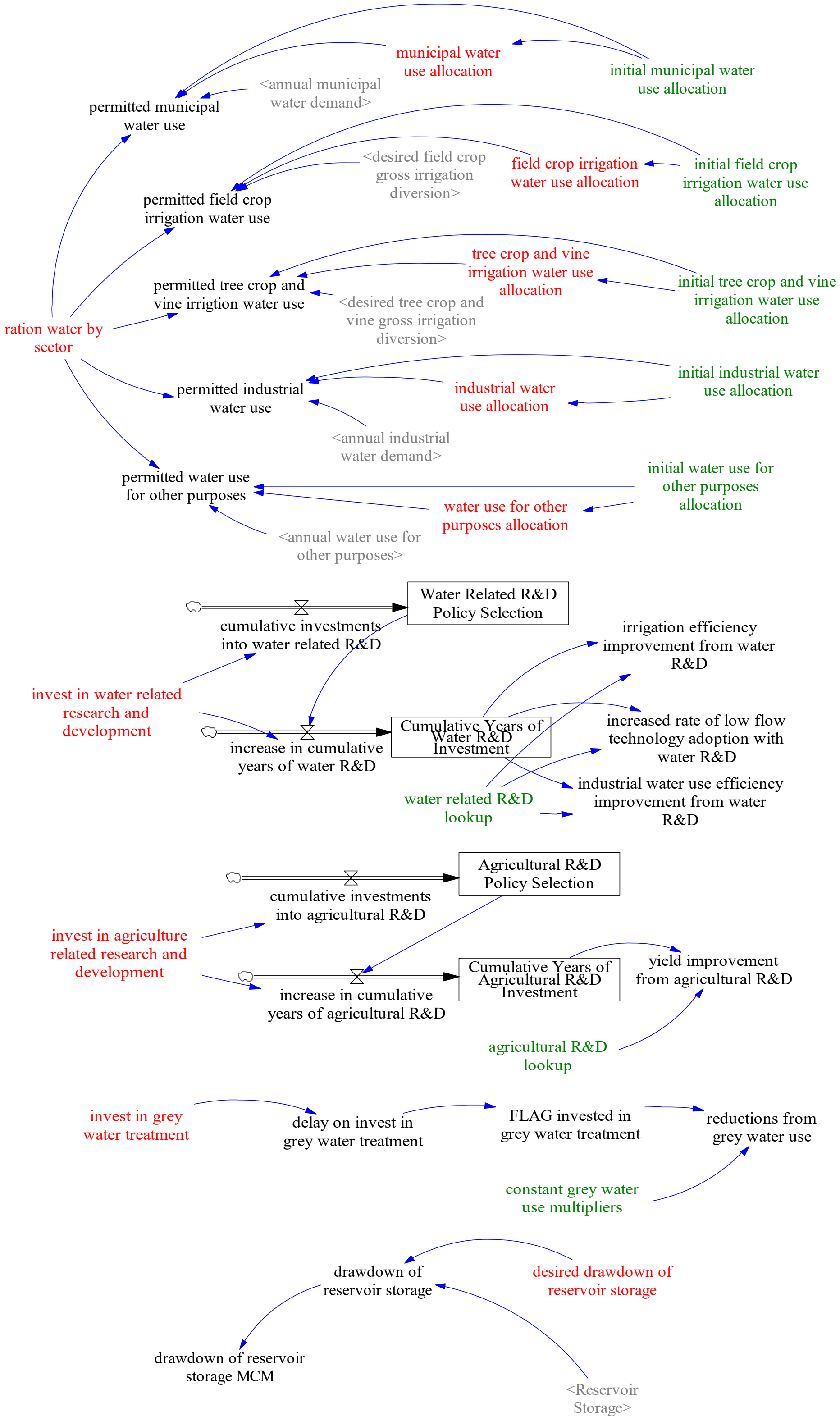

Figure A-2: Management policy simulation (continued)

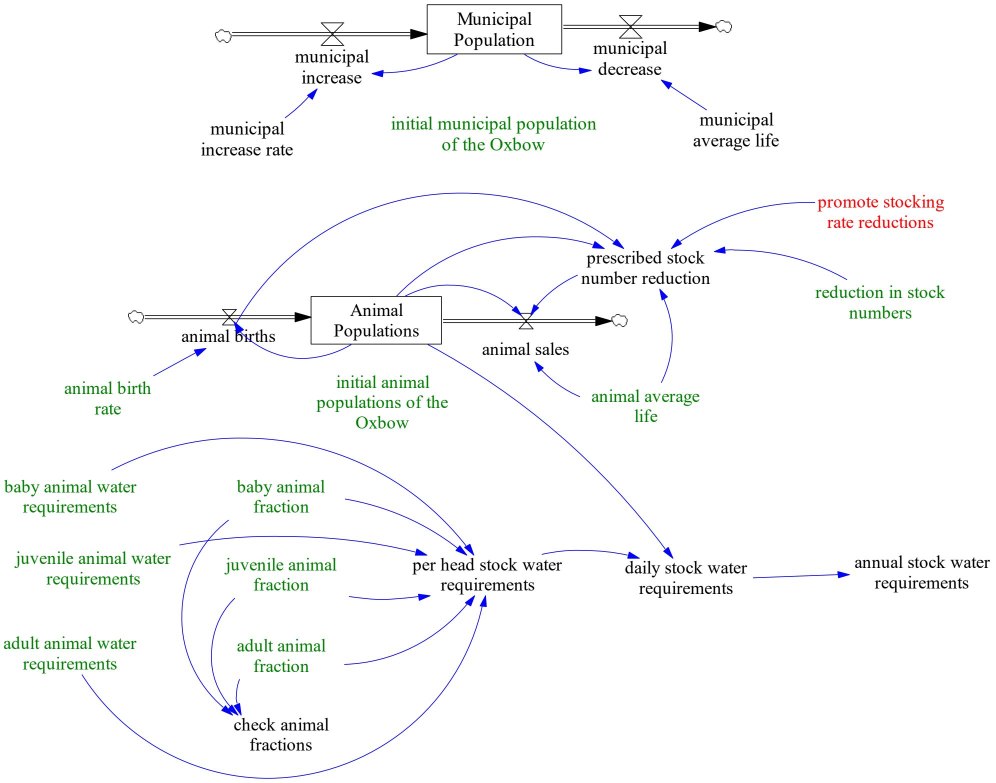

Figure A-3: Municipal and livestock population simulation

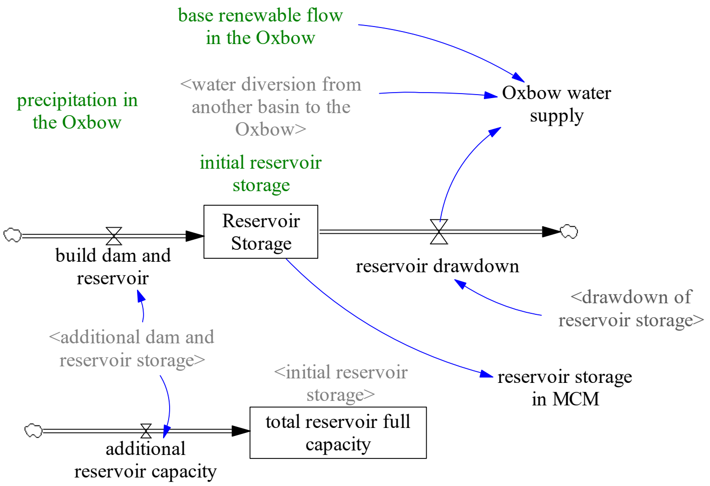

Figure A-4: Water supply simulation

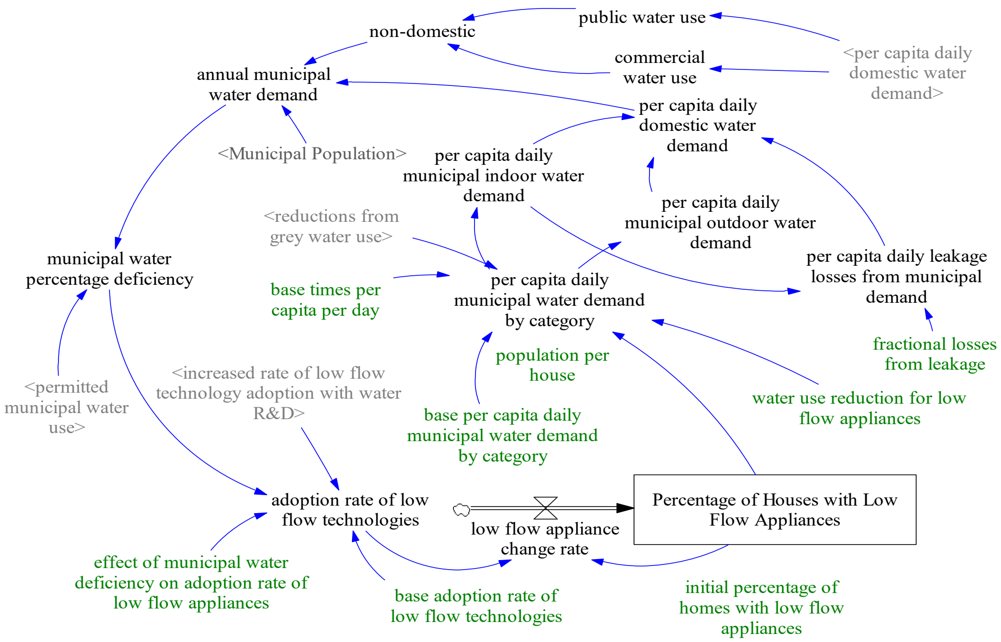

Figure A-5: Municipal sector simulation

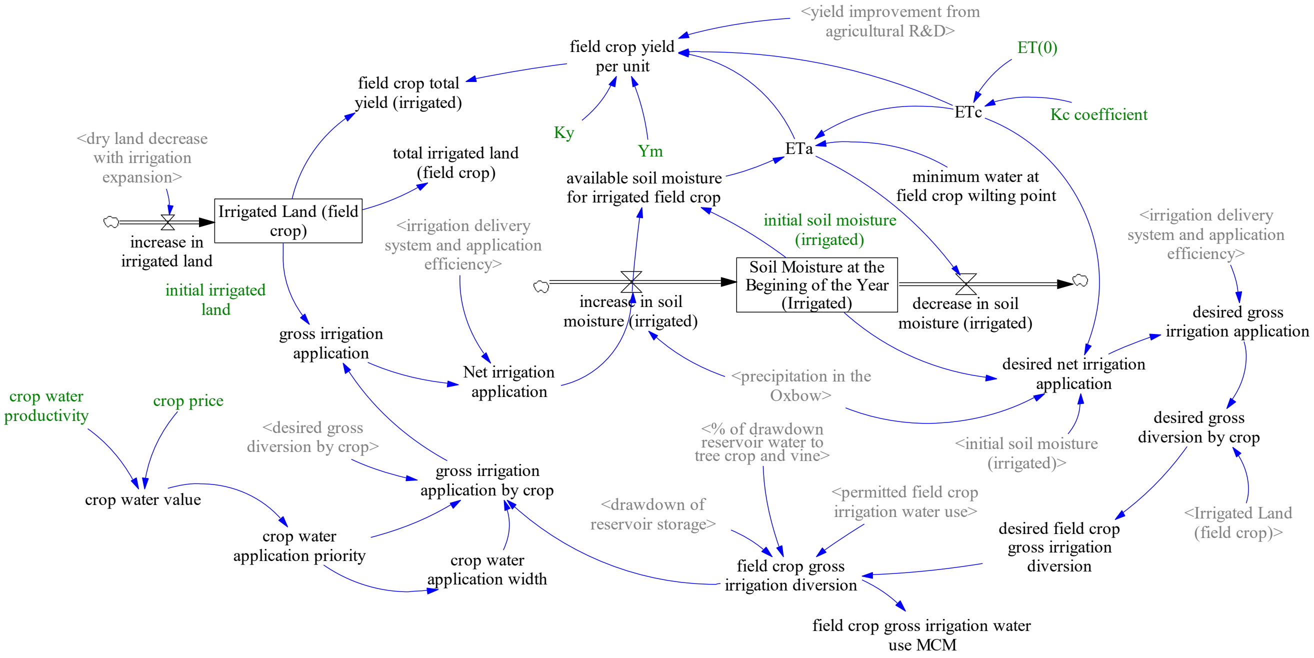

Figure A-6: Agricultural sector (irrigated land) simulation

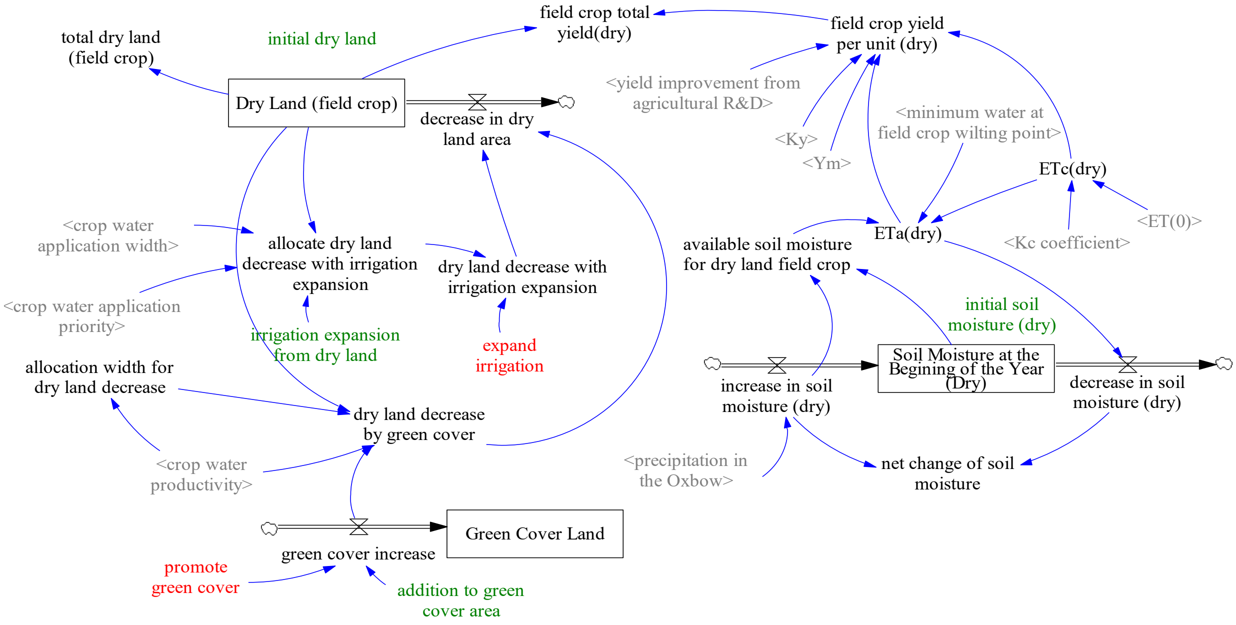

Figure A-7: Agricultural sector (dry land) simulation

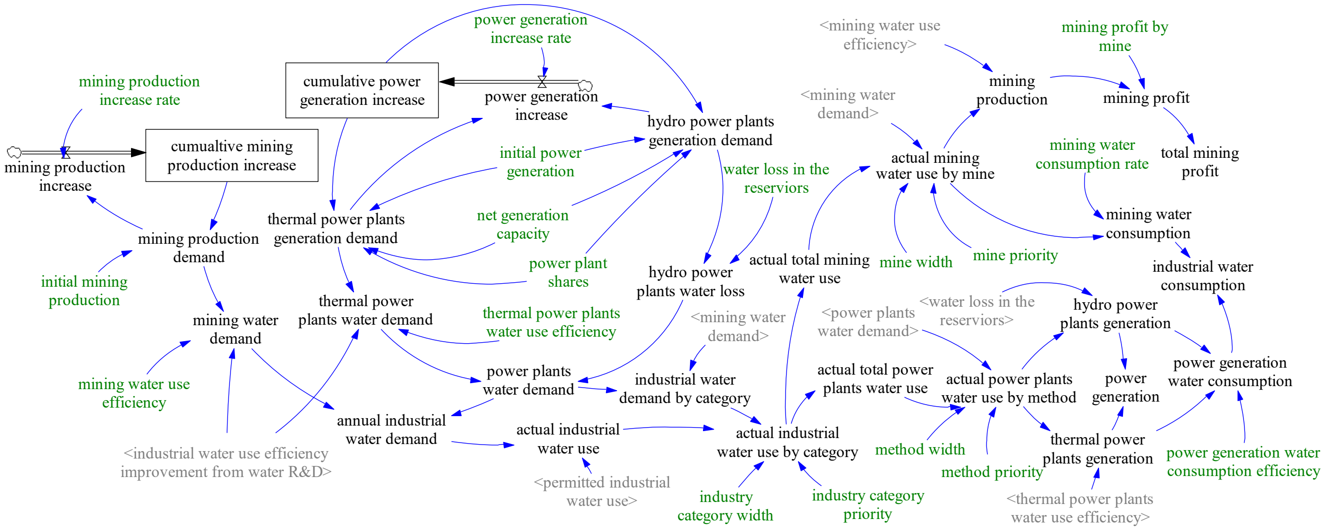

Figure A-8: Industrial sector simulation

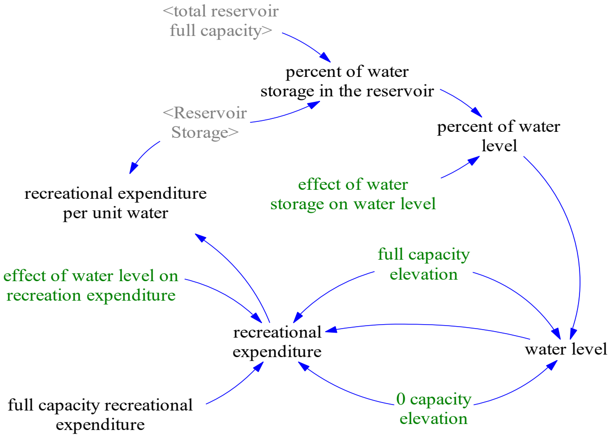

Figure A-9: Recreational sector simulation

"% of drawdown reservoir water to tree crop and vine"=GET XLS CONSTANTS ('?IDT Model input', 'Agriculture', 'B98')

"% of industrial demand been satisfied"=MIN(industrial water use MCM/industrial water demand MCM,1), {Dmnl}

"% of irrigation demand been satisfied"=IF THEN ELSE(irrigation water demand MCM, irrigation water use MCM/irrigation water demand MCM,1), {Dmnl}

"% of municipal demand been satisfied"=MIN(municipal water use MCM/municipal water demand MCM,1), {Dmnl}

"% of other purpose demand been satisfied"=MIN(water use for other purposes MCM/other purpose water demand MCM,1), {Dmnl}

"% of total demand been satisfied"=total Oxbow Basin water use/total Oxbow Basin water demand, {Dmnl}

"0 capacity elevation"=GET XLS CONSTANTS('?IDT Model input.', 'Recreation', 'F2'), {m}

"agricultural R&D lookup"(GET XLS LOOKUPS('?IDT Model input','Dynamic' , '28' , 'B29')), {Dmnl}

"Agricultural R&D Policy Selection"= INTEG ("cumulative investments into agricultural R&D",0), {Dmnl}

"budget funds allocated to inter-basin transfer to the Oxbow"=IF THEN ELSE("PRE-GAME inter-basin transfer complete"=0,"FLAG budget funds already allocated to inter-basin transfer to the Oxbow"-"delay on FLAG budget funds for inter-basin transfer to the Oxbow",0), {Dmnl}

"cumulative investments into agricultural R&D"=invest in agriculture related research and development, {Dmnl}

"cumulative investments into water related R&D"=invest in water related research and development, {Dmnl}

"Cumulative Years of Agricultural R&D Investment"=INTEG ("increase in cumulative years of agricultural R&D",0), {year}

"Cumulative Years of Water R&D Investment"=INTEG ("increase in cumulative years of water R&D", 0), {year}

"decrease in soil moisture (bearing area)"[fruit tree]=tree crop and vine ETa[fruit tree], {mm}

"decrease in soil moisture (dry)"[crop]="ETa(dry)"[crop], {mm}

"decrease in soil moisture (irrigated)"[crop]=ETa[crop], {mm}

"delay on completion of inter-basin transfer to the Oxbow"= DELAY FIXED ("inter-basin transfer to the Oxbow",10,"PRE-GAME inter-basin transfer complete"), {m*m*m}

"delay on FLAG budget funds for inter-basin transfer to the Oxbow"=DELAY FIXED("FLAG budget funds already allocated to inter-basin transfer to the Oxbow", 1, "PRE-GAME inter-basin transfer complete")

"desired gross diversion for non-bearing area by tree crop"[fruit tree]=(desired gross irrigation application for non-bearing area[fruit tree]/1000)*(non-bearing area[fruit tree]*10000), {m*m*m/year}

"Dry Land (field crop)"[crop]= INTEG (decrease in dry land area[crop], initial dry land[crop]), {ha}

"ET(0)"[crop]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B4'), {mm}

"ETa(dry)"[crop]=IF THEN ELSE(available soil moisture for dry land field crop[crop]-"ETc(dry)"[crop]>=minimum water at field crop wilting point [crop],"ETc(dry)"[crop],available soil moisture for dry land field crop[crop]-minimum water at field crop wilting point[crop]), {mm}

"ETc(dry)"[crop]="ET(0)"[crop]*Kc coefficient[crop], {mm}

"EXPENDITURE inter-basin transfer to the Oxbow"="POLICY COST inter-basin transfer to the Oxbow"*"budget funds allocated to inter-basin transfer to the Oxbow", {$}

"EXPENDITURE large-scale water management policy"=EXPENDITURE additional dam and reservoir storage+"EXPENDITURE inter-basin transfer to the Oxbow"+EXPENDITURE irrigation delivery system and application efficiency, {$}

"EXPENDITURE short-term water management policies"=EXPENDITURE drawdown of reservoir storage+ EXPENDITURE ration water, {$}

"field crop total yield (irrigated)"[crop]=field crop yield per unit[crop]*"Irrigated Land (field crop)"[crop], { mg}

"field crop total yield(dry)"[crop]="Dry Land (field crop)"[crop]*"field crop yield per unit (dry)"[crop], {mg}

"field crop yield per unit (dry)"[crop]=((1-Ky[crop]+Ky[crop]*("ETa(dry)"[crop]/"ETc(dry)"[crop]))*Ym[crop])*(1+"yield improvement from agricultural R&D"), {mg/ha}

"FLAG budget funds already allocated to inter-basin transfer to the Oxbow"=SAMPLE IF TRUE("PRE-GAME inter-basin transfer complete"=1 :OR: "inter-basin transfer to the Oxbow"=1, 1, "PRE-GAME inter-basin transfer complete"), {Dmnl}

"FLAG current-year addition to dam and reservoir storage"= DELAY FIXED (FLAG additional dam and reservoir built, 1, FLAG additional dam and reservoir built)

"FLAG inter-basin transfer built"=SAMPLE IF TRUE("delay on completion of inter-basin transfer to the Oxbow"=1, 1, "PRE-GAME inter-basin transfer complete"), {Dmnl} "gross irrigation application by non-bearing tree crop"[fruit tree]=ALLOCATE BY PRIORITY("desired gross diversion for non-bearing area by tree crop"[fruit tree] ,"non-bearing tree crop and vine water application priority"[fruit tree], ELMCOUNT(fruit tree), "non-bearing tree crop and vine water application width", "gross irrigation application for non-bearing area"), {m*m*m/year}

"gross irrigation application for non-bearing area"=gross irrigation application by area[non-bearing], {m*m*m/year}

"increase in cumulative years of agricultural R&D"=invest in agriculture related research and development + "Agricultural R&D Policy Selection" - MODULO("Agricultural R&D Policy Selection",1), {year/year}

"increase in cumulative years of water R&D"=invest in water related research and development + "Water Related R&D Policy Selection" - MODULO("Water Related R&D Policy Selection",1), {year/year}

"increase in soil moisture (bearing area)"[fruit tree]=net irrigation application for bearing area[fruit tree]+precipitation in the Oxbow, {mm}

"increase in soil moisture (dry)"[crop]=precipitation in the Oxbow, {mm}

"increase in soil moisture (irrigated)"[crop]= Net irrigation application[crop]+precipitation in the Oxbow, {mm}

"increased rate of low flow technology adoption with water R&D"="water related R&D lookup"("Cumulative Years of Water R&D Investment"), {Dmnl}

"industrial water use efficiency improvement from water R&D"="water related R&D lookup"("Cumulative Years of Water R&D Investment"), {Dmnl}

"initial soil moisture (bearing area)"[fruit tree]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B82'), { mm}

"initial soil moisture (dry)"[crop]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B18'), {mm}

"initial soil moisture (irrigated)"[crop]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B13'), {mm}

"inter-basin transfer to the Oxbow"= GAME ("Time to complete inter-basin transfer"), {Dmnl}

"inter-basin transfer volume to the Oxbow"=GET XLS CONSTANTS('?IDT Model input', 'Policy', 'B9'), {m*m*m}

"Irrigated Land (field crop)"[crop]=INTEG (increase in irrigated land[crop], initial irrigated land[crop]), {ha}

"irrigation efficiency improvement from water R&D"="water related R&D lookup"("Cumulative Years of Water R&D Investment")/2, {Dmnl}

"net irrigation application for non-bearing area"[fruit tree]=IF THEN ELSE(non-bearing area[fruit tree],"gross irrigation application by non-bearing tree crop"[fruit tree]/(non-bearing area[fruit tree]*10),0), {mm}

"non-bearing tree crop and vine water application priority"[fruit tree]=non-bearing area minimum water demand[fruit tree]/1000, {Dmnl}

"non-bearing tree crop and vine water application width"=VMAX("non-bearing tree crop and vine water application priority"[fruit tree!]),{Dmnl} "non-bearing tree remove"[fruit tree]=non-bearing area[fruit tree]*drought effect on non-bearing area[fruit tree], {ha/year}

"non-domestic"=commercial water use+public water use, {liters/day}

"POLICY COST inter-basin transfer to the Oxbow"=GET XLS CONSTANTS('?IDT Model input','Economics', 'B7'), {$}

"PRE-GAME build additional dam and reservoir"=GET XLS CONSTANTS('?IDT Model input', 'Policy', 'B5'), {Dmnl}

"PRE-GAME inter-basin transfer complete"=GET XLS CONSTANTS('?IDT Model input', 'Policy', 'B4')

"PRE-GAME irrigation system improved"=GET XLS CONSTANTS('?IDT Model input', 'Policy', 'B3')

"Soil Moisture at the Beginning of the Year (bearing area)"[fruit tree]= INTEG ("increase in soil moisture (bearing area)"[fruit tree]-"decrease in soil moisture (bearing area)"[fruit tree], "initial soil moisture (bearing area)"[fruit tree]), {mm}

"Soil Moisture at the Beginning of the Year (Dry)"[crop]= INTEG ("increase in soil moisture (dry)"[crop]-"decrease in soil moisture (dry)"[crop], "initial soil moisture (dry)"[crop]), {mm}

"Soil Moisture at the Beginning of the Year (Irrigated)"[crop]= INTEG ("increase in soil moisture (irrigated)"[crop]-"decrease in soil moisture (irrigated)"[crop], "initial soil moisture (irrigated)"[crop]), {mm}

"Time to complete inter-basin transfer"=0, {Dmnl}

"total dry land (field crop)"=SUM("Dry Land (field crop)"[crop!]), {ha}

"total irrigated land (field crop)"=SUM("Irrigated Land (field crop)"[crop!]), {ha}

"total irrigated land (tree crop and vine)"=total bare area + total bearing area + total non-bearing area, {ha}

"tree crop and vine ET(0)"[fruit tree]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B89'), {mm}

"water related R&D lookup"(GET XLS LOOKUPS('?IDT Model input', 'Dynamic' , '25' , 'B26')), {Dmnl}

"Water Related R&D Policy Selection"= INTEG ("cumulative investments into water related R&D", 0), {Dmnl}

"yield improvement from agricultural R&D"="agricultural R&D lookup"("Cumulative Years of Agricultural R&D Investment")

actual industrial water use by category[industry water]=ALLOCATE BY PRIORITY(industrial water demand by category[industry water] , industry category priority[industry water], ELMCOUNT(industry water) , industry category width , actual industrial water use), {m3}

actual industrial water use=MIN(annual industrial water demand, permitted industrial water use), {m3}

actual mining water use by mine[mine]=ALLOCATE BY PRIORITY(mining water demand[mine], mine priority[mine] , ELMCOUNT(mine), mine width , actual total mining water use), {m3} actual power plants water use by method[electricity]=ALLOCATE BY PRIORITY(power plants water demand[electricity], method priority[electricity] , ELMCOUNT(electricity) , method width , actual total power plants water use), {m3}

actual total mining water use=actual industrial water use by category[mining water], {m3}

actual total power plants water use=actual industrial water use by category[power water], {m3}

addition to green cover area=GET XLS CONSTANTS('?IDT Model input', 'Policy', 'B24')

additional dam and reservoir storage=FLAG build additional storage*increase in reservoir storage, {m*m*m}

additional reservoir capacity=additional dam and reservoir storage, {m*m*m/year}

adoption rate of low flow technologies[use]=base adoption rate of low flow technologies[use]+effect of municipal water deficiency on adoption rate of low flow appliances[use](municipal water percentage deficiency) + "increased rate of low flow technology adoption with water R&D", {Dmnl}

adult animal annual grain ration[animals]=GET XLS CONSTANTS('?IDT Model input', 'Population', 'B17'), {tonnes/year}

adult animal annual total roughage[animals]=GET XLS CONSTANTS('?IDT Model input', 'Population', 'B18'), {tonnes/year}

adult animal fraction[animals]=GET XLS CONSTANTS('?IDT Model input', 'Population', 'B19'), {Dmnl}

adult animal water requirements[animals]=GET XLS CONSTANTS('?IDT Model input', 'Population', 'B16'), {L/day}

allocate dry land decrease with irrigation expansion[crop]=ALLOCATE BY PRIORITY("Dry Land (field crop)"[crop] ,crop water application priority[crop] , ELMCOUNT(crop) , crop water application width, irrigation expansion from dry land), {ha}

allocation width for dry land decrease =VMAX(crop water productivity[crop!])

animal average life[animals]=GET XLS CONSTANTS('?IDT Model input', 'Population', 'B7'), {animals/year}

animal birth rate[animals]=GET XLS CONSTANTS('?IDT Model input', 'Population', 'B6'), {animals/year}

animal births[animals]=animal birth rate[animals]*Animal Populations[animals], {animals/year}

Animal Populations[animals]= INTEG (animal births[animals]-animal sales[animals], initial animal populations of the Oxbow[animals]), {animals}

animal sales[animals]=Animal Populations[animals]/animal average life[animals] + prescribed stock number reduction[animals], {animals/year}

animals:GET XLS SUBSCRIPT('?IDT Model input', 'Population', 'B5', 'E5', '')

annual industrial water demand=SUM(mining water demand[mine!])+SUM(power plants water demand[electricity!]), {m*m*m/year}

annual municipal water demand by category[use]=(per capita daily municipal water demand by category[use]/(1-fractional losses from leakage))*Municipal Population*365/1000, {m*m*m/year}

annual municipal water demand=(per capita daily domestic water demand+"non-domestic")*Municipal Population*365/1000, {m*m*m/year} annual municipal water use by category[use]=ALLOCATE BY PRIORITY(annual municipal water demand by category[use], municipal water use priority[use], ELMCOUNT(use), municipal water use width, permitted municipal water use), {m*m*m/year}

annual stock grain ration=SUM(per head stock annual grain ration[animals!]*Animal Populations [animals!]), {tonnes/year}

annual stock roughage requirements=SUM(per head stock annual total roughage[animals!]*Animal Populations[animals!]), {tonnes/year}

annual stock water requirements=SUM(daily stock water requirements[animals!])*365, {m*m*m}

annual water use for other purposes=GET XLS CONSTANTS('?IDT Model input.', 'Environment', 'B2'), {m*m*m/year}

area priority[tree crop area]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B97'), {Dmnl}

area width=VMAX(area priority[tree crop area!]), {Dmnl}

available soil moisture for dry land field crop[crop]="increase in soil moisture (dry)"[crop]+"Soil Moisture at the Beginning of the Year (Dry)"[crop]

available soil moisture for irrigated field crop[crop]="increase in soil moisture (irrigated)"[crop]+"Soil Moisture at the Beginning of the Year (Irrigated)"[crop], {mm}

available soil moisture for the tree crop and vine[fruit tree]="increase in soil moisture (bearing area)"[fruit tree]+"Soil Moisture at the Beginning of the Year (bearing area)"[fruit tree], {mm}

baby animal annual grain ration[animals]=GET XLS CONSTANTS('?IDT Model input', 'Population', 'B9'), {tonnes/year}

baby animal annual total roughage[animals]=GET XLS CONSTANTS('?IDT Model input', 'Population', 'B10'), {tonnes/year}

baby animal fraction[animals]=GET XLS CONSTANTS('?IDT Model input', 'Population', 'B11'), {Dmnl}

baby animal water requirements[animals]=GET XLS CONSTANTS('?IDT Model input', 'Population', 'B8'), {L/day}

bare area[fruit tree]= INTEG (bearing tree remove[fruit tree]+"non-bearing tree remove"[fruit tree]-replant[fruit tree], initial bare area[fruit tree]), {ha}

base adoption rate of low flow technologies[use]=GET XLS CONSTANTS('?IDT Model input', 'Municipal', 'B7'), {Dmnl}

base per capita daily municipal water demand by category[use]=GET XLS CONSTANTS('?IDT Model input', 'Municipal', 'B3'), {liters/(person*day)}

base renewable flow in the Oxbow:INTERPOLATE::=GET XLS DATA('?IDT Model input', 'Dynamic', '5', 'B6'), {m*m*m/year}

base times per capita per day[use]=GET XLS CONSTANTS('?IDT Model input', 'Municipal', 'B4'), {fraction}

bearing area minimum water demand[fruit tree]=minimum water at tree crop wilting point[fruit tree], {mm} bearing area[fruit tree]= INTEG (mature[fruit tree]-bearing tree remove[fruit tree], initial bearing area[fruit tree]), {ha}

bearing tree crop and vine water application priority[fruit tree]=bearing tree crop and vine water value[fruit tree], dimensionless

bearing tree crop and vine water application width=VMAX(bearing tree crop and vine water application priority[fruit tree!])

bearing tree crop and vine water value[fruit tree]=tree crop and vine water productivity[fruit tree]*tree fruit and vine price[fruit tree], {dollars/(m*m*m)}

bearing tree remove[fruit tree]=bearing area[fruit tree]*mortality rate[fruit tree]+bearing area[fruit tree]*drought effect on bearing area[fruit tree], {ha/year}

budget funds allocated to dam and reservoir=IF THEN ELSE("PRE-GAME build additional dam and reservoir"=0,FLAG budget funds already allocated to dam and reservoir storage -delay on FLAG budget funds for dam and reservoir,0), { Dmnl}

budget funds allocated to irrigation delivery system and application efficiency=IF THEN ELSE("PRE-GAME irrigation system improved"=0, FLAG budget funds already allocated to irrigation system improvement-delay on FLAG budget funds for irrigation system improvement,0), {Dmnl}

BUDGET:INTERPOLATE::=GET XLS DATA('IDT Model Configuration.xls', 'Dynamic', '10','B11'), {$}

build a dam and reservoir= GAME (Time to build additional reservoir storage), {Dmnl}

build dam and reservoir=additional dam and reservoir storage, {m*m*m/year}

capital cost on dry land[crop]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B38'), {$/ha}

capital cost on irrigated land[crop]= GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B30'), {$/ha}

check animal fractions[animals]=baby animal fraction[animals]+adult animal fraction[animals]+juvenile animal fraction[animals], {Dmnl}

chemicals cost on dry land[crop]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B33'), {$/ha}

chemicals cost on irrigated land[crop]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B25'), {$/ha}

commercial water use=0.02*per capita daily domestic water demand, {liters/year}

constant grey water use multipliers[indoor]=GET XLS CONSTANTS('?IDT Model input', 'Policy', 'B39'), {Dmnl}

crop cost per land on dry land[crop]=fertilizer cost on dry land[crop]+insurance cost on dry land[crop]+chemicals cost on dry land[crop]+sowing cost on dry land[crop], {$/ha}

crop cost per land on irrigated land[crop]=chemicals cost on irrigated land[crop]+fertilizer cost on irrigated land[crop]+insurance on irrigated land[crop]+sowing cost on irrigated land[crop], {$/ha}

crop price[crop]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B9'), {$/kg}

crop water application priority[crop]=crop water value[crop]

crop water application width=VMAX(crop water application priority[crop!])

crop water productivity[crop]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B8'), {g/(m*m*m)}

crop water value[crop]=crop price[crop]*crop water productivity[crop], {dollars/(m*m*m)}

crop: GET XLS SUBSCRIPT('?IDT Model input', 'Agriculture', 'B2', 'F2', '')

cumulative mining production increase[mine]= INTEG (mining production increase[mine],0), {ton}

cumulative power generation increase= INTEG (power generation increase, 0), {kwh}

daily stock water requirements[animals]=per head stock water requirements[animals]/1000*Animal Populations[animals], {m*m*m/day}

decrease in dry land area[crop]=dry land decrease by green cover[crop] + dry land decrease with irrigation expansion[crop], {ha}

delay on building dam and additional reservoir storage=DELAY FIXED(build a dam and reservoir, 10, "PRE-GAME build additional dam and reservoir"), {Dmnl}

delay on FLAG budget funds for dam and reservoir=DELAY FIXED(FLAG budget funds already allocated to dam and reservoir storage, 1, "PRE-GAME build additional dam and reservoir")

delay on FLAG budget funds for irrigation system improvement= DELAY FIXED (FLAG budget funds already allocated to irrigation system improvement, 1, "PRE-GAME irrigation system improved")

delay on improvement of irrigation water delivery system and application efficiency=DELAY FIXED (enhance irrigation water delivery system and application efficiency, 5, "PRE-GAME irrigation system improved"), {Dmnl}

delay on invest in grey water treatment=DELAY FIXED(invest in grey water treatment, 1, 0), {Dmnl}

depreciation cost per head[animals]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B63'), {$/head}

desired drawdown of reservoir storage= GAME (0), MCM/year

desired field crop gross irrigation diversion= SUM(desired gross diversion by crop[crop!]), {m*m*m/year}

desired gross diversion by crop[crop]=(desired gross irrigation application[crop]/1000)*("Irrigated Land (field crop)"[crop]*10000), {m*m*m/yr}

desired gross diversion by type of area[bearing]=SUM(desired gross diversion for bearing area by tree crop and vine[fruit tree!])

desired gross diversion by type of area[non-bearing]=SUM("desired gross diversion for non-bearing area by tree crop"[fruit tree!]), {m*m*m/yr}

desired gross diversion for bearing area by tree crop and vine[fruit tree]=(desired gross irrigation application for bearing area[fruit tree]/1000)*(bearing area[fruit tree]*10000), {m*m*m/year}

desired gross irrigation application for bearing area[fruit tree]=desired net irrigation application for bearing area[fruit tree]/irrigation delivery system and application efficiency, {mm}

desired gross irrigation application for non-bearing area[fruit tree]=desired net irrigation application for non-bearing area[fruit tree]/irrigation delivery system and application efficiency, {mm}

desired gross irrigation application[crop]=desired net irrigation application[crop]/irrigation delivery system and application efficiency, {mm} desired net irrigation application for bearing area[fruit tree]=MAX(0, tree crop and vine ETc[fruit tree]-precipitation in the Oxbow+("initial soil moisture (bearing area)"[fruit tree]-"Soil Moisture at the Beginning of the Year (bearing area)"[fruit tree])), {mm}

desired net irrigation application for non-bearing area[fruit tree]=MAX(0, (non-bearing area minimum water demand[fruit tree]/10)-precipitation in the Oxbow), {mm}

desired net irrigation application[crop]=MAX(0, ETc[crop]-precipitation in the Oxbow+ "initial soil moisture (irrigated)"[crop]-"Soil Moisture at the Beginning of the Year (Irrigated)"[crop]), {mm}

desired tree crop and vine gross irrigation diversion=SUM(desired gross diversion by type of area[tree crop area!]), {m*m*m/year}

drawdown of reservoir storage MCM=drawdown of reservoir storage/1e+006, {MCM}

drawdown of reservoir storage=IF THEN ELSE(desired drawdown of reservoir storage, IF THEN ELSE(Reservoir Storage > desired drawdown of reservoir storage*1e+006, desired drawdown of reservoir storage*1e+006, Reservoir Storage), 0), {m*m*m/year}

drought effect on bearing area[fruit tree]=1-MIN("increase in soil moisture (bearing area)"[fruit tree]/bearing area minimum water demand[fruit tree], 1), {Dmnl} |

drought effect on non-bearing area[fruit tree]=1-MIN(("net irrigation application for non-bearing area"[fruit tree]+precipitation in the Oxbow)/(non-bearing area minimum water demand[fruit tree]/10), 1), {Dmnl}

dry land decrease by green cover[crop]=ALLOCATE BY PRIORITY("Dry Land (field crop)"[crop], crop water productivity[crop], ELMCOUNT(crop) , allocation width for dry land decrease , green cover increase), {ha}

dry land decrease with irrigation expansion[crop]=IF THEN ELSE(expand irrigation, allocate dry land decrease with irrigation expansion[crop], 0), {ha}

effect of municipal water deficiency on adoption rate of low flow appliances[use](GET XLS LOOKUPS('?IDT Model input', 'Dynamic' , '17' , 'B18')), {Dmnl}

effect of water level on recreation expenditure=GET XLS LOOKUPS('?IDT Model input.', 'Recreation' , '5' , 'B6')

effect of water storage on water level=GET XLS LOOKUPS('?IDT Model input.', 'Recreation' , '3' , 'B4')

electricity=GET XLS SUBSCRIPT('?IDT Model input', 'Industry', 'E2', 'F2', '')

energy cost on the dry land[crop]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B37'), {$/ha}

energy cost on the irrigated land[crop]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B29'), {$/ha}

enhance irrigation water delivery system and application efficiency= GAME (Time to improve irrigation efficiency), {Dmnl}

ETa[crop]=IF THEN ELSE(available soil moisture for irrigated field crop[crop]-ETc[crop]>=minimum water at field crop wilting point[crop],ETc[crop],available soil moisture for irrigated field crop[crop]-minimum water at field crop wilting point[crop]), {mm}

ETc[crop]="ET(0)"[crop]*Kc coefficient[crop], {mm}

expand irrigation= GAME (0), {Dmnl}

EXPENDITURE additional dam and reservoir storage=POLICY COST additional dam and reservoir storage*budget funds allocated to dam and reservoir, {$}

EXPENDITURE diversification of pasture species composition=POLICY COST diversification of pasture species composition*promote diversification of pasture species composition, {$}

EXPENDITURE drawdown of reservoir storage=IF THEN ELSE(drawdown of reservoir storage, POLICY COST drawdown of reservoir storage, 0), {$}

EXPENDITURE expand irrigation=expand irrigation*POLICY COST expand irrigation, {$}

EXPENDITURE financial management policies=EXPENDITURE relief payout to farmers, {$}

EXPENDITURE invest in agriculture related research and development=invest in agriculture related research and development*POLICY COST invest in agriculture related research and development, {$}

EXPENDITURE invest in grey water treatment=invest in grey water treatment*POLICY COST invest in grey water treatment, {$}

EXPENDITURE invest in water related research and development=invest in water related research and development*POLICY COST invest in water related research and development, {$}

EXPENDITURE irrigation delivery system and application efficiency= POLICY COST enhance irrigation water delivery system and application efficiency*budget funds allocated to irrigation delivery system and application efficiency, {$}

EXPENDITURE land management policies=EXPENDITURE promote green cover+EXPENDITURE promote winter cropping+EXPENDITURE stocking rate reductions+EXPENDITURE diversification of pasture species composition, {$}

EXPENDITURE promote green cover=promote green cover*POLICY COST promote green cover, {$}

EXPENDITURE promote winter cropping=promote winter cropping*POLICY COST promote winter cropping, {$}

EXPENDITURE ration water=ration water by sector*POLICY COST ration water, {$}

EXPENDITURE relief payout to farmers=relief payout to farmers*POLICY COST relief payout to farmers, {$}

EXPENDITURE stocking rate reductions=promote stocking rate reductions*(POLICY COST stocking rate reductions[beef]*prescribed stock number reduction[beef]+POLICY COST stocking rate reductions[pigs]*prescribed stock number reduction[pigs]), {$}

EXPENDITURE technology policies=EXPENDITURE expand irrigation+EXPENDITURE invest in agriculture related research and development+EXPENDITURE invest in grey water treatment+EXPENDITURE invest in water related research and development, {$}

EXPENDITURES total expenses="EXPENDITURE large-scale water management policy"+"EXPENDITURE short-term water management policies"+EXPENDITURE financial management policies+EXPENDITURE land management policies+EXPENDITURE technology policies, {$}

fallow land=1000+Green Cover Land-Green Cover Land, {ha}

farmers cost on dry land[crop]="Dry Land (field crop)"[crop]*farmers cost per dry land[crop], {$}

farmers cost on irrigated land[crop]=farmers cost per irrigated land[crop]*"Irrigated Land (field crop)"[crop], {$}

farmers cost per dry land[crop]=crop cost per land on dry land[crop]+other cost by dry land[crop], {$}

farmers cost per irrigated land[crop]=crop cost per land on irrigated land[crop]+other cost on irrigated land[crop], {$}

farmers cost=SUM(farmers cost on dry land[crop!])+SUM(farmers cost on irrigated land[crop!])+(farmers income*levies)+SUM(total cost for livestock[animals!]), {$}

farmers income=SUM(receipt from irrigated crop[crop!])+receipt from livestock+ SUM(receipt from dry land crop[crop!]), {$}

fertilizer cost on dry land[crop]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B34'), {$/ha}

fertilizer cost on irrigated land[crop]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B26'), {$/ha}

field crop available to requirement irrigation water ratio=IF THEN ELSE(field crop gross irrigation diversion>desired field crop gross irrigation diversion:OR:desired field crop gross irrigation diversion=0, 1 , field crop gross irrigation diversion desired field crop gross irrigation diversion), {Dmnl}

Field Crop Farming Population= INTEG (0, initial field crop farming population of the Oxbow), {person}

field crop gross irrigation diversion=IF THEN ELSE(desired field crop gross irrigation diversion > permitted field crop irrigation water use, permitted field crop irrigation water use+ drawdown of reservoir storage*(1-"% of drawdown reservoir water to tree crop and vine"), desired field crop gross irrigation diversion), {m*m*m/yr}

field crop gross irrigation water use MCM=field crop gross irrigation diversion/1e+006, {MCM/year}

field crop irrigation water use allocation= GAME (initial field crop irrigation water use allocation), {MCM/year}

field crop water cost=(permitted field crop irrigation water use/1e+006)*water price*1000

field crop yield per unit[crop]=((1-Ky[crop]+Ky[crop]*(ETa[crop]/ETc[crop]))*Ym[crop])*(1+"yield improvement from agricultural R&D"), {mg/ha}

final total yield[forage]="field crop total yield (irrigated)"[forage]+"field crop total yield(dry)"[forage]

final total yield[grain]="field crop total yield (irrigated)"[grain]+"field crop total yield(dry)"[grain]

final total yield[grass]="field crop total yield (irrigated)"[grass]+"field crop total yield(dry)"[grass]*Pasture Quality

final total yield[oilseed]="field crop total yield (irrigated)"[oilseed]+"field crop total yield(dry)"[oilseed]

final total yield[vegetables]="field crop total yield (irrigated)"[vegetables]+"field crop total yield(dry)"[vegetables], {mg}

fixed cost per head[animals]=depreciation cost per head[animals]+investment cost per head[animals]

FLAG additional dam and reservoir built=SAMPLE IF TRUE(delay on building dam and additional reservoir storage=1, 1, "PRE-GAME build additional dam and reservoir"), {Dmnl}

FLAG budget funds already allocated to dam and reservoir storage=SAMPLE IF TRUE("PRE-GAME build additional dam and reservoir"=1 :OR: build a dam and reservoir=1, 1, "PRE-GAME build additional dam and reservoir"), {Dmnl}

FLAG budget funds already allocated to irrigation system improvement=SAMPLE IF TRUE("PRE-GAME irrigation system improved"=1 :OR: enhance irrigation water delivery system and application efficiency=1, 1, "PRE-GAME irrigation system improved"), {Dmnl}

FLAG build additional storage=IF THEN ELSE("PRE-GAME build additional dam and reservoir"=0 :AND: FLAG additional dam and reservoir built, 1-"FLAG current-year addition to dam and reservoir storage", 0), {Dmnl}

FLAG invested in grey water treatment=SAMPLE IF TRUE(delay on invest in grey water treatment=1, 1 , 0), {Dmnl}

FLAG irrigation system improved=SAMPLE IF TRUE(delay on improvement of irrigation water delivery system and application efficiency=1, 1, "PRE-GAME irrigation system improved"), {Dmnl}

fractional losses from leakage=GET XLS CONSTANTS('?IDT Model input', 'Municipal', 'B11'), {Dmnl}

fruit tree: apple, cherry, grape|

full capacity elevation=GET XLS CONSTANTS('?IDT Model input.', 'Recreation', 'D2'), {m}

full capacity recreational expenditure=GET XLS CONSTANTS('?IDT Model input.', 'Recreation', 'B7'), {million $}

green cover increase=IF THEN ELSE(promote green cover, addition to green cover area , 0), {ha}

Green Cover Land= INTEG (green cover increase, 0), {ha}

gross irrigation application by area[tree crop area]=ALLOCATE BY PRIORITY(desired gross diversion by type of area[tree crop area] ,area priority [tree crop area], ELMCOUNT(tree crop area), area width, tree crop and vine gross irrigation diversion), {m*m*m/year}

gross irrigation application by bearing tree crop and vine[fruit tree]=ALLOCATE BY PRIORITY(desired gross diversion for bearing area by tree crop and vine[fruit tree] ,bearing tree crop and vine water application priority[fruit tree], ELMCOUNT(fruit tree), bearing tree crop and vine water application width, gross irrigation application for bearing area), {m*m*m/year}

gross irrigation application by crop[crop]=ALLOCATE BY PRIORITY(desired gross diversion by crop[crop] ,crop water application priority[crop] , ELMCOUNT(crop) , crop water application width, field crop gross irrigation diversion), {m*m*m/year}

gross irrigation application for bearing area=gross irrigation application by area[bearing], {m*m*m/year}

gross irrigation application[crop]=(gross irrigation application by crop[crop]*1e+009)/("Irrigated Land (field crop)"[crop]*1e+010), {mm}

hydro power plants generation demand=MIN((initial power generation+ cumulative power generation increase)*power plant shares[hydro],net generation capacity[hydro]), {kwh}

hydro power plants generation=actual power plants water use by method[hydro]/water loss in the reservoirs, {kwh}

hydro power plants water loss=hydro power plants generation demand*water loss in the reservoirs, {m3} improvement=IF THEN ELSE(promote diversification of pasture species composition, 0.1*Pasture Quality, 0)

income of products[animals]=price of products[animals]*product from livestock[animals], {$}

increase in irrigated land[crop]=dry land decrease with irrigation expansion[crop], {ha}

increase in irrigation delivery system and application efficiency=GET XLS CONSTANTS('?IDT Model input', 'Policy', 'B8'), {Dmnl}

increase in reservoir storage=GET XLS CONSTANTS('?IDT Model input', 'Policy', 'B10'), {m*m*m}

indoor: GET XLS SUBSCRIPT('?IDT Model input', 'Municipal', 'B2', 'E2', '')

industrial water consumption=SUM(mining water consumption[mine!])+SUM(power generation water consumption[electricity!]), {m3}

industrial water demand by category[mining water]=SUM(mining water demand[mine!])

industrial water demand by category[power water]=SUM(power plants water demand[electricity!]), {m3}

industrial water demand MCM=annual industrial water demand/1e+006, {MCM/year}

industrial water use allocation= GAME (initial industrial water use allocation), {MCM/year}

industrial water use MCM=permitted industrial water use/1e+006, {MCM/year}

industry category priority[industry water]=GET XLS CONSTANTS('?IDT Model input', 'Industry', 'B11'), {Dmnl}

industry category width=GET XLS CONSTANTS('?IDT Model input', 'Industry', 'G11'), {Dmnl}

industry water=GET XLS SUBSCRIPT('?IDT Model input', 'Industry', 'B1', 'E1', ''), {Dmnl}

initial animal populations of the Oxbow[animals]=GET XLS CONSTANTS('?IDT Model input', 'Population', 'B4'), {animals}

initial bare area[fruit tree]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B77'), {ha}

initial bearing area[fruit tree]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B75'),{ha}

initial dry land[crop]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B19'), {ha}

initial field crop farming population of the Oxbow=GET XLS CONSTANTS('?IDT Model input', 'Population', 'B3'), {person}

initial field crop irrigation water use allocation=GET XLS CONSTANTS('?IDT Model input', 'Policy', 'B16'), {MCM/year}

initial industrial water use allocation=GET XLS CONSTANTS('?IDT Model input', 'Policy', 'B17'), {MCM/year}

initial irrigated land[crop]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B14'), {ha}

initial irrigation delivery system and application efficiency=GET XLS CONSTANTS('?IDT Model input', 'Policy', 'B7')

initial mining production[mine]=GET XLS CONSTANTS('?IDT Model input', 'Industry','B6'), {ton}

initial municipal population of the Oxbow=GET XLS CONSTANTS('?IDT Model input', 'Population', 'B2'), {person} initial municipal water use allocation=GET XLS CONSTANTS('?IDT Model input', 'Policy', 'B15'), {MCM/year}

initial non-bearing area[fruit tree]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B76'), {ha}

initial orchard farming population of the Oxbow=GET XLS CONSTANTS('?IDT Model input', 'Population', 'C3'), {person}

initial per capita daily municipal indoor water demand= INITIAL(SUM(per capita daily municipal water demand by category[indoor!])), {liters/(day*person)}

initial per capita daily municipal outdoor water demand= INITIAL(per capita daily municipal water demand by category[outdoor]), {liters/(day*person)}

initial percentage of homes with low flow appliances[use]=GET XLS CONSTANTS('?IDT Model input', 'Municipal', 'B6')

initial power generation=GET XLS CONSTANTS('?IDT Model input', 'Industry', 'G6'), {kwh}

initial reservoir storage=GET XLS CONSTANTS('?IDT Model input', 'Supply', 'B2'), {m*m*m}

initial tree crop and vine irrigation water use allocation=GET XLS CONSTANTS('?IDT Model input', 'Policy', 'B19'), {MCM/year}

initial water use for other purposes allocation=GET XLS CONSTANTS('?IDT Model input', 'Policy', 'B18'), {MCM/year}

insurance cost on dry land[crop]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B35'), {$/ha}

insurance on irrigated land[crop]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B27'), {$/ha}

invest in agriculture related research and development= GAME (0), {Dmnl}

invest in grey water treatment= GAME (0), {Dmnl}

invest in water related research and development= GAME (0), {Dmnl}

investment cost per head[animals]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B64'), {$/head}

irrigation delivery system and application efficiency for tree crop=0.92, {Dmnl}

irrigation delivery system and application efficiency= MIN(0.95, IF THEN ELSE(FLAG irrigation system improved, initial irrigation delivery system and application efficiency+ increase in irrigation delivery system and application efficiency, initial irrigation delivery system and application efficiency) + "irrigation efficiency improvement from water R&D"), {Dmnl}

irrigation expansion from dry land=GET XLS CONSTANTS('?IDT Model input', 'Policy', 'B36')

irrigation water demand MCM=(desired field crop gross irrigation diversion + desired tree crop and vine gross irrigation diversion)/1e+006, {MCM/year}

irrigation water use MCM=(permitted field crop irrigation water use + permitted tree crop and vine irrigation water use)/1e+006, {MCM/year}

juvenile animal annual grain ration[animals]=GET XLS CONSTANTS('?IDT Model input', 'Population', 'B13'), {tonnes/year} juvenile animal annual total roughage[animals]=GET XLS CONSTANTS('?IDT Model input', 'Population', 'B14'), {tonnes/year}

juvenile animal fraction[animals]=GET XLS CONSTANTS('?IDT Model input', 'Population', 'B15'), {Dmnl}

juvenile animal water requirements[animals]=GET XLS CONSTANTS('?IDT Model input', 'Population', 'B12'), {L/day}

Kc coefficient[crop]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B5'), fraction

Ky[crop]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B6'), {fraction}

labour cost on dry land[crop]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B36'), {$/ha}

labour cost on irrigated land[crop]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B28'), {$/ha}|

labour cost per head[animals]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B65'), {$/head}

levies=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B40'), {$}

livestock costs per head[animals]=fixed cost per head[animals]+labour cost per head[animals]+operating costs per head[animals], {$}

low flow appliance change rate[use]=IF THEN ELSE(Percentage of Houses with Low Flow Appliances[use]<1, IF THEN ELSE(Percentage of Houses with Low Flow Appliances[use]+adoption rate of low flow technologies[use]<1,adoption rate of low flow technologies[use], 1-Percentage of Houses with Low Flow Appliances[use]),0), {Dmnl}

marketable rate[fruit tree]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B92')

mature[fruit tree]=(non-bearing area[fruit tree]-"non-bearing tree remove"[fruit tree])/non-bearing years[fruit tree]

method priority[electricity]=GET XLS CONSTANTS('?IDT Model input', 'Industry', 'E10'), {Dmnl}

method width=GET XLS CONSTANTS('?IDT Model input', 'Industry', 'G10'), {Dmnl}

mine priority[mine]=GET XLS CONSTANTS('?IDT Model input', 'Industry', 'B10'), {Dmnl}

mine width=GET XLS CONSTANTS('?IDT Model input', 'Industry', 'G10'), {Dmnl}

mine=GET XLS SUBSCRIPT('?IDT Model input', 'Industry', 'B2', 'D2', '')

minimum water at field crop wilting point[crop]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B109'), {mm}

minimum water at tree crop wilting point[fruit tree]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B117'), {mm}

mining production demand[mine]=initial mining production[mine]+cumulative mining production increase[mine], {ton}

mining production increase rate[mine]=GET XLS CONSTANTS('?IDT Model input', 'Industry', 'B12'), {Dmnl}

mining production increase[mine]=mining production increase rate[mine]*mining production demand[mine], {ton/year} mining production[mine]=actual mining water use by mine[mine]/mining water use efficiency[mine], {ton}

mining profit by mine[mine]=GET XLS CONSTANTS('?IDT Model input', 'Industry', 'B5'), {$/ton}

mining profit loss by mine[mine]=mining production demand[mine]*mining profit by mine[mine]-mining profit[mine], {$}

mining profit[mine]=mining production[mine]*mining profit by mine[mine], {$}

mining water consumption rate=GET XLS CONSTANTS('?IDT Model input', 'Industry', 'B4'), {Dmnl}

mining water consumption[mine]=actual mining water use by mine[mine]*mining water consumption rate, {m3}

mining water demand[mine]=mining production demand[mine]*(mining water use efficiency[mine]*(1-"industrial water use efficiency improvement from water R&D")), {m3}

mining water use efficiency[mine]=GET XLS CONSTANTS('?IDT Model input', 'Industry', 'B3'), {m3/ton}

mortality rate[fruit tree]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B91'), {year}

municipal average life=80, {year}

municipal decrease=Municipal Population/municipal average life, {person/year}

municipal increase rate=0.015, {fraction/year}

municipal increase=Municipal Population*municipal increase rate, {person/year}

Municipal Population= INTEG (municipal increase-municipal decrease, initial municipal population of the Oxbow), {person}

municipal water demand MCM=annual municipal water demand/1e+006, {MCM/year}

municipal water percentage deficiency=MAX(0, (annual municipal water demand-permitted municipal water use)/permitted municipal water use), {Dmnl}

municipal water use allocation= GAME (initial municipal water use allocation), {MCM/year}

municipal water use MCM=permitted municipal water use/1e+006, {MCM/year}

municipal water use priority[use]=GET XLS CONSTANTS('?IDT Model input', 'Municipal', 'B8'), {Dmnl}

municipal water use width=GET XLS CONSTANTS('?IDT Model input', 'Municipal', 'B12')

net change of soil moisture[crop]="increase in soil moisture (dry)"[crop]-"decrease in soil moisture (dry)"[crop], {mm}

net generation capacity[electricity]=GET XLS CONSTANTS('?IDT Model input', 'Industry', 'E13'), {kwh}

net irrigation application for bearing area[fruit tree]=tree crop and vine gross irrigation application[fruit tree]*irrigation delivery system and application efficiency, {mm}

Net irrigation application[crop]=gross irrigation application[crop]*irrigation delivery system and application efficiency, {mm} non-bearing area minimum water demand[fruit tree]=non-bearing tree and vine minimum water demand[fruit tree]*planting density[fruit tree], {m3/ha}

non-bearing area[fruit tree]= INTEG (replant[fruit tree]-mature[fruit tree]-"non-bearing tree remove"[fruit tree], initial non-bearing area[fruit tree]), {ha}

non-bearing tree and vine minimum water demand[fruit tree]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B81'), {m3/tree}

non-bearing years[fruit tree]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B86'), {year}

operating costs per head[animals]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B62'), {$/head}

Orchard Farming Population= INTEG (0, initial orchard farming population of the Oxbow), {person}

other cost by dry land[crop]=capital cost on dry land[crop]+energy cost on the dry land[crop]+labour cost on dry land[crop], {$/ha}

other cost on irrigated land[crop]=capital cost on irrigated land[crop]+energy cost on the irrigated land[crop]+labour cost on irrigated land[crop], {$/ha}

other purpose water demand MCM=annual water use for other purposes/1e+006, {MCM/year}

Oxbow basin water deficiency=MAX(0,(total Oxbow Basin water demand-(Oxbow water supply/1e+006))), {MCM}

Oxbow water supply=base renewable flow in the Oxbow+reservoir drawdown+water diversion from another basin to the Oxbow, {m*m*m/year}

Pasture Quality= INTEG (IF THEN ELSE(Pasture Quality<=2, improvement, 0), 1)

per capita daily domestic water demand=per capita daily municipal indoor water demand+per capita daily leakage losses from municipal demand+per capita daily municipal outdoor water demand, {liters/day}

per capita daily leakage losses from municipal demand=fractional losses from leakage*per capita daily municipal indoor water demand, {liters/day}

per capita daily leakage losses from municipal water use=fractional losses from leakage*SUM(per capita daily municipal water use by category[use!]), {liters/(day*person)}

per capita daily municipal indoor water demand=SUM(per capita daily municipal water demand by category[indoor!])

per capita daily municipal indoor water use=SUM(per capita daily municipal water use by category[indoor!]), {liters/(day*person)}

per capita daily municipal outdoor water demand=per capita daily municipal water demand by category[outdoor], {liters/day}

per capita daily municipal outdoor water use=per capita daily municipal water use by category[outdoor], {liters/(day*person)}

per capita daily municipal water demand by category[indoor]= base per capita daily municipal water demand by category[indoor]*base times per capita per day[indoor]*((1-Percentage of Houses with Low Flow Appliances[indoor]) + Percentage of Houses with Low Flow Appliances[indoor]*(1-water use reduction for low flow appliances[indoor]))*(1-reductions from grey water use[indoor]) per capita daily municipal water demand by category[outdoor]=base per capita daily municipal water demand by category[outdoor]*base times per capita per day[outdoor]*((1-Percentage of Houses with Low Flow Appliances[outdoor]) + Percentage of Houses with Low Flow Appliances[outdoor]*(1-water use reduction for low flow appliances[outdoor])), {liters/day}

per capita daily municipal water use by category[use]=(1-fractional losses from leakage)*annual municipal water use by category[use]/Municipal Population/365*1000 , {liters/(day*person)}

per head stock annual grain ration[animals]=baby animal fraction[animals]*baby animal annual grain ration[animals]+juvenile animal fraction[animals]*juvenile animal annual grain ration[animals]+adult animal fraction[animals]*adult animal annual grain ration[animals], {tonnes/year}

per head stock annual total roughage[animals]=baby animal fraction[animals]*baby animal annual total roughage[animals]+juvenile animal fraction [animals]*juvenile animal annual total roughage[animals]+adult animal fraction[animals]*adult animal annual total roughage[animals], {tonnes/year}

per head stock water requirements[animals]=baby animal fraction[animals]*baby animal water requirements[animals]+juvenile animal fraction[animals]*juvenile animal water requirements[animals]+adult animal fraction[animals]*adult animal water requirements[animals], {L/day}

percent of water level=effect of water storage on water level(percent of water storage in the reservoir), {Dmnl}

percent of water storage in the reservoir=Reservoir Storage/total reservoir full capacity, {Dmnl}

Percentage of Houses with Low Flow Appliances[use]= INTEG (low flow appliance change rate[use], initial percentage of homes with low flow appliances[use]), {Dmnl}

permitted field crop irrigation water use=IF THEN ELSE(ration water by sector, field crop irrigation water use allocation*1e+006, MIN(desired field crop gross irrigation diversion, initial field crop irrigation water use allocation*1e+006)), {m*m*m/year}

permitted industrial water use=IF THEN ELSE(ration water by sector , industrial water use allocation*1e+006, MIN(annual industrial water demand, initial industrial water use allocation*1e+006)), {m*m*m/year}

permitted municipal water use=IF THEN ELSE(ration water by sector , municipal water use allocation*1e+006, MIN(annual municipal water demand ,initial municipal water use allocation*1e+006)), {m*m*m/year}

permitted tree crop and vine irrigation water use=IF THEN ELSE(ration water by sector , tree crop and vine irrigation water use allocation*1e+006, MIN(desired tree crop and vine gross irrigation diversion, initial tree crop and vine irrigation water use allocation*1e+006)), {m*m*m/year}

permitted water use for other purposes=IF THEN ELSE(ration water by sector , water use for other purposes allocation*1e+006, MIN(annual water use for other purposes, initial water use for other purposes allocation*1e+006)), {m*m*m/year}

planting density[fruit tree]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B78'), [tree/ha]

POLICY COST additional dam and reservoir storage=GET XLS CONSTANTS('?IDT Model input','Economics', 'B8'), {$}

POLICY COST diversification of pasture species composition=GET XLS CONSTANTS('?IDT Model input','Economics', 'B24'), {$}

POLICY COST drawdown of reservoir storage=GET XLS CONSTANTS('?IDT Model input','Economics', 'B12'), {$}

POLICY COST enhance irrigation water delivery system and application efficiency=GET XLS CONSTANTS('?IDT Model input', 'Economics', 'B6'), {$}

POLICY COST expand irrigation=GET XLS CONSTANTS('?IDT Model input','Economics', 'B28'), $}

POLICY COST invest in agriculture related research and development=GET XLS CONSTANTS('?IDT Model input','Economics', 'B30'), {$}

POLICY COST invest in grey water treatment=GET XLS CONSTANTS('?IDT Model input','Economics', 'B31'), {$}

POLICY COST invest in water related research and development=GET XLS CONSTANTS('?IDT Model input','Economics', 'B29'), {$}

POLICY COST promote green cover=GET XLS CONSTANTS('?IDT Model input','Economics', 'B21'), {$}

POLICY COST promote winter cropping=GET XLS CONSTANTS('?IDT Model input','Economics', 'B22'), {$}

POLICY COST ration water=GET XLS CONSTANTS('?IDT Model input','Economics', 'B11'), {$}

POLICY COST relief payout to farmers=GET XLS CONSTANTS('?IDT Model input','Economics', 'B16'), {$}

POLICY COST stocking rate reductions[beef]=GET XLS CONSTANTS('?IDT Model input','Economics', 'B23') , {$}

POLICY COST stocking rate reductions[pigs]=GET XLS CONSTANTS('?IDT Model input','Economics', 'C23'), {$}

population per house=GET XLS CONSTANTS('?IDT Model input', 'Municipal', 'B10'), {fraction/house}

power generation gap=thermal power plants generation demand+ hydro power plants generation demand-power generation, {kwh}

power generation increase rate=GET XLS CONSTANTS('?IDT Model input', 'Industry', 'E12'), {Dmnl}

power generation increase=(hydro power plants generation demand+ thermal power plants generation demand)*power generation increase rate, {kwh/year}

power generation water consumption efficiency[electricity]=GET XLS CONSTANTS('?IDT Model input', 'Industry', 'E4'), {m3/kwh}

power generation water consumption[hydro]=hydro power plants generation*power generation water consumption efficiency[hydro],{m3}

power generation water consumption[thermal]=thermal power plants generation*power generation water consumption efficiency[thermal]

power generation=hydro power plants generation+ thermal power plants generation, {kwh} power plant shares[electricity]=GET XLS CONSTANTS('?IDT Model input', 'Industry', 'E7'), {Dmnl}

power plants water demand[hydro]=hydro power plants water loss, {m3}

power plants water demand[thermal]=thermal power plants water demand

precipitation in the Oxbow:INTERPOLATE::=GET XLS DATA('?IDT Model input', 'Dynamic', '5', 'B7'), {mm}

prescribed stock number reduction[animals]=IF THEN ELSE(promote stocking rate reductions, IF THEN ELSE(Animal Populations[animals]+animal births[animals]-(Animal Populations[animals]/animal average life[animals])-reduction in stock numbers[animals]>0, reduction in stock numbers[animals], Animal Populations[animals]+animal births[animals]-(Animal Populations[animals]/animal average life[animals])), 0), {animals/year}

price of livestock[animals]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B45'), {$/head}

price of products[animals]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B49'), {$/kg}

product from livestock[animals]=productivity per animal[animals]*Animal Populations[animals]*adult animal fraction[animals], {kg}

productivity per animal[animals]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B47'), {kg}

profit by category[fruit tree]=profit per unit[fruit tree]*bearing area[fruit tree], {$}

profit on dry land=SUM(receipt from dry land crop[crop!])-SUM(farmers cost on dry land[crop!]), {$}

profit on irrigated land=SUM(receipt from irrigated crop[crop!])-SUM(farmers cost on irrigated land[crop!]),{$}

profit on livestock[animals]=total sales[animals]+income of products[animals]-total cost for livestock[animals]

profit per field crop farmer=total field crop profit/Field Crop Farming Population, {$}

profit per orchard farmer=total tree crop and vine profit/Orchard Farming Population, {$}

profit per unit[fruit tree]=tree crop and vine yield per unit[fruit tree]*marketable rate[fruit tree]*1000*tree fruit and vine price[fruit tree]-tree crop and vine direct cost[fruit tree], {$/ha}

promote diversification of pasture species composition= GAME (0)

promote green cover= GAME (0)

promote stocking rate reductions= GAME (0)

promote winter cropping= GAME (0)

public water use= 0.02*per capita daily domestic water demand, {liters/year}

ration water by sector= GAME (0)

receipt from dry land crop[forage]=IF THEN ELSE("field crop total yield (irrigated)"[forage]-annual stock grain ration>0, crop price[forage]*"field crop total yield(dry)"[forage]*1000, ("field crop total yield(dry)"[forage]-(annual stock grain ration-"field crop total yield (irrigated)"[forage]))*crop price[forage]*1000)

receipt from dry land crop[grain]=crop price[grain]*"field crop total yield(dry)"[grain]*1000 receipt from dry land crop[grass]=IF THEN ELSE("field crop total yield (irrigated)"[grass]-annual stock roughage requirements>0, crop price[grass]*"field crop total yield(dry)"[grass]*1000, ("field crop total yield(dry)"[grass]-(annual stock roughage requirements-"field crop total yield (irrigated)"[grass]))*crop price[grass]*1000), {$}

receipt from dry land crop[oilseed]=crop price[oilseed]*"field crop total yield(dry)"[oilseed]*1000

receipt from dry land crop[vegetables]=crop price[vegetables]*"field crop total yield(dry)"[vegetables]*1000

receipt from irrigated crop[forage]=IF THEN ELSE("field crop total yield (irrigated)"[forage]-annual stock grain ration>0, crop price[forage]*("field crop total yield (irrigated)"[forage]-annual stock grain ration)*1000, 0)

receipt from irrigated crop[grain]=crop price[grain]*"field crop total yield (irrigated)"[grain]*1000

receipt from irrigated crop[grass]=IF THEN ELSE("field crop total yield (irrigated)"[grass]-annual stock roughage requirements>0, crop price[grass]*("field crop total yield (irrigated)"[grass]-annual stock roughage requirements) *1000, 0), {$}

receipt from irrigated crop[oilseed]=crop price[oilseed]*"field crop total yield (irrigated)"[oilseed]*1000

receipt from irrigated crop[vegetables]=crop price[vegetables]*"field crop total yield (irrigated)"[vegetables]*1000

receipt from livestock=SUM(total sales[animals!])+SUM(income of products[animals!]), {$}

recreational expenditure per unit water=IF THEN ELSE (Reservoir Storage, recreational expenditure*1e+006/Reservoir Storage,0), {$/m3}

recreational expenditure=effect of water level on recreation expenditure(full capacity elevation-"0 capacity elevation"-water level)*full capacity recreational expenditure, {million $}

reduction in stock numbers[animals]=GET XLS CONSTANTS('?IDT Model input', 'Policy', 'B27'), {animals}

reductions from grey water use[indoor]=FLAG invested in grey water treatment*constant grey water use multipliers[indoor], {Dmnl}

relief money=GET XLS CONSTANTS('?IDT Model input', 'Economics', 'B16'), {$}

relief payout to farmers= GAME (0), {Dmnl}

remaining funds= BUDGET-EXPENDITURES total expenses, {$}

replant[fruit tree]=bare area[fruit tree], {ha/year}

reservoir drawdown=drawdown of reservoir storage, {m*m*m/year}

reservoir storage in MCM=Reservoir Storage/1e+006, {MCM}

Reservoir Storage= INTEG (build dam and reservoir-reservoir drawdown, IF THEN ELSE("PRE-GAME build additional dam and reservoir", initial reservoir storage+ increase in reservoir storage, initial reservoir storage)), {m*m*m}

sowing cost on dry land[crop]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B32'), {$/ha}

sowing cost on irrigated land[crop]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B24'), {$/ha} sum of cost of livestock=SUM(total cost for livestock[animals!]), {$}

sum of cost on dry land=SUM(farmers cost on dry land[crop!]), {$}

sum of cost on irrigated land=SUM(farmers cost on irrigated land[crop!]), {$}

sum of total cost for livestock=SUM(total cost for livestock[animals!])

thermal power plants generation demand=MIN((initial power generation+ cumulative power generation increase)*power plant shares[thermal],net generation capacity[thermal]), {kwh}

thermal power plants generation=actual power plants water use by method[thermal]/thermal power plants water use efficiency, {kwh}

thermal power plants water demand=thermal power plants generation demand*(thermal power plants water use efficiency*(1\"industrial water use efficiency improvement from water R&D")), {m3}

thermal power plants water use efficiency=GET XLS CONSTANTS('?IDT Model input', 'Industry', 'E3'), {m3/kwh}

Time to build additional reservoir storage=0, {Dmnl}

Time to improve irrigation efficiency=0, {Dmnl}

total bare area=SUM(bare area[fruit tree!]), {ha}

total bearing area=SUM(bearing area[fruit tree!]), {ha}

total cost for livestock[animals]=Animal Populations[animals]*livestock costs per head[animals], {$}

total field crop profit=farmers income-farmers cost-field crop water cost+(relief money*relief payout to farmers*0.9), {$}

Total land=SUM("Dry Land (field crop)"[crop!])+fallow land+ Green Cover Land+ SUM("Irrigated Land (field crop)"[crop!])+"total irrigated land (tree crop and vine)", {ha}

total mining profit loss=SUM(mining profit loss by mine[mine!]), {$}

total mining profit=SUM(mining profit[mine!]), {$}

total non-bearing area=SUM(non-bearing area[fruit tree!]), {ha}

total Oxbow Basin water demand=irrigation water demand MCM+ industrial water demand MCM+ municipal water demand MCM+ other purpose water demand MCM, {MCM/year}

total Oxbow Basin water use=municipal water use MCM+ irrigation water use MCM+ industrial water use MCM+ water use for other purposes MCM, {MCM/year}

total reservoir full capacity= INTEG (additional reservoir capacity, IF THEN ELSE("PRE-GAME build additional dam and reservoir", initial reservoir storage+ increase in reservoir storage, initial reservoir storage)), {m3}

total sales[animals]=animal sales[animals]*price of livestock[animals], {$}

total tree crop and vine profit=SUM(profit by category[fruit tree!])-tree crop and vine water cost+(relief money*relief payout to farmers*0.1), {$}

tree crop and vine available to requirement irrigation water ratio=IF THEN ELSE(tree crop and vine gross irrigation diversion>desired tree crop and vine gross irrigation diversion:OR: desired tree crop and vine gross irrigation diversion=0, 1 , tree crop and vine gross irrigation diversion/desired tree crop and vine gross irrigation diversion), {Dmnl} tree crop and vine direct cost[fruit tree]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B95'), {$/ha}

tree crop and vine ETa[fruit tree]=IF THEN ELSE(available soil moisture for the tree crop and vine[fruit tree]-tree crop and vine ETc[fruit tree]>=minimum water at tree crop wilting point[fruit tree],tree crop and vine ETc[fruit tree],available soil moisture for the tree crop and vine[fruit tree]-minimum water at tree crop wilting point[fruit tree]), {mm}

tree crop and vine ETc[fruit tree]="tree crop and vine ET(0)"[fruit tree]*tree crop and vine Kc coefficient[fruit tree], {mm}

tree crop and vine gross irrigation application[fruit tree]=IF THEN ELSE(bearing area[fruit tree],(gross irrigation application by bearing tree crop and vine[fruit tree]*1e+009)/(bearing area[fruit tree]*1e+010),0), {mm}

tree crop and vine gross irrigation diversion=IF THEN ELSE(desired tree crop and vine gross irrigation diversion > permitted tree crop and vine irrigation water use, permitted tree crop and vine irrigation water use+ drawdown of reservoir storage*"% of drawdown reservoir water to tree crop and vine", desired tree crop and vine gross irrigation diversion), {m*m*m/yr}

tree crop and vine gross irrigation water use MCM=tree crop and vine gross irrigation diversion/1e+006, {MCM/year}

tree crop and vine irrigation water use allocation= GAME (initial tree crop and vine irrigation water use allocation), {MCM/year}

tree crop and vine Kc coefficient[fruit tree]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B88'), {fraction}

tree crop and vine Ky[fruit tree]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B87'), {fraction}

tree crop and vine total yield[fruit tree]=tree crop and vine yield per unit[fruit tree]*bearing area[fruit tree], {ton}

tree crop and vine water cost=(permitted tree crop and vine irrigation water use/1e+006)*water price*1000

tree crop and vine water productivity[fruit tree]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B83'), {g/(m*m*m)}

tree crop and vine yield per unit[fruit tree]=((1-tree crop and vine Ky[fruit tree]+tree crop and vine Ky[fruit tree]*(tree crop and vine ETa[fruit tree]/tree crop and vine ETc[fruit tree]))*tree crop and vine Ym[fruit tree])*(1+"yield improvement from agricultural R&D"), {ton/ha}

tree crop and vine Ym[fruit tree]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B90'), {ton/ha}

tree crop area: bearing, non-bearing

tree fruit and vine price[fruit tree]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B94'), {$/kg}

use: GET XLS SUBSCRIPT('?IDT Model input', 'Municipal', 'B2', 'F2', '')

water diversion from another basin to the Oxbow="FLAG inter-basin transfer built"*"inter-basin transfer volume to the Oxbow", {m*m*m/year}

water level=percent of water level*(full capacity elevation-"0 capacity elevation"), {m} water loss in the reservoirs=GET XLS CONSTANTS('?IDT Model input', 'Industry', 'F4'), {m3/kwh}

water price=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B41'), {$/m3}

water satisfaction=actual industrial water use/annual industrial water demand, {Dmnl}

water use for other purposes allocation= GAME (initial water use for other purposes allocation), {MCM/year}

water use for other purposes MCM=permitted water use for other purposes/1e+006, {MCM/year}

water use reduction for low flow appliances[use]=GET XLS CONSTANTS('?IDT Model input', 'Municipal', 'B5'), {fraction}

Ym[crop]=GET XLS CONSTANTS('?IDT Model input', 'Agriculture', 'B7'), {mg/ha}

Appendix B. Bow River Integrated Model (BRIM) Code

BRIM structures are provided to show how the variables are connected, and model code required to reproduce the model is provided below. Model inputs are shown in green, policies are shown in orange, typical outputs are shown in red, and shadow variables (duplicates of existing variables used for clarity) are shown in grey.

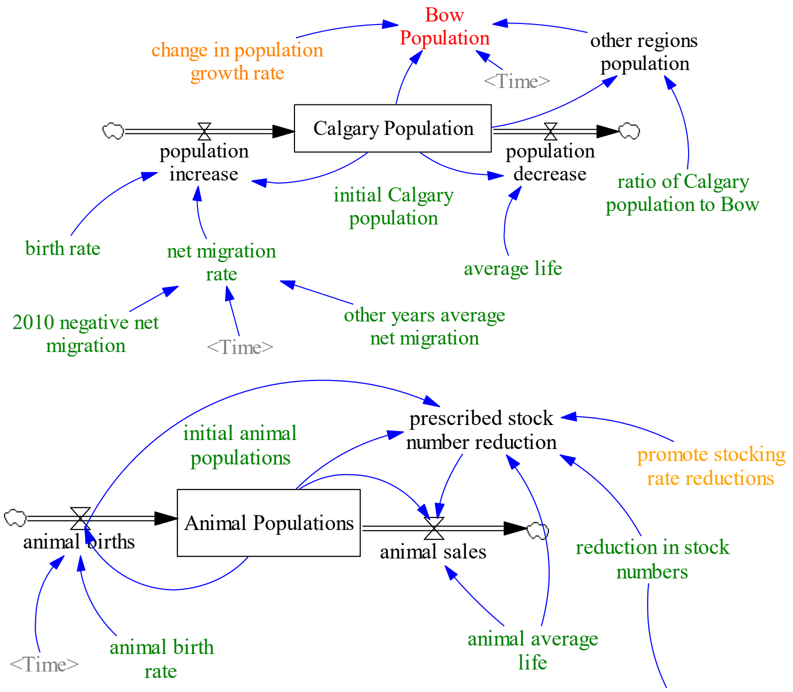

Figure B-1: Municipal and livestock population simulation

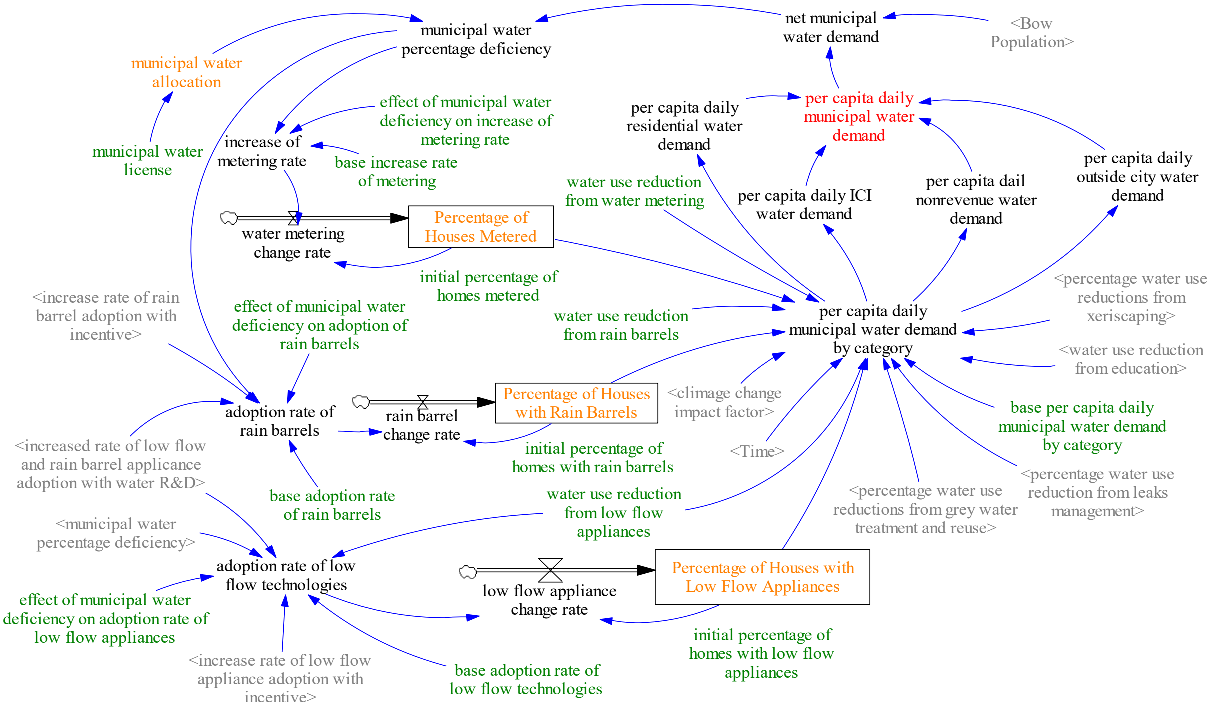

Figure B-2: Municipal water demand simulation

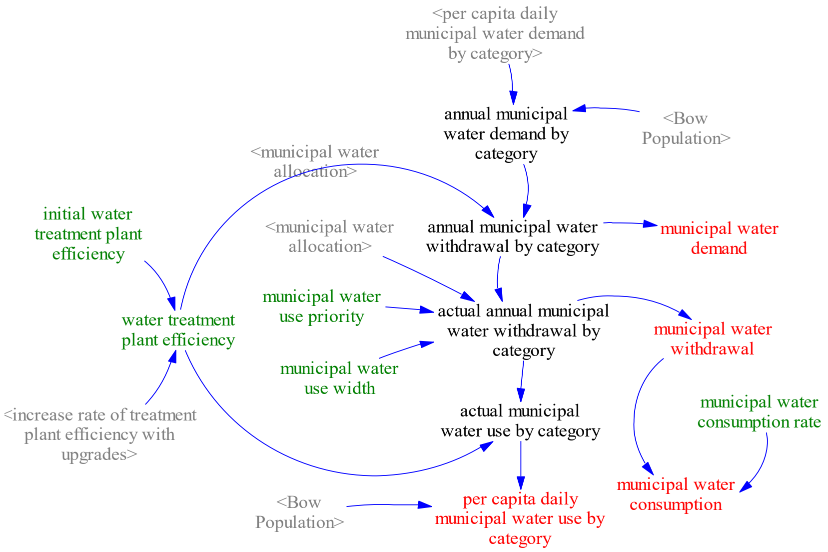

Figure B-3: Municipal water use simulation

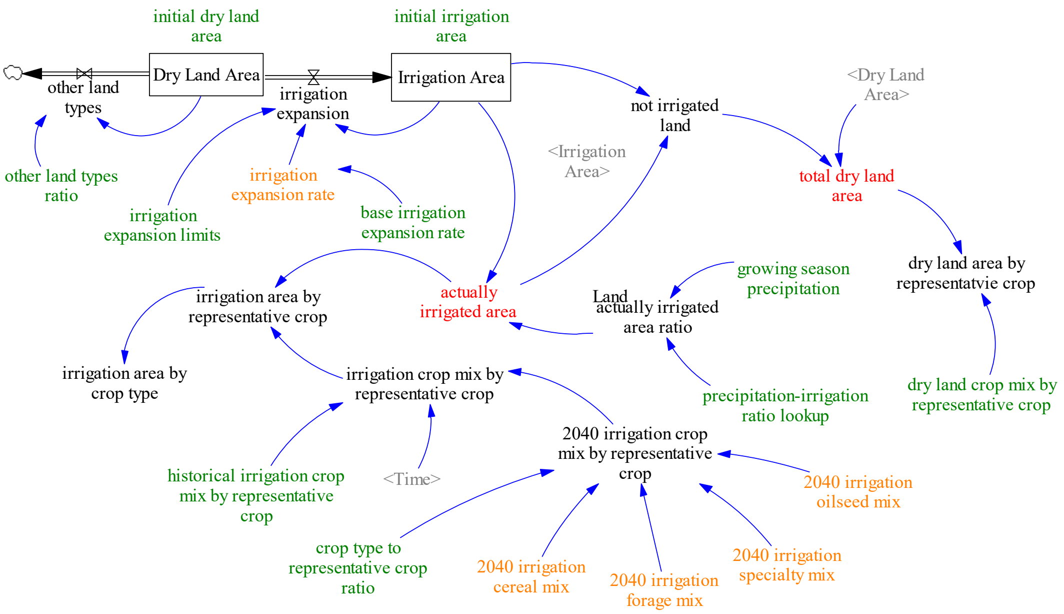

Figure B-4: Agricultural land area simulation

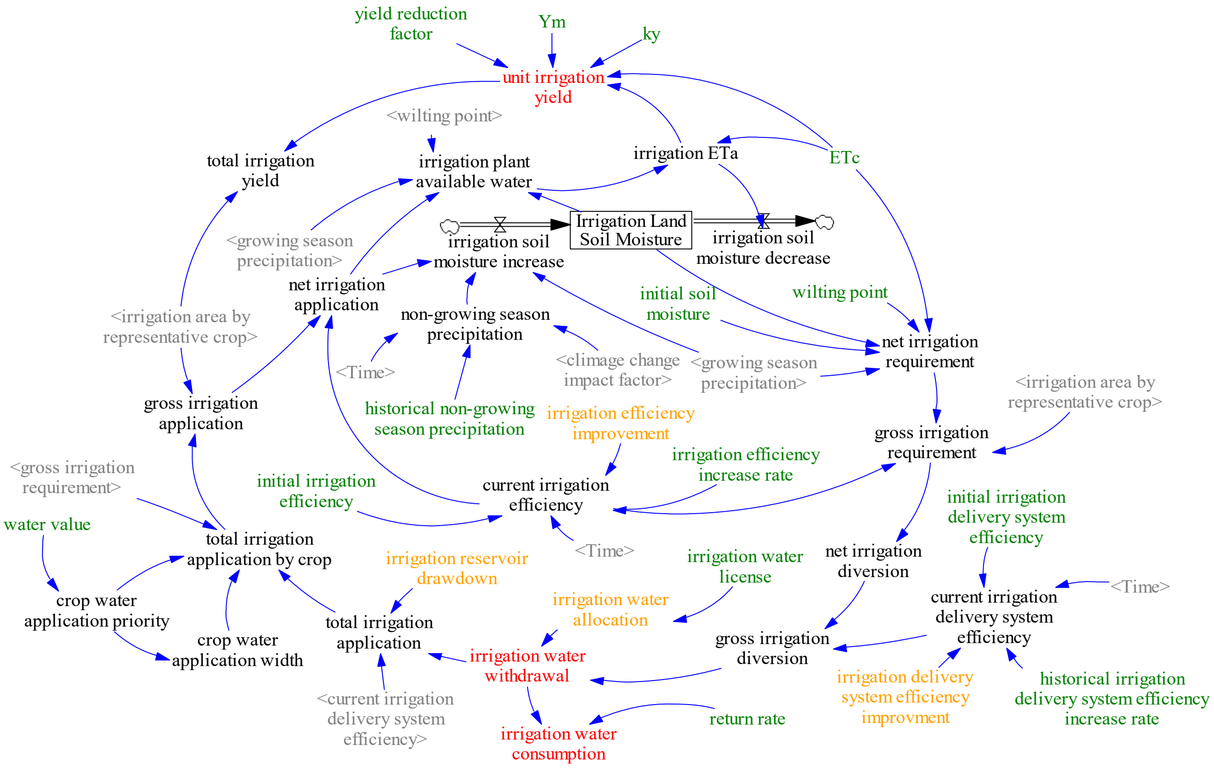

Figure B-5: Irrigation demand and yield simulation

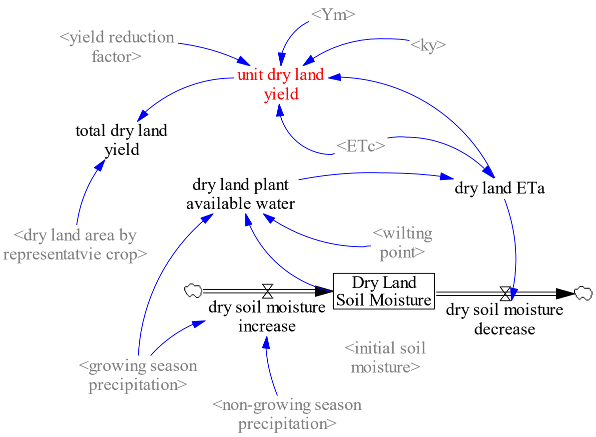

Figure B-6: Dry land crop yield simulation

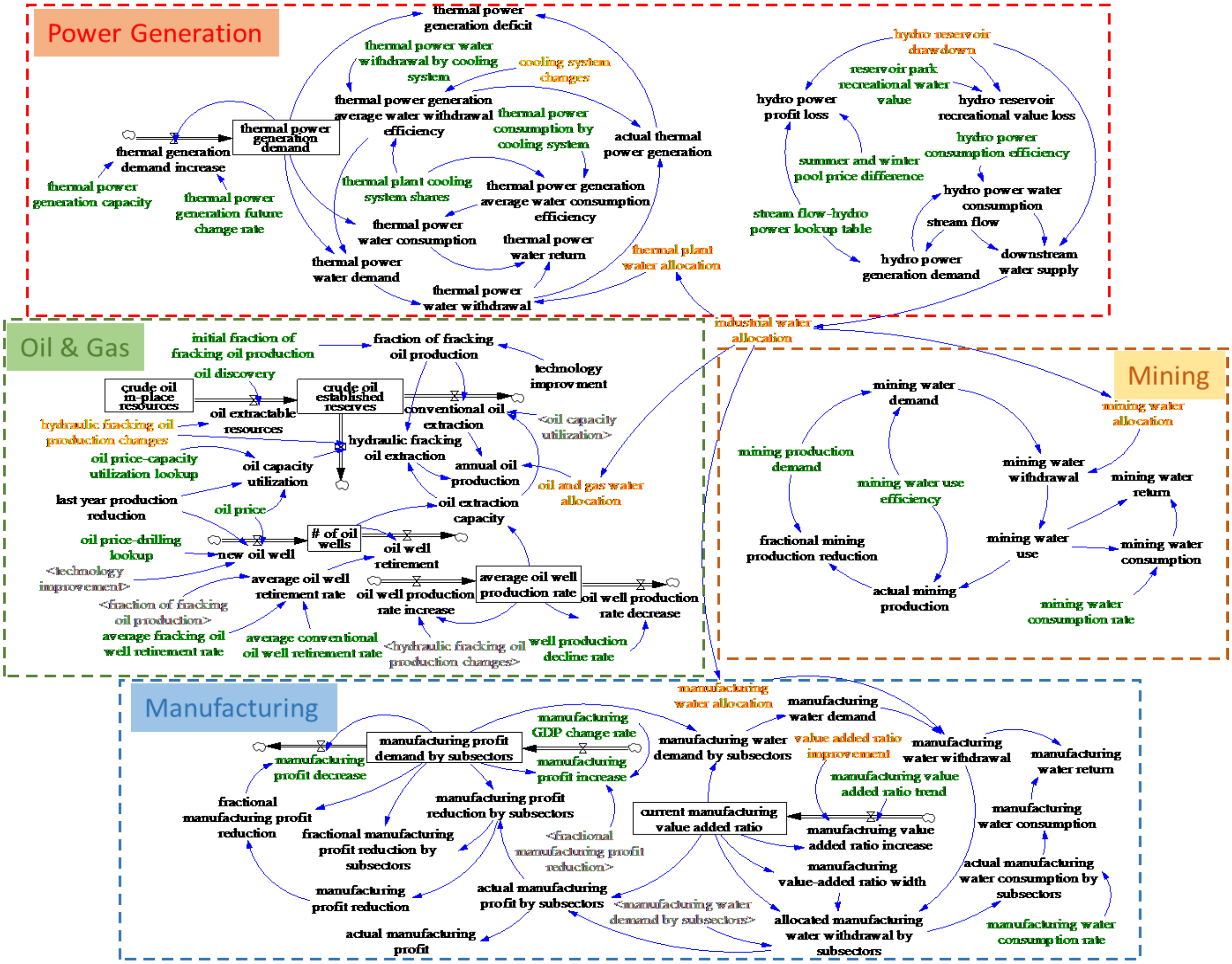

Figure B-7: Industrial sector simulation

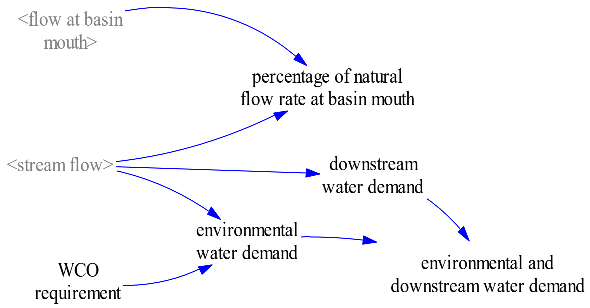

Figure B-8: Environmental sector simulation

"# of gas wells"= INTEG (new gas well-gas well retirement, "initial # of gas wells"), {well}

"# of oil wells"= INTEG (new oil well-oil well retirement, "initial # of oil wells"), {well}

"2010 negative net migration"=GET XLS CONSTANTS('?BRSGM', 'population', 'B6'), {Dmnl}

"2040 gas price"= GAME (0.23), {$/m3}

"2040 irrigation cereal mix"= GAME (0.2), {Dmnl}

"2040 irrigation crop mix by representative crop"[alfalfa]="2040 irrigation forage mix"*0.75*crop type to representative crop ratio[alfalfa]

"2040 irrigation crop mix by representative crop"[barley]="2040 irrigation cereal mix"*0.75*crop type to representative crop ratio[barley]

"2040 irrigation crop mix by representative crop"[beans]="2040 irrigation specialty mix"*0.75*crop type to representative crop ratio[beans]

"2040 irrigation crop mix by representative crop"[canola]="2040 irrigation oilseed mix"*0.75*crop type to representative crop ratio[canola]

"2040 irrigation crop mix by representative crop"[other crops]="2040 irrigation cereal mix"*0.25+"2040 irrigation forage mix"*0.25+"2040 irrigation oilseed mix"*0.25+"2040 irrigation specialty mix"*0.25, {Dmnl}

"2040 irrigation crop mix by representative crop"[potatoes]="2040 irrigation specialty mix"*0.75*crop type to representative crop ratio[potatoes]

"2040 irrigation crop mix by representative crop"[sugar beets]="2040 irrigation specialty mix"*0.75*crop type to representative crop ratio[sugar beets] , {Dmnl}

"2040 irrigation crop mix by representative crop"[tame pasture]="2040 irrigation forage mix"*0.75*crop type to representative crop ratio[tame pasture]

"2040 irrigation crop mix by representative crop"[wheat]="2040 irrigation cereal mix"*0.75*crop type to representative crop ratio[wheat]

"2040 irrigation forage mix"= GAME (0.2), {Dmnl}

"2040 irrigation oilseed mix"= GAME (0.3), {Dmnl}

"2040 irrigation specialty mix"= GAME (0.3), {Dmnl}

"2040 oil price"= GAME (416), {$/m3}

"actual total oil & gas production"=actual gas production+actual oil production, {m3}

"crude oil in-place resources"= INTEG (-oil extractable resources,1e+010), {m3}

"cumulative investments into water related R&D"=water related research and development, {Dmnl}

"Cumulative Years of Water R&D Investment"= INTEG ("increase in cumulative years of water R&D", 0), {Year}

"fractional oil & gas production reduction"="oil & gas production reduction"/"total oil & gas production", {Dmnl}

"gas in-place resources"= INTEG (-gas extractable resources,1e+011), {m3}

"gas price-capacity utilization lookup"=GET XLS LOOKUPS('? BRSGM input' , 'industry' , '107', 'B108')

"gas price-new wells lookup"=GET XLS LOOKUPS('? BRSGM input' , 'industry' , '138', 'B139')

"gas-increase of cumulative year"=gas technology improvement selection+gas technology improvement-MODULO(gas technology improvement selection, 1), {Dmnl}

"historical non-growing season precipitation":=GET XLS DATA('? BRSGM input' , 'agriculture' , '6', 'B23'), {mm}

"increase in cumulative years of water R&D"=water related research and development + "Water Related R&D Policy Selection" - MODULO("Water Related R&D Policy Selection",1), {Year/Year}

"increased rate of low flow and rain barrel appliance adoption with water R&D"="water related R&D lookup table"("Cumulative Years of Water R&D Investment"), {Dmnl}

"initial # of gas wells"=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B137'), {well}

"initial # of oil wells"=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B116'), {well}

"manufacturing value-added ratio width"=VMAX(current manufacturing value added ratio[manufacturing subsectors!]), {$/m3}

"non-growing season precipitation"=IF THEN ELSE(Time<=2015, "historical non-growing season precipitation" , "historical non-growing season precipitation"*(1-climate change impact factor)), {mm}

"oil & gas extraction revenue"=actual oil production*oil revenue+actual gas production*gas revenue-("total oil & gas extraction water demand"*use alternative saline water*unit cost of saline water use), {$}

"oil & gas extraction water consumption rate"=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B60'), {Dmnl}

"oil & gas extraction water consumption"="total available water for oil & gas extraction"*"oil & gas extraction water consumption rate", {million m3}

"oil & gas extraction water demand by category"[oil]=oil extraction water demand/1e+006,

"oil & gas extraction water return"="total available water for oil & gas extraction"-"oil & gas extraction water consumption", {million m3}

"oil & gas extraction water withdrawal by category"[oil and gas]=ALLOCATE BY PRIORITY("oil & gas extraction water demand by category"[oil and gas], water allocation priority[oil and gas], ELMCOUNT(oil and gas) , water allocation width , "total available water for oil & gas extraction"), {million m3}

"oil & gas extraction water withdrawal"=MIN("total oil & gas extraction water demand"*(1-use alternative saline water), oil and gas water allocation), {million m3}

"oil & gas production reduction"=IF THEN ELSE(("total oil & gas production"-"actual total oil & gas production")>=1000 , ("total oil & gas production"-"actual total oil & gas production") , 0), {m3}

"oil price-capacity utilization lookup"=GET XLS LOOKUPS('? BRSGM input' , 'industry' , '113', 'B114')

"oil price-drilling lookup"=GET XLS LOOKUPS('? BRSGM input' , 'industry' , '117', 'B118')

"oil-increase of cumulative year"=oil technology improvement selection+oil technology improvement-MODULO(oil technology improvement selection, 1), {Dmnl}

"precipitation-irrigation ratio lookup"=GET XLS LOOKUPS('? BRSGM input' , 'agriculture' , '21', 'B22'), {Dmnl}

"technology improvement-increase of fraction of fracking gas production lookup"=GET XLS LOOKUPS('? BRSGM input' , 'industry' , '85', 'B86'), {Dmnl}

"technology improvement-increase of fraction of fracking oil production lookup"=GET XLS LOOKUPS('? BRSGM input' , 'industry' , '123', 'B124'), {Dmnl}

"technology improvement-increase of gas well production rate lookup"=GET XLS LOOKUPS('? BRSGM input' , 'industry' , '85', 'B87')

"technology improvement-increase of oil well production rate lookup"=GET XLS LOOKUPS('? BRSGM input' , 'industry' , '123', 'B126')

"technology improvement-increase of oil wells lookup"=GET XLS LOOKUPS('? BRSGM input', 'industry' , '123', 'B125')

"total available water for oil & gas extraction"="oil & gas extraction water withdrawal"+("total oil & gas extraction water demand"*use alternative saline water), {million m3}

"total oil & gas extraction water demand"=SUM("oil & gas extraction water demand by category"[oil and gas!]), {MCM}

"total oil & gas production"=annual gas production+annual oil production, {m3}

"water related R&D lookup table"(GET XLS LOOKUPS('?BRSGM', 'municipal' , '20' , 'B21')), {Dmnl}

"Water Related R&D Policy Selection"= INTEG ("cumulative investments into water related R&D",0), {Dmnl}

actual annual municipal water withdrawal by category[municipal subsectors]=ALLOCATE BY PRIORITY(annual municipal water withdrawal by category[municipal subsectors], municipal water use priority[municipal subsectors], ELMCOUNT(municipal subsectors), municipal water use width, municipal water allocation*1e+006), {m*m*m/Year}

actual annual oil and gas water consumption=estimated Bow oil and gas water consumption, {million m3}

actual annual water demand of Calgary:INTERPOLATE::=GET XLS DATA('? BRSGM input' , 'municipal' , '36', 'B38'), {ML} actual Bow gas production=estimated Bow gas production, {m3}

actual Bow oil production=estimated Bow oil production, {m3}

actual Calgary annual water demand=actual annual water demand of Calgary, {ML}

actual Calgary annual water withdrawal=actual Calgary withdrawal, {ML}

actual Calgary per capita daily y municipal water demand=actual Calgary water demand, {liters/(person*day)}

actual Calgary Population=population of Calgary, {person}

actual Calgary water demand:INTERPOLATE::=GET XLS DATA('? BRSGM input' , 'municipal' , '36', 'B37'), {liters/(person*day)}

actual Calgary withdrawal:INTERPOLATE::=GET XLS DATA('? BRSGM input' , 'municipal' , '36', 'B39'), {ML}

actual discharge at basin mouth:=GET XLS DATA('? BRSGM input' , 'supply' , '1', 'B6'), {MCM}

actual dry land area by representative crop[representative crop]=estimated dry land area by representative crop[representative crop], {acre}

actual dry land area=estimated dry land area, {acre}

actual flow at basin mouth=actual discharge at basin mouth, {MCM}

actual gas production=IF THEN ELSE(gas extraction water withdrawal*1e+006>=gas extraction water demand, annual gas production, IF THEN ELSE(gas extraction water withdrawal*1e+006<=conventional gas extraction*conventional gas extraction water use efficiency, gas extraction water withdrawal*1e+006/conventional gas extraction water use efficiency , conventional gas extraction+(gas extraction water withdrawal*1e+006-conventional gas extraction*conventional gas extraction water use efficiency)/hydraulic fracturing gas extraction water use efficiency)), {m3}

actual hydro power generation=summer power generation+winter power generation, {MWh}

actual irrigated area by crop type[crop type]=estimated irrigated area by crop type[crop type], {acre}

actual irrigated area by representative crop[representative crop]=estimated irrigated area by representative crop[representative crop], {acre}

actual manufacturing revenue by subsectors[manufacturing subsectors]=allocated manufacturing water withdrawal by subsectors[manufacturing subsectors]*current manufacturing value added ratio[manufacturing subsectors], {Million $}

actual manufacturing revenue=SUM(actual manufacturing revenue by subsectors[manufacturing subsectors!]), {Million $}

actual manufacturing water consumption by subsectors[manufacturing subsectors]=allocated manufacturing water withdrawal by subsectors[manufacturing subsectors]*manufacturing water consumption rate[manufacturing subsectors], {million m3}

actual mining production by category[mining]=mining water use by category[mining]/mining water use efficiency[mining], {ton}

actual mining profit by category[mining]=actual mining production by category[mining]*mining profit[mining], {$}

actual municipal water use by category[municipal subsectors]=actual annual municipal water withdrawal by category[municipal subsectors]*water treatment plant efficiency, {m*m*m/Year}

actual oil production=IF THEN ELSE(oil extraction water withdrawal*1e+006>=oil extraction water demand, annual oil production, IF THEN ELSE(oil extraction water withdrawal*1e+006<=conventional oil extraction*conventional oil extraction water use efficiency, oil extraction water withdrawal*1e+006/conventional oil extraction water use efficiency , conventional oil extraction+(oil extraction water withdrawal*1e+006-conventional oil extraction*conventional oil extraction water use efficiency)/hydraulic fracking oil extraction water use efficiency)), {m3}

actual thermal power generation=thermal power water withdrawal*1e+006/SUM(thermal power generation average water withdrawal efficiency[cooling system!]), {MWh}

actual total irrigated land area=estimated total irrigated land area, {acre}

actually irrigated area ratio="precipitation-irrigation ratio lookup"(growing season precipitation), {Dmnl}

actually irrigated area=Irrigation Area*actually irrigated area ratio, {acre}

adoption rate of low flow technologies[municipal subsectors]=IF THEN ELSE(water use reduction from low flow appliances[municipal subsectors]=0 ,(base adoption rate of low flow technologies[municipal subsectors] +increase rate of low flow appliance adoption with incentive[municipal subsectors]) , (base adoption rate of low flow technologies[municipal subsectors]+effect of municipal water deficiency on adoption rate of low flow appliances(municipal water percentage deficiency) +"increased rate of low flow and rain barrel appliance adoption with water R&D"+increase rate of low flow appliance adoption with incentive[municipal subsectors])), {Dmnl}

adoption rate of rain barrels=base adoption rate of rain barrels+effect of municipal water deficiency on adoption of rain barrels(municipal water percentage deficiency)+increase rate of rain barrel adoption with incentive+"increased rate of low flow and rain barrel appliance adoption with water R&D", {Dmnl}

agricultural profit sustainability=IF THEN ELSE(irrigation land margin/max irrigation land margin>=1 , 1, irrigation land margin/max irrigation land margin)*0.7+IF THEN ELSE(promote stocking rate reductions=0, 1, (reduction in stock numbers[pigs]/Animal Populations[pigs]+reduction in stock numbers[beef]/Animal Populations[beef])/2)*0.3, {Dmnl}

agricultural water consumption=irrigation water consumption+livestock surface water requirements, {MCM}

agricultural water demand=gross irrigation diversion+livestock surface water requirements, {MCM}

agricultural water sustainability=IF THEN ELSE(total irrigation application/net irrigation diversion>=1, 1 , total irrigation application/net irrigation diversion), {Dmnl}

agricultural water withdrawal=irrigation water withdrawal+livestock surface water requirements, {MCM}

allocated manufacturing water withdrawal by subsectors[manufacturing subsectors]=ALLOCATE BY PRIORITY(manufacturing water demand by subsectors[manufacturing subsectors] ,current manufacturing value added ratio[manufacturing subsectors] , ELMCOUNT(manufacturing subsectors) , "manufacturing value-added ratio width", manufacturing water withdrawal), {million m3}

animal average life[livestock]=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B133'), {Year} animal birth rate[livestock]=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B132'), {heads/Year}

animal births[beef]=IF THEN ELSE(Time<2012, animal birth rate[beef]*Animal Populations[beef] , (animal birth rate[beef]-0.035)*Animal Populations[beef]), heads/Year

animal births[chickens]=IF THEN ELSE(Time<2012, animal birth rate[chickens]*Animal Populations[chickens] , (animal birth rate[chickens]-0.01)*Animal Populations[chickens]), heads/Year

animal births[dairy]=IF THEN ELSE(Time<2012, animal birth rate[dairy]*Animal Populations[dairy] , (animal birth rate[dairy]-0.06)*Animal Populations[dairy]), heads/Year

animal births[pigs]=IF THEN ELSE(Time<2012,animal birth rate[pigs]*Animal Populations[pigs] , (animal birth rate[pigs]-0.03)*Animal Populations[pigs]), heads/Year

Animal Populations[livestock]= INTEG (animal births[livestock]-animal sales[livestock],initial animal populations[livestock]), {heads}

animal sales[livestock]=Animal Populations[livestock]/animal average life[livestock]+prescribed stock number reduction[livestock], {heads/Year}

annual gas production=conventional gas extraction+hydraulic fracturing gas extraction, {m3}

annual municipal water demand by category[municipal subsectors]=per capita daily y municipal water demand by category[municipal subsectors]*Bow Population*365/1000, {m*m*m/Year}

annual municipal water withdrawal by category[municipal subsectors]=annual municipal water demand by category[municipal subsectors]/water treatment plant efficiency, {m*m*m/Year}

annual oil production=conventional oil extraction+hydraulic fracking oil extraction, {m3}

average conventional gas well retirement rate=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B51'), {Dmnl}

average conventional oil well retirement rate=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B120'), {Dmnl}

average fracking gas well retirement rate=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B52'), {Dmnl}

average fracking oil well retirement rate=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B121'), {Dmnl}

average gas well production rate= INTEG (gas well production increase-gas well production decrease, initial gas well average production rate), {m3/Year}

average gas well retirement rate=average fracking gas well retirement rate*fraction of fracking gas wells+average conventional gas well retirement rate*(1-fraction of fracking gas wells), {Dmnl}

average life=GET XLS CONSTANTS('?BRSGM', 'population', 'B4'), {Year}

average oil well production rate= INTEG (oil well production rate increase-oil well production rate decrease, initial oil well average production rate), {m3/Year}

average oil well retirement rate=average fracking oil well retirement rate*fraction of fracking oil production+average conventional oil well retirement rate*(1-fraction of fracking oil production), {Dmnl} average summer pool price=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B179'), {$/MWh}

average winter pool price=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'C179'), {$/MWh}

base adoption rate of low flow technologies[municipal subsectors]=GET XLS CONSTANTS('?BRSGM', 'municipal', 'B10'), {Dmnl}

base adoption rate of rain barrels=GET XLS CONSTANTS('?BRSGM', 'municipal', 'B12'), {Dmnl}

base decrease rate of leaks with leaks management[municipal subsectors]=GET XLS CONSTANTS('?BRSGM', 'municipal', 'B14'), {Dmnl}

base education water saving[municipal subsectors]=GET XLS CONSTANTS('?BRSGM', 'municipal', 'B18'), {liters/(person*day)}

base increase rate of metering[municipal subsectors]=GET XLS CONSTANTS('?BRSGM', 'municipal', 'B11'), {Dmnl}

base increased rate of low flow appliance adoption with incentive[municipal subsectors]=GET XLS CONSTANTS('?BRSGM', 'municipal', 'B16'), {Dmnl}

base increased rate of treatment plant efficiency with upgrades=GET XLS CONSTANTS('?BRSGM', 'municipal', 'B19'), {fraction}

base irrigation expansion rate=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B3'), {Dmnl}

base per capita daily y municipal water demand by category[municipal subsectors]=GET XLS CONSTANTS('?BRSGM', 'municipal', 'B3'), {liters/(person*day)}

base rain barrel increase rate from incentive=GET XLS CONSTANTS('?BRSGM', 'municipal', 'B17'), {fraction}

basin water consumption=municipal water consumption+agricultural water consumption+industrial water consumption, {MCM}

basin water demand=agricultural water demand+industrial water demand+municipal water demand+environmental and downstream water demand, {MCM}

basin water requirement=basin water consumption+environmental and downstream water demand, {MCM}

basin water supply=stream flow+hydro reservoir drawdown, {MCM}

basin water withdrawal demand=basin water demand-environmental and downstream water demand, {MCM}

basin water withdrawal license=GET XLS CONSTANTS('? BRSGM input' , 'supply' ,'B13'), {MCM}

basin water withdrawal=municipal water withdrawal+agricultural water withdrawal+industrial water withdrawal, {MCM}

birth rate=GET XLS CONSTANTS('?BRSGM', 'population', 'B3'), {Dmnl}

Bow hydro power generation=estimated Bow hydro power generation, {kwh}

Bow Population=IF THEN ELSE(Time<=2015 , Calgary Population+other regions population , (Calgary Population+other regions population)*(1+change in population growth rate)), {person}

Calgary annual water demand=per capita daily y municipal water demand*Calgary Population*365/1e+006, {ML}

Calgary annual water withdrawal=SUM(actual annual municipal water withdrawal by category[municipal subsectors!])/Bow Population*Calgary Population/1000, {ML}

Calgary average summer temp: INTERPOLATE::=GET XLS DATA('? BRSGM input' , 'municipal' , '35', 'B40'), {degree}

Calgary last year average summer temp= DELAY FIXED (Calgary average summer temp, 1, 15.53)

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

Calgary summer temp percentage change=(Calgary average summer temp-Calgary last year average summer temp)/Calgary last year average summer temp, {fraction}

change in manufacturing increase rate= GAME (0), {Dmnl}

change in population growth rate= GAME (0), {Dmnl}

change utilization rate of gas hydraulic fracturing= GAME (0)

change utilization rate of oil hydraulic fracturing= GAME (0)

climate change impact factor= GAME (0)

compensation amount=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B140'), {$/head}

constant grey water and reuse multipliers[municipal subsectors]=GET XLS CONSTANTS('?BRSGM', 'municipal', 'B13'), {Dmnl}

constant xeriscaping multipliers=GET XLS CONSTANTS('?BRSGM', 'municipal', 'B15')

conventional gas extraction water demand=conventional gas extraction*conventional gas extraction water use efficiency, {m3}

conventional gas extraction water use efficiency=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B56'), {m3/m3}

conventional gas extraction=gas extraction capacity*gas capacity utilization*(1-fraction of fracking gas wells), {m3/Year}

conventional oil extraction water demand=conventional oil extraction*conventional oil extraction water use efficiency, {m3}

conventional oil extraction water use efficiency=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B58'), {m3/m3}

conventional oil extraction=oil extraction capacity*oil capacity utilization*(1-fraction of fracking oil production), {m3/Year}

cooling system changes= GAME (0)

cooling system: once through, cooling pond, cooling tower

crop price[representative crop]=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B121'), {$/ton}

crop type to representative crop ratio[representative crop]=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B18'), {Dmnl} crop type:GET XLS SUBSCRIPT('? BRSGM input', 'Agriculture', 'A35', 'A38', ''), {Dmnl}

crop water application priority[representative crop]=water value[representative crop], {Dmnl}

crop water application width=VMAX(crop water application priority[representative crop!]), {Dmnl}

crude oil established reserves= INTEG (oil extractable resources-conventional oil extraction-hydraulic fracking oil extraction,initial oil reserves), {m3}

cumulative year of gas technology improvement= INTEG ("gas-increase of cumulative year", 0), {years}

cumulative year of oil technology improvement= INTEG ("oil-increase of cumulative year",0), {years}

current irrigation delivery system efficiency=IF THEN ELSE(Time<=2015, MIN(1, initial irrigation delivery system efficiency+(Time-1996)*historical irrigation delivery system efficiency increase rate) , MIN(1,initial irrigation delivery system efficiency+(2015-1996)*historical irrigation delivery system efficiency increase rate+irrigation delivery system efficiency improvement*(Time-2015))), {Dmnl}

current irrigation efficiency=IF THEN ELSE(Time<=2015, MIN(1, initial irrigation efficiency+irrigation efficiency increase rate*(Time-1996)) , MIN(1, initial irrigation efficiency+irrigation efficiency increase rate*((2015-1996)+(Time-2015)*irrigation efficiency improvement))), {Dmnl}

current manufacturing value added ratio[manufacturing subsectors]= INTEG (manufacturing value added ratio increase[manufacturing subsectors],initial manufacturing value added ratio[manufacturing subsectors]), {$/m3}

delay of education= DELAY FIXED (education, 1, 0)

delay of grey water treatment and water reuse= DELAY FIXED (grey water treatment and water reuse, 1 , 0)

delay of incentive= DELAY FIXED (incentive, 1, 0)

delay of leaks management= DELAY FIXED (leaks management, 1, 0)

delay of upgrades= DELAY FIXED (water treatment plant upgrades,1,0)

delay of xeriscaping= DELAY FIXED (xeriscaping water use reduction,1,0)

downstream water demand=stream flow*0.5, {MCM}

downstream water supply=stream flow-hydro power water consumption+hydro reservoir drawdown, {MCM}

dry land area by representative crop[representative crop]=total dry land area*dry land crop mix by representative crop[representative crop], {acre}

Dry Land Area= INTEG (-irrigation expansion-other land types, initial dry land area), {acre}

dry land crop cost[representative crop]=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B123'), {$/ha}

dry land crop mix by representative crop[representative crop]:INTERPOLATE::=GET XLS DATA('? BRSGM input' , 'agriculture' , '6', 'B45'), {Dmnl}

dry land ETa[alfalfa]=MIN(dry land plant available water[alfalfa], ETc[alfalfa])

dry land ETa[barley]=MIN(dry land plant available water[barley], ETc[barley])

dry land ETa[beans]=0

dry land ETa[canola]=MIN(dry land plant available water[canola], ETc[canola])

dry land ETa[other crops]=0, {mm}

dry land ETa[potatoes]=0

dry land ETa[sugar beets]=0

dry land ETa[tame pasture]=MIN(dry land plant available water[tame pasture], ETc[tame pasture])

dry land ETa[wheat]=MIN(dry land plant available water[wheat], ETc[wheat])

dry land margin[representative crop]=unit dry land yield[representative crop]*crop price[representative crop]-dry land crop cost[representative crop], {$/ha}

dry land plant available water[representative crop]=Dry Land Soil Moisture[representative crop]-wilting point[representative crop]+growing season precipitation, {mm}

Dry Land Soil Moisture[representative crop]= INTEG (dry soil moisture increase-dry soil moisture decrease[representative crop],initial soil moisture[representative crop]), {mm}

dry soil moisture decrease[representative crop]=dry land ETa[representative crop], {mm/Year}

dry soil moisture increase=growing season precipitation+"non-growing season precipitation", {mm/Year}

Economic Index=(agricultural profit sustainability+hydro power profit sustainability+manufacturing revenue sustainability+mining profit sustainability+oil and gas revenue sustainability+recreational revenue sustainability, {Dmnl}

education application:=GET XLS DATA('? BRSGM input' , 'municipal' , '36', 'B42'), {Dmnl}

education water saving= GAME (base education water saving[outdoor]), {liters/(person*day)}

education= GAME (0), {Dmnl}

effect of municipal water deficiency on adoption of rain barrels=GET XLS LOOKUPS('?BRSGM', 'municipal' , '29' , 'B30'), {Dmnl}

effect of municipal water deficiency on adoption rate of low flow appliances(GET XLS LOOKUPS('?BRSGM', 'municipal' , '23' , 'B24')), {Dmnl}

effect of municipal water deficiency on increase of metering rate=GET XLS LOOKUPS('?BRSGM', 'municipal' , '26' , 'B27'), { fraction }

environmental and downstream water demand=MAX(environmental water demand, downstream water demand), {MCM}

Environmental Index=environmental sustainability, {Dmnl}

environmental sustainability=IF THEN ELSE(flow at basin mouth/environmental and downstream water demand>=1, 1 , flow at basin mouth/environmental and downstream water demand), {Dmnl}

environmental water demand=stream flow*WCO requirement, {MCM}

estimated Bow gas production:=GET XLS DATA('? BRSGM input' , 'industry' , '38', 'B100'), {m3}

estimated Bow hydro power generation:=GET XLS DATA('? BRSGM input' , 'industry' , '38', 'B178'), {kwh}

estimated Bow oil and gas water consumption:=GET XLS DATA('? BRSGM input' , 'industry' , '38', 'B141'), {million m3} estimated Bow oil production:=GET XLS DATA('? BRSGM input' , 'industry' , '38', 'B77'), {m3}

estimated dry land area by representative crop[representative crop]:=GET XLS DATA('? BRSGM input' , 'agriculture' , '6', 'B56'), {acre}

estimated dry land area:=GET XLS DATA('? BRSGM input' , 'agriculture' , '6', 'B65'), {acre}

estimated dry land yield[barley]:INTERPOLATE::=GET XLS DATA('? BRSGM input' , 'agriculture' , '6', 'B98') , {ton/ha}

estimated dry land yield[canola]:=GET XLS DATA('? BRSGM input' , 'agriculture' , '6', 'B102'), {ton/ha}

estimated dry land yield[wheat]:=GET XLS DATA('? BRSGM input' , 'agriculture' , '6', 'B99'), {ton/ha}

estimated irrigated area by crop type[crop type]:=GET XLS DATA('? BRSGM input' , 'agriculture' , '6', 'B35'), {acre}

estimated irrigated area by representative crop[representative crop]:=GET XLS DATA('? BRSGM input' , 'agriculture' , '6', 'B25'), {acre}

estimated irrigation withdrawal:=GET XLS DATA('? BRSGM input' , 'agriculture' , '6', 'B85'), {MCM}

estimated irrigation yield[barley]:INTERPOLATE::=GET XLS DATA('? BRSGM input' , 'agriculture' , '6', 'B88'), {ton/ha}

estimated irrigation yield[beans]:=GET XLS DATA('? BRSGM input' , 'agriculture' , '6', 'B93'), {ton/ha}

estimated irrigation yield[canola]:=GET XLS DATA('? BRSGM input' , 'agriculture' , '6', 'B92'), {ton/ha}

estimated irrigation yield[potatoes]:=GET XLS DATA('? BRSGM input' , 'agriculture' , '6', 'B94'), {ton/ha}

estimated irrigation yield[sugar beets]:=GET XLS DATA('? BRSGM input' , 'agriculture' , '6', 'B95'), {ton/ha}

estimated irrigation yield[wheat]:=GET XLS DATA('? BRSGM input' , 'agriculture' , '6', 'B89'), {ton/ha}

estimated total irrigated land area:INTERPOLATE::=GET XLS DATA('? BRSGM input' , 'agriculture' , '6', 'B5'), {acre}

ETc[representative crop]=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B72'), {mm}

Falkenmark Threshold=1000, {m3/(person*Year)}

Falkenmark=basin water supply*1e+006/Bow Population, {m3/person/Year}

FLAG grey water treatment and reuse=SAMPLE IF TRUE(delay of grey water treatment and water reuse=1, 1, 0), {Dmnl}

FLAG leaks management=MAX(delay of leaks management, leaks management application), {Dmnl}

FLAG xeriscaping=SAMPLE IF TRUE(delay of xeriscaping=1,1,0)

FLGA education=MAX(delay of education , education application), {Dmnl}

FLGA incentive=MAX(delay of incentive, incentive application), {Dmnl}

FLGA upgrades=MAX(delay of upgrades, upgrades application), {Dmnl}

flow at basin mouth=basin water supply-basin water consumption, {MCM}

fracking gas extraction water demand=hydraulic fracturing gas extraction*hydraulic fracturing gas extraction water use efficiency, {m3}

fracking oil extraction water demand=hydraulic fracking oil extraction*hydraulic fracking oil extraction water use efficiency, {m3}

fraction of fracking gas wells=initial fraction of fracking gas production+increase of fraction of fracking gas wells from technology improvement, {Dmnl}

fraction of fracking oil production=increase of fraction of fracking oil production from technology improvement+initial fraction of fracking oil production, {Dmnl}

fractional manufacturing revenue reduction by subsectors[manufacturing subsectors]=manufacturing revenue reduction by subsectors[manufacturing subsectors]/max manufacturing revenue by subsectors[manufacturing subsectors], {Dmnl}

fractional manufacturing revenue reduction=manufacturing revenue reduction/SUM(max manufacturing revenue by subsectors[manufacturing subsectors!]), { Dmnl}

fractional mining profit reduction by category[mining]=(max mining profit by category[mining]-actual mining profit by category[mining])/max mining profit by category[mining], {Dmnl}

fractional mining profit reduction=(SUM(max mining profit by category[mining!])-SUM(actual mining profit by category[mining!]))/SUM(max mining profit by category[mining!]), {Dmnl}

gas average supply cost=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B93'), {$/m3}

gas capacity utilization="gas price-capacity utilization lookup"(gas price)*(1-"last year fraction oil & gas production reduction"*0.2), {Dmnl}

gas cumulative technology improvement=gas technology improvement, {Dmnl}

gas discovery:=GET XLS DATA('? BRSGM input' , 'industry' , '38', 'B102'), {m3/Year}

gas established reserves= INTEG (gas extractable resources-conventional gas extraction-hydraulic fracturing gas extraction, initial gas reserves), {m3}

gas extractable resources=gas discovery*(1+0.8*change utilization rate of gas hydraulic fracturing), {m3/Year}

gas extraction capacity=average gas well production rate*"# of gas wells", {m3/Year}

gas extraction water demand=conventional gas extraction water demand+fracking gas extraction water demand, {m3}

gas extraction water value=gas revenue/conventional gas extraction water use efficiency, {$/m3}

gas extraction water withdrawal="oil & gas extraction water withdrawal by category"[gas], {million m3}

gas price=IF THEN ELSE(Time<=2015, historical gas price , IF THEN ELSE(Time=2040, "2040 gas price", historical gas price+("2040 gas price"-historical gas price)/(2040-2015)*(Time-2015\))), {$/m3}

gas production decline rate=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B133'), {Dmnl}

gas revenue=gas price-gas average supply cost, {$/m3} gas technology improvement selection= INTEG (gas cumulative technology improvement,0), {Dmnl}

gas technology improvement: INTERPOLATE::=GET XLS DATA('? BRSGM input' , 'industry' , '38', 'B84'), {Dmnl}

gas well production decrease=average gas well production rate*gas production decline rate, {m3/Year}

gas well production increase=average gas well production rate*(increase of gas well production rate from technology improvement+0.01*change utilization rate of gas hydraulic fracturing), {m3/Year}

gas well retirement="# of gas wells"*average gas well retirement rate, {well/Year}

grey water treatment and water reuse= GAME (0), {Dmnl}

gross irrigation application[representative crop]=(total irrigation application by crop[representative crop]*1e+006)/(irrigation area by representative crop[representative crop]*4046.86)*1000, {mm}

gross irrigation diversion=net irrigation diversion/current irrigation delivery system efficiency, {MCM}

gross irrigation requirement[representative crop]=(net irrigation requirement[representative crop]/1000*irrigation area by representative crop[representative crop]*4046.86)/current irrigation efficiency/1e+006, {MCM}

gross revenue loss by livestock type[livestock]=per animal gross revenue loss[livestock]*prescribed stock number reduction[livestock], {$}

growing season precipitation:INTERPOLATE::=GET XLS DATA('? BRSGM input' , 'agriculture' , '6', 'B20'), {mm}

historical gas price:=GET XLS DATA('? BRSGM input' , 'industry' , '38', 'B92'), {$/m3}

historical irrigation crop mix by representative crop[representative crop]:INTERPOLATE::=GET XLS DATA('? BRSGM input' , 'agriculture' , '6', 'B7'), {Dmnl}

historical irrigation delivery system efficiency increase rate=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B83'), {Dmnl}

historical oil price:=GET XLS DATA('? BRSGM input' , 'industry' , '38', 'B111'), {$/m3}

hydraulic fracking oil extraction water use efficiency=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B61'), {m3/m3}

hydraulic fracking oil extraction=oil extraction capacity*oil capacity utilization*MIN((fraction of fracking oil production+0.5*change utilization rate of oil hydraulic fracturing),1), {m3}

hydraulic fracturing gas extraction water use efficiency=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B64'), {m3/m3}

hydraulic fracturing gas extraction=gas extraction capacity*gas capacity utilization*MIN((fraction of fracking gas wells+0.5*change utilization rate of gas hydraulic fracturing),1), {m3/Year}

hydro power consumption efficiency=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B177'), {m3/kwh}

hydro power generation demand=supply hydro power lookup table(stream flow), {MWh}

hydro power generation efficiency=hydro power generation demand/stream flow, {MWh/MCM}

hydro power profit loss=hydro power generation efficiency*hydro reservoir drawdown*(average winter pool price-average summer pool price), {$}

hydro power profit sustainability=1-(hydro power profit loss/(average summer pool price*summer power generation+average winter pool price*winter power generation)), {Dmnl}

hydro power water consumption=actual hydro power generation*hydro power consumption efficiency/1000, {MCM}

hydro reservoir drawdown= GAME (0), {MCM}

hydro reservoir recreational value loss=hydro reservoir drawdown*1e+006*reservoir park recreational water value, {$}

IBWSI weight: economic, social, environmental

IBWSI weights[IBWSI weight]=GET XLS CONSTANTS('?BRSGM', 'IBWSI', 'B2')

IBWSI=Social Index*IBWSI weights [social]+Economic Index*IBWSI weights[economic]+Environmental Index*IBWSI weights[environmental], {Dmnl}

incentive application:=GET XLS DATA('? BRSGM input' , 'municipal' , '36', 'B45'), {Dmnl}

incentive= GAME (0), {Dmnl}

increase of fraction of fracking gas wells from technology improvement="technology improvement-increase of fraction of fracking gas production lookup"(cumulative year of gas technology improvement), {Dmnl}

increase of fraction of fracking oil production from technology improvement="technology improvement-increase of fraction of fracking oil production lookup"(cumulative year of oil technology improvement), {Dmnl}

increase of gas well production rate from technology improvement="technology improvement-increase of gas well production rate lookup"(cumulative year of gas technology improvement), {Dmnl}

increase of metering rate[municipal subsectors]=base increase rate of metering[municipal subsectors]+effect of municipal water deficiency on increase of metering rate(municipal water percentage deficiency), {Dmnl}

increase of oil well production rate from technology improvement="technology improvement-increase of oil well production rate lookup"(cumulative year of oil technology improvement), {Dmnl}

increase of oil wells from technology improvement="technology improvement-increase of oil wells lookup"(cumulative year of oil technology improvement), {Dmnl}

increase rate of low flow appliance adoption with incentive[bath]=FLGA incentive*IF THEN ELSE(base increased rate of low flow appliance adoption with incentive[toilet]=low flow increase rate with incentive, base increased rate of low flow appliance adoption with incentive[bath] , low flow increase rate with incentive)

increase rate of low flow appliance adoption with incentive[ici]=FLGA incentive*IF THEN ELSE(base increased rate of low flow appliance adoption with incentive[toilet]=low flow increase rate with incentive, base increased rate of low flow appliance adoption with incentive[ici] , low flow increase rate with incentive)

increase rate of low flow appliance adoption with incentive[kitchen]=FLGA incentive*IF THEN ELSE(base increased rate of low flow appliance adoption with incentive[toilet]=low flow increase rate with incentive, base increased rate of low flow appliance adoption with incentive\[kitchen] , low flow increase rate with incentive) increase rate of low flow appliance adoption with incentive[laundry]=FLGA incentive*IF THEN ELSE(base increased rate of low flow appliance adoption with incentive[toilet]=low flow increase rate with incentive, base increased rate of low flow appliance adoption with incentive[laundry] , low flow increase rate with incentive)

increase rate of low flow appliance adoption with incentive[leaks]=FLGA incentive*base increased rate of low flow appliance adoption with incentive[leaks]

increase rate of low flow appliance adoption with incentive[nonrevenue]=FLGA incentive*base increased rate of low flow appliance adoption with incentive[nonrevenue]

increase rate of low flow appliance adoption with incentive[other]=FLGA incentive*base increased rate of low flow appliance adoption with incentive[other]

increase rate of low flow appliance adoption with incentive[outdoor]=FLGA incentive*base increased rate of low flow appliance adoption with incentive[outdoor]

increase rate of low flow appliance adoption with incentive[outside city]=FLGA incentive*base increased rate of low flow appliance adoption with incentive[outside city], {Dmnl}

increase rate of low flow appliance adoption with incentive[toilet]=FLGA incentive*MAX(base increased rate of low flow appliance adoption with incentive[toilet],low flow increase rate with incentive)

increase rate of rain barrel adoption with incentive=FLGA incentive*MAX(base rain barrel increase rate from incentive, rain barrel increase rate with incentive), {fraction}

increase rate of treatment plant efficiency with upgrades=FLGA upgrades*MAX(base increased rate of treatment plant efficiency with upgrades, water plant efficiency increase rate with plant upgrades), {fraction}

industrial water allocation by category[industry]=ALLOCATE BY PRIORITY(industrial water demand by category[industry], industry water use priority[industry], ELMCOUNT(industry), industry water use width, industrial water allocation), {MCM}

industrial water allocation= GAME (industrial water license), {MCM}

industrial water consumption=hydro power water consumption+thermal power water consumption+manufacturing water consumption+mining water consumption+"oil & gas extraction water consumption", {MCM}

industrial water demand by category[manufacturing water]=manufacturing water demand, {MCM}

industrial water demand by category[mining water]=total mining water demand, {MCM}

industrial water demand by category[oil gas water]="total oil & gas extraction water demand" , {MCM}

industrial water demand by category[power water]=thermal power water demand, {MCM}

industrial water demand=SUM(industrial water demand by category[industry!]), {MCM}

industrial water license=GET XLS CONSTANTS('?BRSGM', 'supply', 'B12'), {MCM}

industrial water withdrawal=manufacturing water withdrawal+mining water withdrawal+"oil & gas extraction water withdrawal"+thermal power water withdrawal, {MCM}

industry water use priority[industry]=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B190'), {Dmnl} industry water use width=VMAX(industry water use priority[industry!]), {Dmnl}

industry:GET XLS SUBSCRIPT('? BRSGM input', 'Industry', 'B189', 'E189', ''), {Dmnl}

initial animal populations[livestock]=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B131'), {heads}

initial Calgary population=GET XLS CONSTANTS('?BRSGM', 'population', 'B2'), {person}

initial dry land area=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B41'), {acre}

initial fraction of fracking gas production=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B74'), {Dmnl}

initial fraction of fracking oil production=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B73'), {Dmnl}

initial gas reserves=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B48'), {m3}

initial gas well average production rate=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B132'), {m3/Year}

initial irrigation area=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B2'), {acre}

initial irrigation delivery system efficiency=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B82'), {Dmnl}

initial irrigation efficiency=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B80'), {Dmnl}

initial manufacturing revenue by subsectors[high value added]=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B4')

initial manufacturing revenue by subsectors[low value added]=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B6'), {Million $}

initial manufacturing revenue by subsectors[medium value added]=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B5')

initial manufacturing value added ratio[high value added]=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B14')

initial manufacturing value added ratio[low value added]=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B16'), {$/m3}

initial manufacturing value added ratio[medium value added]=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B15')

initial mining production[mining]=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B162'), {ton}

initial oil reserves=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B42'), {m3}

initial oil well average production rate=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B129'), {m3/Year}

initial percentage of homes metered[municipal subsectors]=GET XLS CONSTANTS('?BRSGM', 'municipal', 'B5'), {Dmnl}

initial percentage of homes with low flow appliances[municipal subsectors]=GET XLS CONSTANTS('?BRSGM', 'municipal', 'B4'), {Dmnl} initial percentage of homes with rain barrels=GET XLS CONSTANTS('?BRSGM', 'municipal', 'B6'), {Dmnl}

initial soil moisture[representative crop]=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B79'), {mm}

initial thermal power generation increase rate=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B182'), {Dmnl}

initial thermal power generation=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B180'), {MWh}

initial water treatment plant efficiency=GET XLS CONSTANTS('?BRSGM', 'municipal', 'B34'), {Dmnl}

investment decrease impact on new wells:=GET XLS DATA('? BRSGM input' , 'industry' , '38', 'B70')"last year fraction oil & gas production reduction"= DELAY FIXED ("fractional oil & gas production reduction", 1, 0), {Dmnl}

irrigation area by crop type[cereal]=irrigation area by representative crop[barley]+irrigation area by representative crop[wheat]+irrigation area by representative crop[other crops]*0.15

irrigation area by crop type[forage]=irrigation area by representative crop[alfalfa]+irrigation area by representative crop[tame pasture]+irrigation area by representative crop[other crops]*0.5

irrigation area by crop type[oilseed]=irrigation area by representative crop[canola]+irrigation area by representative crop[other crops]*0.1

irrigation area by crop type[specialty]=irrigation area by representative crop[beans]+irrigation area by representative crop[potatoes]+irrigation area by representative crop[sugar beets]+irrigation area by representative crop[other crops]*0.25, {acre}

irrigation area by representative crop[representative crop]=actually irrigated area*irrigation crop mix by representative crop[representative crop], {acre}

Irrigation Area= INTEG (irrigation expansion, initial irrigation area), {acre}

irrigation crop mix by representative crop[representative crop]=IF THEN ELSE(Time>2012, IF THEN ELSE(Time=2040 , "2040 irrigation crop mix by representative crop"[representative crop] , historical irrigation crop mix by representative crop[representative crop]+("2040 irrigation crop mix by representative crop"[representative crop]-historical irrigation crop mix by representative crop[representative crop])/(2040-2012)*(Time-2012)),historical irrigation crop mix by representative crop[representative crop]), {faction}

irrigation delivery system efficiency improvement= GAME (0), {Dmnl}

irrigation efficiency improvement= GAME (0), {Dmnl}

irrigation efficiency increase rate=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B81'), {Dmnl}

irrigation ETa[representative crop]=MIN(irrigation plant available water[representative crop], ETc[representative crop]), {mm}

irrigation expansion limits=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B4'), {acre}

irrigation expansion rate= GAME (base irrigation expansion rate), {Dmnl} irrigation expansion=IF THEN ELSE(Irrigation Area*(1+irrigation expansion rate)<=irrigation expansion limits, irrigation expansion rate*Irrigation Area , irrigation expansion limits-Irrigation Area), {acre/Year}

irrigation land crop cost[representative crop]=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B122'), {$/ha}

irrigation land margin by representative crop[representative crop]=unit irrigation land margin by representative crop[representative crop]*irrigation area by representative crop[representative crop]*0.4047, {$}

irrigation land margin=SUM(irrigation land margin by representative crop[representative crop!]), {$}

Irrigation Land Soil Moisture[representative crop]= INTEG (irrigation soil moisture increase[representative crop]-irrigation soil moisture decrease[representative crop],initial soil moisture[representative crop]), {mm}

irrigation plant available water[representative crop]=Irrigation Land Soil Moisture[representative crop]-wilting point[representative crop]+net irrigation application[representative crop]+growing season precipitation, {mm}

irrigation reservoir drawdown= GAME (0), {MCM}

irrigation reservoir recreational value loss=irrigation reservoir drawdown*1e+006*reservoir park recreational water value, {$}

irrigation soil moisture decrease[representative crop]=irrigation ETa[representative crop], {mm/Year}

irrigation soil moisture increase[representative crop]=net irrigation application[representative crop]+growing season precipitation+"non-growing season precipitation", {mm/Year}

irrigation water allocation= GAME (irrigation water license), {MCM}

irrigation water consumption=irrigation water withdrawal*(1-return rate), {MCM}

irrigation water license=GET XLS CONSTANTS('?BRSGM', 'supply', 'B10'), {MCM}

irrigation water withdrawal=MIN(gross irrigation diversion, irrigation water allocation), {MCM}

ky[representative crop]=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B71'), {Dmnl}

leaks decrease rate with leaks management= GAME (base decrease rate of leaks with leaks management[leaks]), {fraction}

leaks management application:=GET XLS DATA('? BRSGM input' , 'municipal' , '36', 'B43'), {Dmnl}

leaks management= GAME (0), {Dmnl}

livestock grain ration requirements[livestock]=per head stock grain ration requirements[livestock]*Animal Populations[livestock], {ton}

livestock gross revenue loss=SUM(gross revenue loss by livestock type[livestock!])-SUM(reduction in stock numbers[livestock!])*compensation amount*stock reduction compensation, {$}

livestock roughage requirements[livestock]=per head stock roughage requirements[livestock]*Animal Populations[livestock], {ton}

livestock surface water requirements=livestock water requirements*surface water ratio, {MCM}

livestock water license=GET XLS CONSTANTS('?BRSGM', 'supply', 'B11'), {MCM} livestock water requirements by type[livestock]=per head stock water requirements[livestock]*Animal Populations[livestock], {m3}

livestock water requirements=SUM(livestock water requirements by type[livestock!])/1e+006, {MCM}

livestock: GET XLS SUBSCRIPT('? BRSGM input', 'Agriculture', 'B130', 'E130', '')

low flow appliance change rate[municipal subsectors]=IF THEN ELSE(Percentage of Houses with Low Flow Appliances[municipal subsectors]<1, IF THEN ELSE(Percentage of Houses with Low Flow Appliances[municipal subsectors]+adoption rate of low flow technologies[municipal subsectors]<1,adoption rate of low flow technologies[municipal subsectors], 1-Percentage of Houses with Low Flow Appliances[municipal subsectors]),0), {Dmnl}

low flow increase rate with incentive= GAME (base increased rate of low flow appliance adoption with incentive[toilet]), {fraction}

manufacturing GDP annual growth rate[high value added]=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B9')

manufacturing GDP annual growth rate[low value added]=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B11'), {Million $/Year}

manufacturing GDP annual growth rate[medium value added]=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B10')

manufacturing revenue decrease[high value added]=0

manufacturing revenue decrease[low value added]=0.2*fractional manufacturing revenue reduction*max manufacturing revenue by subsectors[low value added], {Million $/Year}

manufacturing revenue decrease[medium value added]=0

manufacturing revenue increase[high value added]=(max manufacturing revenue by subsectors[high value added]*manufacturing GDP annual growth rate[high value added]+0.2*fractional manufacturing revenue reduction*max manufacturing revenue by subsectors[low value added]*0.6)*(1+change in manufacturing increase rate), {Million $/Year}

manufacturing revenue increase[low value added]=(max manufacturing revenue by subsectors[low value added]*manufacturing GDP annual growth rate[low value added])*(1+change in manufacturing increase rate), {Million $/Year}

manufacturing revenue increase[medium value added]=(max manufacturing revenue by subsectors[medium value added]*manufacturing GDP annual growth rate[medium value added]+0.2*fractional manufacturing revenue reduction*max manufacturing revenue by subsectors[low value added]*0.4)*(1+change in manufacturing increase rate), {Million $/Year}

manufacturing revenue reduction by subsectors[manufacturing subsectors]=IF THEN ELSE(ABS(max manufacturing revenue by subsectors[manufacturing subsectors]-actual manufacturing revenue by subsectors[manufacturing subsectors])<0.01, 0 , (max manufacturing revenue by subsectors[manufacturing subsectors]-actual manufacturing revenue by subsectors[manufacturing subsectors])), {Million $}

manufacturing revenue reduction=SUM(manufacturing revenue reduction by subsectors[manufacturing subsectors!]), {Million $}

manufacturing revenue sustainability=1-fractional manufacturing revenue reduction, {Dmnl}

manufacturing subsectors: high value added, medium value added, low value added manufacturing value added ratio increase[manufacturing subsectors]=current manufacturing value added ratio[manufacturing subsectors]*manufacturing value added ratio trend[manufacturing subsectors]+current manufacturing value added ratio[manufacturing subsectors]*value added ratio improvement[manufacturing subsectors], {$/(m3*Year)}

manufacturing value added ratio trend[high value added]:INTERPOLATE::=GET XLS DATA('? BRSGM input' , 'industry' , '3', 'B19')

manufacturing value added ratio trend[low value added]:=GET XLS DATA('? BRSGM input' , 'industry' , '3', 'B21'), {Dmnl}

manufacturing value added ratio trend[medium value added]:=GET XLS DATA('? BRSGM input' , 'industry' , '3', 'B20')

manufacturing water allocation=industrial water allocation by category[manufacturing water], {MCM}

manufacturing water consumption rate[high value added]=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B24')

manufacturing water consumption rate[low value added]=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B26'), {Dmnl}

manufacturing water consumption rate[medium value added]=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B25')

manufacturing water consumption=SUM(actual manufacturing water consumption by subsectors[manufacturing subsectors!]), {million m3}

manufacturing water demand by subsectors[manufacturing subsectors]=max manufacturing revenue by subsectors[manufacturing subsectors]/current manufacturing value added ratio[manufacturing subsectors], {million m3}

manufacturing water demand=SUM(manufacturing water demand by subsectors[manufacturing subsectors!]), {MCM}

manufacturing water return=manufacturing water withdrawal-manufacturing water consumption, {million m3}

manufacturing water withdrawal=MIN(manufacturing water allocation, manufacturing water demand), {million m3}

max irrigation land margin by crop[representative crop]=(Ym[representative crop]*(1-yield reduction factor[representative crop])*crop price[representative crop]-irrigation land crop cost[representative crop])*irrigation area by representative crop[representative crop]*0.4047, {$}

max irrigation land margin=SUM(max irrigation land margin by crop[representative crop!]), {$}

max manufacturing revenue by subsectors[manufacturing subsectors]= INTEG (manufacturing revenue increase[manufacturing subsectors]-manufacturing revenue decrease[manufacturing subsectors],initial manufacturing revenue by subsectors[manufacturing subsectors]), {Million $}

Max Mining Production[mining]=INTEG (mining production increase[mining],initial mining production[mining]), {ton}

max mining profit by category[mining]=Max Mining Production[mining]*mining profit[mining], {$}

mining production increase rate= GAME (0), {Dmnl} mining production increase[mining]=IF THEN ELSE(Time<=2015, IF THEN ELSE(Time=plant expansion year[mining] , plant expansion[mining] , 0) , Max Mining Production[mining]*mining production increase rate), {ton/Year}

mining profit sustainability=1-fractional mining profit reduction, {Dmnl}

mining profit[mining]=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B164'), {$/ton}

mining water allocation=industrial water allocation by category[mining water], {MCM}

mining water consumption by category[mining]=mining water use by category[mining]*mining water consumption rate[mining], {m3}

mining water consumption rate[mining]=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B167'), {Dmnl}

mining water consumption=SUM(mining water consumption by category[mining!])/1e+006, {MCM}

mining water demand by category[mining]=Max Mining Production[mining]*mining water use efficiency[mining], {m3}

mining water return=SUM(mining water use by category[mining!])/1e+006-mining water consumption, {MCM}

mining water use by category[mining]=ALLOCATE BY PRIORITY(mining water demand by category[mining], mining water use priority[mining], ELMCOUNT(mining), mining water use width, mining water withdrawal*1e+006), {m3}

mining water use efficiency[mining]=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B163'), {m3/ton}

mining water use priority[mining]=mining profit[mining]/mining water use efficiency[mining], {$/m3}

mining water use width=VMAX(mining water use priority[mining!]), {Dmnl}

mining water withdrawal=MIN(total mining water demand , mining water allocation), {MCM}

mining: GET XLS SUBSCRIPT('? BRSGM input', 'Industry', 'B161', 'D161', ''), {Dmnl}

municipal demand satisfaction[municipal subsectors]=actual municipal water use by category[municipal subsectors]/annual municipal water demand by category[municipal subsectors], {Dmnl}

municipal subsectors: toilet, bath, laundry, kitchen, leaks, other, outdoor, ici, nonrevenue, outside city

municipal water allocation= GAME (municipal water license), {MCM}

municipal water consumption rate=GET XLS CONSTANTS('?BRSGM', 'municipal', 'B35'), {Dmnl}

municipal water consumption=municipal water withdrawal*municipal water consumption rate, {MCM}

municipal water demand=SUM(annual municipal water withdrawal by category[municipal subsectors!])/1e+006, {MCM}

municipal water license=GET XLS CONSTANTS('?BRSGM', 'supply', 'B9'),{MCM}

municipal water percentage deficiency=MAX(0, (net municipal water demand-municipal water allocation)/municipal water allocation), {Dmnl}

municipal water sustainability=SUM(municipal demand satisfaction[municipal subsectors!])/10 municipal water use priority[municipal subsectors]=GET XLS CONSTANTS('?BRSGM', 'Municipal', 'B32'), {Dmnl}

municipal water use width=GET XLS CONSTANTS('?BRSGM', 'Municipal', 'B33'), {Dmnl}

municipal water withdrawal=SUM(actual annual municipal water withdrawal by category[municipal subsectors!])/1e+006, {MCM}

natural flow at basin mouth: INTERPOLATE::=GET XLS DATA('? BRSGM input' , 'supply' , '1', 'B2'), {MCM}

net irrigation application[representative crop]=gross irrigation application[representative crop]*current irrigation efficiency, {mm}

net irrigation diversion=SUM(gross irrigation requirement[representative crop!]), {MCM}

net irrigation requirement[representative crop]=MAX((ETc[representative crop]-(Irrigation Land Soil Moisture[representative crop]-wilting point[representative crop])-growing season precipitation)+MAX((initial soil moisture[representative crop]-Irrigation Land Soil Moisture[representative crop]),0),0), {mm}

net migration rate=IF THEN ELSE(Time=2009 , "2010 negative net migration" , other years average net migration), {Dmnl}

net municipal water demand=per capita daily y municipal water demand*Bow Population*365/1e+009, {MCM}

new gas well="gas price-new wells lookup"(gas price)*(1-investment decrease impact on new wells)*(1-"last year fraction oil & gas production reduction"*0.2), {well/Year}

new oil well="oil price-drilling lookup"(oil price)*(1+increase of oil wells from technology improvement\)*(1-"last year fraction oil & gas production reduction"*0.2), {well/Year}

not irrigated land=Irrigation Area-actually irrigated area, {acre}

oil & gas extraction water demand by category"[gas]=gas extraction water demand/1e+006, {million m3}

oil and gas revenue sustainability=1-"fractional oil & gas production reduction", {Dmnl}

oil and gas water allocation=industrial water allocation by category[oil gas water], {MCM}

oil average supply cost=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B68'), {$/m3}

oil capacity utilization="oil price-capacity utilization lookup"(oil price)*(1-"last year fraction oil & gas production reduction"*0.2), {Dmnl}

oil cumulative technology improvement=oil technology improvement, {Dmnl}

oil discovery:=GET XLS DATA('? BRSGM input' , 'industry' , '38', 'B79'), {m3/Year}

oil extractable resources=oil discovery*(1+0.8*change utilization rate of oil hydraulic fracturing), {m3/Year}

oil extraction capacity="# of oil wells"*average oil well production rate, {m3}

oil extraction water demand=conventional oil extraction water demand+fracking oil extraction water demand, {m3}

oil extraction water value=oil revenue/conventional oil extraction water use efficiency, {$/m3}

oil extraction water withdrawal="oil & gas extraction water withdrawal by category"[oil], {million m3} oil price=IF THEN ELSE(Time<=2015, historical oil price , IF THEN ELSE(Time=2040, "2040 oil price" , historical oil price+("2040 oil price"-historical oil price)/(2040-2015)*(Time-2015))), {$/m3}

oil revenue=oil price-oil average supply cost, {$/m3}

oil technology improvement selection= INTEG (oil cumulative technology improvement,0), {Dmnl}

oil technology improvement: INTERPOLATE::=GET XLS DATA('? BRSGM input' , 'industry' , '38', 'B122'), {Dmnl}

oil well production rate decrease=average oil well production rate*well production decline rate, {m3/Year}

oil well production rate increase=average oil well production rate*(increase of oil well production rate from technology improvement+0.01*change utilization rate of oil hydraulic fracturing), {m3/Year}

oil well retirement="# of oil wells"*average oil well retirement rate, {well/Year}

other land types ratio=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B42'), {Dmnl}

other land types=Dry Land Area*other land types ratio, {acre}

other regions population=(Calgary Population/ratio of Calgary population to Bow)*(1-ratio of Calgary population to Bow), {person}

other years average net migration=GET XLS CONSTANTS('?BRSGM', 'population', 'B5'), {Dmnl}

per animal gross revenue loss[livestock]=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B135'), {$/head}

per capita daily nonrevenue water demand=per capita daily municipal water demand by category[nonrevenue], {liters/(person*day)}

per capita daily ICI water demand=per capita daily municipal water demand by category[ici], {liters/(person*day)}

per capita daily y municipal water demand by category[bath]=(base per capita daily y municipal water demand by category[bath]*((1-Percentage of Houses with Low Flow Appliances[bath])*1 + Percentage of Houses with Low Flow Appliances[bath]*(1-water use reduction from low flow appliances[bath]))*((1-Percentage of Houses Metered[bath])*1 + Percentage of Houses Metered[bath]*(1-water use reduction from water metering[bath]))*(1-percentage water use reductions from grey water treatment and reuse[bath])*(1-percentage water use reduction from leaks management[bath]))-Percentage of Houses with Rain Barrels*water use reduction from rain barrels[bath]-water use reduction from education[bath] , {liters/(person*day)}

per capita daily y municipal water demand by category[ici]=(base per capita daily y municipal water demand by category[ici]*((1-Percentage of Houses with Low Flow Appliances[ici])*1 + Percentage of Houses with Low Flow Appliances[ici]*(1-water use reduction from low flow appliances[ici]))*((1-Percentage of Houses Metered[ici])*1 + Percentage of Houses Metered[ici]*(1-water use reduction from water metering[ici]))*(1-percentage water use reductions from grey water treatment and reuse[ici])*(1-percentage water use reduction from leaks management[ici]))-Percentage of Houses with Rain Barrels*water use reduction from rain barrels[ici]-water use reduction from education[ici], {liters/(person*day)}

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

Metered[kitchen]*(1-water use reduction from water metering[kitchen]))*(1-percentage water use reductions from grey water treatment and reuse[kitchen])*(1-percentage water use reduction from leaks management[kitchen]))-Percentage of Houses with Rain Barrels*water use reduction from rain barrels[kitchen]-water use reduction from education[kitchen], {liters/(person*day)}

per capita daily y municipal water demand by category[laundry]=(base per capita daily y municipal water demand by category[laundry]*((1-Percentage of Houses with Low Flow Appliances[laundry])*1 + Percentage of Houses with Low Flow Appliances[laundry]*(1-water use reduction from low flow appliances[laundry]))*((1-Percentage of Houses Metered[laundry])*1 + Percentage of Houses Metered[laundry]*(1-water use reduction from water metering[laundry]))*(1-percentage water use reductions from grey water treatment and reuse[laundry])*(1-percentage water use reduction from leaks management[laundry]))-Percentage of Houses with Rain Barrels*water use reduction from rain barrels[laundry]-water use reduction from education[laundry] , {liters/(person*day)}

per capita daily y municipal water demand by category[leaks]=(base per capita daily y municipal water demand by category[leaks]*((1-Percentage of Houses with Low Flow Appliances[leaks])*1 + Percentage of Houses with Low Flow Appliances[leaks]*(1-water use reduction from low flow appliances[leaks]))*((1-Percentage of Houses Metered[leaks])*1 + Percentage of Houses Metered[leaks]*(1-water use reduction from water metering[leaks]))*(1-percentage water use reductions from grey water treatment and reuse[leaks])*(1-percentage water use reduction from leaks management[leaks]))-Percentage of Houses with Rain Barrels*water use reduction from rain barrels[leaks]-water use reduction from education[leaks], {liters/(person*day)}

per capita daily y municipal water demand by category[nonrevenue]=(base per capita daily y municipal water demand by category[nonrevenue]*((1-Percentage of Houses with Low Flow Appliances[nonrevenue])*1 + Percentage of Houses with Low Flow Appliances[nonrevenue]*(1-water use reduction from low flow appliances[nonrevenue]))*((1-Percentage of Houses Metered[nonrevenue])*1 + Percentage of Houses Metered[nonrevenue]*(1-water use reduction from water metering[nonrevenue]))*(1-percentage water use reductions from grey water treatment and reuse[nonrevenue])*(1-percentage water use reduction from leaks management[nonrevenue]))-Percentage of Houses with Rain Barrels*water use reduction from rain barrels[nonrevenue]-water use reduction from education[nonrevenue], {liters/(person*day)}

per capita daily y municipal water demand by category[other]=(base per capita daily y municipal water demand by category[other]*((1-Percentage of Houses with Low Flow Appliances[other])*1 + Percentage of Houses with Low Flow Appliances[other]*(1-water use reduction from low flow appliances[other]))*((1-Percentage of Houses Metered[other])*1 + Percentage of Houses Metered[other]*(1-water use reduction from water metering[other]))*(1-percentage water use reductions from grey water treatment and reuse[other])*(1-percentage water use reduction from leaks management[other]))-Percentage of Houses with Rain Barrels*water use reduction from rain barrels[other]-water use reduction from education[other], {liters/(person*day)}

per capita daily y municipal water demand by category[outdoor]=((base per capita daily y municipal water demand by category[outdoor]*((1-Percentage of Houses with Low Flow Appliances[outdoor])*1 + Percentage of Houses with Low Flow Appliances[outdoor]*(1-water use reduction from low flow appliances[outdoor]))*((1-Percentage of Houses Metered[outdoor])*1 + Percentage of Houses Metered[outdoor]*(1-water use reduction from water metering[outdoor]))*(1-percentage water use reductions from grey water treatment and reuse[outdoor])*(1-percentage water use reduction from leaks management[outdoor]))-Percentage of Houses with Rain Barrels*water use reduction from rain barrels[outdoor]-water use reduction from education[outdoor])*IF THEN ELSE(Time<=2015, 1 , (1+climate change impact factor))*(1-percentage water use reductions from xeriscaping), {liters/(person*day)} per capita daily y municipal water demand by category[outside city]=(base per capita daily y municipal water demand by category[outside city]*((1-Percentage of Houses with Low Flow Appliances[outside city])*1 + Percentage of Houses with Low Flow Appliances[outside city]*(1-water use reduction from low flow appliances[outside city]))*((1-Percentage of Houses Metered[outside city])*1 + Percentage of Houses Metered[outside city\]*(1-water use reduction from water metering[outside city]))*(1-percentage water use reductions from grey water treatment and reuse[outside city])*(1-percentage water use reduction from leaks management[outside city]))-Percentage of Houses with Rain Barrels*water use reduction from rain barrels[outside city]-water use reduction from education[outside city], {liters/(person*day)}

per capita daily y municipal water demand by category[toilet]=(base per capita daily y 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]))*((1-Percentage of Houses Metered[toilet])*1 + Percentage of Houses Metered[toilet]*(1-water use reduction from water metering[toilet]))*(1-percentage water use reductions from grey water treatment and reuse[toilet])*(1-percentage water use reduction from leaks management[toilet]))-Percentage of Houses with Rain Barrels*water use reduction from rain barrels[toilet]-water use reduction from education[toilet] , {liters/(person*day)}

per capita daily y municipal water demand=per capita daily residential water demand+per capita daily ICI water demand+per capita daily nonrevenue water demand+per capita daily outside city water demand, {liters/(person*day)}

per capita daily y municipal water use by category[municipal subsectors]=actual municipal water use by category[municipal subsectors]/Bow Population/365*1000, {liters/(day*person)}

per capita daily y outside city water demand=per capita daily municipal water demand by category[outside city], {liters/(person*day)}

per capita daily y residential water demand=per capita daily y municipal water demand by category[toilet]+per capita daily y municipal water demand by category[bath]+per capita daily y municipal water demand by category[laundry]+per capita daily y municipal water demand by category[kitchen]+per capita daily y municipal water demand by category[leaks]+per capita daily municipal water demand by category[other]+per capita daily y municipal water demand by category[outdoor], {liters/(person*day)}

per head stock grain ration requirements[livestock]=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B137'), {ton/Year}

per head stock roughage requirements[livestock]=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B138'), {ton/Year}

per head stock water requirements[livestock]=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B136'), {m3/head}

Percentage of Houses Metered [municipal subsectors]= INTEG (water metering change rate[municipal subsectors],initial percentage of homes metered[municipal subsectors]), {Dmnl}

Percentage of Houses with Low Flow Appliances[municipal subsectors]= INTEG (low flow appliance change rate[municipal subsectors],initial percentage of homes with low flow appliances[municipal subsectors]), {Dmnl}

Percentage of Houses with Rain Barrels= INTEG (rain barrel change rate, initial percentage of homes with rain barrels), {Dmnl}

percentage of natural flow rate at basin mouth=flow at basin mouth/stream flow, {Dmnl} percentage water use reduction from leaks management[bath]=FLAG leaks management*base decrease rate of leaks with leaks management[bath]

percentage water use reduction from leaks management[ici]=FLAG leaks management*base decrease rate of leaks with leaks management[ici]

percentage water use reduction from leaks management[kitchen]=FLAG leaks management*base decrease rate of leaks with leaks management[kitchen]

percentage water use reduction from leaks management[laundry]=FLAG leaks management*base decrease rate of leaks with leaks management[laundry]

percentage water use reduction from leaks management[leaks]=FLAG leaks management*MAX(base decrease rate of leaks with leaks management[leaks],leaks decrease rate with leaks management\)

percentage water use reduction from leaks management[nonrevenue]=FLAG leaks management*MAX(base decrease rate of leaks with leaks management[nonrevenue],leaks decrease rate with leaks management)

percentage water use reduction from leaks management[other]=FLAG leaks management*base decrease rate of leaks with leaks management[other]

percentage water use reduction from leaks management[outdoor]=FLAG leaks management*base decrease rate of leaks with leaks management[outdoor]

percentage water use reduction from leaks management[outside city]=FLAG leaks management*base decrease rate of leaks with leaks management[outside city], {fraction}

percentage water use reduction from leaks management[toilet]=FLAG leaks management*base decrease rate of leaks with leaks management[toilet]

percentage water use reductions from grey water treatment and reuse[municipal subsectors]=FLAG grey water treatment and reuse*constant grey water and reuse multipliers[municipal subsectors], {fraction}

percentage water use reductions from xeriscaping=constant xeriscaping multipliers*FLAG xeriscaping, {fraction}

permitted municipal water withdrawal=2.5e+008, {m*m*m/Year}

plant expansion year[mining]=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B166'), {Year}

plant expansion[mining]=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B165'), {ton}

population decrease=Calgary Population/average life, {person/Year}

population increase=Calgary Population*(birth rate+net migration rate), {person/Year}

population of Calgary:=GET XLS DATA('? BRSGM input' , 'population' , '11', 'B12'), {person}

power generation sustainability=(IF THEN ELSE(thermal power generation demand=0, 1 , actual thermal power generation/thermal power generation demand)+actual hydro power generation/hydro power generation demand)/2, {Dmnl}

prescribed stock number reduction[livestock]=IF THEN ELSE(promote stocking rate reductions, IF THEN ELSE(Animal Populations[livestock]+animal births[livestock]-(Animal Populations[livestock]/animal average life[livestock])-reduction in stock numbers[livestock]>0, reduction in stock numbers[livestock], Animal Populations[livestock]+animal births[livestock]-(Animal Populations[livestock]/animal average life[livestock])), 0), {heads/Year} promote stocking rate reductions= GAME (0), { Dmnl }

rain barrel change rate=IF THEN ELSE(Percentage of Houses with Rain Barrels<1, IF THEN ELSE(Percentage of Houses with Rain Barrels+adoption rate of rain barrels<1,adoption rate of rain barrels, 1-Percentage of Houses with Rain Barrels),0), {Dmnl}

rain barrel increase rate with incentive= GAME (base rain barrel increase rate from incentive), {fraction}

ratio of Calgary population to Bow=GET XLS CONSTANTS('?BRSGM', 'population', 'B7'), {Dmnl}

recreational revenue sustainability=IF THEN ELSE(1-(recreational value loss/1.8477e+007)<=0 , 0 , 1-(recreational value loss/1.8477e+007)), {Dmnl}

recreational value loss=hydro reservoir recreational value loss+irrigation reservoir recreational value loss, {$}

reduction in stock numbers[livestock]=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B134'), {heads}

relief payout amount=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B125'), {$/ha}

relief payout= GAME (0), {Dmnl}

representative crop: GET XLS SUBSCRIPT('? BRSGM input', 'Agriculture', 'A7', 'A15', ''), {Dmnl}

reservoir park recreational water value=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B176'), {$/m3}

return rate=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B84'), {Dmnl}

SI Threshold=0, {Dmnl}

SI=IF THEN ELSE(basin water supply>basin water requirement, (basin water supply-basin water requirement)/basin water supply , 0), {Dmnl}

Social Index=(agricultural water sustainability+municipal water sustainability+power generation sustainability)/3, {Dmnl}

stock reduction compensation= GAME (0), {Dmnl}

stream flow=IF THEN ELSE(Time<=2018, natural flow at basin mouth , natural flow at basin mouth*(1-climate change impact factor)), {MCM}

summer to winter power generation ratio=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B175'), {Dmnl}

summer power generation=hydro power generation demand*summer to winter power generation ratio/(1+summer to winter power generation ratio), {kwh}

supply hydro power lookup table=GET XLS LOOKUPS('? BRSGM input' , 'industry' , '173', 'B174'), {Dmnl}

surface water ratio=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B139'), {Dmnl}

thermal generation demand increase=IF THEN ELSE(Time=2000, initial thermal power generation , IF THEN ELSE(Time>=2015, IF THEN ELSE(thermal power generation demand<thermal power generation capacity*24*365 , MIN(thermal power generation demand*thermal power generation increase rate, (thermal power generation capacity*24*365-thermal power generation demand)) , 0) , 0)), {MWh/Year}

thermal plant cooling system shares[cooling system]=GET XLS CONSTANTS('? BRSGM input', 'industry', 'B186'), {fraction}

thermal plant water allocation=industrial water allocation by category[power water], {MCM}

thermal power consumption by cooling system[cooling system]=GET XLS CONSTANTS('? BRSGM input', 'industry' , 'B185'), {m3/MWh}

thermal power generation average water consumption efficiency[cooling system]=thermal power consumption by cooling system[cooling system]*thermal plant cooling system shares[cooling system], {m3/MWh}

thermal power generation average water withdrawal efficiency[cooling pond]=thermal power water withdrawal by cooling system[cooling pond]*(thermal plant cooling system shares[cooling pond]-(cooling system changes/2))

thermal power generation average water withdrawal efficiency[cooling tower]=thermal power water withdrawal by cooling system[cooling tower]*(thermal plant cooling system shares[cooling tower]+cooling system changes), {m3/MWh}

thermal power generation average water withdrawal efficiency[once through]=thermal power water withdrawal by cooling system[once through]*(thermal plant cooling system shares[once through]-(cooling system changes/2))

thermal power generation capacity=GET XLS CONSTANTS('? BRSGM input', 'industry' , 'B181'), {MW}

thermal power generation deficit=IF THEN ELSE(ABS(thermal power generation demand-actual thermal power generation)>1000, thermal power generation demand-actual thermal power generation , 0), {MWh}

thermal power generation demand= INTEG (thermal generation demand increase,0), {MWh}

thermal power generation increase rate= GAME (initial thermal power generation increase rate), {Dmnl}

thermal power water consumption=thermal power generation demand*SUM(thermal power generation average water consumption efficiency[cooling system!])/1e+006, {MCM}

thermal power water demand=thermal power generation demand*SUM(thermal power generation average water withdrawal efficiency[cooling system!])/1e+006, {MCM}

thermal power water return=thermal power water withdrawal-thermal power water consumption, {MCM}

thermal power water withdrawal by cooling system[cooling system]=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B184'), {m3/MWh}

thermal power water withdrawal=MIN(thermal plant water allocation, thermal power water demand), {MCM}

total dry land area=Dry Land Area+not irrigated land, {acre}

total dry land yield[representative crop]=unit dry land yield[representative crop]*dry land area by representative crop[representative crop]*0.4047, {ton}

total irrigation application by crop[representative crop]=ALLOCATE BY PRIORITY(gross irrigation requirement[representative crop] ,crop water application priority[representative crop], ELMCOUNT(representative crop) , crop water application width, total irrigation application), {MCM} total irrigation application=(irrigation water withdrawal+irrigation reservoir drawdown)*current irrigation delivery system efficiency, {MCM}

total irrigation yield[representative crop]=unit irrigation yield[representative crop]*irrigation area by representative crop[representative crop]*0.4047, {ton}

total mining water demand=SUM(mining water demand by category[mining!])/1e+006, {MCM}

unit cost of saline water use=GET XLS CONSTANTS('? BRSGM input', 'industry' , 'B63'), {$/m3}

unit dry land yield[representative crop]=MAX((1-ky[representative crop]+ky[representative crop]*(dry land ETa[representative crop]/ETc[representative crop]))*Ym[representative crop]*(1-yield reduction factor[representative crop]), 0), {ton/ha}

unit irrigation land margin by representative crop[representative crop]=unit irrigation yield[representative crop]*crop price[representative crop]-irrigation land crop cost[representative crop]+relief payout*relief payout amount, {$/ha}

unit irrigation yield[representative crop]=(1-ky[representative crop]+ky[representative crop]*(irrigation ETa[representative crop]/ETc[representative crop]))*Ym[representative crop]*(1-yield reduction factor[representative crop]), {ton/ha}

upgrades application:=GET XLS DATA('? BRSGM input', 'municipal' , '36', 'B44'), {Dmnl}

use alternative saline water= GAME (0), {Dmnl}

value added ratio improvement[high value added]= GAME (0)

value added ratio improvement[low value added]= GAME (0), {Dmnl}

value added ratio improvement[medium value added]= GAME (0)

water allocation priority[gas]=gas extraction water value, {Dmnl}

water allocation priority[oil]=oil extraction water value

water allocation width=1e+035, {Dmnl}

water metering change rate[municipal subsectors]=IF THEN ELSE(Percentage of Houses Metered[municipal subsectors]<1, IF THEN ELSE(Percentage of Houses Metered[municipal subsectors]+increase of metering rate[municipal subsectors]<1,increase of metering rate[municipal subsectors], 1-Percentage of Houses Metered[municipal subsectors]),0), {Dmnl}

water plant efficiency increase rate with plant upgrades= GAME (base increased rate of treatment plant efficiency with upgrades), {fraction}

water related research and development= GAME (0), {Dmnl}

water treatment plant efficiency=initial water treatment plant efficiency/(1-increase rate of treatment plant efficiency with upgrades), {Dmnl}

water treatment plant upgrades= GAME (0), {Dmnl}

water use reduction from education[bath]=FLGA education*base education water saving[bath]

water use reduction from education[ici]=FLGA education*base education water saving[ici]

water use reduction from education[kitchen]=FLGA education*base education water saving[kitchen]

water use reduction from education[laundry]=FLGA education*base education water saving[laundry]

water use reduction from education[leaks]=FLGA education*base education water saving[leaks] water use reduction from education[nonrevenue]=FLGA education*base education water saving[nonrevenue]

water use reduction from education[other]=FLGA education*base education water saving[other]

water use reduction from education[outdoor]=FLGA education*MAX(base education water saving[outdoor], education water saving)

water use reduction from education[outside city]=FLGA education*base education water saving[outside city], {liters/(person*day)}

water use reduction from education[toilet]=FLGA education*base education water saving[toilet]

water use reduction from low flow appliances[municipal subsectors]=GET XLS CONSTANTS('?BRSGM', 'municipal', 'B7'), {fraction}

water use reduction from rain barrels[municipal subsectors]=GET XLS CONSTANTS('?BRSGM', 'municipal', 'B9'), {liters/(person*day)}

water use reduction from water metering[municipal subsectors]=GET XLS CONSTANTS('?BRSGM', 'municipal', 'B8'), {fraction}

water value[representative crop]=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B76'), {$/m3}

WCO requirement=GET XLS CONSTANTS('? BRSGM input' , 'environment' , 'B1'), {Dmnl}

well production decline rate=GET XLS CONSTANTS('? BRSGM input' , 'industry' , 'B130'), {Dmnl}

wilting point[representative crop]=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B77'), {mm}

winter power generation=hydro power generation demand/(summer to winter power generation ratio+1), {kwh}

WTA Threshold=0.4, {Dmnl}

WTA=basin water withdrawal/basin water supply, {Dmnl}

xeriscaping water use reduction= GAME (0)

yield reduction factor[representative crop]=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B70'), {Dmnl}

Ym[representative crop]=GET XLS CONSTANTS('? BRSGM input' , 'agriculture' , 'B69'), {ton/ha}

Appendix C. Calgary Water Management Model (CWMM) Code

CWMM structures are provided to show how the variables are connected, and model code required to reproduce the model is provided below. Model inputs are shown in green, policies are shown in orange, typical outputs are shown in red, and shadow variables (duplicates of existing variables used for clarity) are shown in grey.

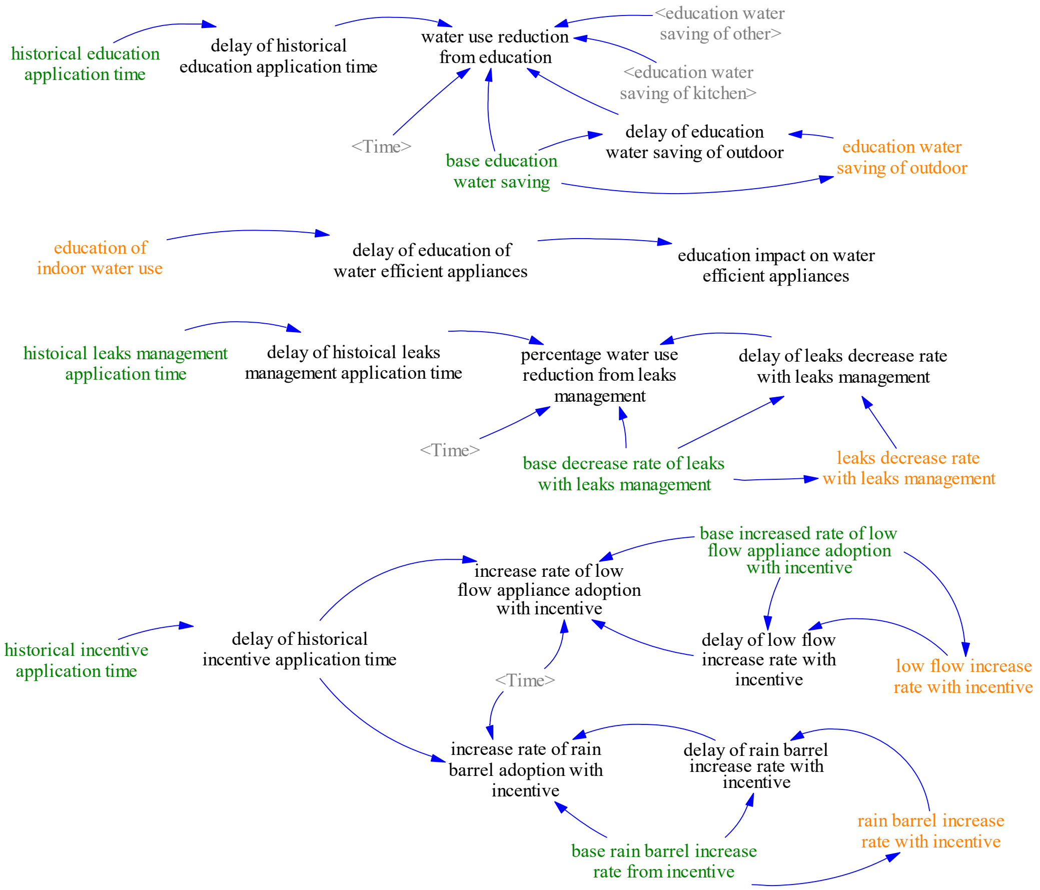

Figure C-1: Municipal management policy simulation

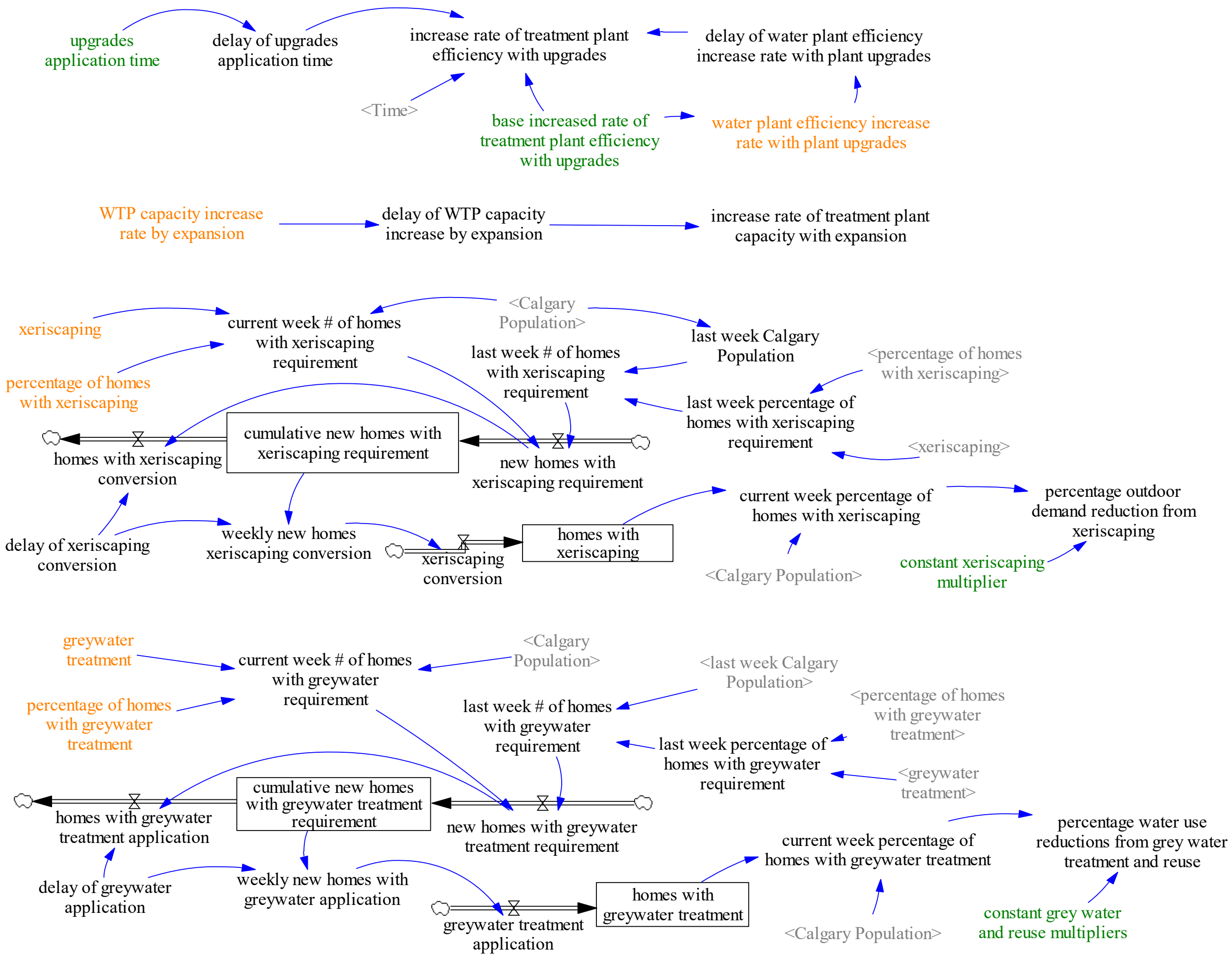

Figure C-2: Municipal management policy simulation (continued)

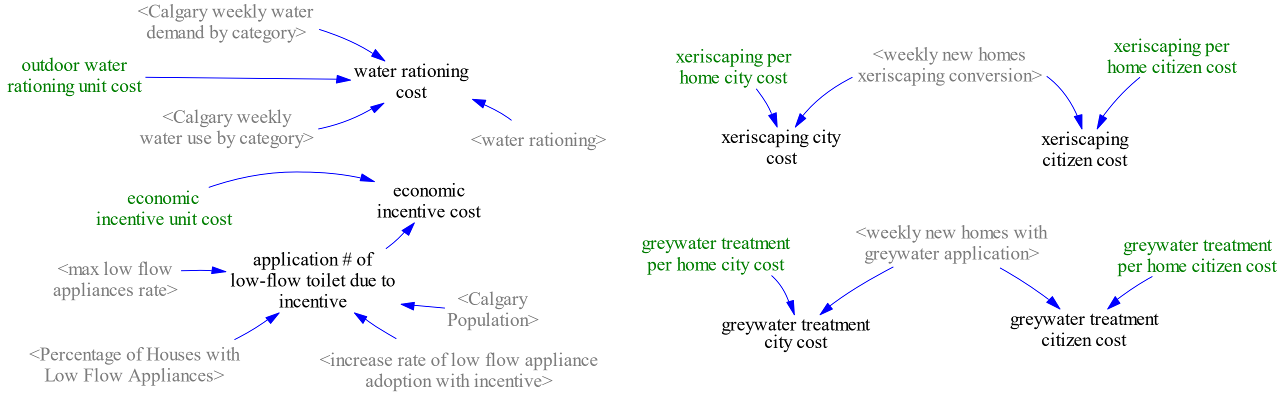

Figure C-3: Municipal management policy cost simulation

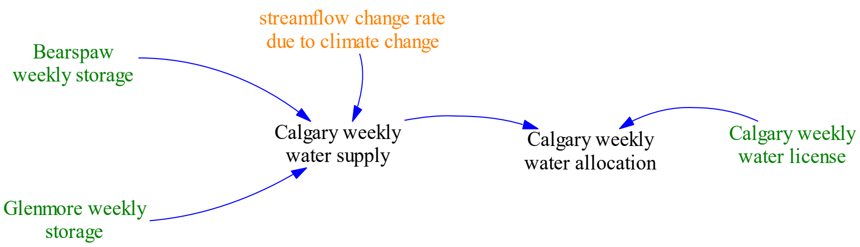

Figure C-4: Municipal supply simulation

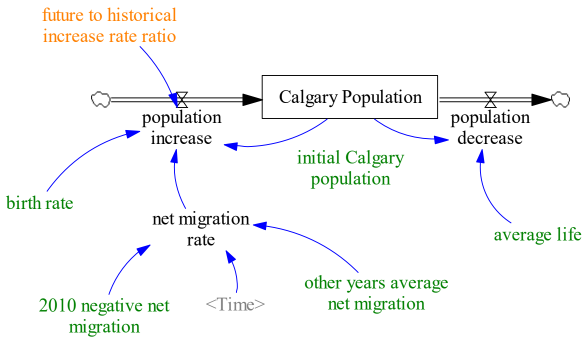

Figure C-5: Municipal population simulation

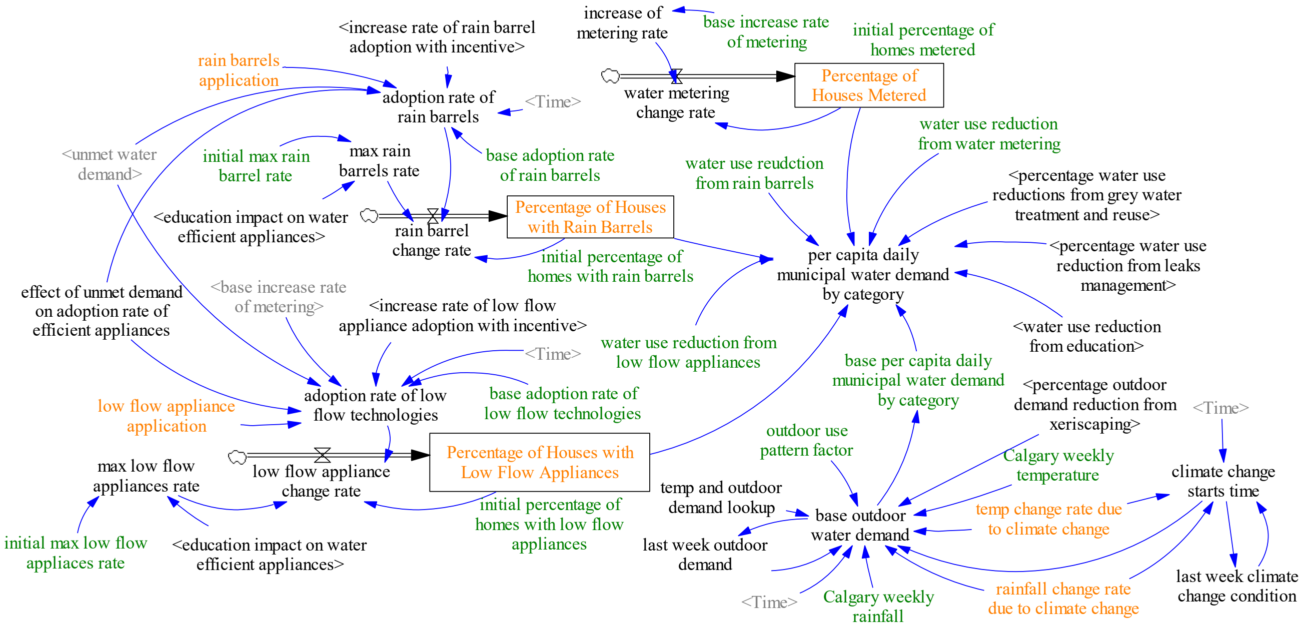

Figure C-6: Municipal water demand simulation

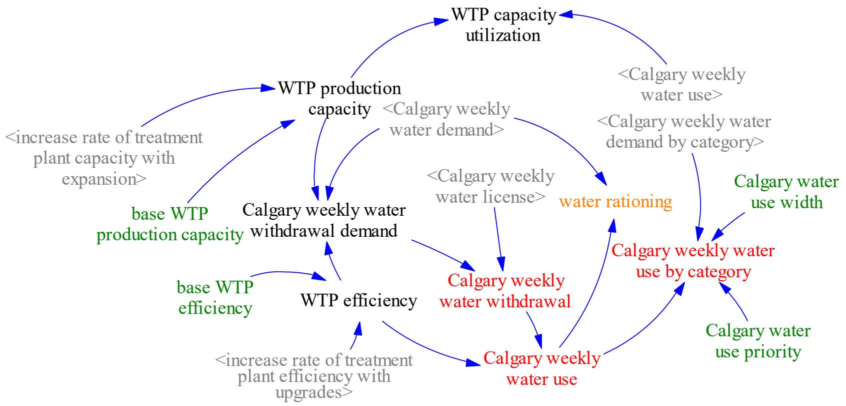

Figure C-7: Municipal water use simulation

"2010 negative net migration"=GET XLS CONSTANTS('?ALI Municipal', 'population', 'B6'), {Dmnl}

"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]*Calgary 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]*Calgary Population/4), {toilet}

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

"current week # of homes with xeriscaping requirement"=Calgary Population/4*percentage of homes with xeriscaping*xeriscaping, {Dmnl}

"increase weeks demand>capacity"=IF THEN ELSE(Calgary weekly water demand>WTP production capacity, 1 , 0), {weeks}

"increase weeks withdrawal demand>supply"=IF THEN ELSE(Calgary weekly water withdrawal demand>Calgary weekly water supply, 1 , 0), {weeks}

"last week # of homes with greywater requirement"=last week Calgary Population/4*last week percentage of homes with greywater requirement, {Dmnl}

"last week # of homes with xeriscaping requirement"=last week Calgary Population/4*last week percentage of homes with xeriscaping requirement {Dmnl}

actual Calgary weekly water demand=GET XLS DATA('? ALI Municipal input' , 'Validation-weekly', 'A' , 'C2'), {MCM}

adoption rate of low flow technologies[bath]=IF THEN ELSE(Time<1043, base adoption rate of low flow technologies[bath]+increase rate of low flow appliance adoption with incentive[bath]+effect of unmet demand on adoption rate of efficient appliances(unmet water demand/100) , (base adoption rate of low flow technologies[bath]+increase rate of low flow appliance adoption with incentive[bath]+effect of unmet demand on adoption rate of efficient appliances(unmet water demand/100))*low flow appliance application), {Dmnl} adoption rate of low flow technologies[ici]=IF THEN ELSE(Time<1043, base adoption rate of low flow technologies[ici]+increase rate of low flow appliance adoption with incentive[ici]+effect of unmet demand on adoption rate of efficient appliances(unmet water demand/100) , (base adoption rate of low flow technologies[ici]+increase rate of low flow appliance adoption with incentive[ici]+effect of unmet demand on adoption rate of efficient appliances(unmet water demand/100))*low flow appliance application), {Dmnl}

adoption rate of low flow technologies[kitchen]=IF THEN ELSE(Time<1043, base adoption rate of low flow technologies[kitchen]+increase rate of low flow appliance adoption with incentive[kitchen]+effect of unmet demand on adoption rate of efficient appliances(unmet water demand/100) , (base adoption rate of low flow technologies[kitchen]+increase rate of low flow appliance adoption with incentive[kitchen]+effect of unmet demand on adoption rate of efficient appliances(unmet water demand/100))*low flow appliance application), {Dmnl}

adoption rate of low flow technologies[laundry]=IF THEN ELSE(Time<1043, base adoption rate of low flow technologies[laundry]+increase rate of low flow appliance adoption with incentive[laundry]+effect of unmet demand on adoption rate of efficient appliances(unmet water demand/100) , (base adoption rate of low flow technologies[laundry]+increase rate of low flow appliance adoption with incentive[laundry]+effect of unmet demand on adoption rate of efficient appliances(unmet water demand/100))*low flow appliance application), {Dmnl}

adoption rate of low flow technologies[leaks]=0, {Dmnl}

adoption rate of low flow technologies[nonrevenue]= IF THEN ELSE(Time<1043, base adoption rate of low flow technologies[nonrevenue]+increase rate of low flow appliance adoption with incentive[nonrevenue], (base adoption rate of low flow technologies[nonrevenue]+increase rate of low flow appliance adoption with incentive[nonrevenue])*low flow appliance application), {Dmnl}

adoption rate of low flow technologies[other]=IF THEN ELSE(Time<1043, base adoption rate of low flow technologies[other]+increase rate of low flow appliance adoption with incentive[other] , (base adoption rate of low flow technologies[other]+increase rate of low flow appliance adoption with incentive [other])*low flow appliance application), {Dmnl}

adoption rate of low flow technologies[outdoor]=IF THEN ELSE(Time<1043, base adoption rate of low flow technologies[outdoor]+increase rate of low flow appliance adoption with incentive[outdoor] , (base adoption rate of low flow technologies[outdoor]+increase rate of low flow appliance adoption with incentive[outdoor])*low flow appliance application), {Dmnl}

adoption rate of low flow technologies[outside city]= IF THEN ELSE(Time<1043, base adoption rate of low flow technologies[outside city]+increase rate of low flow appliance adoption with incentive[outside city] , (base adoption rate of low flow technologies[outside city]+increase rate of low flow appliance adoption with incentive[outside city])*low flow appliance application), {Dmnl}

adoption rate of low flow technologies[toilet]=IF THEN ELSE(Time<1043, base adoption rate of low flow technologies[toilet]+increase rate of low flow appliance adoption with incentive[toilet]+effect of unmet demand on adoption rate of efficient appliances(unmet water demand/100)+base increase rate of metering[toilet]*0.5 , (base adoption rate of low flow technologies [toilet]+increase rate of low flow appliance adoption with incentive[toilet]+effect of unmet demand on adoption rate of efficient appliances(unmet water demand/100))*low flow appliance application), {Dmnl}

adoption rate of rain barrels=IF THEN ELSE(Time<1043, base adoption rate of rain barrels+increase rate of rain barrel adoption with incentive+effect of unmet demand on adoption rate of efficient appliances(unmet water demand/100) , (base adoption rate of rain barrels+increase rate of rain barrel adoption with incentive+effect of unmet demand on adoption rate of efficient appliances(unmet water demand/100))*rain barrels application), {Dmnl}

annual average per capita daily residential water demand=IF THEN ELSE(MODULO(Time, 53)<52, 0 , cumulative per capita daily residential water demand/52), {lpcd}

annual average per capita daily municipal water demand=IF THEN ELSE(annual average per capita daily residential water demand=0, 0, annual average per capita daily residential water demand+per capita daily nonrevenue water demand+per capita daily ICI water demand+per capita daily outside city water demand), {lpcd}

average life=GET XLS CONSTANTS('?ALI Municipal', 'population', 'B4'), {Year}

base adoption rate of low flow technologies[municipal subsectors]=GET XLS CONSTANTS('?ALI Municipal', 'Demand', 'B10'), {Dmnl}

base adoption rate of rain barrels=GET XLS CONSTANTS('?ALI Municipal', 'demand', 'B12'), {Dmnl}

base decrease rate of leaks with leaks management[municipal subsectors]=GET XLS CONSTANTS('?ALI Municipal', 'demand', 'B14'), {Dmnl}

base education water saving[municipal subsectors]=GET XLS CONSTANTS('?ALI Municipal', 'demand', 'B17'), {lpcd}

base increase rate of metering[municipal subsectors]= GET XLS CONSTANTS('?ALI Municipal', 'demand', 'B11'), {Dmnl}

base increased rate of low flow appliance adoption with incentive[municipal subsectors]=GET XLS CONSTANTS('?ALI Municipal', 'demand', 'B15'), {Dmnl}

base increased rate of treatment plant efficiency with upgrades=GET XLS CONSTANTS('?ALI Municipal', 'demand', 'B18'), {Dmnl}

base outdoor water demand=IF THEN ELSE(MODULO(Time, 52)<35:AND:MODULO(Time, 52)>15, temp and outdoor demand lookup(Calgary weekly temperature*(1+RAMP(temp change rate due to climate change/260, climate change starts time , climate change starts time+260)))*(1-percentage outdoor demand reduction from xeriscaping), IF THEN ELSE(last week outdoor demand=0, 0, temp and outdoor demand lookup(Calgary weekly temperature*(1+RAMP(temp change rate due to climate change/260, climate change starts time , climate change starts time+260)))*(1-percentage outdoor demand reduction from xeriscaping)))*IF THEN ELSE(Calgary weekly rainfall*(1+RAMP(rainfall change rate due to climate change/260, climate change starts time , climate change starts time+260))<=20, 1 , IF THEN ELSE(Calgary weekly rainfall*(1+RAMP(rainfall change rate due to climate change/260, climate change starts time, climate change starts time+260))<=40, 0.6 , 0.001)) *outdoor use pattern factor, {lpcd}

base per capita daily municipal water demand by category[bath]=GET XLS CONSTANTS('? ALI Municipal', 'demand', 'C3'), {lpcd}

base per capita daily municipal water demand by category[ici]=GET XLS CONSTANTS('? ALI Municipal', 'demand', 'I3'), {lpcd}

base per capita daily municipal water demand by category[kitchen]=GET XLS CONSTANTS('? ALI Municipal', 'demand', 'E3'), {lpcd}

base per capita daily municipal water demand by category[laundry]=GET XLS CONSTANTS('? ALI Municipal', 'demand', 'D3'), {lpcd} base per capita daily municipal water demand by category[leaks]=GET XLS CONSTANTS('? ALI Municipal', 'demand', 'F3'), {lpcd}

base per capita daily municipal water demand by category[nonrevenue]=GET XLS CONSTANTS('? ALI Municipal', 'demand', 'J3'), {lpcd}

base per capita daily municipal water demand by category[other]=GET XLS CONSTANTS('? ALI Municipal', 'demand', 'G3'), {lpcd}

base per capita daily municipal water demand by category[outdoor]=base outdoor water demand, {lpcd}

base per capita daily municipal water demand by category[outside city]=GET XLS CONSTANTS('? ALI Municipal', 'demand', 'K3'), {lpcd}

base per capita daily municipal water demand by category[toilet]=GET XLS CONSTANTS('? ALI Municipal', 'demand', 'B3'), {lpcd}

base rain barrel increase rate from incentive=GET XLS CONSTANTS('?ALI Municipal', 'demand', 'B16'), {Dmnl}

base WTP efficiency=GET XLS CONSTANTS('? ALI Municipal', 'demand' , 'B32'), {Dmnl}

base WTP production capacity=GET XLS CONSTANTS('? ALI Municipal', 'supply' , 'B5'), {MCM}

Bearspaw weekly storage= 3.5, {MCM}

birth rate=GET XLS CONSTANTS('?ALI Municipal', 'population', 'B3'), {Dmnl}

Calgary daily water demand by category[municipal subsectors]=Calgary Population*per capita daily municipal water demand by category[municipal subsectors]/1e+009, {MCM}

Calgary demand in=Calgary weekly water demand, {MCM}

Calgary demand out=IF THEN ELSE(MODULO(Time, 53)<52, 0 ,cumulative Calgary weekly water demand/TIME STEP), {MCM}

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

Calgary water use priority[municipal subsectors]=GET XLS CONSTANTS('? ALI Municipal', 'demand' , 'B30'), {Dmnl}

Calgary water use width=GET XLS CONSTANTS('? ALI Municipal', 'demand' , 'B31'), {Dmnl}

Calgary weekly rainfall=GET XLS DATA('? ALI Municipal input' , 'climate', 'A' , 'D2'), mm

Calgary weekly temperature:=GET XLS DATA('? ALI Municipal input' , 'climate', 'A' , 'C2'), {°C}

Calgary weekly water allocation= GAME (MIN(Calgary weekly water supply, Calgary weekly water license)), {MCM}

Calgary weekly water demand by category[municipal subsectors]=Calgary daily water demand by category[municipal subsectors]*7, {MCM}

Calgary weekly water demand=SUM(Calgary weekly water demand by category[municipal subsectors!]), {MCM}

Calgary weekly water license=GET XLS CONSTANTS('?ALI Municipal', 'demand', 'B34'), {MCM}

Calgary weekly water supply=(Bearspaw weekly storage+Glenmore weekly storage)*(1+streamflow change rate due to climate change), {MCM}

Calgary weekly water use by category[municipal subsectors]= ALLOCATE BY PRIORITY(Calgary weekly water demand by category[municipal subsectors], Calgary water use priority[municipal subsectors], ELMCOUNT(municipal subsectors), Calgary water use width, Calgary weekly water use), {MCM}

Calgary weekly water use=Calgary weekly water withdrawal*WTP efficiency, {MCM}

Calgary weekly water withdrawal demand=MIN(Calgary weekly water demand, WTP production capacity)/WTP efficiency, {MCM}

Calgary weekly water withdrawal=MIN(Calgary weekly water withdrawal demand, Calgary weekly water allocation), {MCM}

Calgary withdrawal in=Calgary weekly water withdrawal, {MCM}

Calgary withdrawal out=IF THEN ELSE(MODULO(Time, 53)<52, 0 ,cumulative Calgary weekly water withdrawal/TIME STEP), {MCM}

climate change starts time=IF THEN ELSE(rainfall change rate due to climate change=0:AND:temp change rate due to climate change=0,0,IF THEN ELSE(last week climate change condition=0, Time , last week climate change condition)), {Dmnl}

constant grey water and reuse multipliers[municipal subsectors]=GET XLS CONSTANTS('?ALI Munipal', 'demand', 'B13'), {fraction}

constant xeriscaping multiplier=GET XLS CONSTANTS('?ALI Munipal', 'demand', 'B56'), {Dmnl}

cumulative Calgary weekly water demand= INTEG (Calgary demand in-Calgary demand out, 0), {MCM}

cumulative Calgary weekly water withdrawal= INTEG (Calgary withdrawal in-Calgary withdrawal out, 0), {MCM}

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

cumulative new homes with xeriscaping requirement= INTEG (new homes with xeriscaping requirement-homes with xeriscaping conversion,0), {Dmnl}

cumulative per capita daily residential water demand= INTEG (residential in-residential out, 0), {lpcd}

cumulative weeks of Calgary demand exceeds WTP capacity= INTEG ("increase weeks demand>capacity",0), {Week}

cumulative weeks of WTP withdrawal demand exceeds supply= INTEG ("increase weeks withdrawal demand>supply", 0), {Week}

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

current week percentage of homes with greywater treatment=homes with greywater treatment/(Calgary Population/4), {fraction}

current week percentage of homes with xeriscaping=homes with xeriscaping/(Calgary Population/4), {fraction}

delay of dishwasher rebates water saving= DELAY FIXED (dishwasher rebates water saving, 52 , 0), {lpcd}|

delay of education of water efficient appliances= DELAY FIXED (education of indoor water use, 52, 0)

delay of education water saving of outdoor= DELAY FIXED (education water saving of outdoor, IF THEN ELSE(education water saving of outdoor<=base education water saving [outdoor], 0 , 52),0), {lpcd}

delay of garburator prohibition water saving= DELAY FIXED (garburator prohibition water saving, 52 , 0), {lpcd}

delay of greywater application=156, {Dmnl}

delay of historical education application time=historical education application time+52, {Dmnl}

delay of historical incentive application time=historical incentive application time+52, {Dmnl}

delay of historical leaks management application time=historical leaks management application time+52, {Dmnl}|

delay of humidifier standards water saving= DELAY FIXED (humidifier standards water saving, 52 , 0), {lpcd}

delay of leaks decrease rate with leaks management= DELAY FIXED (leaks decrease rate with leaks management, IF THEN ELSE(leaks decrease rate with leaks management<=base decrease rate of leaks with leaks management[leaks], 0 , 52), 0)

delay of low flow increase rate with incentive= DELAY FIXED (low flow increase rate with incentive, IF THEN ELSE(low flow increase rate with incentive<=base increased rate of low flow appliance adoption with incentive[toilet], 0 , 52), 0)

delay of rain barrel increase rate with incentive= DELAY FIXED (rain barrel increase rate with incentive, IF THEN ELSE(rain barrel increase rate with incentive<=base rain barrel increase rate from incentive, 0, 52), 0)

delay of softener standards water saving= DELAY FIXED (softener standards water saving, 52 , 0), {lpcd}

delay of upgrades application time=upgrades application time+52

delay of water plant efficiency increase rate with plant upgrades= DELAY FIXED (water plant efficiency increase rate with plant upgrades,52,water plant efficiency increase rate with plant upgrades)

delay of WTP capacity increase by expansion= DELAY FIXED (WTP capacity increase rate by expansion, 52 , 0), {Week}

delay of xeriscaping conversion=52, {Dmnl}

dishwasher rebates water saving= GAME (0), {lpcd}

economic incentive cost="application # of low-flow toilet due to incentive"*economic incentive unit cost, {$/Week}

economic incentive unit cost=GET XLS CONSTANTS('?ALI Municipal', 'demand', 'B41'), {$/toilet}

education impact on water efficient appliances=delay of education of water efficient appliances*0.05, {Dmnl}

education of indoor water use= GAME (0), {Dmnl}

education unit water saving cost[municipal subsectors]=GET XLS CONSTANTS('?ALI Municipal', 'demand', 'B38'), {$/L} education water saving of kitchen=(delay of dishwasher rebates water saving+delay of garburator prohibition water saving)*percentage of homes with water saving appliances of kitchen, {lpcd}

education water saving of other=(delay of humidifier standards water saving+delay of softener standards water saving)*percentage of homes with water saving appliances of other, {lpcd}

education water saving of outdoor= GAME (base education water saving[outdoor]), {liters/(person*day)}

effect of unmet demand on adoption rate of efficient appliances(GET XLS LOOKUPS('?BRSGM', 'demand' , '51' , 'B52')), {Dmnl}

future to historical increase rate ratio= GAME (0), {Dmnl}

garburator prohibition water saving= GAME (0), {lpcd}|

Glenmore weekly storage=3.5, {MCM}

greywater treatment application=weekly new homes with greywater application, {Dmnl}

greywater treatment citizen cost=greywater treatment per home citizen cost*weekly new homes with greywater application, {$/Week}

greywater treatment city cost=greywater treatment per home city cost*weekly new homes with greywater application, {$/Week}

greywater treatment per home citizen cost=GET XLS CONSTANTS('?ALI Municipal', 'demand', 'B45'), {$/home}

greywater treatment per home city cost=GET XLS CONSTANTS('?ALI Municipal', 'demand', 'B44'), {$/home}

greywater treatment= GAME (0)

historical education application time=GET XLS CONSTANTS('? ALI Municipal', 'demand' , 'B24'), {Dmnl}

historical incentive application time=GET XLS CONSTANTS('? ALI Municipal', 'demand' , 'B26'), {Dmnl}|

historical leaks management application time=GET XLS CONSTANTS('? ALI Municipal', 'demand', 'B25'), {Dmnl}

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

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

homes with xeriscaping conversion= DELAY FIXED (new homes with xeriscaping requirement, delay of xeriscaping conversion,0), {Dmnl}

homes with xeriscaping= INTEG (xeriscaping conversion,0), {Dmnl}

humidifier standards water saving= GAME (0), {lpcd}

increase of metering rate[municipal subsectors]=base increase rate of metering[municipal subsectors], {Dmnl}

increase rate of low flow appliance adoption with incentive[bath]=IF THEN ELSE(Time<delay of historical incentive application time, 0, IF THEN ELSE(Time<1042, base increased rate of low flow appliance adoption with incentive[bath] , delay of low flow increase rate with incentive)), {Dmnl} increase rate of low flow appliance adoption with incentive[ici]=IF THEN ELSE(Time<delay of historical incentive application time, 0, IF THEN ELSE(Time<1042, base increased rate of low flow appliance adoption with incentive[ici] , delay of low flow increase rate with incentive)), {Dmnl}

increase rate of low flow appliance adoption with incentive[kitchen]=IF THEN ELSE(Time<delay of historical incentive application time, 0, IF THEN ELSE(Time<1042, base increased rate of low flow appliance adoption with incentive[kitchen] , delay of low flow increase rate with incentive)), {Dmnl}

increase rate of low flow appliance adoption with incentive[laundry]=IF THEN ELSE(Time<delay of historical incentive application time, 0, IF THEN ELSE(Time<1042, base increased rate of low flow appliance adoption with incentive[laundry] , delay of low flow increase rate with incentive)), {Dmnl}

increase rate of low flow appliance adoption with incentive[leaks]=IF THEN ELSE(Time<delay of historical incentive application time,0, base increased rate of low flow appliance adoption with incentive[leaks]), {Dmnl}

increase rate of low flow appliance adoption with incentive[nonrevenue]=IF THEN ELSE(Time<delay of historical incentive application time,0, base increased rate of low flow appliance adoption with incentive[nonrevenue]), {Dmnl}

increase rate of low flow appliance adoption with incentive[other]=IF THEN ELSE(Time<delay of historical incentive application time,0, base increased rate of low flow appliance adoption with incentive[other]), {Dmnl}

increase rate of low flow appliance adoption with incentive[outdoor]=IF THEN ELSE(Time<delay of historical incentive application time,0, base increased rate of low flow appliance adoption with incentive[outdoor]), {Dmnl}

increase rate of low flow appliance adoption with incentive[outside city]=IF THEN ELSE(Time<delay of historical incentive application time,0, base increased rate of low flow appliance adoption with incentive[outside city]), {Dmnl}

increase rate of low flow appliance adoption with incentive[toilet]=IF THEN ELSE(Time<delay of historical incentive application time, 0, IF THEN ELSE(Time<1042, base increased rate of low flow appliance adoption with incentive[toilet] , delay of low flow increase rate with incentive)), {Dmnl}

increase rate of rain barrel adoption with incentive=IF THEN ELSE(Time<delay of historical incentive application time, 0 , IF THEN ELSE(Time<1042, base rain barrel increase rate from incentive , delay of rain barrel increase rate with incentive)), {fraction}

increase rate of treatment plant capacity with expansion=delay of WTP capacity increase by expansion, {Dmnl}

increase rate of treatment plant efficiency with upgrades=IF THEN ELSE(Time<delay of upgrades application time, 0 , IF THEN ELSE(Time<1042, base increased rate of treatment plant efficiency with upgrades, delay of water plant efficiency increase rate with plant upgrades)), {fraction}

initial Calgary population=GET XLS CONSTANTS('?ALI Municipal', 'population', 'B2'), {person}

initial max low flow appliances rate[municipal subsectors]=GET XLS CONSTANTS('?ALI Municipal', 'demand', 'B55'), {Dmnl}

initial max rain barrel rate=GET XLS CONSTANTS('?ALI Municipal', 'demand', 'B54'), {Dmnl}

initial percentage of homes metered[municipal subsectors]=GET XLS CONSTANTS('?ALI Municipal', 'demand', 'B5'), {Dmnl} initial percentage of homes with low flow appliances[municipal subsectors]=GET XLS CONSTANTS('?ALI Municipal', 'demand', 'B4'), {Dmnl}

initial percentage of homes with rain barrels=GET XLS CONSTANTS('?ALI Municipal', 'demand', 'B6'), {Dmnl}

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

last week climate change condition= DELAY FIXED (climate change starts time,1,0)

last week outdoor demand= DELAY FIXED (base outdoor water demand,1,0)

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

last week percentage of homes with xeriscaping requirement= DELAY FIXED (percentage of homes with xeriscaping*xeriscaping,1,0)

leak management cost=current week per capita daily leak demand*percentage water use reduction from leaks management[leaks]*leak management unit water saving cost, {$}

leak management unit water saving cost=GET XLS CONSTANTS('?ALI Municipal', 'demand', 'B39'), {$/lpcd}

leaks decrease rate with leaks management= GAME (base decrease rate of leaks with leaks management[leaks]), {fraction}

low flow appliance application= GAME (1), {Dmnl}

low flow appliance change rate[bath]=IF THEN ELSE(Percentage of Houses with Low Flow Appliances[bath]<max low flow appliances rate[bath], IF THEN ELSE(Percentage of Houses with Low Flow Appliances[bath]<=0.8,adoption rate of low flow technologies[bath], (max low flow appliances rate[bath]-Percentage of Houses with Low Flow Appliances[bath])*10*adoption rate of low flow technologies[bath]),0), {Dmnl}

low flow appliance change rate[ici]=IF THEN ELSE(Percentage of Houses with Low Flow Appliances[ici]<max low flow appliances rate[ici], IF THEN ELSE(Percentage of Houses with Low Flow Appliances[ici]<=0.3,adoption rate of low flow technologies[ici], (max low flow appliances rate[ici]-Percentage of Houses with Low Flow Appliances[ici])*2*adoption rate of low flow technologies[ici]),0), {Dmnl}

low flow appliance change rate[kitchen]=IF THEN ELSE(Percentage of Houses with Low Flow Appliances[kitchen]<max low flow appliances rate [kitchen], IF THEN ELSE(Percentage of Houses with Low Flow Appliances[kitchen]<=0.3,adoption rate of low flow technologies[kitchen], (max low flow appliances rate[kitchen]-Percentage of Houses with Low Flow Appliances[kitchen])*1.3*adoption rate of low flow technologies[kitchen]),0), {Dmnl}

low flow appliance change rate[laundry]=IF THEN ELSE(Percentage of Houses with Low Flow Appliances[laundry]<max low flow appliances rate[laundry], IF THEN ELSE(Percentage of Houses with Low Flow Appliances[laundry]<=0.5,adoption rate of low flow technologies[laundry], (max low flow appliances rate[laundry]-Percentage of Houses with Low Flow Appliances[laundry])*3*adoption rate of low flow technologies[laundry]),0), {Dmnl}

low flow appliance change rate[leaks]=adoption rate of low flow technologies[leaks], {Dmnl}

low flow appliance change rate[nonrevenue]=adoption rate of low flow technologies[nonrevenue], {Dmnl} low flow appliance change rate[other]=adoption rate of low flow technologies[other], {Dmnl}

low flow appliance change rate[outdoor]=adoption rate of low flow technologies[outdoor], {Dmnl}

low flow appliance change rate[outside city]=adoption rate of low flow technologies[outside city], {Dmnl}

low flow appliance change rate[toilet]=IF THEN ELSE(Percentage of Houses with Low Flow Appliances[toilet]<max low flow appliances rate[toilet], IF THEN ELSE(Percentage of Houses with Low Flow Appliances[toilet]<=0.5,adoption rate of low flow technologies[toilet], (max low flow appliances rate[toilet]-Percentage of Houses with Low Flow Appliances[toilet])*3*adoption rate of low flow technologies[toilet]),0), {Dmnl}

low flow increase rate with incentive= GAME (base increased rate of low flow appliance adoption with incentive[toilet]), {fraction}

max low flow appliances rate[municipal subsectors]=initial max low flow appliances rate[municipal subsectors]*(1+education impact on water efficient appliances), {Dmnl}

max rain barrels rate=initial max rain barrel rate*(1+education impact on water efficient appliances), {Dmnl}

municipal subsectors: toilet, bath, laundry, kitchen, leaks, other, outdoor, ici, nonrevenue, outside city

net migration rate=IF THEN ELSE(Time>=730:AND:Time<=782 , "2010 negative net migration" , other years average net migration), {Dmnl}

new homes with greywater treatment requirement=IF THEN ELSE("current week # of homes with greywater requirement">="last week # of homes with greywater requirement","current week # of homes with greywater requirement"-"last week # of homes with greywater requirement" , 0), {Dmnl}

new homes with xeriscaping requirement=IF THEN ELSE("current week # of homes with xeriscaping requirement">="last week # of homes with xeriscaping requirement", "current week # of homes with xeriscaping requirement"-"last week # of homes with xeriscaping requirement" , 0), {Dmnl}

other years average net migration=GET XLS CONSTANTS('?ALI Municipal', 'population', 'B5'), {Dmnl}

outdoor use pattern factor=1-RAMP(0.2/(1045-628), 628 , 1045), {Dmnl}

outdoor water rationing unit cost=GET XLS CONSTANTS('?ALI Municipal', 'demand', 'B40'), {$/m3}

per capita daily ICI water demand=per capita daily municipal water demand by category[ici], {lpcd}

per capita daily municipal water demand by category[bath]=(base per capita daily municipal water demand by category[bath]-(water use reduction from rain barrels[bath]*Percentage of Houses with Rain Barrels+water use reduction from education[bath]))*((1-Percentage of Houses Metered[bath])*1+Percentage of Houses Metered[bath]*(1-water use reduction from water metering[bath]))*((1-Percentage of Houses with Low Flow Appliances[bath])*1+Percentage of Houses with Low Flow Appliances[bath]*(1-water use reduction from low flow appliances[bath]))*(1-percentage water use reductions from grey water treatment and reuse[bath])*(1-percentage water use reduction from leaks management[bath])

per capita daily municipal water demand by category[ici]=(base per capita daily municipal water demand by category[ici]-(water use reduction from rain barrels[ici]*Percentage of Houses with Rain Barrels+water use reduction from education[ici]))*((1-Percentage of Houses Metered[ici])*1+Percentage of Houses Metered[ici]*(1-water use reduction from water metering[ici]))*((1-Percentage of Houses with Low Flow Appliances[ici])*1+Percentage of Houses with Low Flow Appliances[ici]*(1-water use reduction from low flow appliances[ici]))*(1-percentage water use reductions from grey water treatment and reuse[ici])*(1-percentage water use reduction from leaks management[ici])

per capita daily municipal water demand by category[kitchen]=(base per capita daily municipal water demand by category[kitchen]-(water use reduction from rain barrels[kitchen]*Percentage of Houses with Rain Barrels))*((1-Percentage of Houses Metered[kitchen])*1+Percentage of Houses Metered[kitchen]*(1-water use reduction from water metering[kitchen])) *((1-Percentage of Houses with Low Flow Appliances[kitchen])*1+Percentage of Houses with Low Flow Appliances[kitchen]*(1-water use reduction from low flow appliances[kitchen]))*(1-percentage water use reductions from grey water treatment and reuse[kitchen])*(1-percentage water use reduction from leaks management[kitchen])-water use reduction from education[kitchen]

per capita daily municipal water demand by category[laundry]=(base per capita daily municipal water demand by category[laundry]-(water use reduction from rain barrels[laundry]*Percentage of Houses with Rain Barrels+water use reduction from education[laundry]))*((1-Percentage of Houses Metered[laundry])*1+Percentage of Houses Metered[laundry]*(1-water use reduction from water metering[laundry]))*((1-Percentage of Houses with Low Flow Appliances[laundry])*1+Percentage of Houses with Low Flow Appliances[laundry]*(1-water use reduction from low flow appliances[laundry]))*(1-percentage water use reductions from grey water treatment and reuse[laundry])*(1-percentage water use reduction from leaks management[laundry])

per capita daily municipal water demand by category[leaks]=(base per capita daily municipal water demand by category[leaks]-(water use reduction from rain barrels[leaks]*Percentage of Houses with Rain Barrels+water use reduction from education[leaks]))*((1-Percentage of Houses Metered[leaks])*1+Percentage of Houses Metered[leaks]*(1-water use reduction from water metering[leaks]))*((1-Percentage of Houses with Low Flow Appliances[leaks])*1+Percentage of Houses with Low Flow Appliances[leaks]*(1-water use reduction from low flow appliances[leaks]))*(1-percentage water use reductions from grey water treatment and reuse[leaks])*(1-percentage water use reduction from leaks management[leaks])

per capita daily municipal water demand by category[nonrevenue]=(base per capita daily municipal water demand by category[nonrevenue]-(water use reduction from rain barrels[nonrevenue]*Percentage of Houses with Rain Barrels+water use reduction from education[nonrevenue]))*((1-Percentage of Houses Metered[nonrevenue])*1+Percentage of Houses Metered[nonrevenue]*(1-water use reduction from water metering [nonrevenue]))*((1-Percentage of Houses with Low Flow Appliances[nonrevenue])*1+Percentage of Houses with Low Flow Appliances[nonrevenue]*(1-water use reduction from low flow appliances[nonrevenue]))*(1-percentage water use reductions from grey water treatment and reuse[nonrevenue])*(1-percentage water use reduction from leaks management[nonrevenue])

per capita daily municipal water demand by category[other]=(base per capita daily municipal water demand by category[other]-(water use reduction from rain barrels[other]*Percentage of Houses with Rain Barrels))*((1-Percentage of Houses Metered[other])*1+Percentage of Houses Metered[other]*(1-water use reduction from water metering[other]))*((1-Percentage of Houses with Low Flow Appliances[other])*1+Percentage of Houses with Low Flow Appliances[other]*(1-water use reduction from low flow appliances[other]))*(1-percentage water use reductions from grey water treatment and reuse[other])*(1-percentage water use reduction from leaks management[other])-water use reduction from education[other]

per capita daily municipal water demand by category[outdoor]=(base per capita daily municipal water demand by category[outdoor]-IF THEN ELSE(base per capita daily municipal water demand by category[outdoor]<(water use reduction from rain barrels[outdoor]*Percentage of Houses with Rain

Barrels+water use reduction from education[outdoor]), 0 , water use reduction from rain barrels[outdoor]*Percentage of Houses with Rain Barrels+water use reduction from education[outdoor]))*((1-Percentage of Houses Metered[outdoor])*1+Percentage of Houses Metered[outdoor]*(1-water use reduction from water metering[outdoor]))*((1-Percentage of Houses with Low Flow Appliances[outdoor])*1+Percentage of Houses with Low Flow Appliances[outdoor]*(1-water use reduction from low flow appliances[outdoor]))*(1-percentage water use reductions from grey water treatment and reuse[outdoor])*(1-percentage water use reduction from leaks management[outdoor])

per capita daily municipal water demand by category[outside city]=(base per capita daily municipal water demand by category[outside city]-(water use reduction from rain barrels[outside city]*Percentage of Houses with Rain Barrels+water use reduction from education[outside city]))*((1-Percentage of Houses Metered[outside city])*1+Percentage of Houses Metered[outside city]*(1-water use reduction from water metering [outside city]))*((1-Percentage of Houses with Low Flow Appliances[outside city])*1+Percentage of Houses with Low Flow Appliances[outside city]*(1-water use reduction from low flow appliances[outside city]))*(1-percentage water use reductions from grey water treatment and reuse[outside city]) *(1-percentage water use reduction from leaks management[outside city]), {lpcd}

per capita daily municipal water demand by category[toilet]=(base per capita daily municipal water demand by category[toilet]-(water use reduction from rain barrels[toilet]*Percentage of Houses with Rain Barrels+water use reduction from education[toilet]))*((1-Percentage of Houses Metered[toilet])*1+Percentage of Houses Metered[toilet]*(1-water use reduction from water metering[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]))*(1-percentage water use reductions from grey water treatment and reuse[toilet])*(1-percentage water use reduction from leaks management[toilet])

per capita daily municipal water demand=per capita daily nonrevenue water demand+per capita daily ICI water demand+per capita daily outside city water demand+per capita daily residential water demand, {lpcd}

per capita daily nonrevenue water demand=per capita daily municipal water demand by category[nonrevenue], {lpcd}

per capita daily outside city water demand=per capita daily municipal water demand by category[outside city], {lpcd}

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}

percentage of homes with greywater treatment= GAME (0), {Dmnl}

percentage of homes with water saving appliances of kitchen= GAME (1), {Dmnl}

percentage of homes with water saving appliances of other= GAME (1), {Dmnl}

percentage of homes with xeriscaping= GAME (0), {Dmnl}

Percentage of Houses Metered[municipal subsectors]= INTEG (water metering change rate[municipal subsectors], initial percentage of homes metered[municipal subsectors]), {Dmnl}

Percentage of Houses with Low Flow Appliances[municipal subsectors]= INTEG (low flow appliance change rate[municipal subsectors], initial percentage of homes with low flow appliances[municipal subsectors]), {Dmnl}

Percentage of Houses with Rain Barrels= INTEG (rain barrel change rate, initial percentage of homes with rain barrels), {fraction}

percentage outdoor demand reduction from xeriscaping=current week percentage of homes with xeriscaping*constant xeriscaping multiplier, {Dmnl}

percentage water use reduction from leaks management[bath]=IF THEN ELSE(Time<delay of historical leaks management application time, 0 , base decrease rate of leaks with leaks management[bath]), {fraction}

percentage water use reduction from leaks management[ici]=IF THEN ELSE(Time<delay of historical leaks management application time, 0 , base decrease rate of leaks with leaks management[ici]) , {fraction}

percentage water use reduction from leaks management[kitchen]=IF THEN ELSE(Time<delay of historical leaks management application time, 0 , base decrease rate of leaks with leaks management[kitchen]), {fraction}

percentage water use reduction from leaks management[laundry]=IF THEN ELSE(Time<delay of historical leaks management application time, 0 , base decrease rate of leaks with leaks management[laundry]), {fraction}

percentage water use reduction from leaks management[leaks]=IF THEN ELSE(Time<delay of historical leaks management application time, 0 , IF THEN ELSE(Time<1042, base decrease rate of leaks with leaks management[leaks] , delay of leaks decrease rate with leaks management)), {fraction}

percentage water use reduction from leaks management[nonrevenue]=IF THEN ELSE(Time<delay of historical leaks management application time, 0 , IF THEN ELSE (Time<1042, base decrease rate of leaks with leaks management[nonrevenue] , delay of leaks decrease rate with leaks management)), {fraction}

percentage water use reduction from leaks management[other]=IF THEN ELSE(Time<delay of historical leaks management application time, 0 , base decrease rate of leaks with leaks management[other]), {fraction}

percentage water use reduction from leaks management[outdoor]=IF THEN ELSE(Time<delay of historical leaks management application time, 0 , base decrease rate of leaks with leaks management[outdoor]), {fraction}

percentage water use reduction from leaks management[outside city]=IF THEN ELSE(Time<delay of historical leaks management application time, 0 , base decrease rate of leaks with leaks management[outside city]), {fraction}

percentage water use reduction from leaks management[toilet]=IF THEN ELSE(Time<delay of historical leaks management application time, 0 , base decrease rate of leaks with leaks management[toilet]), {fraction}

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

population decrease=Calgary Population/(average life*52), {person/Week} population increase=(Calgary Population*(birth rate+net migration rate))*(1+future to historical increase rate ratio), {person/Week}

rain barrel change rate=IF THEN ELSE(Percentage of Houses with Rain Barrels<max rain barrels rate, IF THEN ELSE(Percentage of Houses with Rain Barrels<0.3,adoption rate of rain barrels, (max rain barrels rate-Percentage of Houses with Rain Barrels)*2.5*adoption rate of rain barrels),0), {Dmnl}

rain barrel increase rate with incentive= GAME (base rain barrel increase rate from incentive), {fraction}

rain barrels application= GAME (1)

rainfall change rate due to climate change= GAME (0)

residential in=per capita daily residential water demand, {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}

residential out=IF THEN ELSE(MODULO(Time, 53)<52, 0 , cumulative per capita daily residential water demand/TIME STEP), {lpcd}

softener standards water saving= GAME (0), {lpcd}

streamflow change rate due to climate change= GAME (0), {Dmnl}

temp and outdoor demand lookup=GET XLS LOOKUPS('?ALI Municipal', 'demand' , '20' , 'B21'), {Dmnl}

temp change rate due to climate change= GAME (0), {Dmnl}

total weekly water saving from education=SUM(weekly water saving from education by category[municipal subsectors!])/1e+009, {MCM}

unmet water demand=IF THEN ELSE(ABS((1-(Calgary weekly water use/Calgary weekly water demand))*100)<=0.1, 0 , (1-(Calgary weekly water use/Calgary weekly water demand))*100), {percentage}

upgrades application time=GET XLS CONSTANTS('? ALI Municipal', 'demand' , 'B27'), {Dmnl}

water metering change rate[municipal subsectors]=IF THEN ELSE(Percentage of Houses Metered[municipal subsectors]<1, IF THEN ELSE(Percentage of Houses Metered [municipal subsectors]+increase of metering rate[municipal subsectors]<1,increase of metering rate[municipal subsectors], 1-Percentage of Houses Metered[municipal subsectors]),0)

water plant efficiency increase rate with plant upgrades= GAME (base increased rate of treatment plant efficiency with upgrades), {fraction}

water rationing cost=(Calgary weekly water demand by category[outdoor]-Calgary weekly water use by category [outdoor])*water rationing*1000*outdoor water rationing unit cost, {$/Week}

water rationing=IF THEN ELSE(Calgary weekly water demand>Calgary weekly water use, 1 , 0), {Dmnl}

water sustainability=IF THEN ELSE(Calgary weekly water supply<=Calgary weekly water withdrawal demand, 0, (Calgary weekly water supply-Calgary weekly water withdrawal demand)/Calgary weekly water supply), {Dmnl} water use reduction from education[bath]=IF THEN ELSE(Time<delay of historical education application time, 0 , base education water saving[bath]), {liters/(person*day)}

water use reduction from education[ici]=IF THEN ELSE(Time<delay of historical education application time, 0 , base education water saving[ici]), {liters/(person*day)}

water use reduction from education[kitchen]=IF THEN ELSE(Time<delay of historical education application time, 0 , IF THEN ELSE(Time<1042, base education water saving[kitchen], education water saving of kitchen)), {liters/(person*day)}

water use reduction from education[laundry]=IF THEN ELSE(Time<delay of historical education application time, 0 , base education water saving[laundry]), {liters/(person*day)}

water use reduction from education[leaks]=IF THEN ELSE(Time<delay of historical education application time, 0 , base education water saving[leaks]), {liters/(person*day)}

water use reduction from education[nonrevenue]=IF THEN ELSE(Time<delay of historical education application time, 0 , base education water saving[nonrevenue]), {liters/(person*day)}

water use reduction from education[other]=IF THEN ELSE(Time<delay of historical education application time, 0 , IF THEN ELSE(Time<1042, base education water saving[other], education water saving of other)), {liters/(person*day)}

water use reduction from education[outdoor]=IF THEN ELSE(Time<delay of historical education application time, 0 , IF THEN ELSE(Time<1042, base education water saving[outdoor], delay of education water saving of outdoor)), {liters/(person*day)}

water use reduction from education[outside city]=IF THEN ELSE(Time<delay of historical education application time, 0 , base education water saving[outside city]), {liters/(person*day)}

water use reduction from education[toilet]=IF THEN ELSE(Time<delay of historical education application time, 0 , base education water saving[toilet]), {liters/(person*day)}

water use reduction from low flow appliances[municipal subsectors]=GET XLS CONSTANTS('?ALI Municipal', 'demand', 'B7'), {Dmnl}

water use reduction from rain barrels[municipal subsectors]=GET XLS CONSTANTS('?ALI Municipal', 'demand', 'B9'), {lpcd}

water use reduction from water metering[municipal subsectors]=GET XLS CONSTANTS('?ALI Municipal', 'demand', 'B8'), {fraction}

weekly education cost by category[municipal subsectors]=weekly water saving from education by category[municipal subsectors]*education unit water saving cost[municipal subsectors], {$}

weekly education cost=SUM(weekly education cost by category[municipal subsectors!]), {$}

weekly new homes with greywater application=cumulative new homes with greywater treatment requirement/delay of greywater application, {Dmnl}

weekly new homes xeriscaping conversion=cumulative new homes with xeriscaping requirement/delay of xeriscaping conversion, {Dmnl}

weekly water saving from education by category[municipal subsectors]=water use reduction from education[municipal subsectors]*Calgary Population*7, {liter}

WTP capacity increase rate by expansion= GAME (0), {Dmnl}

WTP capacity utilization= Calgary weekly water use/WTP production capacity, {Dmnl}

WTP efficiency= MIN(base WTP efficiency+increase rate of treatment plant efficiency with upgrades, 1), {Dmnl}

WTP production capacity=base WTP production capacity*(1+increase rate of treatment plant capacity with expansion), {MCM}

xeriscaping citizen cost=xeriscaping per home citizen cost*weekly new homes xeriscaping conversion, {$/Week}

xeriscaping city cost=xeriscaping per home city cost*weekly new homes xeriscaping conversion, {$/Week}

xeriscaping conversion=weekly new homes xeriscaping conversion, {Dmnl}

xeriscaping per home citizen cost=GET XLS CONSTANTS('?ALI Municipal', 'demand', 'B43'), {$/home}

xeriscaping per home city cost=GET XLS CONSTANTS('?ALI Municipal', 'demand', 'B42'), {$/home}

xeriscaping= GAME (0)