University of Alberta

A dynamic water balance model for drought management: A case study of the Invitational Drought Tournament

by

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Abstract

System dynamics modelling provides an effective approach for water management, as shown in this thesis, using Agriculture Canada's Invitational Drought Tournament (IDT) as a case study. The objectives of the research are to simulate basin-scale management of the fictitious Western Canadian "Oxbow Basin" and to obtain the responses of several environmental and socio-economic sub-systems to different drought management policies. The model represents five major sub-systems: population, municipal water use, agricultural water use and crop production, land use and water supply. Model use for an Invitational Drought Tournament adequately represented the basin-scale water use system of the Oxbow Basin and the broader consequences of drought policies, according to feedback from Agriculture Canada and student teams of University of Alberta, University of Saskatchewan, University of Regina and University of Manitoba. Model development also helped to identify strengths and limitations of system dynamics models, as applied to basin-scale management. The IDT model was found to be a valuable tool for studying and simulating water management.

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1 INTRODUCTION

1.1 Drought

Drought is a natural phenomenon that has attracted the attention of scientists from various fields, such as natural science, environment and social science (Mishra and Singh, 2010), and consists of an extended period of several months or even years of abnormal dry weather that results from a shortage of rainfall and causes a serious deficiency between water supplies and demands (Huschke, 1959). Drought impacts the volume of surface and groundwater resources by reducing water supply. It also can potentially affect water quality as well (Webster et al., 1996). Moreover, drought is also a social phenomenon that has a significant effect on agricultural production, livestock, as well as farmer's income. Thus drought is a very important subject in water resource management.

According to the National Drought Mitigation Center (National Drought Mitigation Centre, 2011), drought can be classified in three main categories:

1. Meteorological drought "…is usually an expression of precipitation's departure from normal over some period of time" (Thorburn et al., 2005: 3). However, whether meteorological drought conditions exist depends on local conditions. For example, in South Africa, less than 75% of normal rainfall could be regarded as a severe meteorological drought (South African Weather Service, 2012), while in Taiwan, less

than 60% of normal rainfall can be defined as meteorological drought (Encyclopedia of Taiwan, 2012).

2. Agricultural drought "…refers to situations in which the moisture in the soil is no longer sufficient to meet the needs of the crops growing in the area" (National Drought Mitigation Center, 2011). Agricultural drought always occurs after an extended period of meteorological drought – in other words, when a region has been short of precipitation for a long period, water in this district cannot meet crop requirements, and there is consequently a gap between water supplies and water demands.
3. Hydrological drought is related to water deficiency in surface and subsurface water supply systems, such as the water level of streams, rivers, lakes, reservoirs or underground water (Linsley et al., 1975). The most significant difference between hydrological drought and the other two is that hydrological droughts do not usually occur at the same time as the others, but instead lag behind (National Drought Mitigation Center, 2011). Hydrological droughts usually lead to more significant social impacts than other (NOAA, 2008).

Some other references, like National Drought Mitigation Center (NDMC, 2012a), include a fourth drought category – they add "socio-economic drought", which occurs when a water shortage begins to affect peoples' lives. Specifically, a socio-economic drought is present when the demands for economic goods, e.g. agricultural products, are greater than the supply due to weather-related shortfall in water supply.

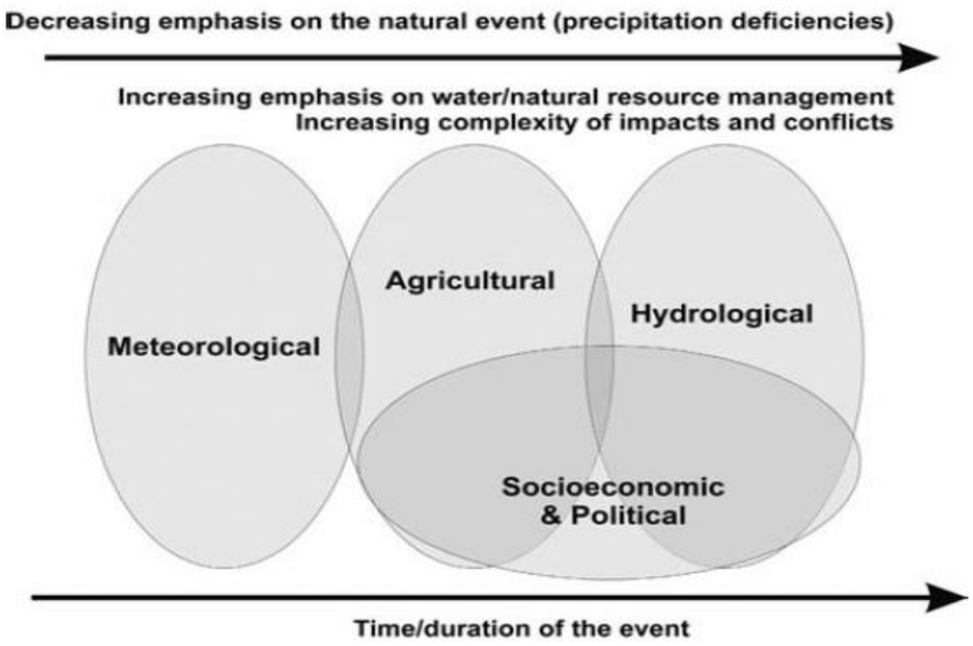


Figure 1: Interrelationships between the four types of droughts (Wilhite, 2007).

Socio-economic drought leads to the most significant social impacts of all types of drought, which makes it a major concern for both researchers and governments. However, socio-economic drought has the greatest complexity in terms of impacts and conflicts, because it involves both socio-economic and natural factors (Figure 1) – such complexity makes socio-economic drought difficult to manage and control.

1.2 Drought Management

Drought management aims to minimize drought damage by reducing the risks to society and the environment, or even eliminating adverse impacts in the best-case scenario. These general aims are incorporated into three drought management objectives provided by the European Commission (2008: 6):

> 1. Guarantee water availability in sufficient quantities to meet essential human needs to ensure population's health and life.
>
> 2. Avoid or minimize negative drought impacts on the status of water bodies, especially on ecological flows and quantitative status for groundwater.
>
> 3. Minimize negative effects on economic activities, according to the priority given to established uses in the River Basin Management Plans, in the linked plans and strategies (e.g. land use planning).

Drought management always has the same three chief goals, but implementation is context-dependent. Normally, drought management can be developed at three levels: national level, river basin level and local level (European Commission, 2008). At the national level, drought management focuses on policy, legal and institutional aspects; in extreme droughts, finance is also considered. On a river basin scale, the focus should be placed on delaying and mitigating the adverse impacts of drought through methods that identify the activation of mitigation measures. Finally, at a local level, drought plans mainly deal with the imbalance of water supply and water demand (ibid., 2008). The goals of drought management at local level are forced to meet and guarantee essential water supply.

In theory, drought management includes three major components (Sivakumar and Wilhite, 2002):

1. Monitoring and early warning, which are used to improve crop production by providing valuable information about precipitation, evapotranspiration, temperature, soil moisture, as well as available water in water supply systems including natural

streams and rivers and man-made reservoirs. According to Sivakumar and Wilhite (2002: 5), necessary outputs of the analysis include “timing of droughts, drought intensity, drought duration, spatial extent of a specific drought episode and analysis of the risk of the phenomenon and its likely effect on agricultural production”.

2. Risk and impact assessment must be completed before a drought occurs, and can help to understand the adverse impacts of a drought more clearly and determine measures to mitigate the damage, risk and impact assessment, as well as to indicate the interplay between a natural event and human behaviour. According to the U.S. National Drought Mitigation Center (NDMC, 2012b), six tasks must be completed in this component: assembly of the team, evaluation of the effects of past droughts, ranking of impacts, identification of underlying causes, identification of ways to reduce risk, and the preparation of a “to do” list. This process identifies activities that can decrease drought impacts in the long run (Sivakumar and Wilhite, 2002).
3. Finally, mitigation and response are the product and overall purpose of risk and impact assessment. “Mitigation is defined as short- and long-term actions, programs, or policies implemented in advance of and during drought that reduce the degree of risk to human life, property, and productive capacity”(Sivakumar and Wilhite, 2002: 13). In contrast to mitigation, response actions are taken after a severe drought happens in an area and “are intended to address impacts and expedite recovery of the affected area” (Sivakumar and Wilhite, 2002: 13). Wilhite(1997) divided mitigation and response into nine parts, (1) monitoring and assessment, (2)

legislation and public policy, (3) water supply augmentation, (4) public education programs, (5) technical assistance, (6) demand reduction, (7) emergency response, (8) water use conflict resolution, and (9) drought planning.

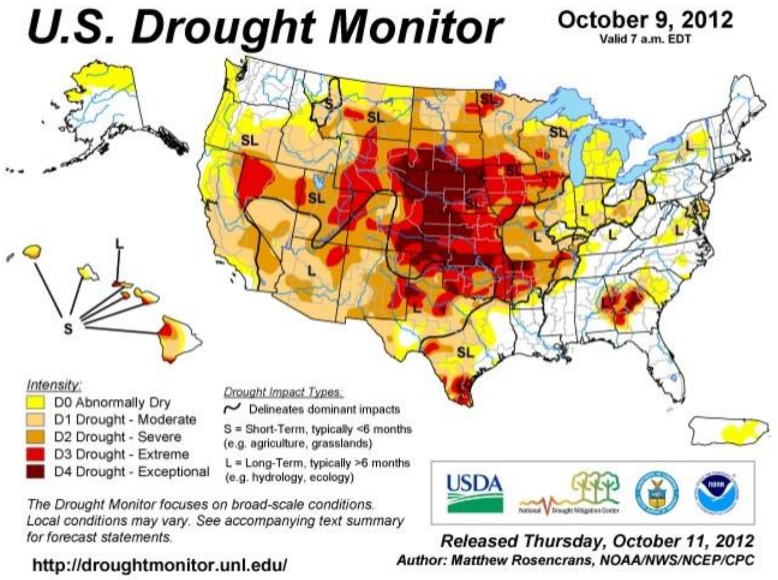
In practice, many alternative methods can be applied to manage a drought, but two, the reactive approach and the proactive approach, are most common.

The less-desirable reactive approach is taken after a drought event happens, and therefore usually occurs in an emergency situation. Historically, crisis management is one of the most common methods of reactive approach. Based on the specific characteristics of the crisis, actions are targeted to the current situation, and can be implemented by an organization of stakeholders, the government or the general public – as a result, crisis management can increase society's reliance on government or other organizations (NDMC, 2012c). However, because of a short decision time, management actions are usually ineffective and unsustainable.

In contrast to the reactive approach, the proactive approach is designed in advance. It focuses on risk management and includes both short- and long-term measures. The goal of proactive approach is to prevent minimize drought impacts, or to minimize those that occur. Generally, the approach is more complex but more effective than the reactive approach (International Centre for Advanced Mediterranean Agronomic Studies, 2012). There are several methods that are used for proactive drought management. The most common methods are: early warning system, workshops and tournaments, all of which concern about agricultural, hydrological and socio-economic drought.

Early warning systems integrate data collection, information development, modes of dissemination, and action-triggering mechanisms (United Nations Environment Programme, 2012). Data collection involves monitoring the situation while information development is based on predicting capabilities of drought preparedness and anticipated climatic conditions for providing a timely estimate of the potential risk. Modes of dissemination are used to provide warning messages to potentially affected districts (Grasso, 2012), and action triggering mechanisms are carried out by designated agencies or community members in preparing for droughts. Public awareness and educations make drought mitigation more effective. Early warning systems are a major element of drought management – as well as disaster management, more broadly – and improve public safety and protect resources. For example, people may save water with early warning system but they have no idea how much water they should save and by which methods is the best for mitigating the upcoming drought.

The U.S. Drought Monitor, which is prepared on a monthly basis, provides an example of an early warning system (Figure 2). The Drought Monitor describes current drought conditions, and drought impacts are shown on the map through the labels ”S” for short-term drought impact on agriculture-crops, livestock, range or pasture, and “L” for long-term drought impact on hydrology and ecology. For example, an area shaded in orange and labeled as D2(L) (see Figure 2) means that the related district is experiencing severe drought conditions (D2) that are affecting the hydrology and ecology in the long term (L; typically > 6 months).



The U.S. Drought Monitor is produced in partnership between the National Drought Mitigation Center at the University of Nebraska-Lincoln, the United States Department Agriculture, and the National Oceanic and Atmospheric Administration.

Figure 2: Sample U.S. drought monitor map (NDMC, 2012)

Workshops are a second form of proactive drought management. Some workshops are designed for regional events and others are useful world-wide. The common feature of those workshops is that they always focus on “science” part and a specific aspect of drought management. For instance, a workshop was held by World Climate Research Programme (WCRP, 2011) in Spain, in March 2011, to which were invited many scientists who addressed drought predictability and prediction in a changing climate. The main objectives of the workshop were to develop drought forecasting capabilities and products for stakeholders by improving prediction of drought on weekly, even centennial scale. Also in 2011, NASA organized a workshop for drought management and made an effort to improve global drought monitoring. The NASA workshop discussed strategic issues such as maximizing the use of global products (such as global drought monitor) in local area, technical issues related to the drought monitoring systems they are currently using and institutionalizing developments in global drought monitoring services (NASA, 2011). Worldwide experts from every related scientific field can be brought together by workshops. They share experiences and ideas and thus improve the understanding of droughts and their management. To summarize, all those workshops mentioned above focus on “science”.

Finally, drought tournaments are a third tool for proactive drought planning. Drought tournaments provide a communication platform for multi-disciplinary discussions and participatory policy-making processes (Mayer, 2009). Games, or “tournaments”, are an effective way to embed people in a policy-making process for experimentation and learning. A game that used for natural resource management usually combined a role-play game with a simulation model. With the participatory modelling approach, players and policy makers can improve their understanding of simulated situation by taking actions and by experiencing their effects (Mayer, 2009); further, according to Zhou and Mayer (2010: 1) ”science can enrich its body of knowledge and gain social credibility” through participation.

At present, there are many tournaments for natural resources management (Garcia-Barrios et al., 2008; Taylor, 1997), but drought management tournaments are a recent development. Drought tournaments have been developed for three locations: the U.S., the Canadian Prairies, and the Okanagan. The first drought tournament was the

“Invitational Drought Tournament”, the case study described in this thesis, which was originally developed by Agriculture and Agri-foods Canada (AAFC), and has been run in the Canadian Prairies on several occasions over the past three years, as well as in Colorado and British Columbia. Note that the Colorado Drought Tournament was designed by AMEC Environment and Infrastructure with the support of Agriculture and Agri-foods Canada, and run in November 2012. Drought tournaments have been proved a useful tool for drought planning – they improve players’ understanding of drought and drought policies by discussion and the actions they take in the game. They also engages water stakeholders in planning, preparing and responding to drought and generate realistic solutions to a complex issue that involves both technical-physical and social-political policy problems.

1.3 Study Background

Both workshops and drought tournament are technical methods to drought management and planning, and can benefit from the application of decision-support technologies to help planning groups make more informed decisions regarding complex issues (Buchanan et al., 2012).

However, although there are many tournaments for natural resources management based on the advantages described above, few games deal with drought management, especially for socio-economic drought, because of the complexity of the problem. A means of addressing socio-economic drought is valuable, and that is why it was chosen for the topic of this thesis. This project fills in some of these gaps. The study presented in this thesis was based on a newly-developed drought management tournament called the "Invitational Drought Tournament" (IDT) developed and run by the National Agro-Information Services branch of Agriculture Canada. The purpose of the IDT is to build capacity for drought preparedness by providing a forum for multi-disciplinary stakeholders to discuss climate preparedness and adaptation strategies (AAFC, 2012). Thus, the goal of this study is to develop a model that can simulate a water system during a drought event and demonstrate the effectiveness of each drought management policies. The model, therefore deals with three main subjects: basin-scale water resources simulation, assessment of multi-disciplinary policies, and gaming decision-support.

A variety of modelling approaches are available for IDT model development. The most common management models can give an optimal operation schedule for water supply or predict water demand for various water consumers; in contrast, water system models like the one developed here focus more broadly on the trade-offs between water supply and demand, and water use for socio-economic purposes such as agriculture, industry and recreation, and the effects of various management policies on the water balance. Examples of these types of models include the MIKE BASIN model, a simulation model for multi-purpose and multi-reservoir systems (DHI, 2008), the IMPACT model, a global scale simulation model for water and food management (Rosegrant et al., 2000), and a set of models developed for river-basin management using a methodology called system dynamics (Simonovic, 2002). In this case study, a system dynamics model was developed to represent a complex system to understand and prioritize the management options. Based on the feedbacks from participants of a related series of workshops (IDT), the model was found to present and simulate drought conditions and response clearly and reasonably.

The reason for choosing system dynamic modelling approach includes:

1. The comprehensiveness of the discipline. System dynamics provides a means of connecting natural science and social science (Wang, 1994), and is therefore an appropriate choice for a project dealing with socio-economic drought problem. Also, the IDT is a forum for people to discuss adaptation strategies, and system dynamics is “a rigorous method of system description that facilitates feedback analysis of the effects of alternative system structure and control policies on system behaviour” (Simonovic, 2007). Therefore, system dynamic can represent the broader effects of strategies and works as a “laboratory” of the real world to show the path to potential solutions.
2. Its utility as a communication tool. System dynamics can improve the public’s understanding of system structure and system behaviour (Davies and Simonovic, 2011), which is the main purpose of the Invitational Drought Tournament.

1.4 Chapter Overview

The thesis is organized as follows: Chapter 2 reviews the basic concepts related to drought tournaments and simulation games, and introduces a variety of water resources management models. Chapter 2 also introduces the system dynamics modelling approach and reviews its applications to water management field. Chapter 3 explains the Invitational Drought Tournament as a case study for development of games decision-support model, and then describes the resulting IDT model and its behaviour. Finally, conclusions and recommendations are presented in Chapter 4.

2 SIMULATION MODELLING GAMES AND MANAGEMENT

This chapter provides the theoretical context and reviews the basic concepts of drought tournament, simulation games and modelling approaches that have been used in water resources management.

Section 2.1 introduces the concept of drought tournament and simulation games. The characteristics of simulation games are provided in this section as well.

Next, Section 2.2 provides a literature review of water management models which can also be applied to drought management. The models are introduced and compared according to their varying purposes, time and spatial scales and typical applications.

2.1 Drought Tournament and Simulation Games

Drought tournaments are a proactive tool for drought planning and management, and form a subset of a larger group of simulation gaming models that have been widely used or natural resources management (Barreteau et al., 2007). As explained above the Invitational Drought Tournament is novel approach to drought tournament, and is held in the form of a simulation game.

Several important concepts underlie a drought tournament. These include simulation and simulation games. First, what is simulation? According to Banks (1999: 1), “simulation is the imitation of the operation of a real-world process or system over time”. Guizani et al. (2010: 1) adds that simulation involves “a computational re-enactment of a real-world system's behaviour according to the rules described in a mathematical model". Thus, simulation is used to represent a real system or process through modelling. The approach is used widely, including in business, engineering and technology, and also in education, since it can transform the typical passive learning methodology into an active learning methodology (Yarger et al., 2003).

Next, why simulate? Simulation models make possible the prediction of system performance (Robinson, 1964). Winz et al. (2009: 1302) adds that simulation "provides an informed and scientifically defensible basis for proactive management strategies, enhancing our prospects to maximise the adaptive capacity of the system as a whole". With simulations, we can compare alternative system designs and determine the effect of alternative polices through simulations of system performance (Robinson, 1964). Simulation can also reduce risk since it lets users "test every aspect of a proposed change or addition without committing resources to their acquisition" (Banks, 1998: 10).

Simulation is always combined with simulation models, of which many have been developed to solve different problems. Some modelling approaches attempt to find optimal solutions to well-defined problems, through approaches like linear programming, but such is not the case for simulation models (Robinson, 1964). Instead, simulation models are typically more experimental, and attempt to provide for a "what-if" analytical approach. They are useful because, while the value of optimization models lies in giving direct solutions, most of time there is no single, optimal answer in the real world. People prefer to know the broader consequences of alternative policies – for which simulation is best.

Second, the concept of simulation gaming needs to be explained. A simulation game is a game that uses mathematical models to simulate various activities in real-life to aid decision-making or evaluation of alternatives. Various previous studies have proven that simulation gaming is a useful tool for resources management. For example, Mayer (2009) and Barreteau et al. (2007) both argue that simulation game is an extreme, yet effective way to embed stakeholders and the public in a modelling process for experimentation and learning. According to Mayer (2009: .826)

> “Simulation games can be defined as 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”.

Similarly, Zhou and Mayer (2010) observe that play and games can enhance experimentation, safety, engagement and motivation, making simulation games potentially useful tools for drought planning.

Generally, the objectives for a simulation game are (Barreteau et al., 2007: 186):

1. Helping those who would like to know;
2. Teaching those who need to learn;
3. Opening new perspectives for those who already know (or think they know); and,

4. Facilitating collective decision-making processes.

Thus, in the context of drought tournament, policy makers and players can improve their understanding of droughts and their proposed actions through discussion and experimentation. Both technical-physical and social-political policy problems are considered and integrated in a drought tournament (Mayer, 2009).

Usually, tournaments constitute very specific settings out of time and context (Barreteau et al., 2007). The recent Colorado Drought Tournament in September 2012, sponsored by the Colorado Water Conservation Board and National Integrated Drought Information System, is taken as an example here. For the tournament, players created their own multi-disciplinary teams and selected three mitigation strategies for a multi-year drought scenario of unknown length and severity in the first round of the game. Teams then used the available mitigation strategies, as set out in tournament workbooks distributed to the teams, during the subsequent rounds to reduce drought-related impacts. At the ends of each round, teams presented their drought response plans, with justification, to the other teams. The best combinations of available policies maximized economic benefits (or minimized costs) and reduced social and ecological stress. Scoring of each team was based on how well the team addressed drought vulnerability, identified potential drought impacts and the effects of their selections (AMEC, 2012). Through the tournament, participants were educated on the multi-disciplinary and multi-sectoral implications of drought. Other aims were to encourage participants to collaborate with stakeholders from other fields – agriculture, water management, municipalities and non-government organizations, for example, and to help institutions to build capacity for around drought preparedness through game discussion.

2.2 Water Resources Management Models

Water management has a variety of goals. Water suppliers aim to minimize the waste of resource and optimize water delivery schedules. Planners attempt to predict accurately water demands from various consumers. Governments try to control the deficit between water supply and demand and minimize the consequences of shortfalls. Typically, water management is therefore a complicated process that aims to balance supply and demand or decrease gaps between water supply and water demand (Hurlimann et al., 2009). A wide range of solutions has been developed, which can be broadly categorized into two approaches: (1) increase the water availability or water supply and (2) decrease the water demand (ibid., 2009). Water management models have been developed to support management decisions, and can be grouped into three types: models for water supply management, models for water demand management, and models for water system management.

Historically, many water resources models have focused on a single side of water management, either the water supply-side or the water-demand side – whether municipal, industrial, or agricultural. Supply-side models concentrate on simulating water supply operations or predicting the water production as well as the water supply costs (Voivontas et al., 2003; Tyagi et al., 2005; Nickel et al., 2005; Uchegbu, 2009;

Okeola and Sule, 2012). Demand-side models focus on investigating the behaviour of water users, water use projections and evaluating the demand management aspects of water policies (Kolokytha et al., 2002; Mulwafu et al., 2003). For example, AquaCrop is an agricultural water demand-driven simulation model that focuses on simulating yield response to water (Geerts et al., 2010), while ARSP is an optimization model water-supply management that focuses on optimizing the operating decision for reservoirs for the upcoming time period (Bonsona and Gebresenbet, 2010). Both supply- and demand-side models focus on one specific aspect of water management, but their representation of that system is very detailed. For example, ARSP considers not only hydrological and river control information, but also detailed weather and climatic data.

With the growth of the scale and complexity of water system, water management has become more comprehensive over time, which requires managing water on both the demand and supply simultaneously. As a result, water system models have been developed (Rotmans and de Vries, 1997; de Fraiture, 2007; Hanasaki, 2008; Davies and Simonovic, 2011). These “water system models” incorporate both changing water supply and demand, and occasionally water quality, and can be used to assess the broader outcomes of water management policies. For example, while people can use ARSP model to support reservoir operation policies, the IMPACT model, a simulation model for estimation of food and related water supply and demand, can be used to assess both socio-economic and hydrological factors (Rosegrant et al., 2000). Note that all of the models mentioned above described in greater detail below.

This section first describes supply-side water resources management models, followed by demand-side water resources management models, and finally water system models. The models are discussed and compared in terms of their use, time scale, data requirements, features and limitations.

2.2.1 Water resources management models on supply side

There are various models for reservoir and river system – supply and hydrology – management. Table 1 lists a variety of models that support actual planning/operations decisions, several of which (ARSP, MIKE BASIN, StateMod, WBalMo, and WRAP) are then described in greater detail below.

Table 1: Generalized reservoir/river system models (Adapted from Wurbs, 2005)

Short Name	Descriptive Name	Model Development Organization
StateMOD	State of Colorado Stream Simulation Model	Colorado Water Conservation Board and Colorado Division of Water Resources, *http://cdss.state.co.us/*
OASIS	Operational Analysis and Simulation of Integrated Systems	HydroLogics, Inc. *http://www.hydrologics.net/*
ARSP	Acres Reservoir Simulation Program	Acres International, BOSS International *http://civilcentral.com/html/arsp_tech_info.html*
MIKE BASIN	GIS-Based Decision Support for Water Planning & Management	Danish Hydraulic Institute *http://www.dhisoftware.com/mikebasin/*
RIBASIM	River Basin Simulation	Delft Hydraulics, *http://www.wldelft.nl*

SUPER	SWD Reservoir System Model	USACE Southwestern Division *http://www.swd.usace.army.mil/*
HEC-ResSim	Reservoir System Simulation	USACE Hydrologic Engineering Center *http://www.hec.usace.army.mil/*
RiverWare	River and Reservoir Operations	Bureau of Reclamation, TVA, CADSWES *http://animas.colorado.edu/riverware/*
MODSIM	Generalized River Basin Network Flow Model	Colorado State University *http://modsim.engr.colostate.edu/modsim.html*
WRAP	Water Rights Analysis Package	Texas Commission on Environmental Quality, USACE, TWRI, *http://ceprofs.tamu.edu/rwurbs/wrap.htm*

The Acres Reservoir Simulation Program (ARSP) is applicable for real-time operation of multi-purpose and multi-reservoir systems, with time steps from hours, days, and weeks to months (Bosona and Gebresenbet, 2010). It is designed to simulate operating policies in a wide range, and can therefore also be used for long-range planning (Wurbs, 2005a). Through input of the initial state of the water system, the program can optimize the operating decision for the upcoming time period. The detailed data that ARSP requires includes inflow, precipitation, evaporation, the number of reservoirs, reservoir areas, reservoir reference numbers for rainfall and inflow series, number of net basin inflow series, number of precipitation gauge stations, codes to specify units of basin runoff, domestic and industrial water demand, irrigation water demand, hydropower generation demands, minimum flow requirements, power house and turbine features and irrigation return flow (Government of India, 2005). However, ARSP is a linear program, which means that all constraints in the model must be linear as well as relationships like tail water rating curves and head loss functions (ibid, 2005).

Like ARSP, MIKE BASIN can also simulate multi-purpose and multi-reservoir systems. MIKE BASIN was developed by DHI Water & Environment (DHI Water & Environment, 2012). It is designed to investigate water sharing issues and environment problems from an interstate to an international level. With MIKE BASIN, several solutions can be provided, such as improving and optimizing reservoir and hydropower operations, evaluating irrigation performance, establishing cost-benefit measures for water quality and conducting transparent water resources assessment. The model can also simulate the performance of operating policies during a drought or flooding by using associated operating rule curves, a function of water level, the time of year, water demand and inflows (DHI, 2008). The basic input data of MIKE BASIN are catchment run-off, diversion and water allocation for the off-river nodes (ibid, 2008). Unlike ARSP, MIKE BASIN integrates a Geographic Information System (GIS) so that it can represent a modeled system in both space and time, and can simulate groundwater and water quality. However, although MIKE BASIN can deal with the physical and optimization aspects of water resources, such as pollutant loads and operating policies, it does not incorporate socio-economic aspects of water issues. Moreover, precipitation is the only inflow included in the model (Ireson et al., 2006).

Several other models in Table 1 have a broader purpose, and can be used to assess sectoral – agricultural, municipal, industrial or environmental – water uses. StateMod was developed for water allocation and accounting with monthly or daily time steps. The model represents hydrology, water rights and system operating rules, including diversions, well pumping, reservoirs and in-stream flow demand (DWR and CWCB, 2008). RIBASIM (River Basin Simulation), developed by Delft Hydraulics (van der Krogt and Will, 2003), is also used for river basin planning and management. RIBASIM can schematize the river network, both surface and ground water, especially for irrigation water management in a drought event (Chen et al., 2005). Further, the water supply-demand balance for a reservoir/river/use system can also be analyzed and modeled at various locations and time steps through the hydrologic inputs of RIBASIM, and water demand priorities for various water users at different locations can be defined. RIBSIM also considers economic aspects, such as crop damage due to water shortages. Thus, it is a more comprehensive model, compared with other water supply models, but it requires significantly more data for a detailed analysis.

WBalMo (Water Balance Model) was developed in the 1970s, and simulates the natural runoff, water utilizations, surface water demand and water resources management policies for a river basin (Koch and Grunewald, 2009). Simulation time steps range of this model is from 1 month to long time intervals of several years. Similar to RIBASIM, the key inputs of WBalMo also include water demand components, such as water withdrawals at power stations, industrial plants and irrigation districts, and water supply components, like reservoir capacities, evaporation rates and reservoir management policies (Assaf et al., 2008). However, the model cannot be used to assess socio-economic impacts of water issues.

WRAP (Water Rights Analysis Package) was introduced first in the 1980s, and developed at Texas A&M University (Wurbs, 2005b). It can be used for water allocations both in one river basin and in multiple basin regions at a monthly time step. WRAP provides the assessment of hydrologic and institutional water availability in terms of natural flows, water withdrawals and reservoir storages (Koch and Grunewald, 2009) to support water allocation decisions, especially in a severe drought event. Like WBalMo, various options for modelling operating policies can be simulated by WRAP based on water demand priority. In practice, WRAP and WBalMo can be applied in the same situation due to the same scales and the same objectives. The major difference between WRAP and WBalMo is data units – users have more flexibility with WBalMo in unit selections.

2.2.2 Water resources management models on demand side

As consequences of population growth and economic development, as well as climate change, there is no guarantee that sufficient water will be available as water demand increases. Butler and Memon (2006) list water stress for the world, as shown in Table 2. – clearly, there has been an apparent increase in population and water stress over the years. However, the problem is not just for “the worlds”, but also for Albertans specifically. According to Christensen and Droitsh (2008), Alberta’s population constitutes 7% of Canada’s, and its share is growing. But its water supply only makes up

2% of the total water supply in Canada. Besides, agricultural lands is responsible for a very large proportion of the total land use, but the Rocky Mountains make it become one of the driest areas in Canada (Schindler and Donahue, 2006). Consequently, Alberta is particularly vulnerable to water shortages and faces increasing demand. Thus, increase in the water supply is no longer the best solution for water issues. Water demand management is becoming increasingly important for bridging the gap between water demand and water supply.

Table 2: Observed and predicted water stress in 1985 and 2025 (Butler and Memon, 2006: 3)

Area	**Population (millions)**		**Available water (km3/yr)**		**Changes in water stress relative to 1985, in 2025 (%)**		
	1985	2025	1985	2025	climate	population	combined
Africa	543	1440	4520	4100	10	73	92
Asia	2930	4800	13700	13300	2.3	60	66
Australia	22	33	714	692	2.0	30	44
Europe	667	682	2770	2790	-1.9	30	31
North America	395	601	5890	5870	-4.4	23	28
South America	267	454	11700	10400	12	93	121
Globe	4830	8010	39300	37100	4.0	50	61

Water demand management "…stresses making better use of existing supplies, rather than developing new ones" by Winpenny (1997: 297). Thus, most models focus on simulating or predicting the water use and water availability for a variety of water uses, which can be roughly classified into four categories: agricultural, industrial, domestic and water for other uses (Shiklomanov, 2000; UNESCO, 2009). Thus, there are many case studies that focus on a specific part of water management, such as domestic or agricultural water management, instead of simulating the whole water system, which is complicated and typically unnecessary for most problems. This review focuses on domestic and agricultural water demand management, since they are the key components of water use in the agricultural basins of the Canadian Prairies (AMEC, 2007).

Domestic Water Use

Domestic water use is classified into indoor *versus* outdoor use, with indoor water used for kitchen, laundry, bathing, and toilet purposes, and also lost to leakages (Ahmad and Prashar, 2010). EPCOR(2010) reports that about 65% of indoor water use occurs in bathrooms, with the average distribution in North America of bathing and showering (29%), toilet (34%), laundry (19%), kitchen and drinking (10%), and cleaning (4%, including hand washing) (shown in Figure 3). Modelling approaches for domestics water use usually concentrate on predicting major water demands and finding the key factors that affect them, as such understanding can help in determining potential water savings and in developing related policies.

The majority of municipal water use studies focus on short-term water use projections for operations and infrastructure planning. From House-Peters and Chang (2011), a variety of methods used for water use projections are summarized in Table 13, while

Table 4 lists their applications, characteristics and limitations. A similar review is also available from Qi and Chang (2011).

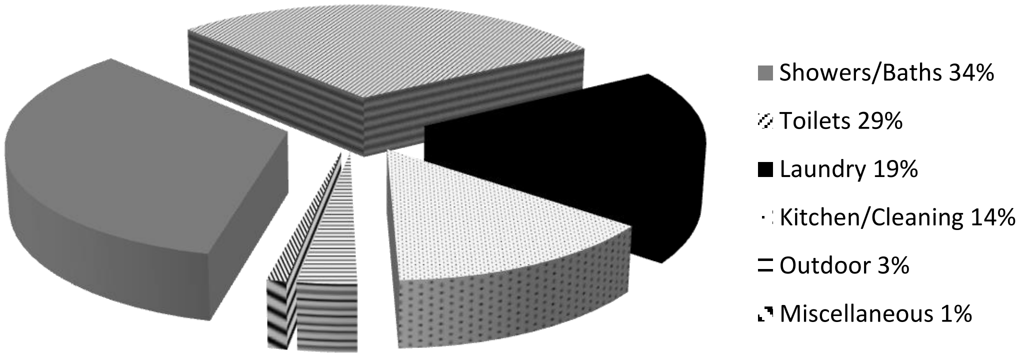


Figure 3: Typical North American Household Water Use (EPCOR, 2010)

Table 3: Selected short-term urban water demand modelling approaches (House-Peters and Chang, 2011)

Method	Data	Time Scale	Model Scale	Sources
Multiple regression	Time series data	Daily, monthly, seasonal	Municipal	Maidment et al. (1985), Maidment and Miaou (1986), Miaou [1990], Zhou et al. (2000), Syme et al. (2004), Gutzler and Nims (2005), Gato et al. (2007), Praskievicz and Chang (2009), Wong et al. (2010)
Spatially explicit ordinary least squares (OLS)	Cross-sectional data; geotagged	Monthly, bimonthly	Census block group scale or census	Chang et al. (2010), House-Peters et al. (2010), Shandas and Parandvash (2010), Guhathakurta and

regression	data		tract scale	Gober (2007), Wentz and Gober (2007), Balling et al. (2008), Lee and Wentz (2008), Lee et al. (2010)
Simultaneous equation demand model	Panel data	Monthly	Municipal	Agthe et al. (1986), Espey et al. (1997), Torregrosa et al. (2010)
State-space forecasting model	Time series data	Monthly	Municipal	Billings and Agthe (1998)
Bayesian maximum entropy (BME)	Cross-sectional data; soft data	Monthly	Census tract scale	Lee and Wentz (2008), Lee et al. (2010)

Table 4: Key characteristics of selected urban water modelling approach (House-Peters and Chang, 2011)

Method	Applications/Characteristics	Limitations
Multiple regression	(1) Short-term forecasting, (2) examine climatic effects on demand, (3) separate water use into two components: weather-insensitive base use (winter or indoor) and weather-sensitive seasonal use (summer or outdoor).	(1) Lacking or highly aggregated spatial data, (2) difficult to determine the correct functional form of the model, (3) conventional models may underestimate water use response to climate variables because of the influence of stochastic events on seasonal use
Spatially explicit ordinary least squares (OLS) regression	(1) visualize and quantify water use patterns at fine spatial scales, (2) elucidate spatial patterns of clustering and dispersion of high and low water users, (3) model individual household level consumption data, (4) correct for heterogeneity due to spatial autocorrelation, which otherwise	(1) water provider service areas do not match administrative boundaries (e.g., census block), (2) data usually must be aggregated to protect customer privacy, (3) no consistency between water providers regarding collection of water use

	causes biased parameter estimation	data
Simultaneous equation demand model	(1) simultaneously and jointly determines the endogenous dependent variables on the basis of exogenous variables, (2) corrects for multi-collinearity and serial autocorrelation	(1) data aggregation at large spatial scales, (2) violation of the economic assumption that households are perfectly informed of water price
State-space forecasting model	(1) computes forecasts based on the dependence of a variable upon its own lags and the cross lags of the independent variable, (2) simpler than ARIMA	(1) The values of the independent variables must be forecasted in order to compute a forecast of the dependent variable
Bayesian maximum entropy (BME)	(1) assimilates data uncertainty into the data extrapolation and mapping process, (2) obtain downscaled estimates from spatially aggregated data, (3) project future water use, (4) inclusion of data uncertainty as soft data	(1) data extrapolation can lead to dubious results because the values are estimated beyond the scope of the known data, (2) computationally intensive, (3) variances can be overestimated if interaction terms are neglected in the models used to build the probabilistic soft data

A variety of authors (Arbues et al., 2003; Jorgensen et al., 2009; Ahmad and Prashar, 2010; Rockaway, 2011; House-Peters and Chang, 2011) discuss policy options that can contribute to domestic water saving, including (1) the use, mandatory or optional, of low flow appliances; (2) xeriscaping; and (3) water pricing. However, shorter-term demand simulation models, such as those described by House-Peters ad Chang (2011), focus on water demand forecasting, and typically omit policy effects. Further, many other water demand studies analyze policies based on reviews of previous research or previously collected data. For water pricing, for example, several analytical approaches, as well as economic models, have been used, including cross-sectional analyses, which consider the behaviours of water consumers at a single point in time, time series analyses, which consider the behaviours of consumers over time, and panel analyses, which consider the behaviour of the cross-section over time (Brookshire et al., 2002). Such studies find that variables such as household size, income, climatic variables and public education are critical determinants of urban water demands (Howe and Linaweaver, 1967; Gibbs, 1978; Dalhuisen et al., 2003; Arbus et al., 2003). They also typically conclude that water demand is inelastic – in other words, there is no significant change in water demand by changing in water price.

Agricultural Water Use

Agricultural water is used for crop irrigation and livestock watering. Because irrigation water requirements are influenced by many factors – climate, soil characteristics, crop types, on-farm irrigation system efficiency, and water distribution efficiency – water consumption is quite different from one region to another. In general, agricultural water demand models aim to predict crop water demand and crop yields, and therefore simulate the crop growth and irrigation system. Given the complexity of agricultural management, a variety of computer models has been developed. This review introduces and compares AquaCrop, CropSyst, CROPWAT, SWAP and MACROP in terms of their objectives, capabilities, time and spatial scales.

One of the most popular agricultural water management models is AquaCrop, which was developed by the Food and Agricultural Organization (FAO) of the United Nations (FAO, 2012). AquaCrop is a water focused simulation model which can simulate the yield response to water of the major herbaceous crops (including fruit or grain producing crops, leafy vegetable crops, roots and tubers and forage crops) at a daily time step. It has been used for deriving deficit irrigation schedules as well (Geerts et al., 2010; Akhtar et al., 2011). Compared with other crop models, AquaCrop describes the crop water system using a smaller number of parameters: soil evaporation, crop transpiration, harvest index, air temperature, reference ET, water productivity coefficient, water stress coefficient, atmospheric carbon dioxide concentration and irrigation water (Steduto et al., 2008). It is also applicable to various water management situations, such as rainfed agriculture and supplemental, deficit, and full irrigation, and has been used by extension services practitioners, consulting engineers, governmental agencies, NGOs and farmer associations (ibid, 2008) at scales from individual farms to irrigation districts. The main limitation of this model is that drought stress is the only stress it considers during a simulation – factors like pests, disease, weeds and salinity which can affect crop yield, are not included.

The Cropping System Simulation Model (CropSyst) is a multi-year, multi-crop, daily time-step cropping systems model developed at Washington State University. It includes components of the water, and nitrogen budgets, crop phenology, biomass accumulation, leaf area development, root growth, yield, crop growth response to elevated atmospheric CO2 and crop rotations, and can help to assess farm production and manage nutrients (Stockle et al., 2003). A key difference from AquaCrop is that CropSyst links GIS software, a weather generator, and economic and risk analysis models which permits the model to incorporate salinity, pests and fertilization. Due to its simplifications, CropSyst is easily calibrated and applied for both small-scale irrigation and large-scale simulation (Todorovic et al., 2009).

CROPWAT was developed by Smith (1992). It is a practical tool intended to support agricultural water management, irrigation scheduling (Marica, 2012) and the development of water supply schemes, by calculating reference ET, crop water requirements and crop irrigation requirements. The principles and calculations are based on methodologies presented in FAO Irrigation and Drainage papers (Doorenbos and Pruitt, 1977; Doorenbos and Kassam, 1979; Opaluch, 1984; Arbus et al., 2003). Similar to AquaCrop, CROPWAT is applicable to irrigation schedules planning under varying water supply conditions and to production assessment under rainfed conditions or deficit irrigation (SDNP, 2012). Like most agricultural water management models, climatic, crop and soil data are required inputs, and the time-step for results can be daily, weekly, monthly or even decadal.

Finally, agricultural models can also focus on specific components of the water cycle. SWAP and MACRO, for example, are soil-process models. The Soil-Water-Atmosphere-Plant (SWAP) model is used to solve vertical soil-water flow, salt transport and crop growth (Noorya et al., 2011), and has been used to simulate the water cycle and the evaluation of irrigation practices at a field scale level for both growing seasons and long term time series (Ma et al., 2011). MACRO is a physically-based 1D simulation model for the soil water system. For soil water balance issues, it allows users to consider about soil matrix (micropores) and macropore flows at an hourly to daily scale (Akhand et al., 2006). MACRO uses the same equation and theory as CropSyst and SWAP, but has been found to produce poorer results in soil simulation by Bonfante (2010), who compared the three models in a case study in Northern Italy. He remarked that “SWAP had the best performance especially in simulating surface infiltration and drying processes, followed by CropSyst and then MACRO” (ibid, 2010: 1051).

2.2.3 Water system models

Through the above model approaches – demand or supply side – water resources can be managed and used in a more reasonable, efficient and specific way. Yet water issues are usually caught between growing water demand on one side and limited water supplies on the other (FBC, 2011). Thus, a more comprehensive method of water management that includes both sides of is defined as a water systems model here.

Water system models focus on providing a consistent framework for assessment of the water balance at a basin scale. Such models attempt to simulate a water system rather than specifically forecasting water which is the main difference between water system models and water supply or demand models. Examples of system models reviewed here include IMPACT and WaterGAP2. The scale of these models is varied, with some at a basin scale, like the Maipo River Basin Model (WRBM) while others, work at a global scale, such as IMPACT and WaterGAP2. Water system models allow people to understand the structure of a complex water system and link with socio-economic effects to provide a more comprehensive way to manage water issues (Winz et al., 2009; Williams et al., 2009).

IMPACT, the International Model for Policy Analysis of Agricultural Commodities and Trade, was developed by International Food Policy Research Institute in 1990s (IFPRI, 2012). The goal of IMPACT is to estimate the global food supply, demand, trade, prices and food security for the future. Therefore, IMPACT is a global scale simulation model. It has also been employed in regional studies (Rosegrant et al., 2000), which analyzed the effects from the Asian financial crisis of 1997 on food economy in Rio Grande Basin. More recently, IMPACT has been combined with the Water Simulation Mode, and is called IMPACT-WATER (Rosegrant et al., 2008). This updated model includes water demand for irrigation, livestock, industry and municipalities, water supply, effective rainfall, crop yield and price impact on water demand. Figure 3 shows the parameters in IMPACT-FOOD required as model inputs in the first simulation year. Based on these values, the model will calculate water demand based on the outputs from IMPACT-FOOD Module. The Water Simulation Module also provides water supply information according to climate scenarios. After those simulations, model will compare and analyse the demand projection, supply projection and domestic prices to determine whether the word trade is in balance, which means that imports equal exports. If not, the model will adjust the world prices and start a new set of computations; if yes, it will step into the next year and update inputs for model itself. Thus, the water supply and demand are simulated first at a basin scale, then crop production is assessed, followed by food demand and trade simulation, and the water demand is updated based on food demand to complete a feedback (ibid., 2008). IMPACT-WATER connects socio-economics and hydrology; however, domestic water demands not related to food production are not included, since agriculture and food demand is the model focus.

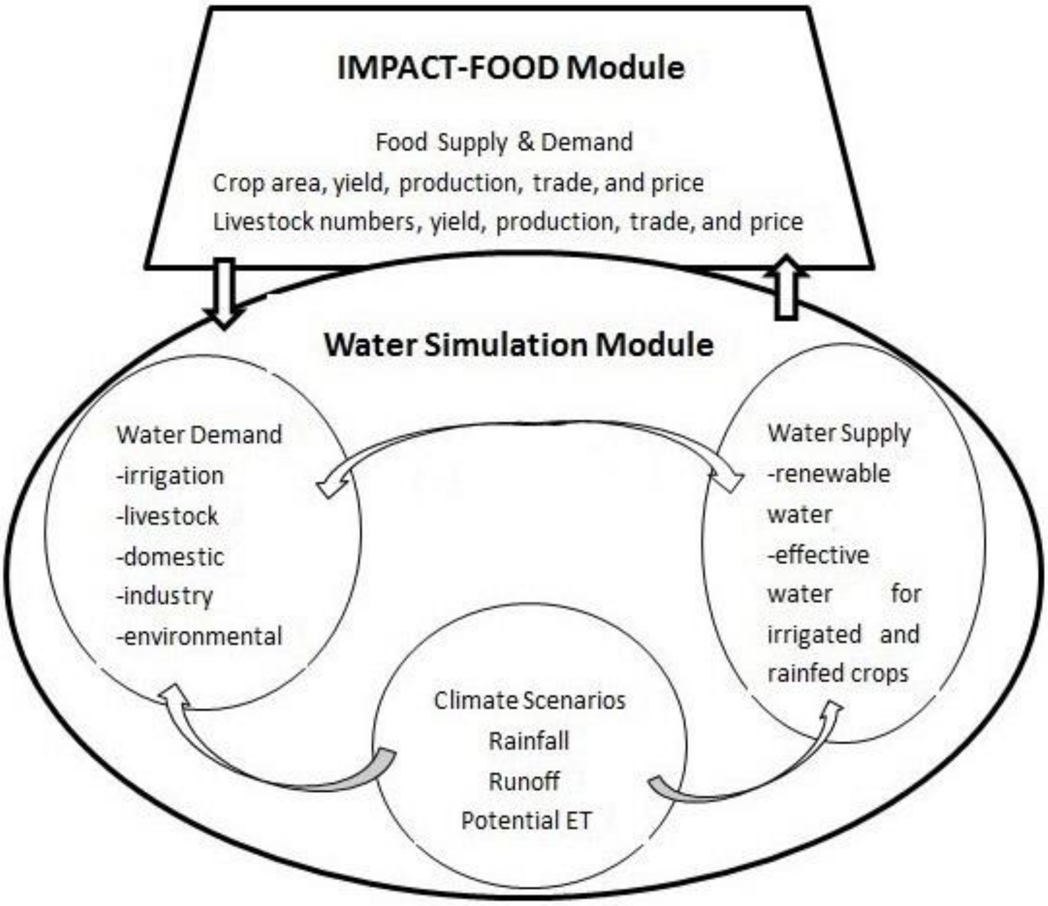


Figure 4: Structure of the IMPACT water model structure (Rosegrant et al., 2008)

Like the IMPACT model, most water resources studies concentrate on agriculture since it is typically the main users of water at a basin scale (Shiklomanov, 2000). The WaterGAP2 model also works at a global scale, and includes a broader range of water issues for large river basin on all continents. The model is an integrated water management model developed at the Center for Environmental Systems Research at the University of Kassel, Germany, in cooperation with the National Institute of Public Health and the Environment of the Netherlands (Alcamo et al., 2007). It combines two models: a water use model and a water availability (or hydrology) model (Alcamo et al., 2003). The key parameters of the hydrology model are climate, drainage direction, land cover, soil, slop, hydrogeology and permafrost, and the model is used to simulate water availability in terms of surface runoff, groundwater recharge and river discharge. The water use model includes climatic variables, irrigated areas, livestock, population and national estimates of domestic and industrial use, which it uses to simulate water withdrawals and consumptive. WaterGAP2 has been applied to global water resources management, and has been used to simulate 4000 river basins covering most of the world (Alcamo et al., 2002) by computing water supply capacity, water flow and storage, and water use for both domestic water and agricultural water. WaterGAP2 can estimate the impacts of global change on the water sector and simulate the characteristic macro-scale behaviour of worldwide water cycle from an integrated long-term perspective (Anon, 2012a).

The Maipo River Basin Model was developed by Cai et al. (2006). It runs at a monthly time step, and combines an optimization model with a simulation model to optimize water allocation, reservoir operation and scheduling after simulating the flow, salinity balances and crop growth in the Maipo River Basin, Santiago, Chile. The integrated modelling framework involves hydrological modelling, which accounts for water storage and flow, diversions at various locations along the river, and spatial econometrics, and also incorporates crop production profits, hydropower production and profits, municipal and industrial benefits and salt concentration/environmental use of the water. The model therefore provides a complete depiction of the physical and socioeconomic characteristics of the river basin. However, as the purpose of the model is maximizing economic benefits, it does not permit exploration of “what-if’ problems, even though it includes a simulation component.

2.3 System Dynamics

Other recent studies have developed water system model using a simulation methodology called “system dynamics”. For example, Gober et al. (2011) examined rising water demand in the context of rapid population growth and climate change in Phoenix, Arizona. Prodanovic and Simonovic (2010) studied effects of hydrological extremes in the Upper Thames basin, Canada, with a coupled hydrological and socio-economic model. Williams et al. (2009) developed an educational model that connects historical flows in several Arizona rivers with dynamic water use models to evaluate policies for greater water-use efficiency. Langsdale et al. (2007) connected river flows from climate and hydrological models with dynamic water demands in the Okanagan basin. This section introduces system dynamics in detail, along with some sample model studies. The difference of system dynamics models and other water system models which were reviewed in this chapter will also be described.

System dynamics was originally developed by J.W. Forrester in the 1950s at the Massachusetts Institute of Technology, and was first applied to industrial management to deal with problems such as fluctuations in production and staffing, and the instabilities of the stock market (Forrester, 1961). By the 1970s, system dynamics was being used to simulate the entire world – population, natural resources, industry, agriculture and pollution – in the World3 or “Club of Rome” model (Meadows et al., 1972; Meadows et al., 1974). Since that time, system dynamics has been used widely in management (Georgantzas, 2003), policy analysis (Meadows et al., 1992), economics (Radzicki and Sterman, 1994), biology (Arquitt and Johnstone, 2004), medicine (Dangerfield et al., 2001), water resources management (Simonovic, 2002; Davies and Simonovic, 2011), and climate change research (Sterman and Booth Sweeney, 2007).

Overall, system dynamics is a comprehensive discipline which is also a computer-based modelling approach.

As a comprehensive discipline, system dynamics connects natural science and social science (Wang, 1994). A system is defined as a set of interacting and interdependent components that work together to perform a particular task or set of tasks. System dynamics emphasizes feedbacks; therefore, the biggest difference between system dynamics and other simulation methods is that system dynamics aims to see how changes in a single element of the system affects the behaviour of the whole system, rather than predicting future events. System dynamics can therefore also function as an education tool to improve our understanding of system structure and system behaviour (Williams et al., 2009).

As a modelling approach, system dynamics models can be developed in two forms: qualitative/conceptual and quantitative/numerical (Dolado, 1992). Qualitative models improve our understanding of system structure and of the relationships between each component by using “causal loop diagrams”. In contrast, quantitative models are numerical, and allow the investigation and visualization of the effects of management “policies” (Winz et al., 2009). To build a quantitative model, explicit, mathematical statements of relations between each component, or variable, are required. Assumptions are allowed to be used as well because of the uncertainties of a complex system. Further, nonlinearity and circular causality are important characteristics of system dynamics models, and make system dynamics can simulate high-order nonlinear system, and it can handle multiple feedbacks without becoming unstable. Using first-order ordinary differential equations, system behaviours can be easily represented by feedbacks, stocks and flows. However, ordinary differential equation is also the main cause of the limitations. As a computer-based simulation, the arithmetic speed and model study are also strengthened (Sterman, 2000).

Therefore, for investigation of complex system, the methodology has five key features (Wang, 1994): (1) System Dynamics theory can be used for both macroscopic and microscopic studies, and particularly those that deal with sophisticated systems, involving social and economic dimensions; (2) open systems are the primary focus –

specifically, dynamic structures and feedback mechanisms; (3) system dynamics links qualitative and quantitative analysis; (4) system dynamics can be regarded as the "laboratory of the real world". It is not only a tool for real world simulation but can also show the path to potential solutions; and (5) system dynamics has been widely used in scientific studies, and has gained scientific credibility.

Based on these characteristics, system dynamics is very useful for a variety of groups: policy-makers and managers can use system dynamics to assess proposed management actions, researchers can use system dynamics to explore the dynamics of complex system and identify trade-offs, and the public can improve its understanding of system structure and behaviour (Williams et al., 2009).

2.3.1 Key Concepts in System Dynamics

Key concepts in system dynamics models include stocks, flows, delays, nonlinearity and feedback.

Stocks are at the root of decision-making, form the memory of a system, and represent accumulations of information or material (Forrester, 2009). Examples of stocks include money in a bank account, water in a reservoir, or crops in a field. Flows are the means of change in stocks values. Thus, deposits to a bank account increase the balance, releases from a reservoir decrease its level, and harvesting removes crops from a field. Figure 5 shows an example of a stock and flow diagram.

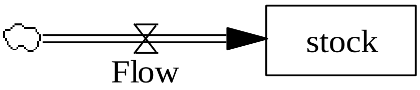


Figure 5: Stock and flow diagram – a stock with a single inflow

Delays are a consequence of stocks. The peak flow in a river after a heavy rainfall is attenuated by a reservoir, which smoothes the peak into a longer-duration, but lower-intensity event. In system dynamics modelling, identifying delays is an important step in the modelling process because they often alter a system's behaviour in significant and unpredictable ways. Further, the longer the delay between cause and effect, the more likely it is that a decision maker will not perceive a connection between the two. Figure 6 presents the simple example of a reservoir with a single inflow and a single outflow – clearly, the water that enters the reservoir from upstream remains in the reservoir for some period, and thus experiences a delay, before it is released to flow downstream.

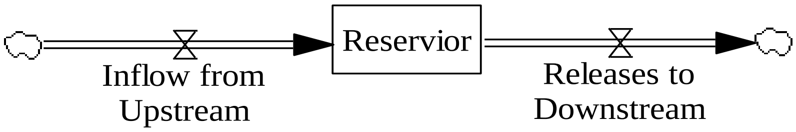


Figure 6: A reservoir decouples inflows and outflows, causing a delay

Finally, feedback – and particularly "positive" and "negative" feedbacks – are the most important element of a system dynamics model.

Keesing (1981: 556) explains that a “positive feedback occurs when ‘A’ produces more of ‘B’ which in turn produces more of ‘A’”. Thus, exponential growth always occurs in cases of positive feedback where no other process acts to limit the growth.

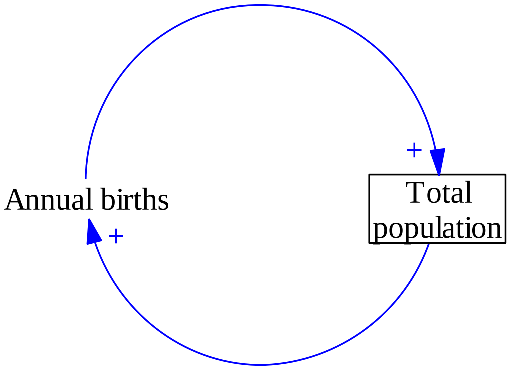


Figure 7: A sample positive feedback – Population growth

For the simple example in Figure 7, suppose that the population cannot decrease – in other words, births dramatically outnumber deaths, as might occur in a bacterial culture during the initial colonization of a new culturing medium. In this loop, daily cellular divisions cause the total population to rise. A larger population leads to more births, which increase the population again. Thus, the population increases exponentially.

Drought can be identified as a positive feedback (Figure 8), since a lack of precipitation reduces soil moisture, which causes damage to plants. Fewer plants means less water will be evaporated through plant transpiration. Consequently, rainfall will decrease due to the limited cloud formation, and a positive feedback loop is complete.

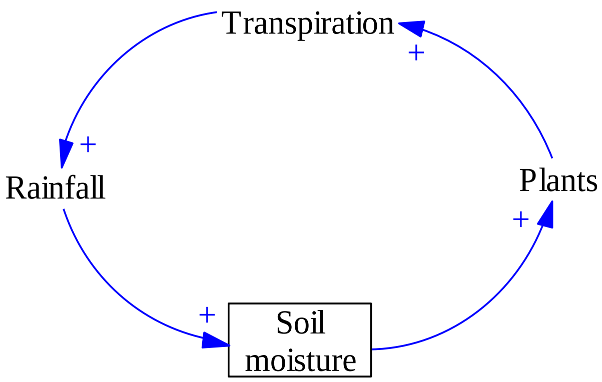


Figure 8: A sample positive feedback: soil moisture and drought

According to Meadows (1997: 6), "positive feedback loops are sources of growth, explosion, erosion, and collapse in systems. A system with an unchecked positive loop ultimately will destroy itself."

In reality, positive feedback is typically counteracted, and eventually controlled, either by limiting conditions or by negative feedback loops. Carrying capacity is an example for biological communities, while reservoir capacity and operating rules limit water storage. Negative feedbacks are goal-seeking and lead to system stability. Figure 9 shows an example of a negative feedback, in the form of a thermostat. In this system, cooling depends on the outside temperature, while heating depends on the difference between the current inside temperature and a target, or "desired", temperature. When the inside temperature has diverged sufficiently from the target temperature, because of heat loss to the outdoors, the furnace turns on. The interior of the home heats and the temperature difference between desired and actual temperatures lessens. Once the temperature difference is sufficiently small, and typically slightly above the target temperature, the furnace turns off and the home begins to cool again. The thermostat maintains the indoor temperature close to the target – the system "seeks" its pre-set temperature. Thus, negative feedback balances a system by reducing discrepancies between desired and actual output.

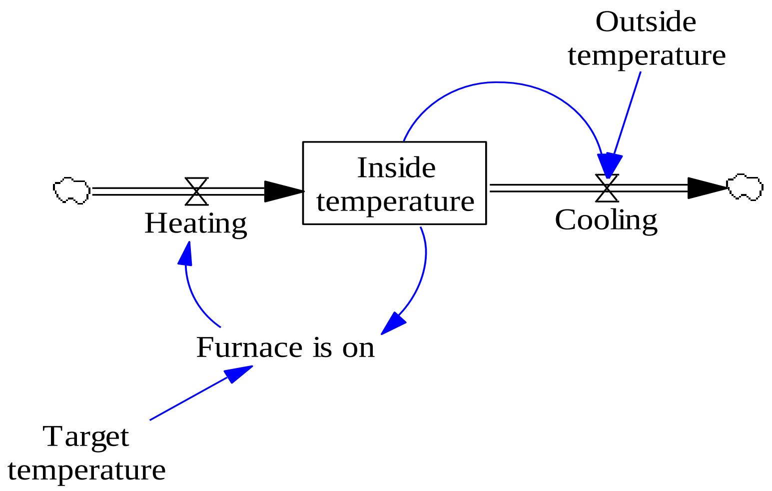


Figure 9: A sample negative feedback: A thermostat

2.3.2 Model Development with System Dynamics

To develop a system dynamics model, there are six steps (Richardson and Pugh, 1981; Stave, 2003):

1. Clearly define the goal of a model.
2. Describe the system. Determine the boundaries, integral variables, rate variables and other important variables. To complete this task, a team with experts from various professional fields is often assembled.

3. Develop the model. Establish the relationships between variables with mathematical expressions.
4. Build confidence in the model. Simulate and verify model by analyzing model behaviours or comparing with an existing result.
5. Implement the model for policy analysis.
6. Use the model for public education and for researches purposes.

In this case study, we developed the IDT model according to these six steps, as explained in the nest chapter.

2.3.3 System Dynamics Models for Water Management

System dynamics is suited to both short- and long-term water management and allows people to observe and improve their understanding of the behaviour of a modeled system (Winz et al., 2009), as evidenced by many case studies. For example, system dynamics has been applied successfully to a variety aspects of water management, such as hydrological simulation (Williams et al., 2009; Prodanovic and Simonovic, 2010; Gober et al., 2011) and water use and water demand management (Xu et al., 2002; Davies and Simonovic, 2011). According to Winz et al. (2009), those system dynamics applications in water management can be categorized by their main problem foci, whether regional analysis and river basin planning, urban water, flooding, irrigation or pure process models. Further, system dynamics has been applied at a wide range of spatial scales, from regional (Xu et al., 2002; Stave, 2003; Tidwell et al., 2004; Williams et al., 2009) to national (Simonovic and Rajasekaram, 2004) and finally to global (Davies and Simonovic, 2011).

A system dynamics model for water resources planning, called the Water Resources System Dynamics (WRSD) model, was developed by Xu et al. (2002) for a basin scale, the Yellow River basin in China. The WRSD model focuses on analysis of the sustainability of water resources in the Yellow River Basin, and through estimation of the annual amount of water demand and water supply, permits various assumptions (scenarios) to be assessed in terms of their effects on the behaviour of environmental, agricultural, industrial, domestic water use variables, as well as on return flows. The WRSD model presented a tool for the simulation of potential solutions to satisfy numerous demands related to regional development, environmental concerns and ecological needs in the Yellow River Basin; however, it did not include economic factors and water management policies. Instead, the feedbacks in the model are just between scenarios and various water uses and demands.

Stave (2003) described and applied a system dynamics model for water resources management in Las Vegas at an annual scale. The model has two parts, a demand system and supply system. On the demand side, six forms of water use are represented, including residential outdoor and indoor water use, commercial water use, industrial water use, demand from government, schools and hotels and non-residential irrigation. On the supply side, the model includes wastewater treatment water in lake and natural flow and Las Vegas distribution system. Policy analysis with the model relates to increase water supply, water conservation by hotels and casinos, a decrease in residential indoor and outdoor water use, a decrease in population or urban growth, and a combination of the various strategies. In all, the Las Vegas water system model is a simple but highly effective model. Specifically, there are only five stocks adopted in the model, related to water in wastewater treatment plants, in the Las Vegas Wash (river), in Lake Mead, in the Las Vegas Distribution System and the Las Vegas Valley Population. However, despite its simplicity, it improved public understanding of water management options and encouraged the public to support water conservation. The model does not allow people to consider costs, but it still engaged people's interest and showed a result that reducing water use has a greater effect than increasing water supply.

Williams et al. (2009) developed a water resources education model for a semi-arid region of the U.S. south-west. Similar to the Las Vegas water system model, the model also functions at an annual scale and consists of two sections, water demand and water supply. In the regional water supply system, the model has more detail than the Las Vegas water system model, and includes a river, reservoir, groundwater aquifer, treated wastewater effluent, imported water and trail water rights. Combined with the supply model, the model of regional water demand system incorporates water use for agriculture, industry, non-residential turf and indoor and outdoor residential use. Population is the most important determinant of demand growth, while the implementation of various conservation measures in the model reduce water demands. Like the Las Vegas water system model, the wastewater treatment plant is also included;

however, the biggest difference is that Williams et al. (2009) include economic factors, such as supply costs, farmers' incomes, and even environmental economics, based on recreation demographics and economic studies of “willingness to pay”. The model is educational because it stresses experimentation with options for learning purposes, and has 30 user interface pages and about 75 control objects and results objects. It allows people to select their own sets of policy options and to view the different outputs.

The key elements of water resources system are also identified by Tidwell et al. (2004) in a casual loop diagram. They described a community-based planning model for the Middle Rio Grande river basin that runs at an annual time step. As in other system dynamics studies on water resources management, river inflows, groundwater pumping, waste water return flows, water storage in reservoir, agricultural consumption, municipal use and population are the critical components in this model. The difference is the author considered more detailed hydrology, such as climatic factors, mountain front recharge and open water evaporation. By setting different options, users can view the different impacts of each policy option on water savings and stakeholders can find more effective policies by simulating the effects of various alternatives. This work builds a quantitative platform for exploring alternative water management strategies and the preparation of a 50-year water plan, and is intended to support policy making for stakeholders and education and engagement for the publics.

System dynamics can be used for global water system as well. Davies and Simonovic (2010; 2011) introduced a global-scale system dynamics model named ANEMI. ANEMI is a model which is applied for a simulation of the social-economic-environmental system with nonlinear feedbacks at an annual scale. It mainly deals with policy making for global climate change and focuses on simulating the feedback effects of global change, on eight different sectors that are regarded as the primary concerns. These sectors are climate, carbon cycle, economy, land use, population, the hydrological cycle, water use, and water quality. With the feedback system they presented in ANEMI, change in the value of one key variable will feed through to other sectors at every time step. Compared with other models for climate and global change, ANEMI functions at much lower spatial resolution but simulates the broad, nonlinear feedback effects of various policies and scientific uncertainties on the entire system. It links natural science and socio-economics, and represents the real-world system by using system dynamics theory. Overall, ANEMI prominently embodies the key characteristics of system dynamics models that closed loops "cause model behaviour to emerge from the interactions between different sectors rather than from input data or driving functions" (Davies and Simonovic, 2011: 133).

2.3.4 Comparison of System Dynamics with other modelling approaches

Like other modelling approaches, system dynamics models have made numerous contributions to a range of water management areas, including decision making and operations. However, the biggest difference between system dynamics model and other models is that water system structure and internal dynamic feedbacks of water system are not captured in other models but in system dynamics model due to different objectives. They treat water sector with varying levels of detail. In system dynamics model, understanding the system structure and analysis of each component's behaviours are the most important goals rather than providing explicit predictions or exact solutions to a single problem.

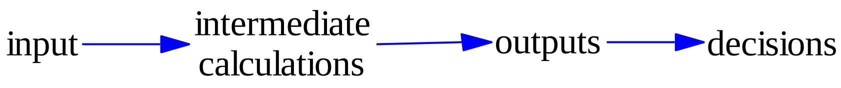


Figure 10: The linear thinking paradigm as a contrast with system thinking

Specifically, system dynamics models use a different thinking paradigm to build the model structure. For many general models, a linear thinking method is adopted (Sterman, 2000). This linear thinking mode follows the order, "inputs – intermediate calculations of a model – outputs – decisions" (Figure 10), a unidirectional thinking paradigm that provides direct solutions for model users. System dynamics models, in contrast, it uses the systems-thinking paradigm which is "inputs – intermediate calculations of a model – new outputs – decisions – take decisions as new inputs – intermediate calculations – another outputs –new decisions" (Figure 11). With this thinking mode, one decision affects the available options, or possible "decision", at the next time interval. Thus, system dynamics models aim to show the accumulative effects. Users can see how and why the simulated system changes with their decisions rather than obtaining some data or direct solutions for a problem.

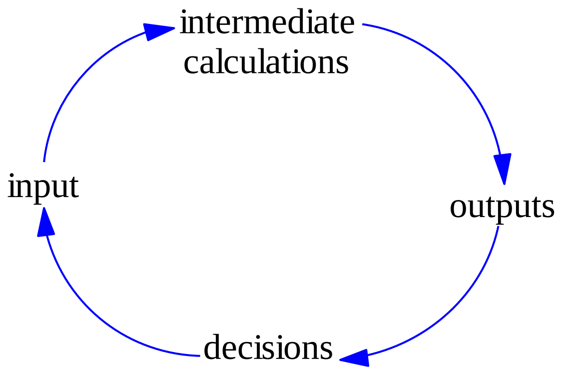


Figure 11: The feedback-based thinking paradigm

Water is a key resource that affects all other human and environmental systems. Competing intra- and inter-sectorial demands, as well as an uncertain supply, explain why it is difficult to manage water successfully – particularly where conflicts may arise, as in the case of droughts. Therefore, in many cases, understanding how decisions affect the whole system and identifying the key drivers of water resources problems is more important than finding a single, optimal solution for the problem, because there may be no single, best solution. The complexity of water management leads to the necessity of a methodology that can (1) handle connections, or feedbacks, between society, economics and the environment, (2) represent both physical processes and alternative policies, and (3) communicate results with stakeholders. These are the strengths of system dynamics. Therefore, researchers and managers should identify the goals of their model study and be aware of the strengths and limitations of system dynamics before using it.

3 CASE STUDY: INVITATIONAL DROUGHT TOURNAMENT (IDT)

This chapter presents the case study and its methodology. Section 3.1 introduces the project (Invitational Drought Tournament) and describes the background of the simulated basin, the Oxbow Basin. Section 3.2 describes the IDT Model in detail. It is divided into six parts. Each part is a sub-model of the IDT model. Finally, section 3.3 and 3.4 validates and tests the IDT Model and gives its behaviour and analysis.

3.1 Introduction of Invitational Drought Tournament and the Oxbow Basin

The Invitational Drought Tournament (IDT) was developed by Agriculture and Agri-Foods Canada (AAFC). The purpose of the IDT is to build capacity for drought preparedness by providing a forum for multi-disciplinary stakeholders to discuss climate preparedness and adaptation strategies. The tournament follows a game format in which participants form their own teams of typically five players, and are then guided through a drought scenario of undisclosed length, which is also unknown if the drought happens in the reality. Teams are assessed on the basis of the adaptation options they select; the winner is the team judged to have adapted best to the drought according to social, economic, and environmental criteria.

The first IDT was held in February 2011 at the Delta Calgary Airport Hotel in Calgary, Alberta, and included forty six people: thirty team members, four referees, twelve observers as well as the organizing committee and facilitators.

The second IDT was held at the Saskatoon Inn, Saskatoon, Saskatchewan, on March 1 and 2, 2012. In total, 45 people were present, with twenty-six student participants competing in five teams in the game, four university professors serving as coaches, four referees and three observers as well as the organizing committee and facilitators.

The Saskatoon tournament introduced a new decision support tool, a system dynamics simulation model, which is described in this thesis. The new tool is intended to provide “memory” to the game – so that policy decisions selected in one game turn continue to affect the evolution of the drought scenario over time – as well as a concrete basis for identifying and judging the effects of game decisions. It is also intended to remain flexible so that it can be adjusted from one Tournament to the next as new adaptations and policies are proposed.

The Invitational Drought Tournament (IDT) occurs in a fictitious basin (the Oxbow basin) in the near future, where an imbalance between water supply and demand is just beginning. Game participants are told that the Oxbow Basin lies in a semi-arid area, and that precipitation is decreasing in the years leading up to the game (AAFC, 2011). Reduced rainfall means that there is not enough water to meet regular municipal, industrial and agricultural demands.

The Oxbow is intended to be representative of a typical Canadian Prairies river basin, and spans an area of 175,000 km^2, with a population of 3,000,000 people. The primary consumer of water is agriculture which accounts for 75% of water demand, and is mainly used for irrigation. Municipal water demand, on the other hand, accounts for 14% of total water demand. The characteristic of water use is similar to the Bow River Basin, in which the agricultural sector accounts for 77 percent of total water use and the municipal sector accounts for 20 percent (shown in Figure 13). But note that the Bow Basin only has 25,000 km^2 area and 1,009,865 people (AMEC, 2007).

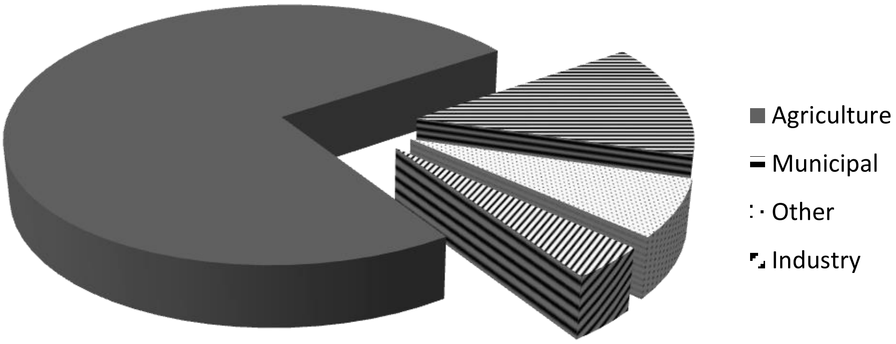


Figure 12: Water demands in the Oxbow Basin by sector

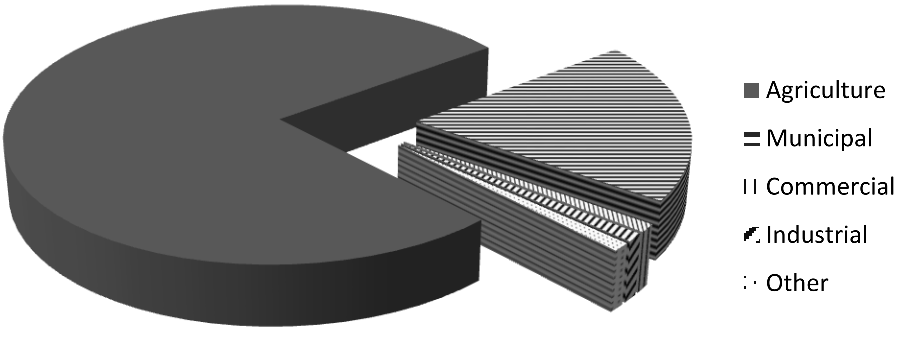


Figure 13: Water use in the Bow Basin (AMEC, 2007)

There are several land uses in this basin. Over 90% of the basin's landbase is used for agriculture. Irrigation, as the largest consumer of water, is applied to 10% of the agricultural land (4,300,000 acres). Cropping land accounts for 50% of the agricultural land, pasture makes up about 45% and the remainder is summerfallow land or others. A variety of products are produced in this basin, including dairy, beef, hog, poultry, grain, oilseed, fruit and vegetables.

To play the game, IDT participants first create their own teams, and they are not told the duration of the drought, and thus must plan for at least several years of water shortages. Each team is given a typically large (hundreds of millions of dollars) pre-tournament adaptation budget, as well as additional funds each year, which they can allocate to a variety of infrastructure and policy options. These options belong to four main categories, as shown in Table 5: water management, financial management, land management, and technical improvements. Further, at the beginning of each game year, participants are given a new document describing current conditions, both in terms of drought characteristics and sectoral water demands, and are then asked to allocate their budget – which is designed to be varied from one year to the next, just like the real situation – to the adaptation options in Table 5. Note that both the costs and effects of the IDT policies may vary from one Tournament to another. At the end of each game year, referees assign marks based on the ability of the selected options to reduce ecological, economic and social drought risk and address short-term and long-term needs in the basin.

Table 5: Drought management options in the IDT (AAFC, 2011)

Adaptation option	Adaptation type	Details	Price
Water Management			
Enhance irrigation water diversion/application efficiency by 25%	Long-term technology and infrastructure focused strategy that takes 5 years to implement	Convert 300,000 acres to high efficiency irrigation and line 1000 km of canal with concrete to reduce seepage	$193,000,000
Divert water from another basin to the Oxbox	Long-term Infrastructure strategy that takes 10 years to implement	Inter-basin water transfer of 250 MCM every year. This diversion Involves the construction of a pipeline and reservoir	$840,100,000 (includes construction of diversion, reservoir and maintenance)
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	$477,000,000 (includes maintenance)
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	$350,000
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	$200,000
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 $35 per acre to producers affected by drought	$100,000,000
Land Management			
Promote green cover	Long-term operation management strategy aimed at changing land use in the basin	Provide producers with $85 per acre over 10 years to cover 150,000 acres of marginal annual cropped land at-risk of soil degradation to perennial cover	$12,750,000
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	$510,000
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	$125,000,000
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	$1,000,000
Technology			
Expand irrigation	Long-term strategy to convert dryland to irrigated farming	Add 500,000 acres of high efficiency irrigation to the basin	$149,000,000

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	$102,000,000
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	$102,000,000
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	$51,000,000
Consultation			
Left justify	Assess the strength of your team's strategy by bringing an expert third party into the discussion	Consult either your coach or referee. Teams must keep track of the time spent in consultation, and deduct the necessary funds from their budget	$11,000,000 / minute

3.2 IDT Model Description

Based on the introduction above, the model was developed to represent the main characteristics of the water system in the Oxbow Basin by using Vensim software. To be useful for a drought-focused game, the model is intended to be comprehensive, covering the key of components of economy, land use, agriculture, water demand, water supply and human and animal populations. Because the policies in the IDT (see Table 5 above) affect both the water supply and demand side, we divided the model into three main parts: (1) water supply; (2) water demand; and (3) water management policies. Moreover, as in other similar water resources management models (Langsdale et al., 2007; Winz et al., 2009) , the water demand component can be further divided into two pieces: municipal (residential) water use and agricultural water use. Each of these components is a sub-model of the system dynamics model that is coupled to the others by feedbacks and affected by water policies. The basic logical framework of the water components of the model are shown in Figure 14 below. Besides, all of the sub-models connect with each other like Figure 15.

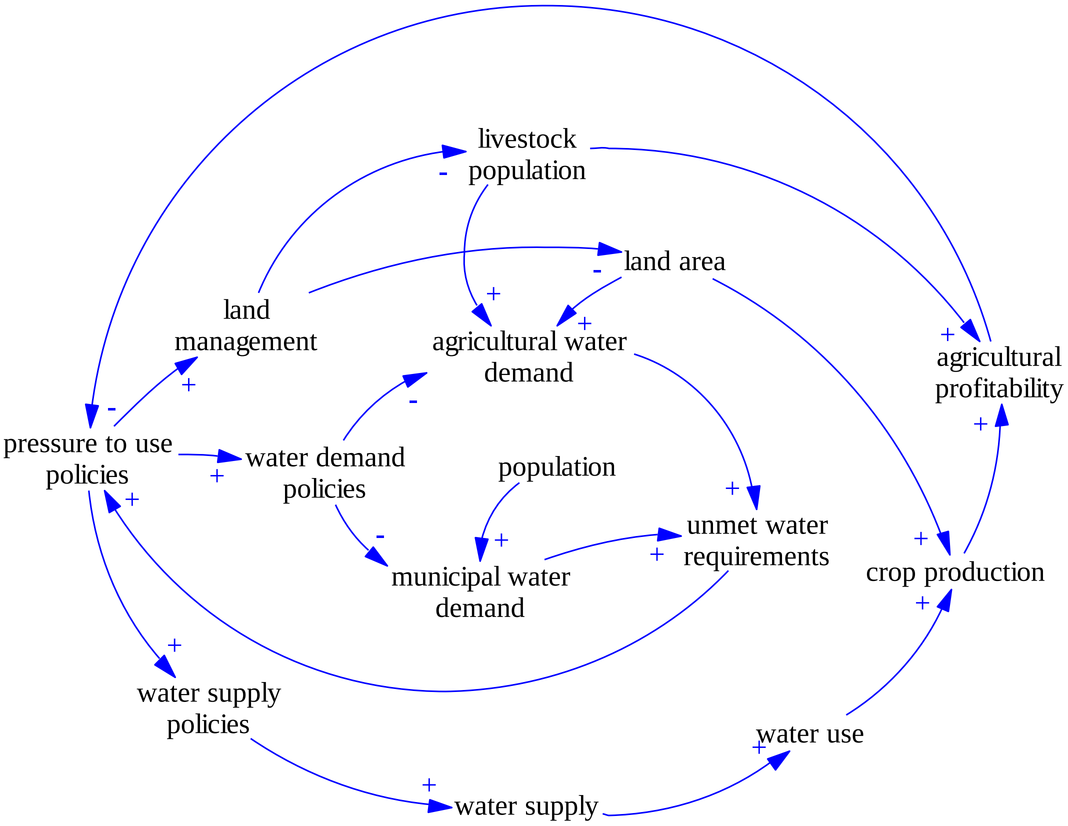


Figure 14： The basic feedback structure of the IDT model

The main idea for this model could be presented as a closed feedback. As shown in Figure 14, these factors are interrelated and interact with each other. How much water supply is available in the basin can determine whether the water demands will be met. If the water requirement cannot be satisfied, some water policies need to be executed to either reduce the water demand or increase the water supply to decrease the water shortfall. This relationship between supply, demand and policy is the key in the development of the decision-support model. However, water supply, demand and policies are not the only considerations for water management. People also need to regard the agricultural profitability, land use, budget and even human needs.

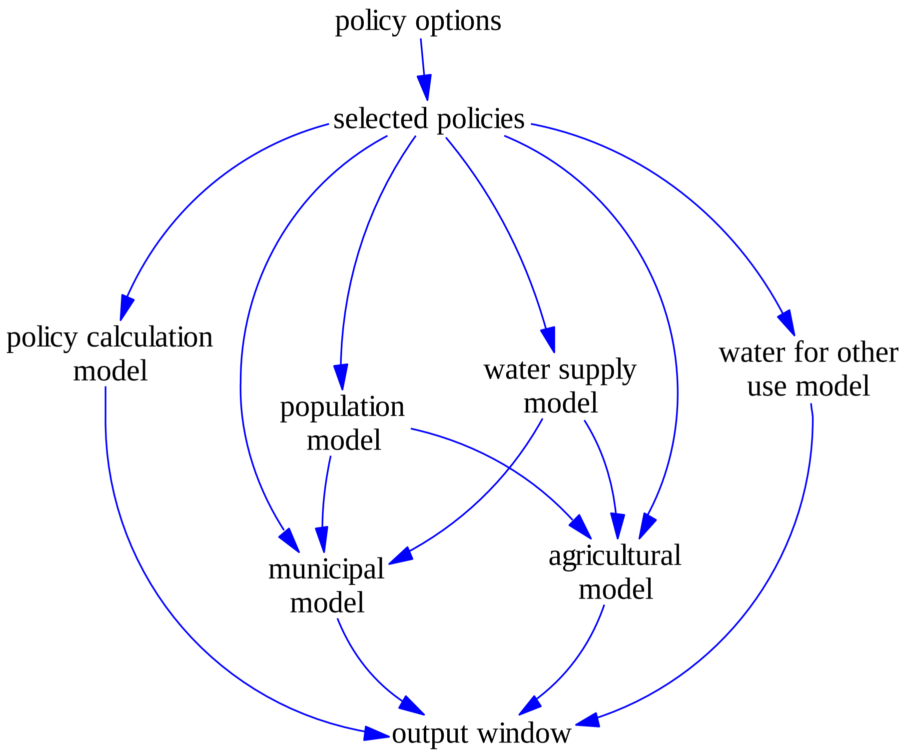


Figure 15: Interconnections between the components of the IDT model

From the basic decomposition based on water supply and demand, we further broke the land use sectors up to represent specific uses – irrigated land, dry land, which is based on the land classification from Zhao et al. (2007), and green cover land (i.e. fallow land) – and the agricultural components into specific crops.

All of the important characteristics and relationships in the model, whether socio-economic or physical, are modeled at the annual scale to match the timescale used in the IDT. Further, the model is typically run for three years, from 2013 to 2015, and all of the given information is based on the fictitious Oxbow Basin. These simplifications mean that the behaviours in the model should be understood in the proper context, based on a whole river-basin scale and an annual timestep. Crop type is an example of these simplifications. Based on the IDT documents (AAFC, 2011), only five crop types are modeled in the model, forage, grain, oilseed, vegetables and grass, for which we use parameters for water requirement and crop yield based on alfalfa, barley, canola, potato and grass. Further, if people choose to increase the agricultural profitability, farmers are assumed to change the sown area of each crop instead of changing crop type during these three years.

We describe the model structure in the next sections. For clarity, the model is broken down into eight sectors or “Views” in Vensim’s terminology:

- Model output window; this sector shows the results of the policies selected by each team.

- Policy selection window; teams can choose their policies by sliding policy in each game year level. It is convenient to those people who have never used Vensim before.
- Policies calculations; all expenditures and effects of policies are calculated here.
- Populations; this sector simulates human populations and animal populations in Oxbow Basin. Water and feed requirements of animals are included in this part as well.
- Water supply; this sector represents the total amount of available water which can be supplied to the basin, as well as the effects of supply-side policies.
- Municipal water use; municipal water use is calculated by category.
- Irrigated agricultural water use; this view presents agricultural water use for irrigated crops.
- Dryland agricultural water use; this view represents agricultural water use for non-irrigated crops.
- Water for other use; this sector simulated the amount of industrial and environmental water use.

Note that the “policy calculations” sector is mainly used for calculating the effects of policies and tracking their costs. Specifically, this sector includes the calculations of irrigation delivery system and application efficiency; water diversion from another basin to the Oxbow; additional dam and reservoir storage; permitted municipal water use; total water use in Oxbow Basin; drawdown of reservoir storage; irrigation efficiency improvement from water R&D; yield improvement from agricultural R&D; reductions from grey water use; expenditures total expenses and remaining funds.

All the policies available to players, and their effects are listed in Table 5 – effects, like those of agriculture-related research and development or promotion of green cover, are described in their associated sectors, below.

As the assumption in the IDT documents (AAFC, 2011), industrial and environmental water uses are minor at the annual scale. Thus, they are represented as constants in the model. All of the components mentioned above will be introduced in details in this section and data sources will be listed as well.

In the section 3.3, model validation is described. Several important factors, municipal and agricultural water use, land area, yield and water-yield response, are compared with the data from the real world. Model behaviours are highlighted in the section 3.4, which show the policies selections by University of Alberta Team 1 and University of Saskatchewan and their effects as examples. It also includes extreme value test and the changes after the Saskatoon tournament.

3.2.1 Basin population

The IDT includes several different populations that must be differentiated from one another, and that change over time: municipal population, rural population, and animal populations. All of these are represented in the model as stocks (see Figure 16 and 17).

Population is the major driving force behind the change in water consumed in the municipal sector from one year to the next, and so its changes, while small, are included in the model. Rural populations are more critical as a variety of IDT policies have economic consequences for the farming population – although these policies are not yet modeled in any detail, the explicit inclusion of a rural population will allow incorporation of rural economics at a later date.

Municipal and rural populations are represented similarly, and the municipal population equations are provided here as an example. The flows that affect the municipal population consist of births and deaths, as shown in equation (1),

$$\int_t^{t+1} MPopulation\,dt = MBirths(t) - MDeaths(t) \tag{1}$$

in which, “MPopulation” is the municipal population (people), “MBirths” is the municipal births (people/year) at time t, and “MDeaths” is the municipal deaths (people/year) at time t.

“Birth rate” and “Average life” act as the driving variables on “Mbirths” and “Mdeaths” (equation 2 and 3)

$$M\mathrm{Bi}rths(t+1) = MPopulation(t) \times MBirth\,rate \tag{2}$$

$$MDeaths(t+1) = MPopulation(t) \div MAverage\ life \tag{3}$$

In which, “MBirth rate” is the birth rate of municipal population (people/year), “MAverage life” is average life of municipal population (year).

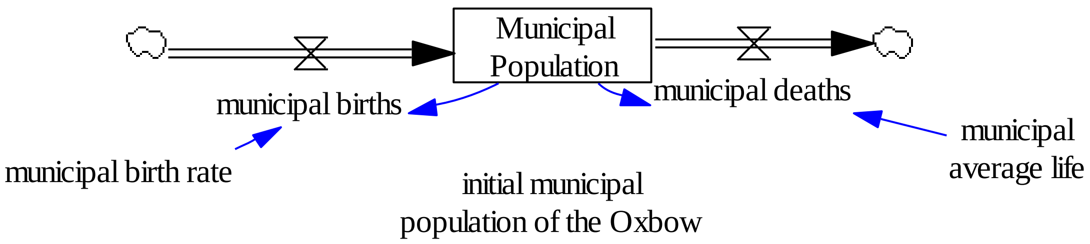


Figure 16: Stock and flow structure of the municipal population component

Shifts in population are therefore influenced by birth and death only i.e. no immigration or emigration in Oxbow Basin; however, "birth" and "death" can also be understood here to represent generic increases and decreases.

The basic idea of the animal population simulation is the same as for the municipal population – see equations (1) and (3) above. Like the municipal population, it assumed that the change in the animal population is normally related to the animal birth rate and animal average life expectancy – the death rate here is termed "animal sales", as most animals are slaughtered. However, the IDT includes a policy called "promote stocking rate reductions", which can reduce the animal population. This stocking rate reduction is expressed by equation 4:

$$ASales(t+1) = APopulation(t) \div AAverage\ life + stock\ number\ reduction \qquad (4)$$

in which, "ASales" is the number of animals which are sold and slaughtered; "APopulation" is animal population (number); "AAverage life" is average life of animal population (year).

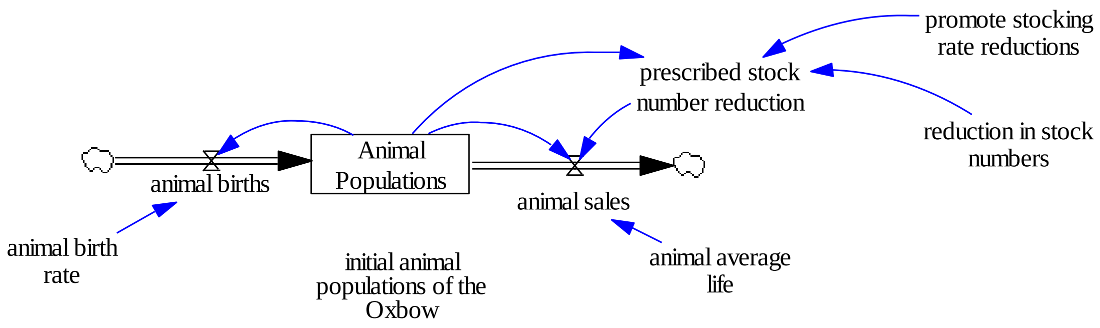


Figure 17: Stock and flow structure of the animal population component

Water and feed requirements of animals are also important considerations that affect agricultural water use and cropping patterns, whether during a drought or not, and can be represented on a per capita basis (Alcamo et al., 1997). They are calculated in this sector as well. Animals at each growth stage have different water and feed requirements. Thus, we divided animals into three groups: baby, juvenile and adult. Further, according to IDT documents (AAFC, 2011: 11), "there are over 15,000 farmers engaged in a wide array of agricultural production types, including dairy, beef, hog, poultry, grain, oilseed, fruit and vegetables". Therefore, four types of animals are simulated in the model: dairy cattle, beef cattle, pigs and chickens.

The annual stock water requirements for each of the four animal populations is calculated by daily requirements multiply by 365 days. The governing equation is expressed in equation (5). Note that the annual stock feed requirements are calculated in the same way.

$$annual\ stock\ water\ \ requirements =$$

$$(baby\ animal\ fraction \times baby\ animal\ water\ requirements +$$

$$juvenile\ animal\ fraction\ \times juvenile\ anmial\ water\ requirements +$$

$$adult\ animal\ fraction\ \times adult\ animal\ water\ requirements) \times$$

$$animal\ populations\ \times 365 \tag{5}$$

Parameters related to water requirements of baby, juvenile and adult animals are selected from the Ontario Ministry of Agriculture (Ward and McKague, 2007). While animal annual grain and roughage requirements come from Statistics Canada (2001). Table 6 shows the water consumption for each livestock (Ward and McKague, 2007) and compares with the data we used for the IDT Model.

Table 6: Water requirements for livestock (Ward and McKague, 2007)

Livestock	Water requirement (l/day)	Data in the IDT Model (l/day)
Dairy calves	4.9-13.2	9
Dairy heifers	14.4-36.3	25
Milking cows	63-155	115
Dry cows	22-54	46
Baby swine	1.0-3.2	2
Juvenile swine	3.2-10	4.5
Adult swine	13.6-22.7	17.5
Chickens	0.05-0.77	0.34

All the inputs and parameters used in this sector are listed in Table 7.

Table 7: Population sector initial settings for the IDT Model

Population and Stock	Units

Settings					
initial municipal population[1]	3.00E+06				people
initial farming population[1]	15000				people
initial animal populations[1]	60000	3.50E+06	1.20E+06	4.00E+07	animals
animal subscripts	dairy	beef	pigs	chickens	
animal birth rate	0.333333	0.2	0.75	0.75	fraction
animal average life	3	5	1.3333	1.3333	years
baby animal water requirements[2]	9	9	2	0	L/day
baby animal annual grain ration[3]	0	0	0.013	0	tonnes/yr
baby animal annual total roughage[3]	0	0	0	0	tonnes/yr
baby animal fraction	0	0.3411	0.2988	0	fraction
juvenile animal water requirements[2]	25	35	4.5	0	L/day
juvenile animal annual grain ration[3]	0.528	1.968	0.297	0	tonnes/yr
juvenile animal annual total roughage[3]	2.2	2.634	0	0	tonnes/yr
juvenile animal fraction	0.31666	0.3256	0.6063	0	fraction
adult animal water requirements[2]	115	46	17.5	0.34	L/day
adult animal annual grain ration[3]	3.073	0.247	0.998	0.0029	tonnes/yr
adult animal annual total roughage[3]	3.7	4.5	0	0	tonnes/yr
adult animal fraction	0.68333	0.3333	0.0949	1	fraction

Table sources: [1] AAFC, 2012; [2] Ward and McKague, 2007; [3] Statistics Canada, 2001.

3.2.2 Municipal water use

The municipal water use sector simulates changes in municipal water demand resulting from population variations and the implementation of the policies chosen by each team. Therefore, the municipal water use model has three parts: water demand, actual water use and IDT water policies. Distinction between water use and water demand is necessary because the water demand may not be met in a drought year, causing the actual use to be below the ideal demand.

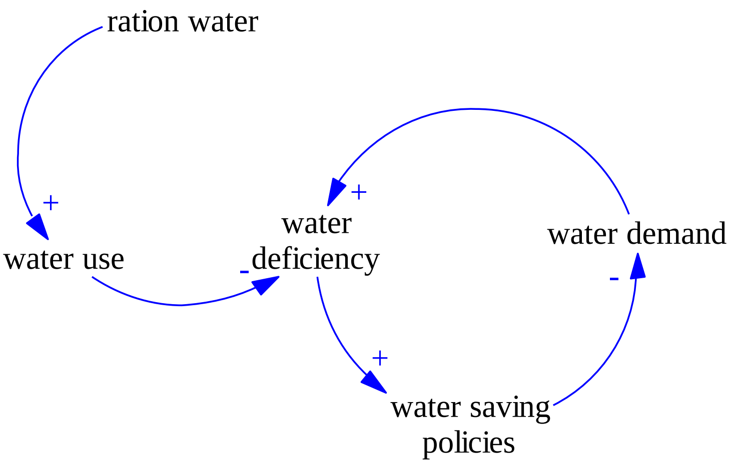


Figure 18: Municipal water use feedbacks

The main idea behind the structure of the municipal water system model is shown in the feedbacks of Figure 18. In normal years, people typically use as much water as they like, but when water must be rationed in a drought year – a team selects the “ration water” policy in the IDT – people can be expected to reallocate their water for each household use. If municipal water demand cannot be satisfied because of rationing during a drought, households would need to execute water saving policies to reduce their water demand. Some of these changes will be longer-term, as a result of structural changes in municipal water use through the adoption of low-flow appliances or conversion of residential landscaping, and so will affect the water demand in the subsequent year. The effect is a decrease in the deficiency in the municipal water availability.

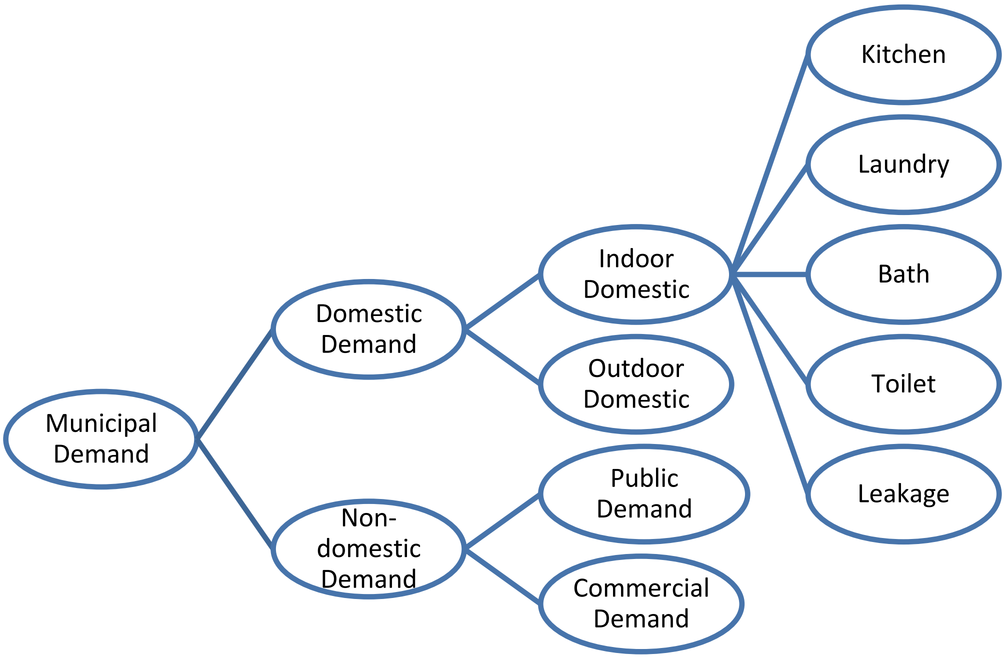


Figure 19: Municipal water demand (Ahmad and Prashar, 2010)

Following Ahmad and Prashar (2010) and Gober et al. (2011), municipal water is used for domestic (larger volume) and non-domestic (smaller volume) water use. Figure 19 provides a hierarchical representation of municipal water use to complement. In terms of indoor use, there are five key categories: kitchen, laundry, bath, toilet and leakages (Mayer and DeOreo, 1999; Williams et al., 2009b; Ahmad and Prashar, 2010). Each demand is calculated in the mode as the water use per action and the number of actions per day (e.g. number of toilet flushes per person per day), which produces the per capita use per day. Each of the daily per capita demand is then multiplied by population, since the residential demand is strongly based on population (Stave, 2003; Williams et al., 2009; Qaiser et al., 2011).

The rationale for the disaggregation of domestic water use into these five parts is that the water saving policies in the IDT (and in reality) cause water use reductions in different areas of the home. For example, grey water policies can reduce toilet water use but not kitchen water use; low-flow appliances can reduce laundry, bath and toilet water use rather than outdoor water use.

Figure 20 shows the municipal water demand model. The model variables on the left side of Figure 20 show the actions available to reduce water use. According to Ahmad and Prashar (2010), low-flow appliances represent an effective means of decreasing water use. The “municipal water percentage deficiency” variable is the key driver of adoption rate (fraction of households) of low flow appliances. This municipal water percentage deficiency calculates the gap between the actual water use as affected by rationing during a drought and the ideal water demand, based on regular, pre-drought water usage. The percentage of households with low-flow appliances is a stock – these low-flow appliances represent household capital that is fixed from one model year to the next, since appliances and toilets tend not to be replaced quickly in homes, once installed. The “adoption rate of low flow technologies” at the bottom left of Figure 20 increases as the value of the water deficiency increases, which represents the installation of low-flow appliances by urban households. Water related research and development can also simulate a rise in the “adoption rate of low flow technologies”.

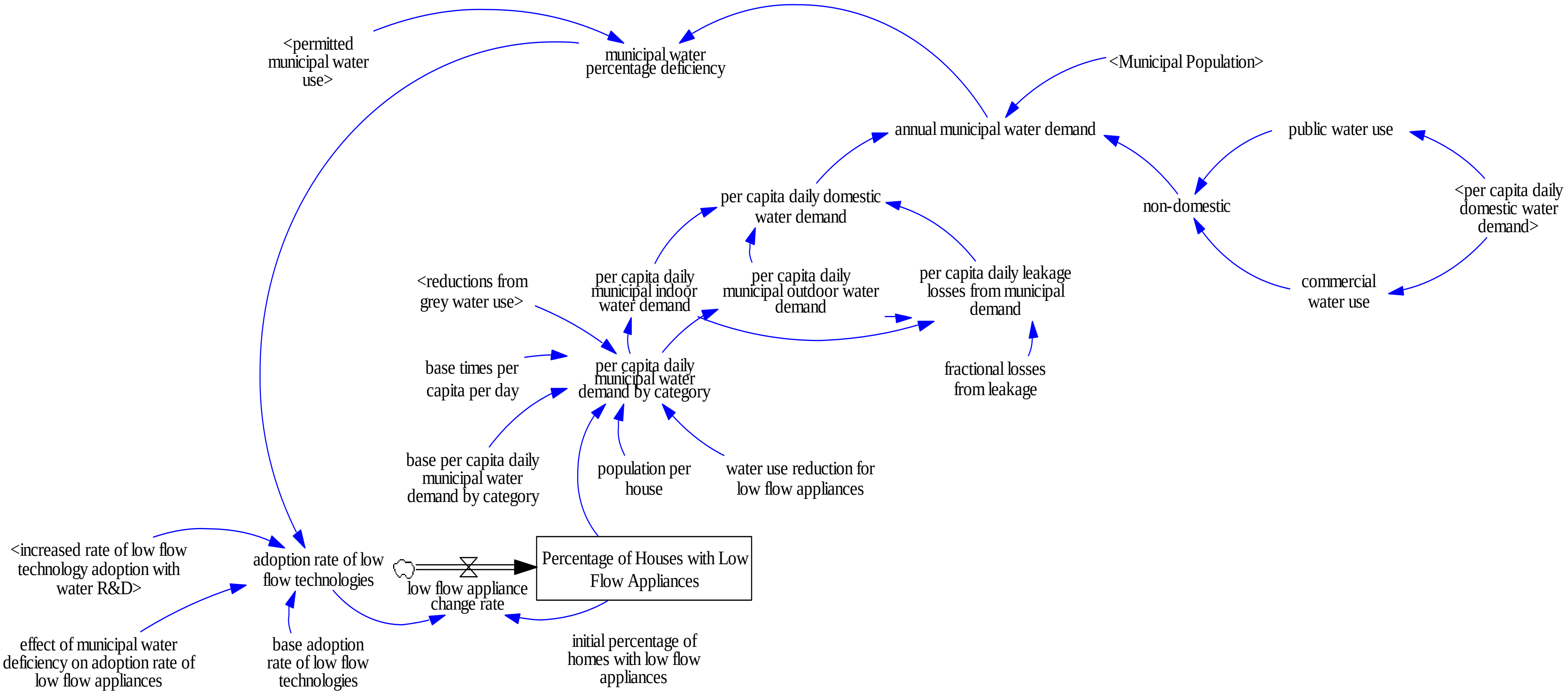


Figure 20: Screen-capture of the stock and flow structure for the municipal water demand calculations

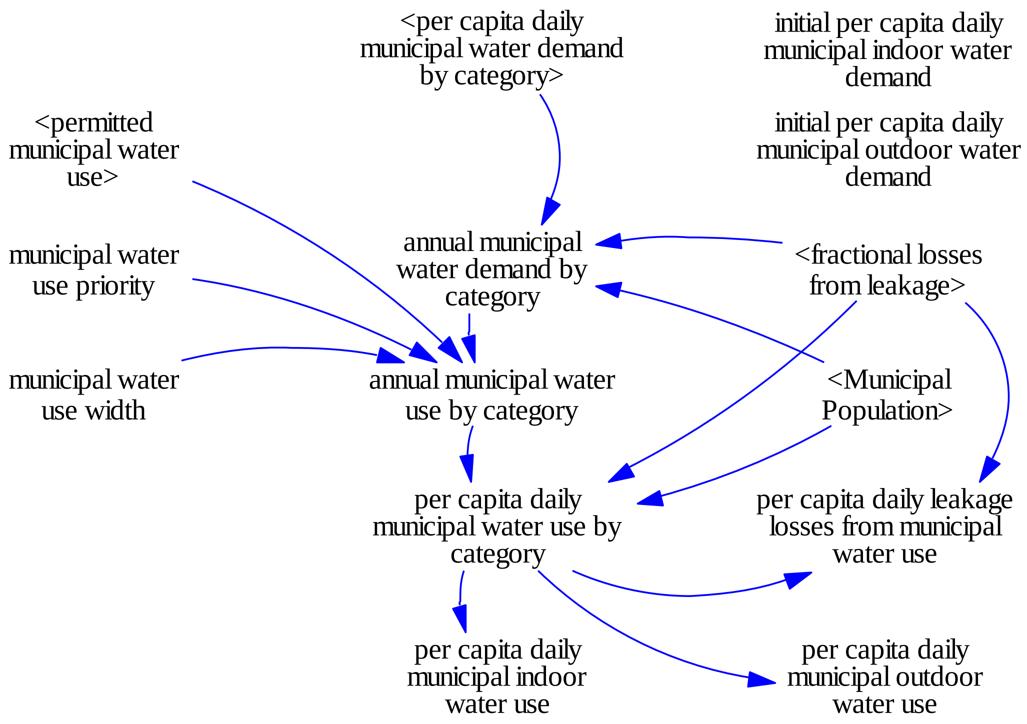


Figure 21: Screen-capture of the model structure for the municipal water use calculations

Municipal water use – as compared with municipal water demand in Figure 20 – is calculated in the sub-model shown in Figure 21. Recall that water use equals water demand in a normal year; however, when a team selects the “ration water” policy, water use equals the rationed amount, or the “permitted municipal water use”, if the full water demand cannot be satisfied. For realism, the rationed water is allocated to each water use type by a priority. The highest water use priority is given to kitchen water, which is used for drinking, cooking and cleaning. In contrast, the lowest-priority indoor water use in toilet water use, and outdoor water use for lawn-watering is a lower priority than all indoor uses. The lowest priority water uses receive a smaller fraction of their demand than the higher-priority uses, rather than higher priority uses receiving all of their demands and the lowest receiving none – in other words, some sharing occurs.

Next, we provide the major equations for municipal water system and the associated assumptions, beginning with municipal water demand. The key equation for each municipal water demand is,

$$W_d = \{p_l \times (1 - f_l) \times P \times k + (1 - p_l) \times P \times k + W_{non-d} + W_{out} + L - R\} \div 1000 \quad (6)$$

where, W_d is the total municipal water demand (MCM per year), p_l is percentage of people with low flow appliances (%), f_l is the reduction coefficient of low flow appliances (fractional), P is population (people), k is water use per capita (liters per capita), W_{out} is outdoor water demand (liters per year) , W_{non-d} is non-domestic water demand (liters per year), L is leakage losses (liters per year), R is water reduction from grey water treatment (liters per year).

Low-flow technologies are a very important factor in the model, since a household can achieve 44% water savings by using low flow appliances (Vickers 2001). The “Adoption rate of low flow technologies” defined in equation (7) is an important variable for low flow appliances, because it determines how many households adopt low flow appliances.

$$\begin{aligned}&adoption\ rate\ of\ low\ flow\ technologies =\\&base\ adoption\ rate\ of\ low\ flow\ technologies +\\&effect\ of\ municipal\ water\ deficiency\ on\ adoption\ rate\ of\ low\ flow\ appliances \times\\&municipal\ water\ percentage\ dificiency +\\&increased\ rate\ of\ low\ flow\ technology\ adoption\ with\ water\ r\&d\end{aligned} \tag{7}$$

where, the “municipal water percentage deficiency” can be calculated from:

$$\begin{aligned}&municipal\ water\ percentage\ deficiency = (annual\ municipal\ water\ demand -\\&permitted\ municipal\ water\ use)/annual\ municipal\ water\ demand\end{aligned} \tag{8}$$

where, the “permitted municipal water use” is the “municipal water demand” in a normal year and the “water allocation” in a drought rationing year.

The behaviours of the “base adoption rate of low flow technologies”, “effect of municipal water deficiency on adoption rate of low flow appliances” and “increased rate of low flow technology adoption with water research and development” in equation (7) are based on the following assumptions. First, municipal residents are assumed to invest in low-flow technologies when they perceive that water is scarce, and that a municipality is therefore likely to ration water. For example, if the municipal water deficiency is 5%, the hypothetical value of the adoption rate of low-flow appliances is 3%, or 0.03 see Figure 22 for the assumed relationship between water deficiency and low-flow appliance adoption. Further, investment in water-related R&D is assumed to drive a progressive decrease in the amount of water required for various domestic purposes, so that cumulative years of investment (and therefore cumulative experience, or “technical know-how”) drive increasing improvement in low-flow technologies and lead to greater adoption. In other words, if the “invest in water-related research and development” policy is chosen by teams, it will affect the adoption rate of low-flow appliances by having more people replace their existing appliances with low-flow versions. In reality, water-related research and development is flexible and diversified, and can be classified as one of two types: quantity-related (i.e. use efficiency, environment factors, climate change, ability to reuse and ability to transport) and quality-related (i.e. contamination by emissions, addition of liquids and addition of solids) (Mallawatantri, 2011). The IDT represents water-related research and development in terms of quantity: “new and innovative ways to adapt to dry conditions have been developed” (AAFC, 2011: 20). Therefore, for the purposes of the game, the policy is simply assumed to affect water quantities through the adoption of low-flow appliances.

Figure 22 and 23 show the relationships, as “look-up” tables, used in the calculations. A “lookup” is a simple way to represent a mathematical function without specifying an equation. In other words, users can create their own specialized functions by representing a figure in a lookup table like Figure 22 and 23. Note that there is an upper constraint on the “percentage of houses with low flow appliances” of 100%.

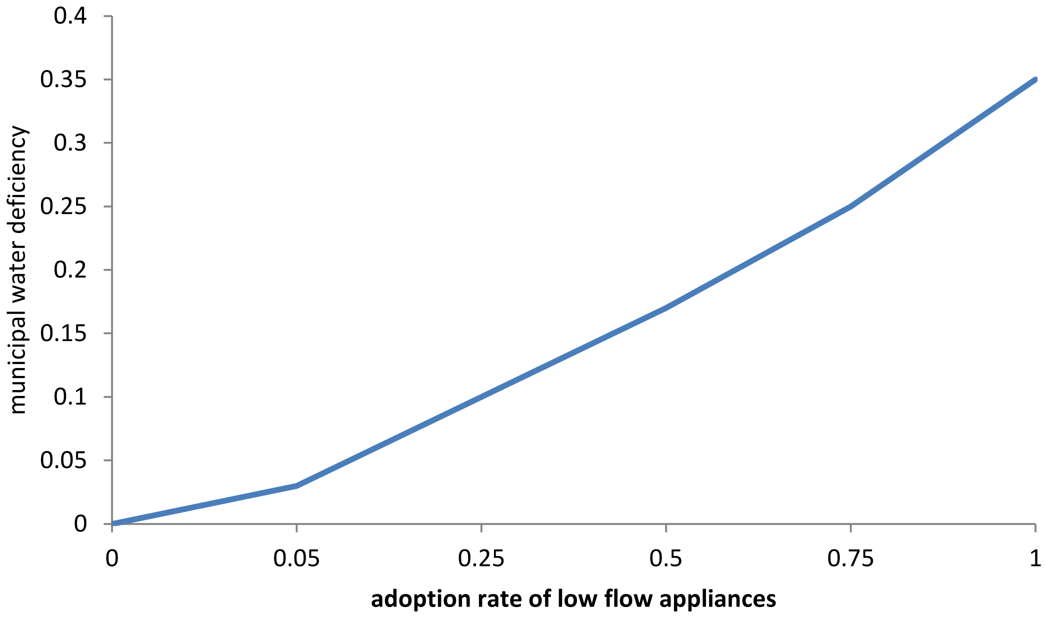


Figure 22: Effect of municipal water deficiency on adoption rate of low flow appliances

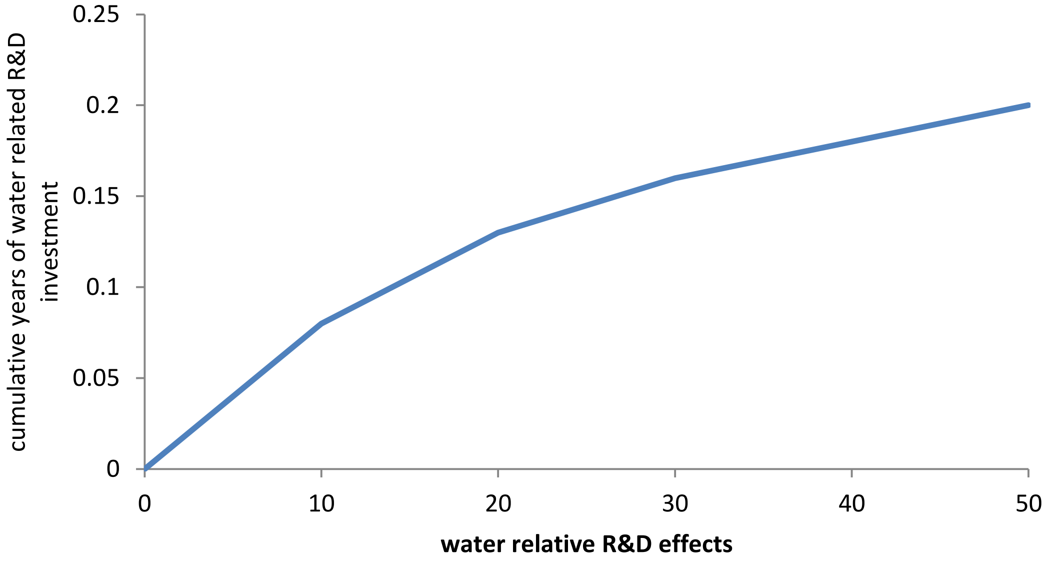


Figure 23: Effect of cumulative investment in water-related research and development

In most cases, the municipal water use in the IDT Model typically equals the municipal water demand of equation (9), since "permitted municipal water use" is simply the "municipal water demand" all water demand are satisfied. However, in a drought rationing year, the "permitted municipal water use" is less than the "municipal water demand" so that water use no longer meets the demand. Thus, to allocate resource properly, water is supplied based on the priority of each household use. Specifically, the annual municipal water use is calculated as,

$$annual\ municipal\ water\ use\ by\ category\ [use] = \\ ALLOCATE\ BY\ PRIORITY\ (\ annual\ municipal\ water\ demand\ by\ category[use], \\ municipal\ water\ use\ priority\ [use], \\ ELMCOUNT\ (use), municipal\ water\ use\ width, permitted\ municipal\ water\ use) \tag{9}$$

in which the "annual municipal water use by category[use]" means the amount of water use for each of the five categories (m^3 per year); "annual municipal water demand by category[use]" means annual water demand of each use (m^3 per year); "municipal water use priority[use]" means that the lower priority uses face greater reduction during water shortages; "ELMCOUNT(use)" means the number of elements across which allocation is being made – in this case, five; "width" specifies how big a gap in priority is required to have the allocation go first to higher priority with only leftovers going to lower priority; permitted municipal water use is the total water use (m^3 per year).

The initial water use amount for the municipal water system is given in Table 8 below. To generate reasonable numbers for municipal water use, we adopted values from the academic literature – specifically, Mayer and DeOreo (1999), which is now somewhat dated but represents the most comprehensive survey of North American household water use. For water use reductions by low-flow appliances, we also selected values from Ahmad and Prashar (2010). The "municipal water use priority" values determine how water use is allocated within a home in times of scarcity-rationing, with high values indicating that the water use category will receive water and low values indicating a lower likelihood of water being used for that purpose, as explained above. Note that "base" in the Table 8 means the initial values of those parameters.

Table 8: Municipal water use inputs to the IDT Model

Municipal Water Use						
municipal uses[1]	laundry	bath	toilet	kitchen	outdoor	units
base per capita daily municipal water demand by category[2]	56.78	58.56	13.86	6.06	1050	L/day
base times per capita per day	1	0.75	5.05	1	1	
water use reduction for low flow appliances	0.117	0.09	0.1	0	0.3	
initial fraction of homes with low flow appliances	0.2	0.2	0.2	0	0.2	
base adoption rate of low flow technologies	0.01	0.01	0.01	0	0.01	
municipal water use priority	5	5	3	10	1	
population per house	4					
fractional losses from	0.1					

leakage	
municipal water use width	1

Table sources: [1] Mayer and Deoreo, 1999; [2] Ahmad and Prashar, 2010.

3.2.3 Agricultural land and water use, and crop production

In consideration of the different productivities and water use characteristics of irrigated *versus* dry land agriculture (Ghorbani et al., 2011), we divided the agricultural sector and land use type into three parts: irrigated land and dry (or non-irrigated) land, which also includes fallow land, and green cover (or non-agricultural land). Because the Oxbow is based on river basins of the Canadian Prairies, irrigated and dry land uses are then further divided among typical crops types for the region: forages, grains, oilseeds, vegetables and grass based on the crop type classifications from Alberta Agriculture and Rural Development's Alberta Irrigation Information reports (Goverment of Alberta, 2010). Each crop type is represented by data from real crops common to the Canadian Prairies, alfalfa for forages, barley for grains, canola for oilseeds, potato for vegetables and grass.

Figure 25 shows the variables and their connections for the representation of irrigated agriculture in the model – note that "irrigated land" and "soil moisture" are the only stocks in the sector. The key assumption in the agricultural sectors, both irrigated and dry land, is that all the water in the soil, "soil moisture", is available for evapotranspiration, which is used to determine both crop water requirements and crop yield. In reality, crops cannot extract all of the water in the soil for their evapotranspiration (Brouwer and Heibloem, 1986; Allen et al., 1998). There is also always some water transfer between surface and ground water. However, because ground water is not used for irrigation in Alberta, it can be neglected. Further, as the model addresses drought conditions, runoff is omitted. Thus, hydrological cycle in agricultural sector of the model is represented as in Figure 24. Note that the three circled variables, capillary rise, deep percolation and runoff, are not considered in the model.

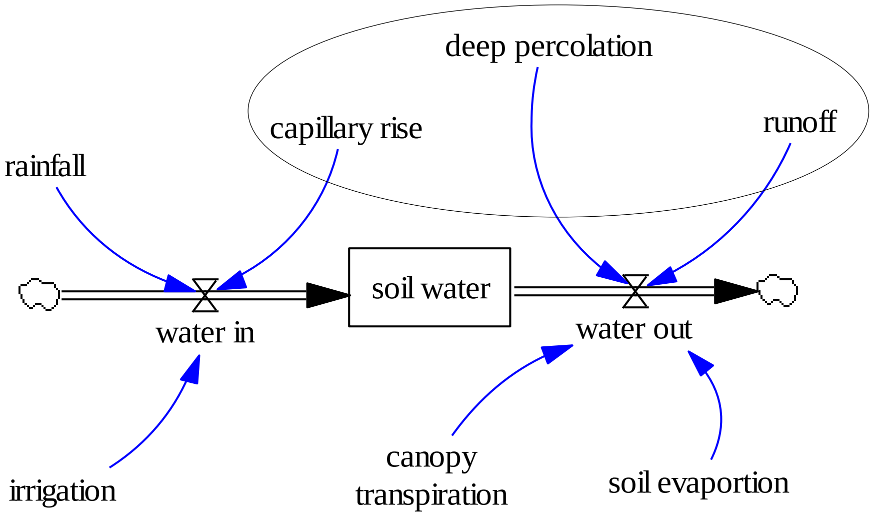


Figure 24: Components of the hydrological cycle in the IDT Model

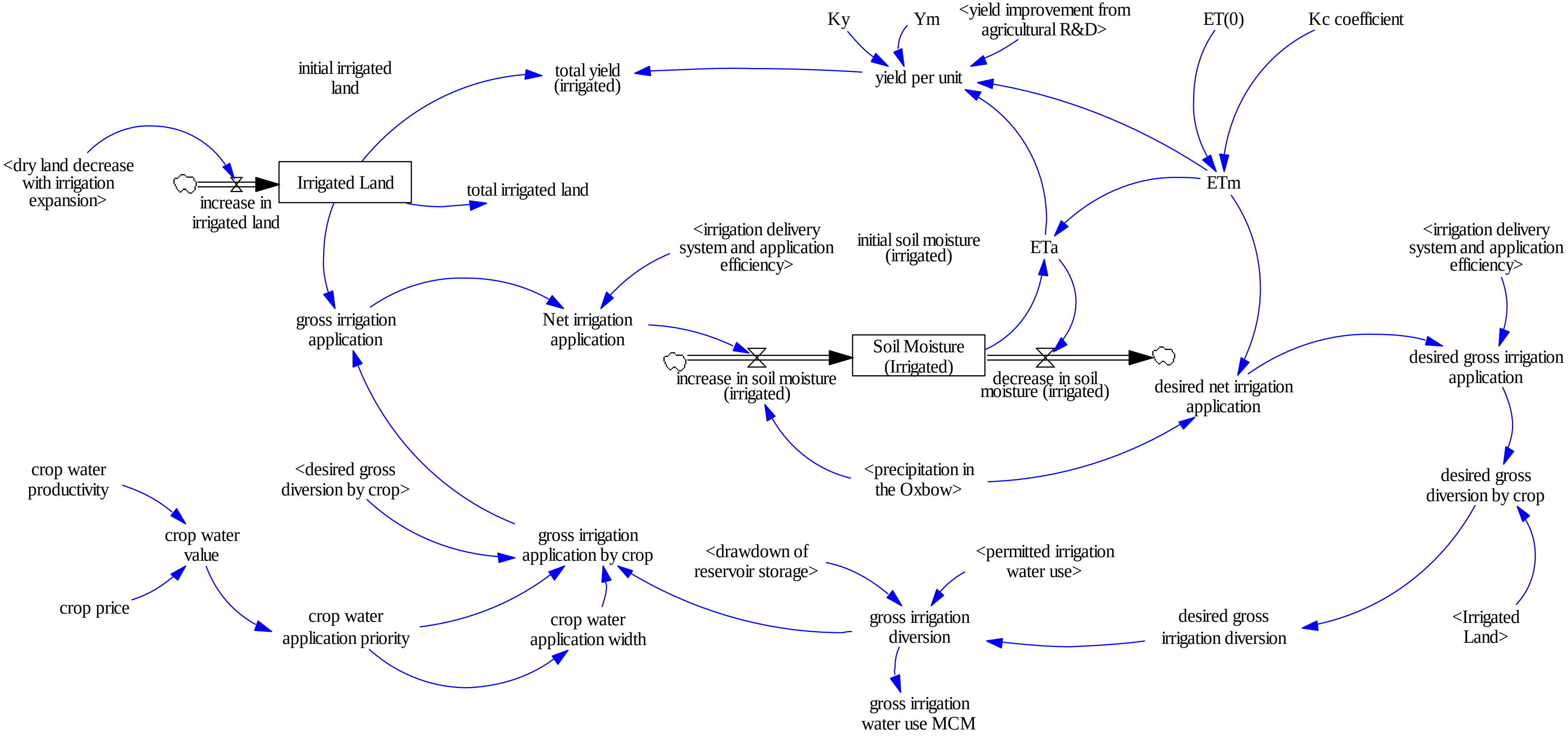


Figure 25: Screen-capture of the stock and flow structure of irrigated agriculture calculations

Based on (Bennett and Harms, 2011), a reasonable simplification of water-yield relations is that crop yield has a positive linear correlation with irrigation water, and reaches its maximum value once the irrigation water applied satisfies the maximum annual evapotranspiration of the crop. Therefore, the main idea in the IDT model is that the maximum profit will be achieve – when crops receive the irrigation application which is sufficient for the maximum annual evapotranspiration of each crop when water is plentiful, but that if the desired gross irrigation diversion is over the permitted irrigation water use, irrigation water will be allocated to the crops which have the highest value for each unit of water applied. Here, crop values are taken from crop price data (USDA, 2011) and from crop water productivity values (Siebert and Doell, 2010) – see equation 20 below. This approach ensures that water is given to the crops with the greatest profit.

The structure of the second agricultural sub-system, dry-land agriculture, is presented in Figure 26, and is generally similar to the "irrigated agriculture" model in Figure 25. However, in addition to "soil moisture" and land area, there is another stock called "green cover", which permits modelling of a policy for land management – "increase green cover" (see Table 5). "Green cover" is a term usually applied to plants grown with the intention of working the grass into soil, where it will decompose and add nutrients, and since it is also used to protect soil from erosion in drought conditions, it is also called "green manuring". Therefore, green cover is assumed to be implemented on dry land only, because irrigated land provides better crop productivity than dry land and farmers will not irrigate fallow land.

Clearly, the other major difference between irrigated land and dry land is that no irrigation water is applied to dry land fields. Crops on the dry land absorb water from the available soil moisture and only from precipitation. As soil moisture is depleted during a drought, the crop yield is increasingly related to the amount of annual precipitation in Oxbow Basin, rather than to moisture stored in the soil. Dry land agriculture is affected by two polices, “expand irrigation” and “promote green cover”. The “promote green cover” will convert 150000 acres of dry land to perennial green cover land for each year the policy is selected. “Expand irrigation” coverts 500000 acres of dry land in total to irrigated land for each selection of the policy (see Table 5).

The major equations for the agricultural water system, and the values of their associated parameters, are provided below, beginning with the calculation of yield per hectare.

In accordance with the work of Bennett and Harms (2011), the relative yield reductions from different levels of water stress can be derived from equation (10), which was developed by Doorenbos and Kassam (1979).

$$1 - Y_a/Y_m = k_y(1 - ET_c/ET_m) \tag{10}$$

where Y_a is predicted crop yield (Mg/ha), and the units are Megagrams per hectare or tonnes per hectare, Y_m is maximum potential yield (Mg/ha); ET_c is the annual crop evapotranspiration (mm), ET_m is the maximum annual crop evapotranspiration (mm) and k_y is a crop-specific yield response factor (unitless). Note that by rearranging the terms in equation (10) above, the equation becomes,

$$Y_a = (1 - k_y + k_y \times ET_c/ET_m) \times Y_m \tag{11}$$

where the terms are as defined above. Further, ET_c is the annual crop evapotranspiration and is given by,

$$ET_c = Soil\ moisture \tag{12}$$

in which, ET_c equals ET_m, the maximum annual crop evapotranspiration, if the amount of soil moisture(mm) available is larger than the maximum requirement, ET_m.

Next, the model calculates the net irrigation application as,

$$desired\ net\ irrigation\ application = \ ET_m - P \tag{13}$$

where, the desired net irrigation application is measured in mm and P is the precipitation in the Oxbow(mm), as prescribed in the IDT workbooks provided to game participants (AAFC, 2011).

Because of irrigation losses, the irrigation delivery system and application efficiencies are not one hundred percent; therefore, the desired gross irrigation application is greater than the net application and is given by,

$$desired\ gross\ irrigation\ application = desired\ net\ irrigation\ application / k_e \tag{14}$$

where, k_e is a fractional irrigation delivery system and application efficiency factor (unitless). The value of k_e ranges from 0.6 to 0.95, depending on whether the "enhance irrigation water application efficiency "or the "invest in agriculture-related R&D" policies have been implemented by teams (see Table 5).

The I_g is represented by,

$$I_g = \begin{cases} I_p + S_r, & if\ I_d > I_p \\ I_d, & if\ I_d \leq I_p \end{cases} \tag{15}$$

Where, I_g (m^3 per year) is the gross irrigation diversion, I_p (m^3 per year) is the permitted or licensed, irrigation water use, S_r (m^3 per year) is the drawdown of reservoir storage, and I_d (m^3 per year) is the desired gross irrigation diversion and is the sum of desired gross diversion by each crop for maximum yield.

Based on the assumption that irrigation water will be allocated to the crops that have higher value per unit of water supply, the gross irrigation application for each crop is expressed in Vensim as,

$$gross\ irrigation\ application\ by\ crop[crop]$$
$$= ALLOCATE\ BY\ PRIORITY(desired\ gross\ diversion\ by\ crop[crop]\ ,$$
$$crop\ water\ application\ priority[crop], ELMCOUNT(crop),$$

$crop\ water\ application\ width, gross\ irrigation\ diversion)$ (16)

where the “gross irrigation application by crop[crop]” is the amount of irrigation water for each of the five crops (mm), the “desired gross diversion by crop [crop]” is the desired gross diversion of each crop, or the difference between the maximum evapotranspiration of each crop and the precipitation in the Oxbow, the “crop water application priority[crop]” is the priority parameter, which is the crop water value ($ per m^3), where a higher priority means a higher chance of receiving irrigation water, “ELMCOUNT(crop)” means the number of elements across which the allocation is being made (in this case, five), and the “width” specifies how evenly the available water is shared. With greater widths values, competitors shares become more equal. In contrast, when the distance between any two priorities exceeds the defined “width” and the higher priority does not receive its full request, the lower priority will receive nothing. Finally, the “gross irrigation diversion” is the total volume of irrigation water available for irrigation (see equation 15).

The crop water value is determined by the crop water productivity, which expresses “the amount of harvested crop that can be achieved per unit of crop water use” (Siebert and Doell, 2010: 204) in combination with reported crop prices for 2011 (USDA, 2011), so that the,

$$crop\ water\ value = crop\ price \times crop\ water\ productivity \quad (20)$$

where the units of “crop water value”, “crop water productivity” and “crop price” are dollars per cubic meters (\$ per m^3), kilograms per cubic meters (kg per m^3) and dollars per kilogram (\$ per kg), respectively.

The dry land agriculture sector (see Figure 26 for the sector structure) uses the same calculation procedure as the irrigated agriculture sector for yield calculations as function of evapotranspiration, and also includes potential switches between land use types. As mentioned above, there are two policies that can alter land use, “expand irrigation” and “promote green cover”. The effects of the selection of the “expand irrigation policy” are given by equation (17),

$$dL_i/dt = \begin{cases} 202430, when \text{ "}expand\ irrigation\ policy\text{" } is\ selected \\ 0\ , \quad otherwise \end{cases} \tag{17}$$

where L_i is the "irrigated land" area in hectares (ha).

To make the model more realistic, farmers are assumed to expand the irrigation area of the most valuable crops. Consequently, once the “expand irrigation policy” is selected, the model allocates the new area to irrigated land by priority of “crop value”. Thus, the crop land which can create more value by per unit water would be converted first to irrigation. The equity of the sharing is determined by the “width” parameter in an “allocate by priority” function, like that of equation (9).

Similarly, when dry land is converted to irrigation, it must likewise be determined from which crops type the conversion occurs. Therefore, we use the same equation to express this in Vensim:

$$dD[crop]/dt = \ ALLOCATE\ BY\ PRIORITY(dry\ land[crop], crop\ value(priority),$$
$$ELMCOUNT(crop), width, 202430(ha) \qquad (18)$$

Where the D[crop] is “Dry land decrease by expand irrigation [crop]”, is the area for each crop that is decreased through the irrigation expansion policy, the “dry land[crop]” is the initial area for each crop (ha), the “crop value” is the priority parameter, “ELMCOUNT(crop)” is the number of elements across which allocation is being made, “width” specifies how evenly the available land is shared, and 202430 hectare (500000 acres) is the total area need to be transformed to irrigated land. In the extreme case that 202430 hectares is more than the actual amount of dry land – supposing that the policy has been selected many times during the IDT – then all the remaining dry land would be changed to irrigated land.

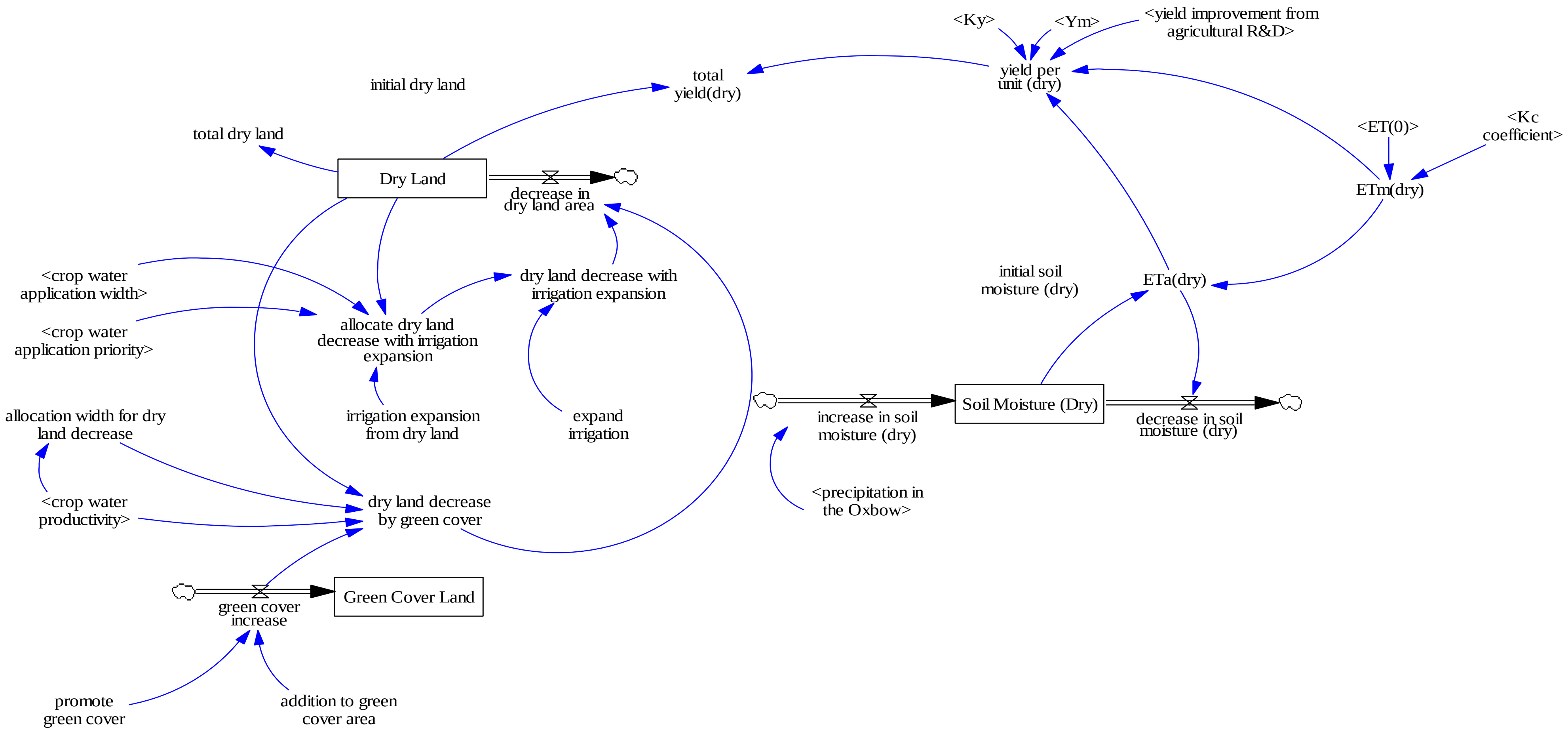


Figure 26: Screen-capture of the stock and flow structure of dryland agriculture calculations

Likewise, for the “promote green cover” policy,

$$dL_g/dt = \begin{cases} 60730, when\ "green\ cover\ policy"\ is\ selected \\ 0, otherwise \end{cases} \tag{19}$$

where, L_g is the "green cover" land area in hectares (ha).

The green cover policy is assumed to be applied only to dry land. The water requirement of crops, as a bottleneck factor for dry land area, determines the amount of land use for each crop; therefore, the “crop water productivity” is used to decide the allocation of land use here. Once “green cover” policy is selected, the model allocates land by priority of “crop water productivity”, so that the crop land that needs the most water would be converted to green cover first. The form of the equation is similar to that of equation (18), except that the amount of land switched to green cover is given by equation (19) rather than equation (17). As in equation (19), if 60730 hectares is greater than the remainder of the dry land, then all the remaining dry land will be changed to “Green Cover Land”.

The “Promote diversification of pasture species composition” policy also affects the agricultural system. According to Mahmud et al. (1994), promote diversification of crop species composition can increase the physical yields. Thus, the policy is assumed to alter the “quality of pasture” – a multiplier for grass production (t/ha) on dry land. Pasture quality begins with a value of 1 at the start of the drought, and will be made to decrease slowly based on animal numbers and other factors in future versions of the model – the pasture quality is currently not simulated specifically.

The effect of “quality of pasture” on pasture yield can be expressed as,

$$y_a = y_b \times (1 + e_d) \tag{20}$$

where y_a is the "yield per unit" of pasture (tons per hectare) after promoting diversification of pasture species" composition; y_b is the initial "yield per unit" of pasture before promoting diversification of pasture species composition (tons per hectare), and $\mathrm{e_d}$ is the effect of this policy, with a default value of 0.1.

Pasture quality can change only within a certain range of values, tentatively set to 1 to 2, which means that the maximum pasture yield from promoting pasture quality is twice the initial value. This can be shown in Figure 27 and 28 below where the “reference” line shows the reference case, and “game” shows the policy effect.

Figure 27 shows the increase in pasture quality from implementation of the policy and Figure 28 shows the effect on pasture yield. In reality, many additional factors should be considered in the policy, such as the types of pastures and seeding seasons (Mahmud et al., 1994). But as there is a lack of information, the relationship between pasture quality and pasture yield is currently an assumption in the model.

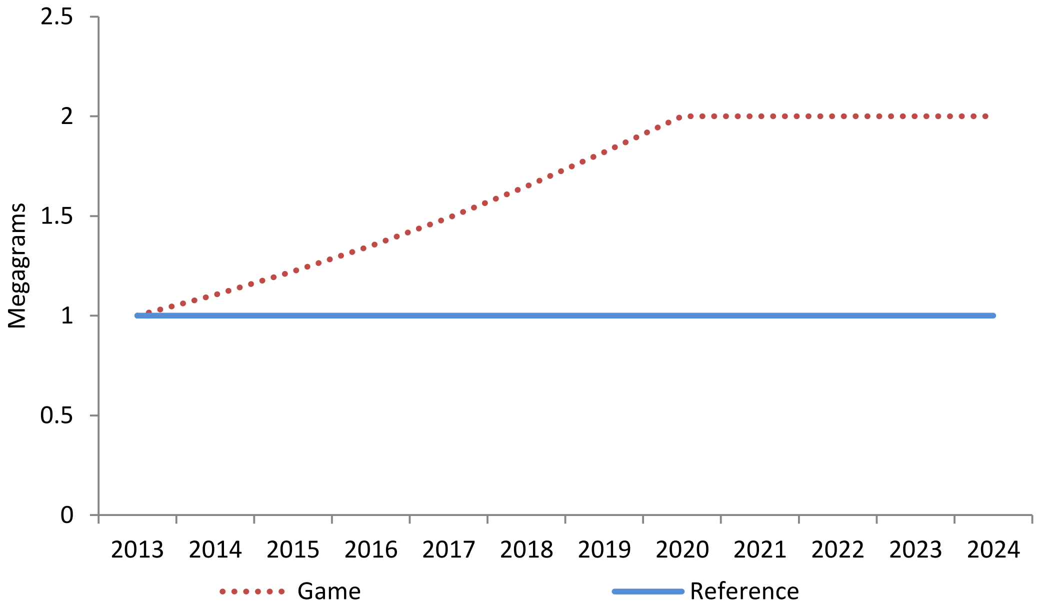


Figure 27: The simulated change in "pasture quality" over time

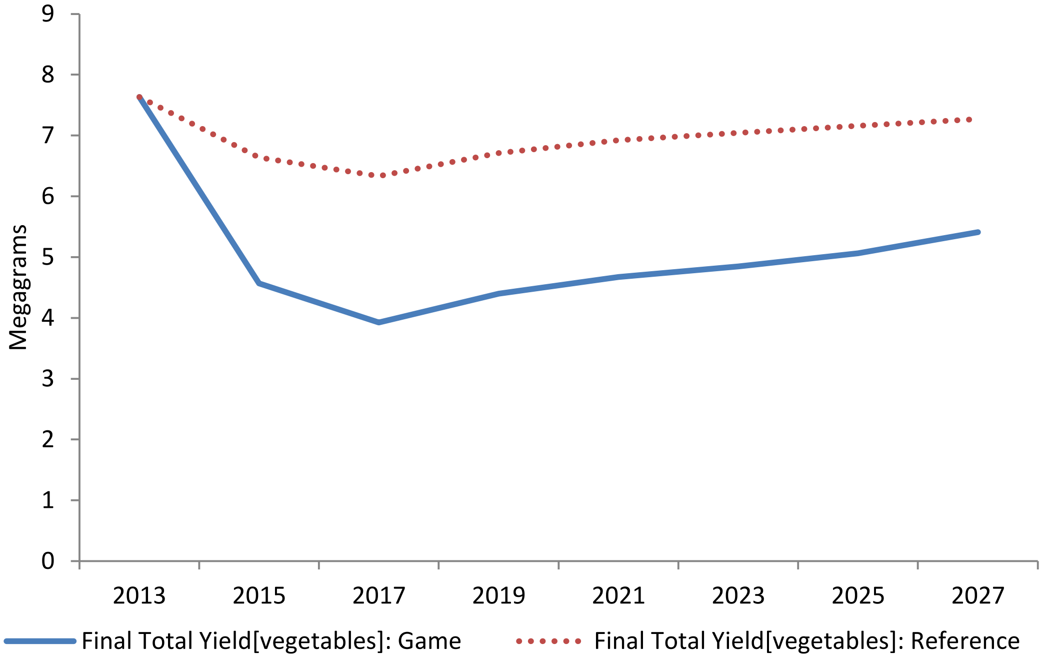


Figure 28: Comparison of simulated pasture yields with increased pasture quality

The final policy related to the agricultural components is "invest in agriculture-related research and development". Based on the description in Table 5, this policy is assumed to increase the yield per crop area (tonnes per hectare) of each crop as compared with the reference case. The effect of the policy on the yield-water relation is shown in Figure 29, which includes two simulations: “On”, in which the “agriculture-related R&D” policy is activated in the first year of the drought, and “Off”, in which the policy is not used. The model represents agriculture related research and development as accumulating over time. In other words, once funds are invested in agriculture-related research and development, the policy effect persists. Therefore, the model tracks cumulative years of investment and “looks up” the increase in productivity in a function represented in Figure 30. Note that the behaviour is assumed but is based on in Alston (2009), in which the effects of agricultural research and development accumulate, but decrease with the passage of time.

The policy effect is represented by equation (21):

$$y_a = y_b \times (1 + e_{r\&d}) \tag{21}$$

where y_a is the "yield per unit"(tonnes per hectare) including the effects of research and development, y_b is the initial "yield per unit", and $e_{r\&d}$ is the yield improvement factor from Figure 30.

All the parameters used in the agricultural sectors are listed in Table 9 below. To ensure the validity of this model, besides the data taken from the IDT documents, such as land area, all of the data are adopted from the academic literature. For example, ET(0) (the reference evapotranspiration), K_y (yield response factors) and Y_m (the maximum yield) are taken from Bennett and Harms (2011). The K_c coefficients (crop coefficient)are from

Allen et al. (1998). The value of crop water productivity come from Siebert and Doell (2010), and crop price is based on USDA (2011).

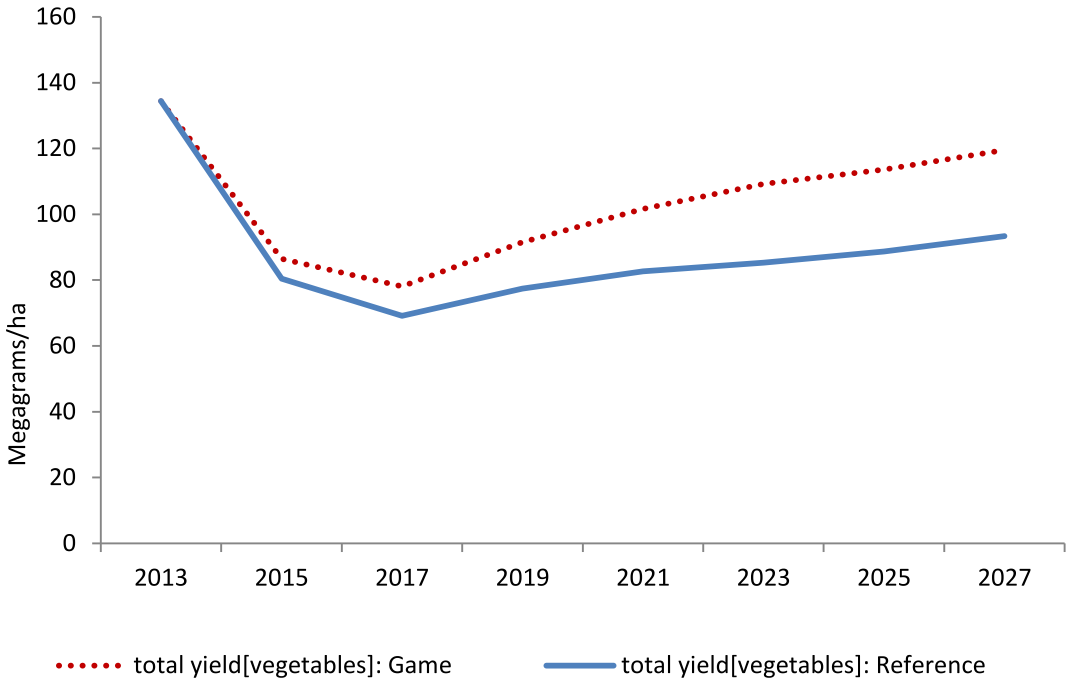


Figure 29: Change of yield from agriculture related research and development

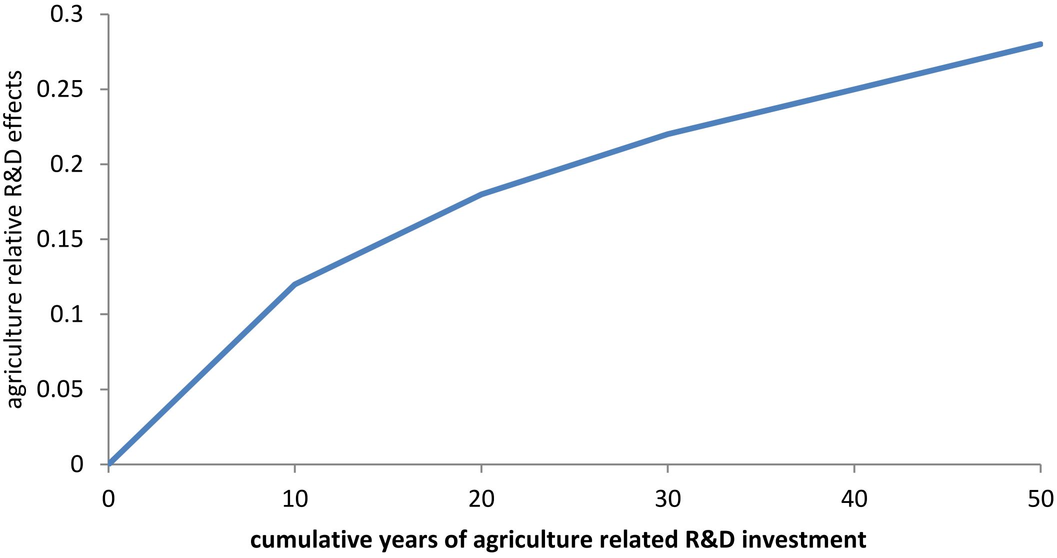


Figure 30: “Lookup” table for effects of agriculture-related research and development

Table 9: Agricultural water use inputs to the IDT Model

Crop subscripts	Forage	Grain	Oilseed	Vegetable	Grass	Units
Representative crop	alfalfa	barley	canola	potato	grass	
ET(0)[1]	786.32	388.7	432.73	520.87	513.33	mm
K_c coefficient[2]	0.95	1.15	1.1	1.15	1.05	dmnl
K_y[1]	1.05	1.15	1.15	1.1	1.05	dmnl
Y_m[1]	18	7.3	3.9	67.2	13.4	Mg/ha
crop water productivity[3]	5.961	0.845	1.037	4.162	0.644	kg/m^3
crop price[4]	0.118	0.111	0.441	0.194	0.096	$/kg
Irrigated Agriculture						
initial soil moisture (irrigated)	750	450	480	600	540	mm
initial irrigated land[5]	500000	600000	500000	100000	40890	ha
Dryland Agriculture						
initial soil moisture (dry)	750	450	480	600	540	mm
initial dry land[5]	1000000	3500000	2450000	13560	7834000	ha

Table sources: [1] Bennett and Harms, 2011; [2] Allen et al., 1998; [3] Siebert and Doell, 2010;[4] USDA, 2011;[5] AAFC, 2012.

3.2.4 Water for other uses

The “water for other uses” sector is comparatively simple, since the values of industrial water demand and annual water use for other purposes are small, and few polices – other than rationing – affect their water use. Thus, we set those two values as parameters, or constants, in the model, with values given in AAFC (2011). Future versions of the model will modify this representation.

3.2.5 Water supply

The water supply model (see Figure 31) includes three water sources as the Oxbow basin water supply: precipitation, water diversion from another basin to the Oxbow and drawdown of reservoir storage. The sector is relatively simple because that the IDT Model focuses on water demand rather than water supply, and the structure used allows the supply to vary from one year to the next as required for the IDT.

The units for the flows are cubic meters per year. Values for the base renewable flow and precipitation vary by year and are taken directly from IDT documents (AAFC, 2011).

The Oxbow water supply can be described as equation (22),

$$\begin{aligned}&Oxbow\ water\ supply = \\ &base\ renewable\ flow\ in\ the\ Oxbow + reservoir\ drawdown + \\ &water\ diversion\ from\ another\ basin\ to\ the\ Oxbow\end{aligned} \tag{22}$$

Finally, the driver variables for the “reservoir storage” are “additional dam and reservoir storage” and “drawdown of reservoir storage”. Both variables reflect by IDT policies described in Table 5.

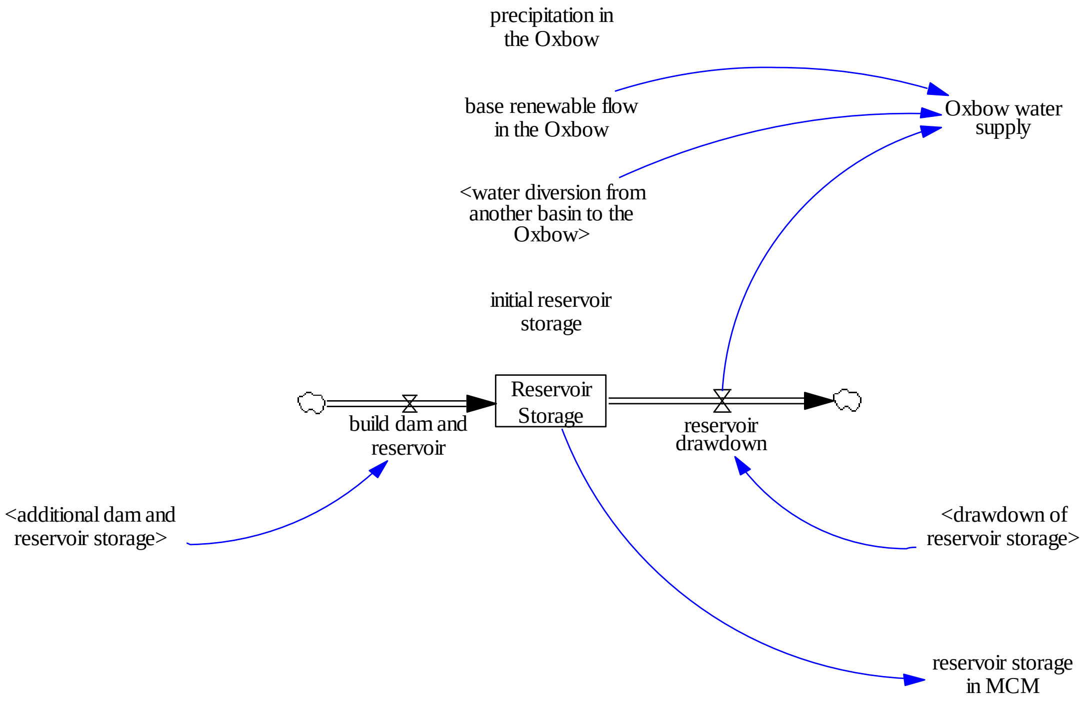


Figure 31: Stock and flow structure of the water supply component

3.3 Model Validation

Model validation was defined by Barlas (1994: 2) as “establishing confidence in the usefulness of model with respect to its purpose”. Thackers et al. (2004, pp2) also mentioned that validation is the primary process for building confidence and “determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model”. In short, model validation is possibly the most important step in the model building sequence. It is a necessary but also complicated process for numerical models. It is necessary because it determines whether the simulation model is appropriate, and even valuable. It is complicated because it is time consuming and difficult (Dudley, 2011) – model validation takes place in every stage, which is from the starting of model conceptualization building to implementation of policy recommendations, and models cannot be authenticated. Based on Forrester (1968), a model is developed for purpose so it should be valid for its purpose but it may be incorrect for other purposes. Thus, a “model cannot be expected to have absolute validity” (Forrester, 1968: 613). Moreover, Barlas and Carpenter (1990) also mentioned that no model can claim absolute objectivity. For example, system dynamics aims to represent real world behaviour, but in reality, it is difficult to find identical situation to test the broader consequences of policy choices in our model, and the required data are often lacking (Grcic and Munitic, 2013). Furthermore, models are the imperfect representations of the reality and always have some assumptions. Sterman (1984) states that the model is a representation of reality, but not a reality. Therefore, although a model is hard to be proved valid its behaviour but can be judged – which is the ultimate purpose of validation. In other words, the purpose of validation is to prove that it is a good model, and “a good model” means it is useful but not true (Oreskes et al., 1994).

There are a lot of ways to validate a model, involves both quantitative and qualitative validation (Barlas, 1996). For validation of the IDT Model, two steps were conducted to calibrate and validate the IDT model. The first one was “Performance Testing”, which is the qualitative validation of the IDT Model and described in the next section. Through the model behaviour analysis, the performance of the IDT model was found to conform to model logic as explained in section 3.2. The second step for validating model is “Data Comparison”, which is the quantitative component of the validation procedure. Here, the data comparison component is presented first. Note that the IDT Model is developed for a fictitious basin, and so, although most data used in the model are taken from basins of the Canadian Prairies, the match is not exact. In this study, we validate the model by comparing model results with data from districts with roughly the same weather, water resources, agricultural conditions and so on to support the model reliability and behaviour.

For the "data comparison" component of model validation, the data from several studies and reports are used, including municipal water use and agricultural water use, land use, water-yield response and crop yield. Note that the hydrological component of the IDT Model is pre-set as explained above. The hydrological factors are not validated for the model, since the data come directly from an earlier study conducted for Agriculture Canada – for example, the streamflow source data is from the Prairies Provinces Water Board) (AAFC, 2011).

3.3.1 Municipal and agricultural water use

Municipal water use and agricultural water use are the main water consumers not only in the Oxbow Basin, but also in most basins of the Canadian Prairies (AMEC, 2007). Although municipal water use is usually less than half the water consumption in a basin, it involves essential human needs, such as water for drinking, washing and cooking. Thus, municipal water is a very important part of water demand. Since the settings of Oxbow Basin are based on the Canadian Prairies, we compared the municipal water use of Oxbow Basin with the South Saskatchewan River Basin. According to Table 10 (from

Pernitsky and Guy, 2010), the average per capita water use of the South Saskatchewan Basin is 497 liters per day (l/d), while the output from the IDT Model is 486 (l/d) (the error is about 2.2%).

For land use, we compared the IDT Model with data for Alberta (ARD, 2007; AMEC, 2007), Saskatchewan (SMA, 2013), Manitoba (Statistics Canada, 2006; AIM, 2007) – see Table 11, below. Land uses differ widely from every district due to the different conditions of climate, landscape and soils and economics. Therefore, we compared the ratio of irrigated land to dry land area. Agricultural water use accounted for 78.7% of total water use on average in 2005, while it is about 75% in the IDT Model, for a difference of about 4.7%). Note that percentages are listed in Table 11 for comparison, because the land areas are very different between the data and the IDT so that agricultural water uses differ from each other.

Note that "error" or "difference" is expressed by equation (23),

$$\%error = \frac{|model\ results - accepted\ value|}{accepted\ value} \tag{23}$$

Table 10: Municipal water use in the South Saskatchewan Basin in 2005 (Pernitsky and Guy, 2010)

Community	Serviced Population	Annual Water Consumption (m3/yr)	Average Per Capita Water Use (l/d)
Airdrie	27,069	3,664,600	371
Banff	8,352	3,504,000	1,149
Bighorn	641	100,605	430

Black Diamond	1,866	421,575	618
Calgary	856,078	174,484,235	500
Canmore	15,232	2,675,815	481
Chestermere	7,904	974,678	338
Cochrane	12,688	1,960,050	423
Crossfield	2,603	349,305	368
Foothills	1,520	249,660	450
High River	9,900	2,811,303	778
Nanton	2,100	318,098	415
Okotoks	15,420	1,852,375	329
Redwood Meadows	1,150	147,825	352
Rocky View	12,232	2,009,106,450	450
Strathmore	9,653	1,307,161	371
Tsuu Tina Nation	1,292	212,211	450
Wheatland County	2,106	345,911	450
Total Population	1,089,592		Avg: 497
IDT	3,000,000		486

Table 11: Agricultural water and land use in Canada in 2006

Region	**Alberta**	**Saskatchewan**[3]	**Manitoba**	**IDT**
Irrigated land	1,301,647[1]	135,707	29,825[4]	1,741,000
Dryland	22,262,407[1]	12,624,436	4,664,528[4]	14,800,000
Ratio	0.06	0.01	0.01	0.11
Water use in %	60-65%[2]	70%	50%[5]	79%
Water use (dam^3)	2,104,563[2]	557,400	300000[5]	2,816,000

Table sources: [1] ARD, 2007;[2] AMEC, 2007; [3] SMA, 2013; [4] AIM, 2007; [5] Statistics Canada, 2006.

3.3.2 Crop yield

The purpose of the irrigation water supply is to increase crop yield. To validate the model's water-yield response, the IDT Model was compared with a study of agricultural water demand for the Okanagan Basin from van der Gulik et al. (2010) whose model simulates the irrigation requirement of alfalfa and grass. For comparison, same parameters for reference evapotranspiration (ET), precipitation and crop coefficients were input into the IDT model and the irrigation requirements of alfalfa and grass were simulated. The average difference between mode results was 6.1%. Table 12 shows the average requirement from these two studies and weather information for the Okanagan Basin (Farmwest, 2013). Note that the "average requirement" is defined as the water requirements of the crops to maximize their yields. Further, the model from van der Gulik et al. (2010) runs at a weekly scale, while the IDT model runs at an annual timescale.

Table 13 compares IDT model results against yield data for barley and canola yields in Alberta (Government of Alberta, 2006), Saskatchewan (Saskatchewan Agriculture and Food, 2007), Manitoba (Honey, 2011), Quebec (Statics Canada, 2012; Quebec Institute, 2012) and Ontario (OMAFRA, 2010), US (USDA, 2012). These yield data combine dry land and irrigated production averages. Note that in the IDT Model, those crops with the higher economic value are assumed to receive more irrigation water (see section 3.3.3, equation 19 and 20). Therefore, potato and alfalfa have the highest irrigation priority and their yield differs significantly from dry land yields. In contrast, the yield differences for barley, canola and grass are not significant.

Table 12: Crop water demand in the Okanagan Basin in 2003

Crop	van der Gulik (2010)				IDT Irrigation (mm)
	Reference ET (mm)	Precipitation (mm)	Crop Coefficients	Ref Irrigation Req. (mm)	
Alfalfa	987	455	1.15	694	650
Grass	1042	46	0.85	892	840

Table 13: Crop yield in Alberta, Saskatchewan and the IDT Model

Crop (tons/acre)	Alfalfa	Barley	Canola	Grass	Potato
Alberta[1]	-	1.7	0.9	-	17.0
Saskatchewan[2]	1.9	2.2-3.3	0.1-1.9	-	13.5
Manitoba[3]	-	1.0-1.6	0.6-0.9	-	-
Quebec[4]	-	1.0	0.9	-	11.6
Ontario[5]	-	1.2-1.4	0.6-1.0	2.3-2.7	12.1
US[6]	3.7	1.4	0.7	2.4	19.7
IDT Model (dry)	3.3	2.2	1.1	3.4	14.8
IDT Model (irri.)	5.2	2.3	1.2	3.5	21.2

Table sources: [1] Government of Alberta, 2006; [2] Saskatchewan Agriculture and Food, 2007; [3] Honey, 2011; [4] Statics Canada, 2012 and Quebec Institute, 2012; [5] OMAFRA, 2010; [6] USDA, 2012.

3.3.3 Discussion of validation results

To summarize, differences between model results and the data for per capita municipal water use are about 2.2%, for agricultural water use about 4.7% and for crop yield about

6.1% (in comparison with van der Gulik et al., 2010). The crop yield simulated by the IDT Model in Table 13 is slightly higher than the data, because (1) the natural conditions are different than each region; and (2) the Oxbow basin parameters, such as maximum yields and reference evapotranspiration, come from studies, like Bennett and Harms (2011), rather from field data. The study area of Bennett and Harms (2011) is southern Alberta, so the maximum yields and reference evapotranspiration may be higher than the simulated system. Most importantly, the IDT Model is an annual scale simulation model, and as a result cannot achieve the same level of accuracy as the one on a shorter time scale. From Table 12, it is apparent that the model has acceptable performance. However, the irrigated land area is larger than in Canadian Prairie basins in the reality. The reason is that Agriculture Canada may have used total land area of a province for the game, but used the ratio of irrigated land to dry land from on a specific basin. The IDT Model presented in this thesis is still under development, and its initial values will be modified in the future.

3.4 Model Behaviour

The model was used during the second Invitational Drought Tournament in Saskatoon, Saskatchewan, in March 2012. According to feedback from Agriculture Canada and teams of students from the University of Alberta, University of Saskatchewan, University of Regina and University of Manitoba, the IDT Model represented the policy effects and water system of Oxbow Basin well. The participants remarked that the IDT Model was valuable for understanding the effects of their decisions on the water balance in the game, and for differentiating the results between the teams.

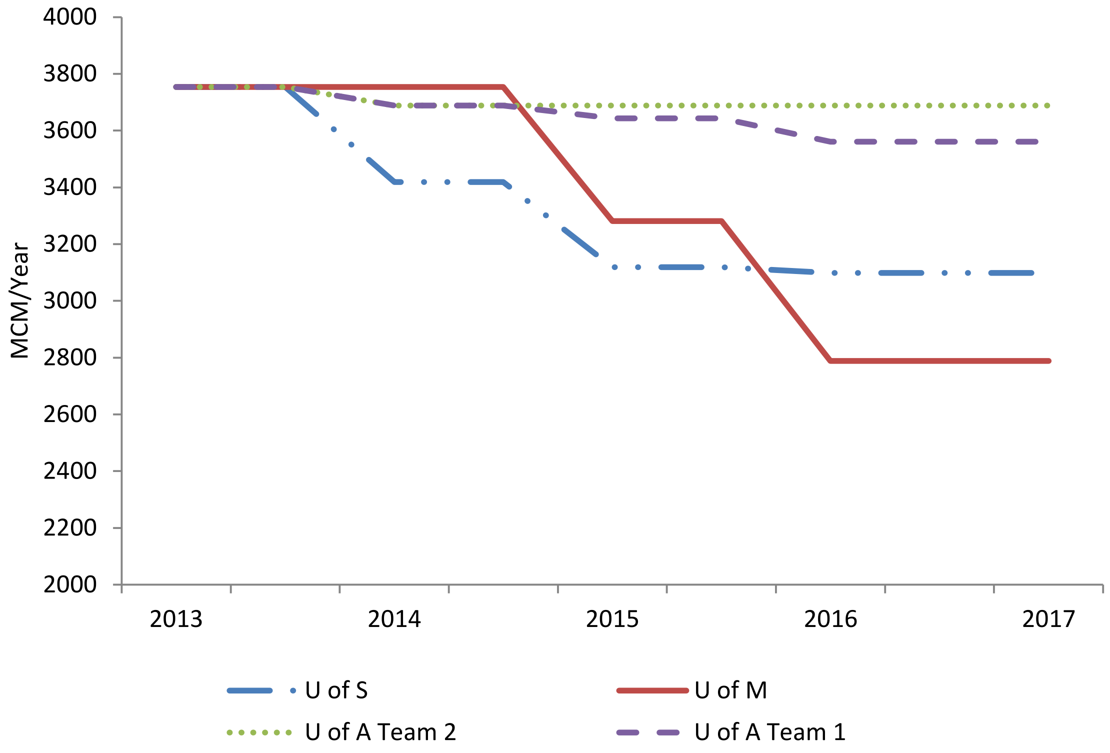


Figure 32: Total water use in drought years in the Oxbow Basin for each IDT team

In this section, two examples and accompanying figures are provided to illustrate how the model works. Both examples are taken from the second IDT. The detailed analysis for the first example explains the model behaviour and the underlying model logic. The second example provided as a point of comparison – Figure 32 compares the water balance in the Oxbow Basin that resulted from the policy choices of the five teams. Participants in the Saskatoon Tournament were able to view model results between model rounds, but the model itself was not used during the tournament – thus, all figures in this section were developed by running the policy selections of each team through the IDT model after the tournament itself – in other words, these are "offline results".

3.4.1 Policy selections and effects for Team A

First, the results from team 1 – from the University of Alberta, called "Team A", are used to show the effects of IDT policy selections on the Oxbow water system. The policy selections of Team A are listed in Table 14, and the results are described in the paragraphs below. Note that a "0" in Table 14 means that the team did not choose the associated policy, while a "1" means that the policy was selected in this year – the two numbers represent binary "on/off" switches.

Table 14: Policy selections of the University of Alberta Team 1, called "Team A"

Time (year)	2013	2014	2015	2016	2017
Inter-basin Transfer	0	0	0	0	0
Enhance irrigation system	0	1	0	0	0
Build Dam and Reservoir	0	1	0	0	0
Ration Water	0	1	1	1	1
Municipal allocation	526	460	415	333	333
Irrigation allocation	2,816	2,816	2,816	2,816	2,816
Industrial allocation	150	150	150	150	150
Other use allocation	262	262	262	262	262
Reservoir Draw-down	0	0	200M	0	0
Relief Payout	0	1	1	1	1
Promote Green Cover	0	1	1	1	1
Promote Winter Cropping	0	1	1	1	1
Promote Stock Reductions	0	0	1	1	1
Pasture Species Composition	0	1	0	0	0
Expand Irrigated Area	0	0	0	0	0
Invest in Agricultural R&D	0	1	1	1	1

Invest in Water Related R&D	0	0	1	0	0
Invest in Grey Water Treatment	0	1	0	0	0

For Team A, the results of the policy selections can be presented in several figures. First, Figure 33 shows the change of municipal water use, as a result of the selection in 2014 of the “ration water” policy for municipal water use with 460 MCM (million cubic meters) allocated in 2014 as compared with the initial 526 MCM in 2013.

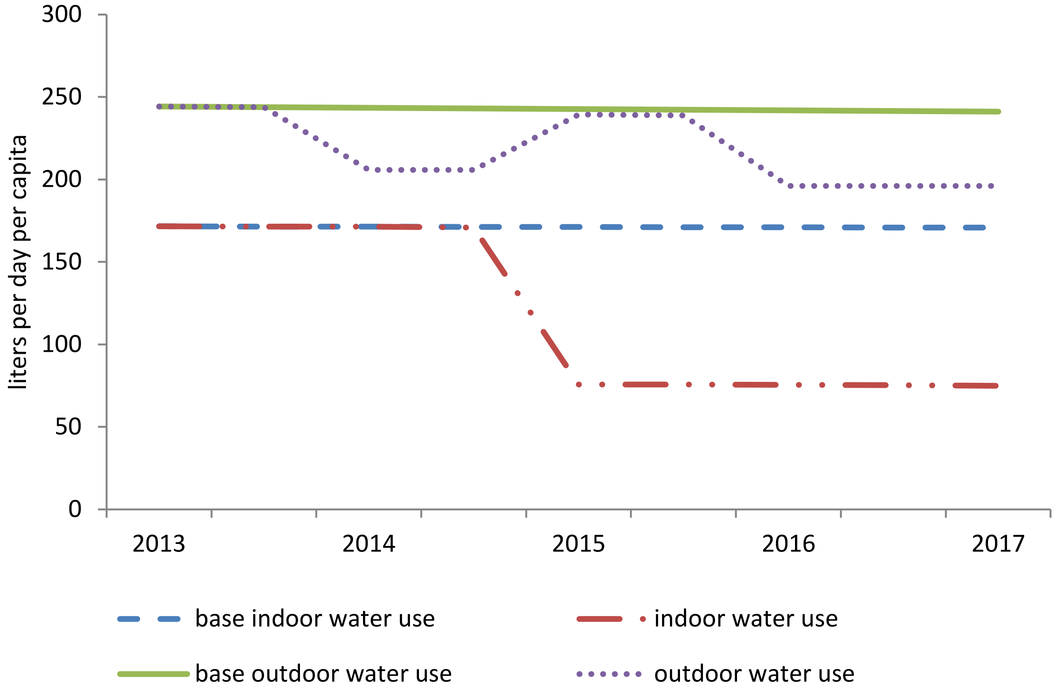


Figure 33: Changes in municipal water use for Team A

Figure 33 shows that the “allocate by priority” function in equation (12), reduces primarily the outdoor water use (shown as the “outdoor water use” line). In the first year, 2014, Team A also selected “grey water” policies (see Table 14), which decreases indoor water use. However, the effect of the policy only becomes apparent in the second year, with a decrease in the indoor water use in 2015, since the policy requires one year to take effect.

In 2016, they continued to reduce the outdoor water use by rationing water, with 333 MCM for municipal water use. Thus, outdoor water use declined again. Figure 34 shows the total water use and water use for each sector in Oxbow Basin. Municipal use is clearly a small, and decreasing, component of the total.

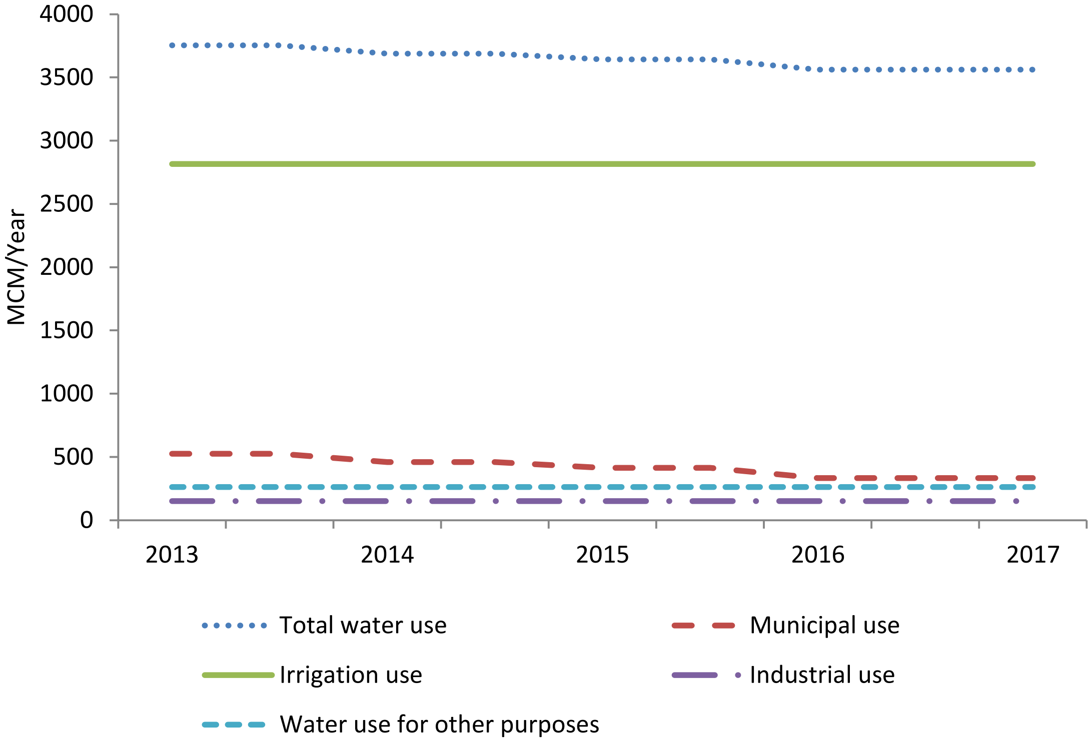


Figure 34: Changes in Oxbow Basin sectoral water use for Team A

Further, at the end of 2014 Team A decided to reduce the animal stock and continued the policy in 2015, causing the total water and feed requirements to decrease for animal stock from 2015 onward with the reduction of the animal population (see the animal stock water requirements in Figure 35 and the feed requirements in Figure 36).

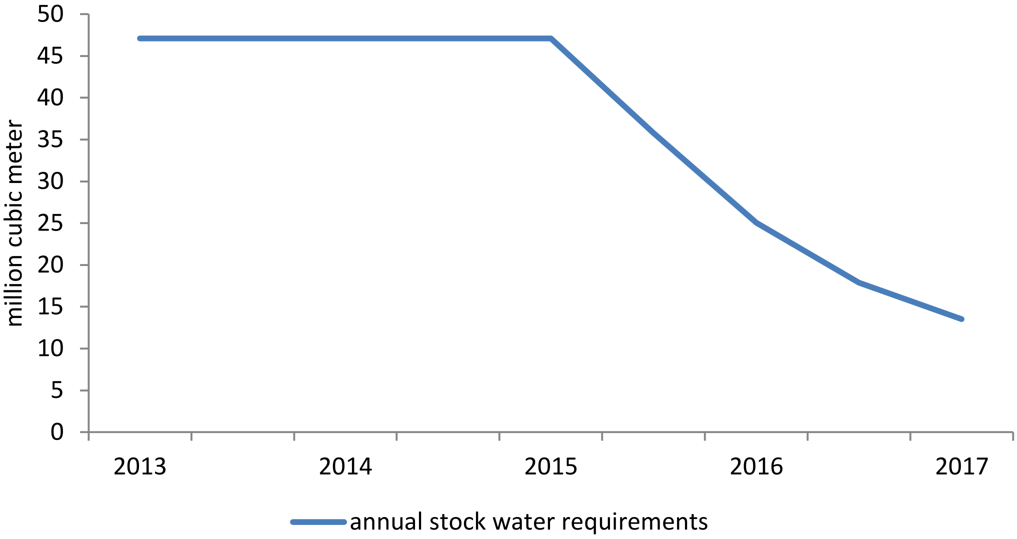


Figure 35: Changes in water requirements for the animals of Team A

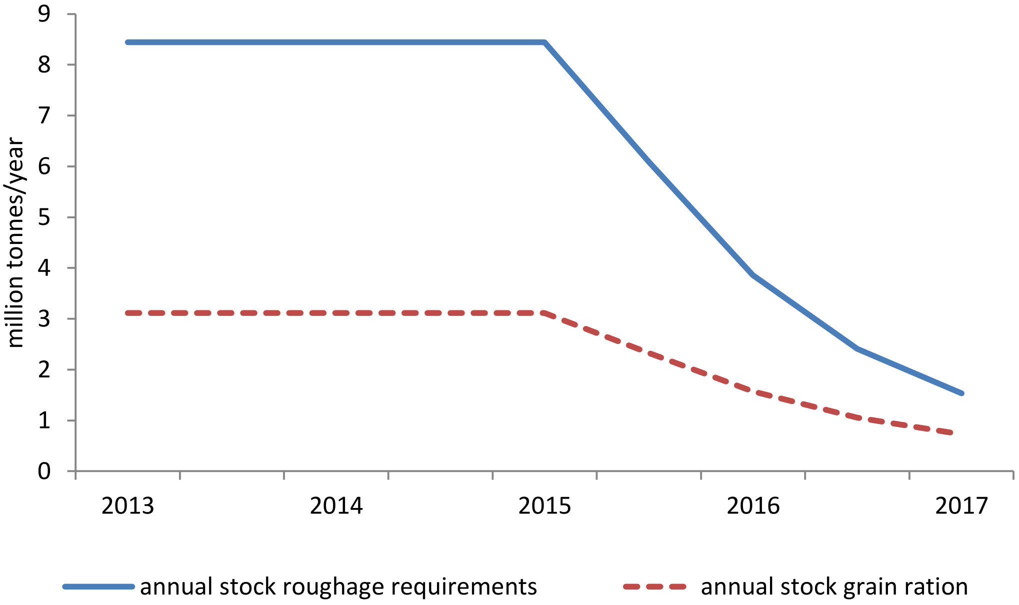


Figure 36: Changes in the feed requirements for the animals of Team

Because there is no irrigation application on dry land, soil moisture falls continuously over the course of the drought, as shown in Figure 37. As a result, the yield from dry land agriculture showed a downward trend as well (see Figure 38).

In terms of land management, Team A chose to promote green cover each year of the game – a policy that affects dry land agriculture. Based on the model logic, the model allocates land on the basis of "crop water productivity", so that the crop land with the highest water requirements would be converted first. Since forage has the highest crop water requirement, forage land is the main source for conversion to green cover when Team A turned on "green cover" policy, as shown in Figure 39.

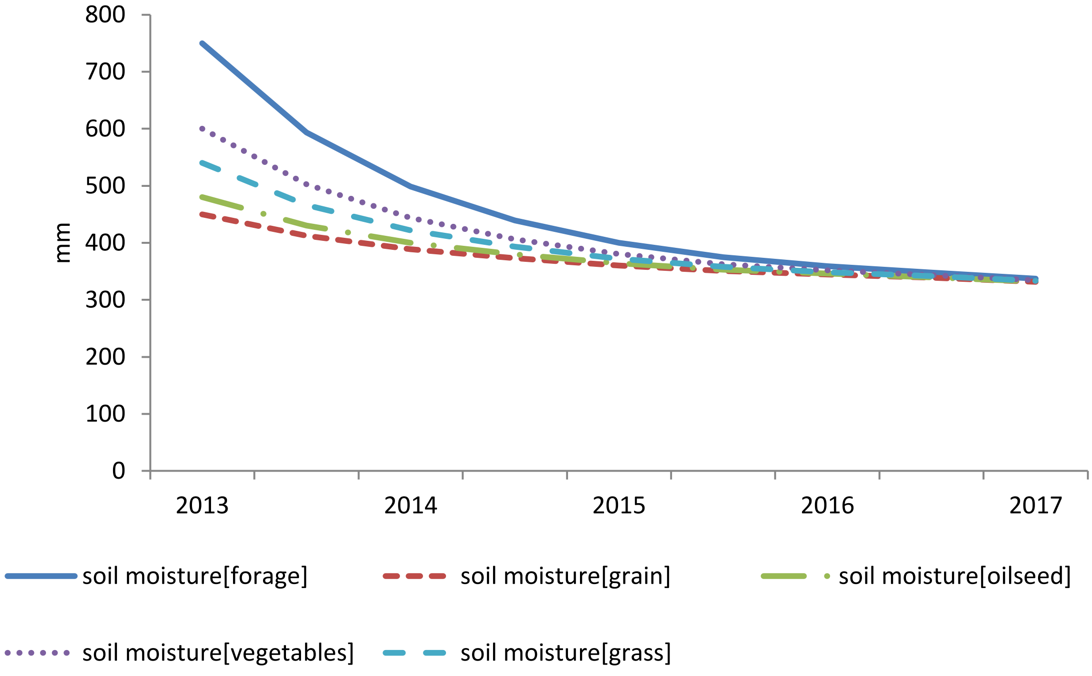


Figure 37: Changes in the soil moisture content for the dry land crops of Team A

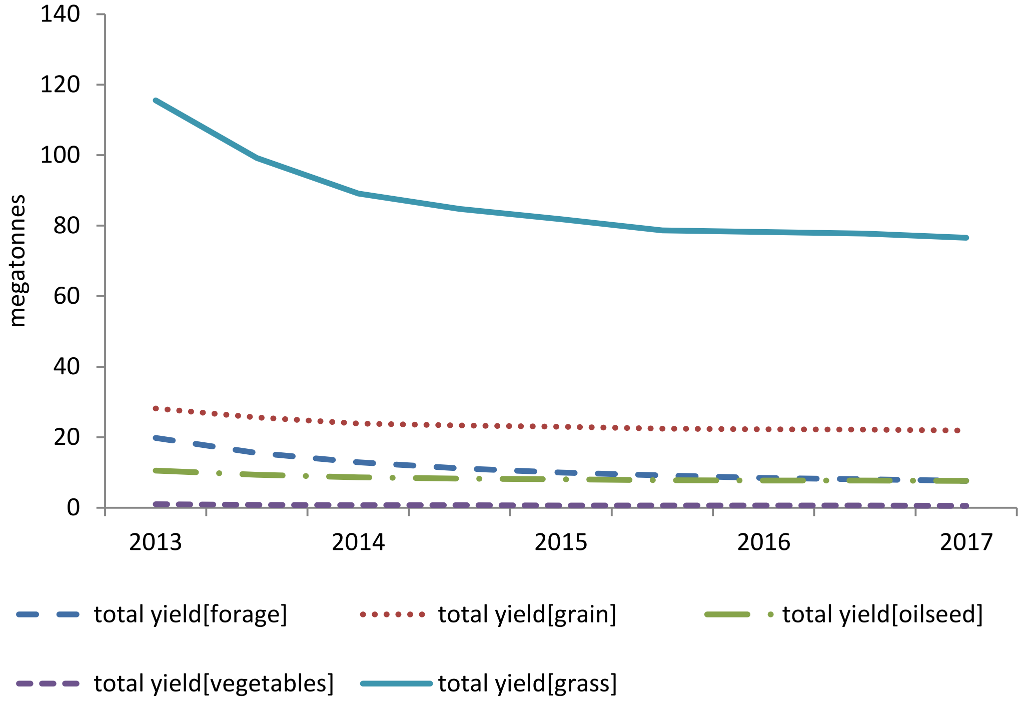


Figure 38: Changes in the total yield for the dry-land agriculture of Team A

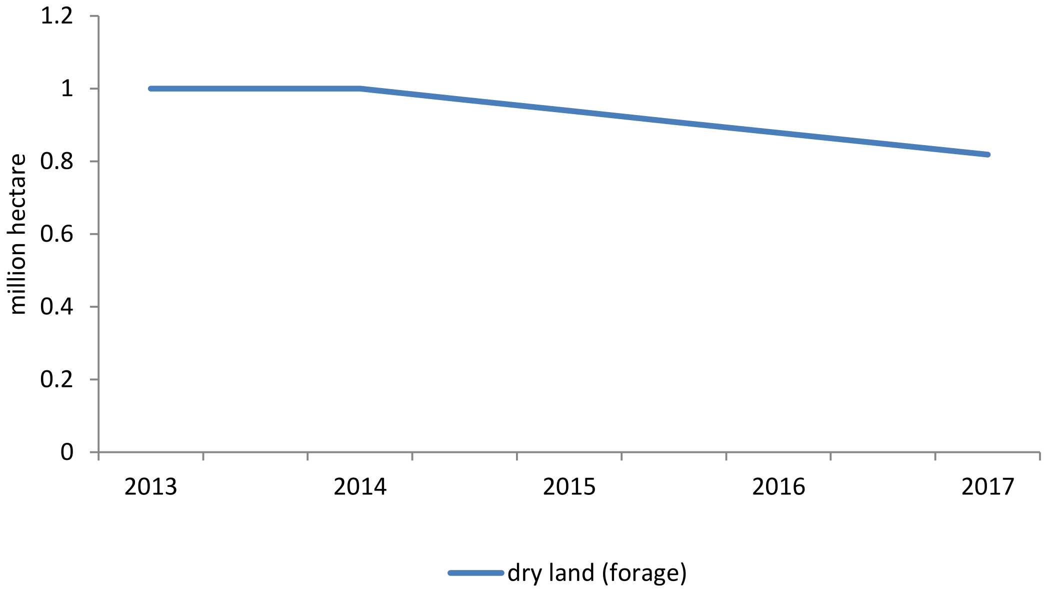


Figure 39: Forage coverage in dry land area agriculture (ha)

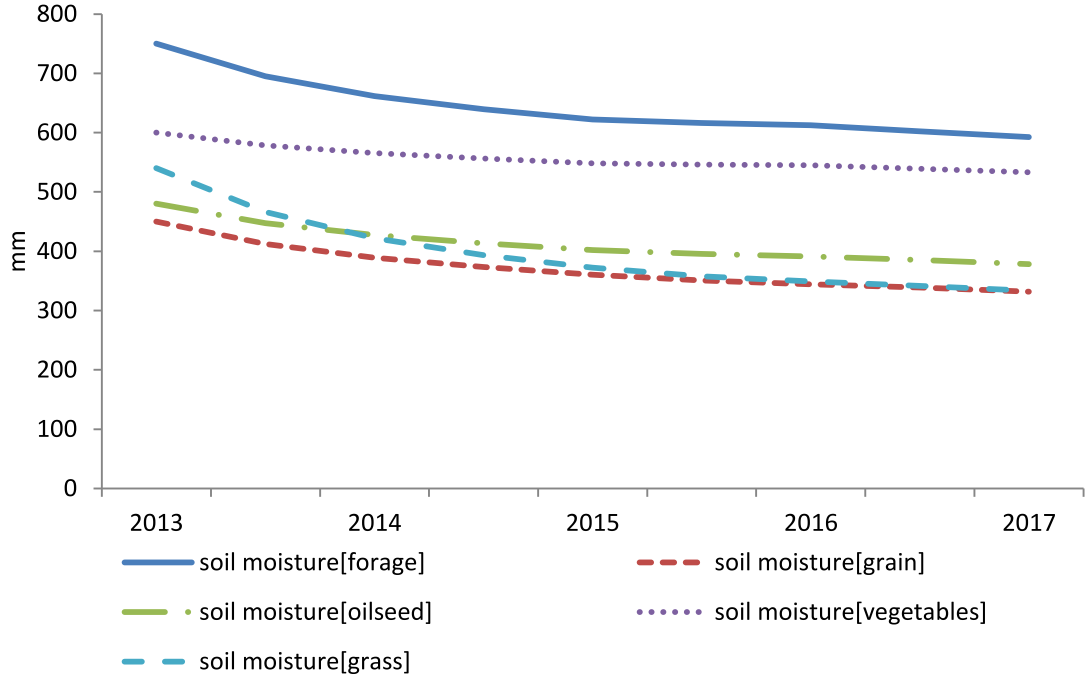


Figure 40: The soil moisture content of irrigated land

For irrigated agriculture, the soil moisture also decreased over the course of the drought because of insufficient precipitation, as shown in Figure 40. However, Figure 41 demonstrates that except for the first year (2013), the total yield of irrigated land did not decrease significantly, since the "agricultural related research and development" policy was selected in the second year and caused the yield to be higher than under initial conditions even with the same soil and water conditions.

The model also tracks each team's budget during the game as they select among the IDT policies of Table 5 – see Table 15 for the University of Alberta Team A's budget details.

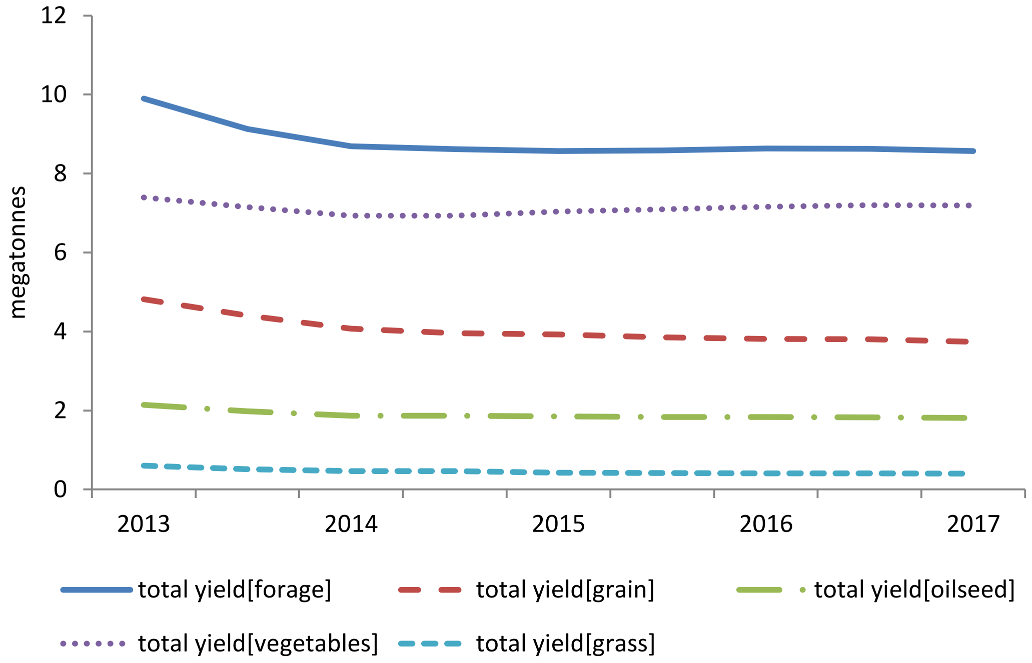


Figure 41: Changes in total yield of irrigated land for Team A

Table 15: Changes in budget and expenditures of Team A over the IDT game turns

Time (year)	**2013**	**2014**	**2015**	**2016**	**2017**
Total Expenses	-	937.61M	442.81M	340.61M	340.61M
Large-scale Water Mgt	-	670M	0	0	0
Short-term Water Mgt	-	350,000	550,000	350,000	350,000
Financial Mgt	-	100M	100M	100M	100M
Land Management	-	14.26M	138.26M	138.26M	138.26M
Technology policies	-	153M	204M	102M	102M

3.4.2 Comparison of Team policy selections, Team A versus Team S

This section compares the results of two teams from the Saskatoon IDT. Belw, the team from the University of Saskatchewan is referred to as “Team S”, while Team A continues to refer to Team 1 from the University of Alberta. For comparison with Table 14, Table 16 lists the choices of Team S.

Table 16: Policy selections of the University of Saskatchewan team, called "Team S"

Time (year)	2013	2014	2015	2016	2017
Inter-basin Transfer	0	0	0	0	0
Enhance irrigation system	0	1	0	0	0
Build Dam and Reservoir	0	0	0	0	0
Ration Water	0	1	1	1	1
Municipal allocation	526	473	426	405	405
Irrigation allocation	2,816	2534	2281	2281	2281
Industrial allocation	150	150	150	150	150
Other use allocation	262	262	262	262	262
Reservoir Draw-down	0	0	0	0	0
Relief Payout	0	0	1	1	1
Promote Green Cover	0	1	0	1	1
Promote Winter Cropping	0	0	1	0	0
Promote Stock Reductions	0	0	1	0	0
Pasture Species Composition	0	0	0	0	0
Expand Irrigated Area	0	1	1	0	0
Invest in Agricultural R&D	0	0	0	0	0
Invest in Water Related R&D	0	0	1	0	0
Invest in Grey Water Treatment	0	1	0	1	1

Based on their selections, the most significant difference between Tem S and Team A is the agricultural water use. As shown in Figure 42, the gross irrigation application of Team S to each crop progressively decreases year by year. By 2016, the irrigation application of Team S is approximately a half of Team A's. The main reason is that Team S chose to reduce the irrigation allocation from 2014, while Team A kept its irrigation application constant from the first year.

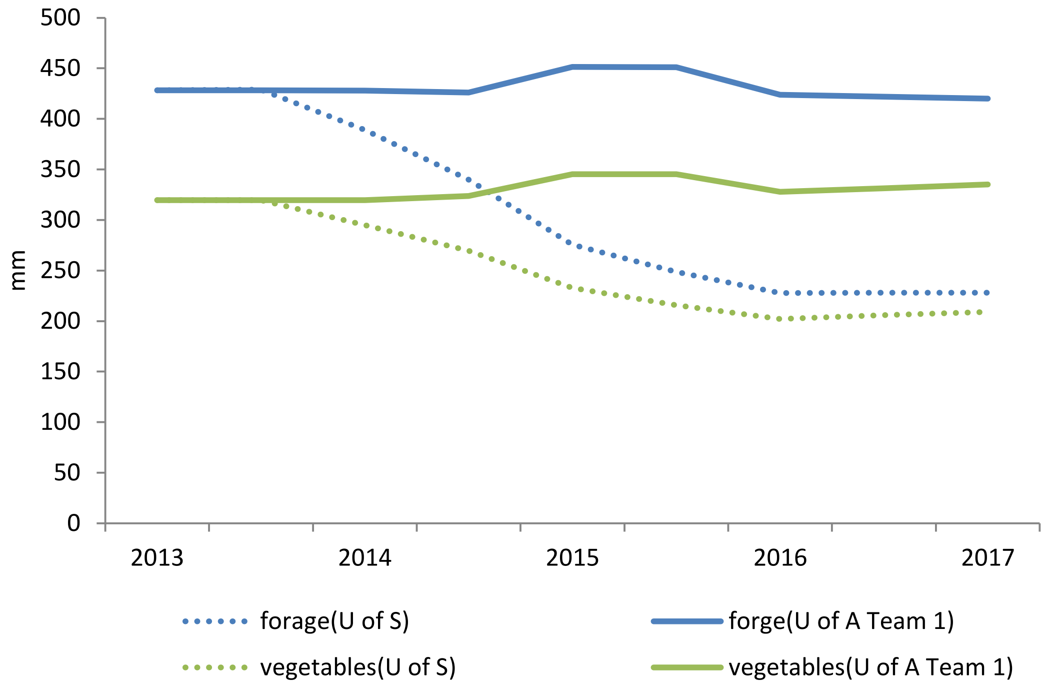


Figure 42: Differences in gross irrigation application of Team A and Team S

Interestingly, the total forage yield on irrigated land of Team S dose not decrease with the decreasing irrigation allocation; instead, it shows growth 1.4 times (from 8 million to 11 million), see Figure 43, in the next few years. The reason is that Team S selected another policy, the expansion of irrigated land (Figure 44), to protect the total yield in this basin, so that dry land area and total yield on dry land dropped considerably (Figure 45). However, unlike forage, the total vegetables yield sill decreases with the decreasing irrigation allocation. The reason is that because forage has the higher crop economic value than vegetables, so that the “expansion of irrigated land” policy expands irrigated forage land instead of irrigated vegetables land.

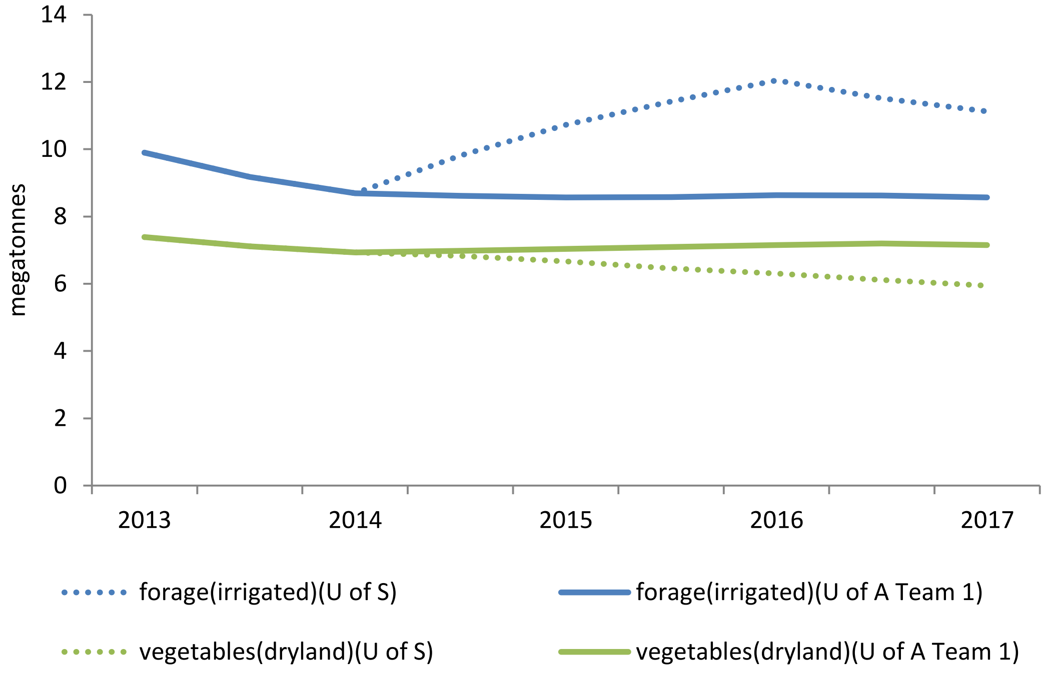


Figure 43: Differences in total yield (irrigated) for Team A and Team S

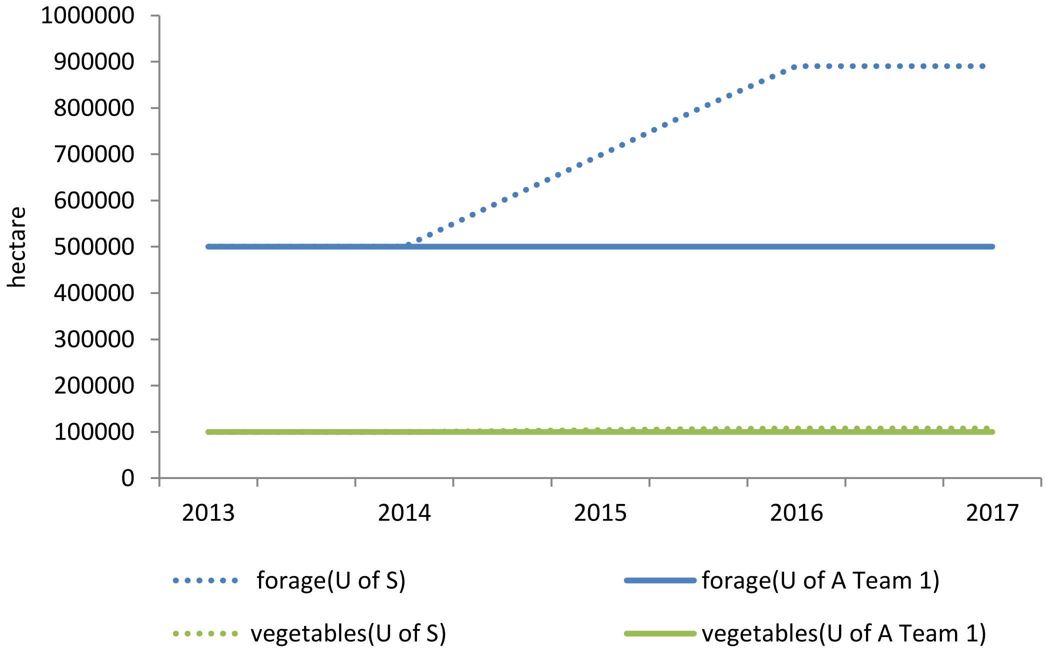


Figure 44: Differences in irrigated land areas of Team A and Team S

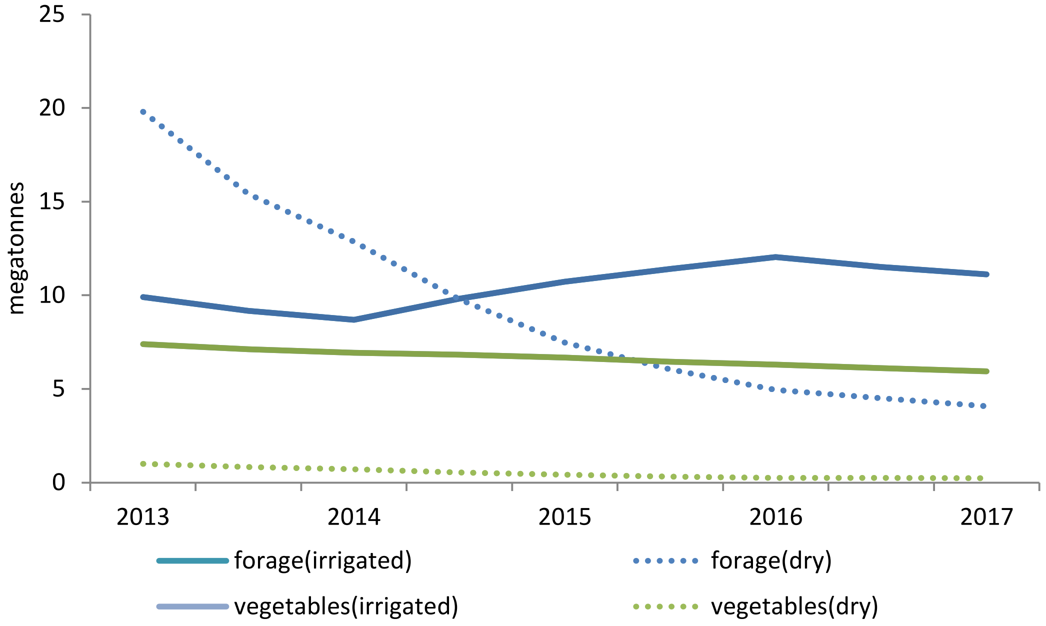


Figure 45: Changes in total yields on irrigated and dry land for Team S

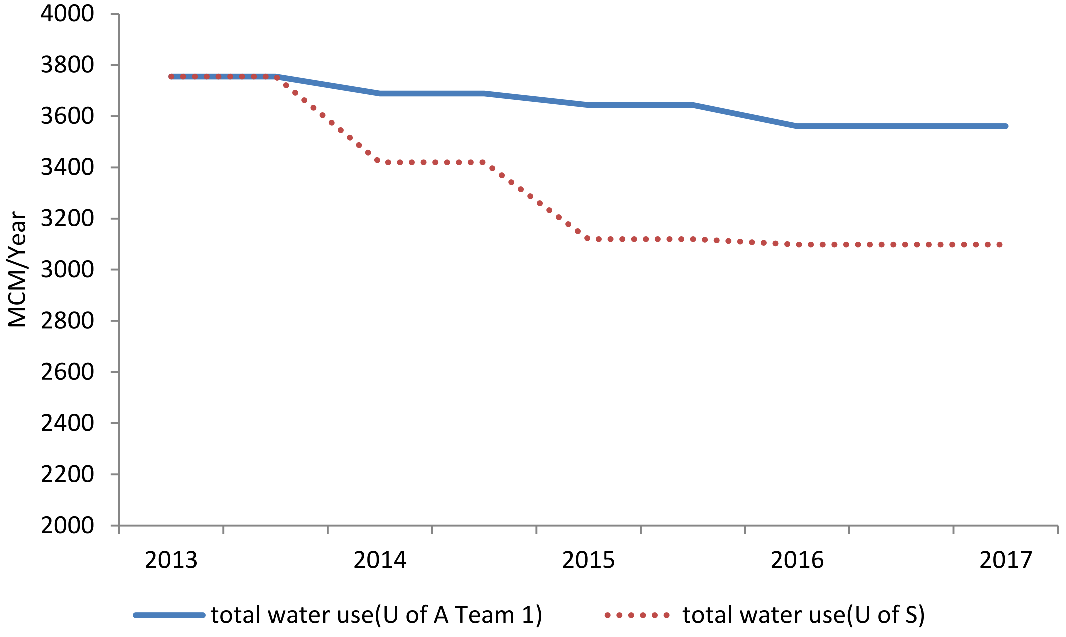


Figure 46: Difference in total water use by Team A and Team S

In summary, there are notable differences between the total water use of Team A and Team S due to their different selection of water management policies. Yet all those selections have one thing in common: water use reduction. Total water use of Team A and Team S both showed a downward trend after those polices are implemented, although Team S was more efficiently though (shown in Figure 46).

One point must be clarified here: the figures and results above were taken from the model results obtained at the Saskatoon IDT. These results were intended to show model behaviour and to test the model logic rather than give accurate results. Modifications to model parameters since March 2012 have improved the model performance. For example, outdoor water use for households has been changed, with old and new values as shown in Table 17. Outdoor water is the most diverse use in municipal water consumer. A report from EPA (2013) states that daily outdoor water use during the growing season could reach more than three times the annual average. Regarding the purpose of the IDT model – dealing with drought issues – the growing season, or “peak”, value is more important than the annual average. Therefore, outdoor water use has been changed to 1050 liter per day – which also ensures that municipal water use exceeds the licensed volume during droughts unless water conservation policies are adopted.

Table 17: The change of outdoor water use parameter (unit: liters per day)

Parameter	Initial water use	Revised IDT Model
Outdoor water use	381	1050

A sensitivity analysis was also conducted to test the extreme values of “water supply”, “irrigation application”, “irrigated land”, “dry land” and “soil moisture” in the model. From the outputs, the model gives logical results. Here, we take “land use” as an example. If the price of forage parameter is set to an unrealistic 100 dollars per kilogram (almost 800 times the original price), the effect is that all the dry land is converted to irrigated land due to the high crop value (shown in Figure 47).

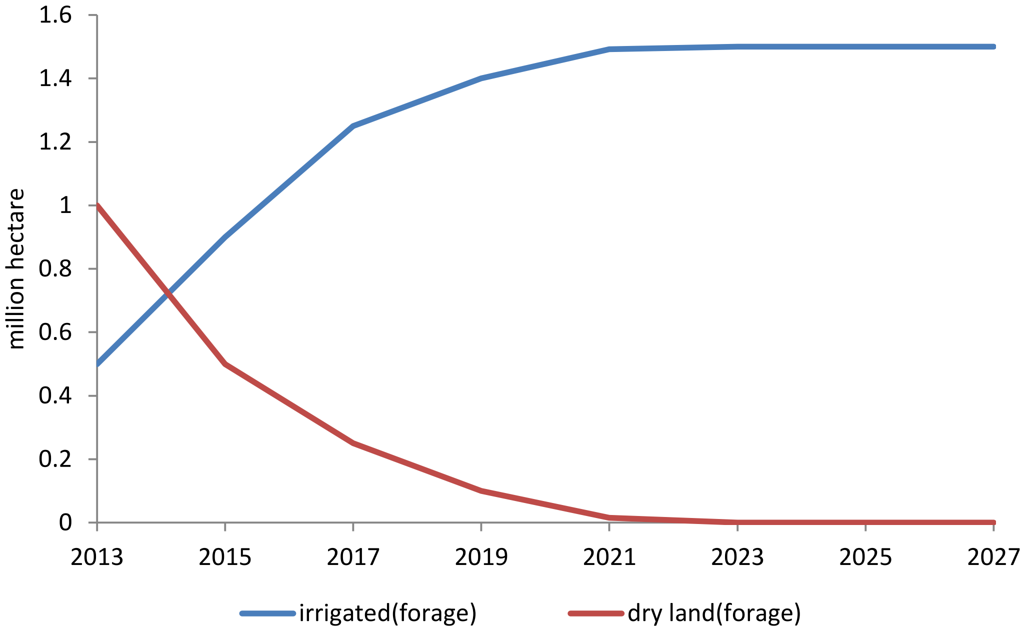


Figure 47: Changes in forage land area

4 CONCLUSIONS and RECOMMENDATIONS

4.1 Conclusions

Drought is a very important subject for the planning and management of water resources, and many water management models exist that could be further developed to include drought management issues. For example, the models used to predict water demand and optimize the water supply (see chapter 2) can be applied for drought management to conserve water resources and minimize the waste. In comparison with most water management models, system dynamics offers an alternative approach that has been applied successfully to model hydrology, water use and water demand in many basins of the world. In terms of specific characteristics of the methodology, system dynamics,

1. Produces both qualitative, conceptual models and quantitative, numerical models of complex system. The conceptual models can help to illustrate and improve people's understanding of the modeled system structure, while the numerical models shows both direct and indirect effects of policies so that people can easily identify the factors that cause the changes in important components of the modeled system as well as their feedback effects on other components of the system.
2. Produces simulation models. Rather than application to optimization problems, system dynamics focuses on analysis of "what-if" problems. For

example, a system dynamics model for an irrigation system could be used to predict what happened if crops do not receive enough irrigated water over time; however, the model would not produce an optimal irrigation schedule for each week of a growing season. In the case of the IDT model, rather than giving an optimized solution or obtaining a predicted value of water use or demand, which is the aim of most other water resources models, system dynamics allows us to observe the water balance and various other model variables in the Oxbow Basin, and how each variable responds to interventions such as IDT policies over time. With simulation of the whole system, users can more easily consider the trade-offs between the various water demands – municipal, agricultural, industrial and environmental water uses – and the available supply, as well as the economic and environmental state of the Oxbow Basin.

3. Is not constrained by temporal or spatial scales. System dynamics models have been developed for the water use of a single plant or for the water system of the entire world, with time scales from sub-daily to annual.

In general, the system dynamics modelling approach differs significantly from a traditional water management model method. In addition to flexibility of the time and spatial scales in system dynamics models, as described above, such models focus on feedbacks between model sectors. In other words, unlike traditional water management models, system dynamics do not use a linear-thinking mode – which can be characterized as “input-decision-output” – to develop a model; instead, the most important idea of system dynamics is “feedback”, so that a system can be represented as “input-decision-output-input”, which means the whole water system is dynamic. Feedbacks means that, in the simulated system, one decision can affect the decisions available at the next time-step, which is exactly how the exactly how the real world works.

However, there are some limitations of system dynamics. They can be summarized as several points:

1. Although the objective of system dynamics is try to present a reproduction of real-world structure, it is difficult to know that structure or to give the accurate equations required to simulate every relation and feedback of a system. Moreover, system dynamics is often used for very uncertain problems. Thus, system dynamics is hard to be validated.
2. With a system dynamics model, we can investigate the effects of any policies over time through simulation. However, the simulated structure of a system cannot be proved right, because there may be some important feedbacks is omitted that people did not know about. It could therefore be argued that the system structure may be wrong.
3. Rather than prediction, system dynamics models are intended to represent the endogenous connections and relationships of a system and are used to explore

and understand system behaviour. System dynamics is not intended for prediction.

Based on the above characteristics, this study developed a new system dynamics model for Agriculture Canada's IDT project. The model was intended to simulate the effects of drought management on the Oxbow Basin. In the IDT model, four related sub-systems were linked: human and animal populations, municipal water use, agricultural water and land use and crop production, and the water supply. According to the model results from the second IDT in Saskatoon, Saskatchewan, held in March 2012, the methodology presented here satisfied the project requirements. The IDT model developed here represented the fictitious Oxbow basin developed by Agriculture Canada, with the majority of the functions and parameters used in the IDT model matching those from previous studies that have been tested and authenticated. Further, model behaviour replicated the characteristics of typical agricultural basins in the Canadian Prairies.

The value of the IDT model lies in its representation of the feedback interactions between model components of each model sector and multiple policies. Use of a system dynamics model allows straightforward identification of the causes and effects of system changes. For example, both reduction of agricultural water supply and enhancement of irrigation water diversion efficiency can reduce the agricultural water demand in next year. However, we can also see the changes of crop yields by each policy through simulating the IDT model. Moreover, the effects of different combinations of policy selections – by the different teams involved in the tournament – can be easily presented by the model. Thus, policy makers can see the effects of various decisions by comparing the amount of water reduction, the resulting crop yields and even by comparing team budgets. The IDT case study indicates that system dynamics can improve water management strategies, deal with complex and multi-disciplinary problems and provide a critical tool to support water management decision-makers.

4.2 Recommendations

Future model development should focus on the following areas:

1. Economic Factors. There is currently no feedback between IDT financial policies and the Oxbow basin in the model. For example, how do IDT financial policies affect crop yields, animal stocks and so on? Model revisions could create a socio-economic sector that focuses on farm income. Further, the water economy has matured in many places, such as some Member States of the European Union (Gomez-Limon and Riesgo, 2004). Thus, financial policy, such as water pricing, could also be included as an important factor in water management (Wang et al., 2010), and is recognized as a very efficient way to relieve increasing irrigation water demand (Johansson et al., 2002; Gomez-Limon and Riesgo, 2004). Therefore, simulation of economic factors would make the IDT model more comprehensive.
2. Industrial Water Use**.** As mentioned before, industrial water use could actually

change considerably in the simulated years, as businesses react to water scarcity. A revised model would include a representation of water use for mining, power generation, and manufacturing in the Oxbow basin.

3. Environment. To establish and improve the comprehensiveness of water management, environmental flow requirements are one of the most important considerations. Thus, environmental policies and water quality could be added to the IDT model. Moreover, industrial water use and domestic water use also affect and are affected by the environment (Zhang et al., 2010). For comprehensive water management, the model should include the local aquatic environment. Furthermore, a revised model should include a means of representing in-stream flow needs.

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